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International Advanced Robotics Programme First Workshop on Manipulators, Sensors and Steps Towards Mobility

Proceedings
Karlsruhe, May 11 - 13, 1987

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Projektträgerschaft Fertigungstechnik

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KERNFORSCHUNGSZENTRUM KARLSRUHE
Projektträgerschaft Fertigungstechnik

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INTERNATIONAL ADVANCED ROBOTICS PROGRAMME
FIRST WORKSHOP ON
MANIPULATORS, SENSORS AND STEPS
TOWARDS MOBILITY

PROCEEDINGS

Karlsruhe, May 11 - 13, 1987

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International Advanced Robotics Programme
First Workshop on "Manipulators, Sensors and Steps Towards Mobility"
Proceedings

Abstract

This Workshop was held within the framework of the international collaboration in the area of advanced robotics, formerly initiated by the Economic Summit, called the International Advanced Robotics Programme (IARP). It was hosted by the Nuclear Research Center Karlsruhe on May 11-13, 1987.
Ninety scientists of eight countries presented and discussed 32 R&D projects. The Proceedings contain full papers of most contributions (and summaries of the remaining ones) and summary reports on all of the eight sessions. The material presented reflects well the present endeavor to integrate advanced robotics and teleoperation techniques for difficult applications in harsh, demanding or dangerous conditions or environment.
The Second Workshop on this topic is planned for Fall 1988 in UK.

International Advanced Robotics Programme
Workshop on "Manipulators, Sensors and Steps Towards Mobility"
Proceedings

Zusammenfassung

Der Workshop fand im Rahmen der internationalen Zusammenarbeit auf dem Gebiet fortgeschrittener, Roboter und Handhabungssysteme statt, dem sogenannten International Advanced Robotics Programme (IARP), die seinerzeit vom Wirtschaftsgipfel angeregt worden war. Gastgeber war das Kernforschungszentrum Karlsruhe vom 11 bis 13 Mai 1987.
Neunzig Wissenschaftler aus acht Ländern präsentierten und diskutierten 32 F&E-Projekte. Die Proceedings enthalten vollständige Aufsätze der meisten Beiträge (und Zusammenfassungen der übrigen) sowie zusammenfassende Berichte über alle acht Sitzungen. Der Bericht bietet somit eine gute Darstellung des gegenwärtigen Bemühens, fortgeschritaene Roboter- und Fernhantierungstechnik zu integrieren, um dem Menschen die Arbeit unter schwierigen Bedingungen oder an gefährlichen Arbeitsplätzen zu erleichtern oder abzunehmen.
Der Zweite Workshop zum gleichen Thema ist für Herbst 1988 in Großbritannien geplant.

FOREWORD

Background of the Workshop

At the Versailles Economic Summit of 1982, an international collaborative project "Advanced Robotics" was initiated. Participating countries of this collaborative activity presently include Austria, Canada, EEC, France, Germany, Italy, Japan, Netherlands, Norway, UK and USA.

All of these countries agreed that it was imperative for a healthy development of our society, to develop advanced robot systems able to dispense with human exposure to difficult activities in harsh, demanding or dangerous conditions or environment.

The different application areas under consideration are space, underwater, nuclear plants, mining and tunnelling, agriculture, medical and health care, civil engineering and construction, plant operations, fire fighting and emergency rescue operations and services including domestic.

To date co-operation has been effectively performed by means of information exchange, workshops, study missions and the preparation of joint site studies. Beyond the initial impetus of the Economic Summit Initiative, the participant countries have decided to continue their co-operation under the name "International Advanced Robotics Programme" (IARP).

Scope of the Workshop

Advanced handling systems or robots, designed to work properly in the application environments mentioned above, must be able to function during time intervals unattended by operators. They must, therefore, include advanced features such as multi-sensor data evaluation, autonomous control and various forms of mobility. Some speak of such systems as revolutionary third generation robots, others look upon them as an evolutionary integration of existing robotics and teleoperation techniques.

At this Workshop, novel research projects and results were presented in a fashion fitting the purpose of a workshop, i.e. compact presentation with ample time for discussion. In view of the novelty of this developing technology, the organisers were keen to offer newcomers an opportunity to present their work, and to discuss newly proposed international co-operation. Working language of the Workshop was English.

Selection of Contribution

Participation was by invitation only. Proposals were co-ordinated by the respective country's IARP contact person.

Final contribution selection was decided by the following Programme Committee:

T. Martin, Nuclear Research Center Karlsruhe, Germany (Chairman)

U. Rembold, University of Karlsruhe, Germany

M. C. Wanner, IPA Institute, Germany

D. Walker, Moog Controls, Ltd., UK

J. Howe, University of Edingburgh, UK

R. Egginton, Department of Trade and Industry, UK

Organisation

The Workshop was organised by both Germany and the United Kingdom, represented by

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Acknowledgements

First of all, I wish to thank all authors and participants for their contributions who, in addition to their expertise, enriched the Workshop by their lively discussions.

Next, I am grateful for the excellent cooperation offered by the members of the Programme Committee who selected the contributions, chaired the sessions and wrote summary session reports (which are printed in these Proceedings at the beginning of each session paper section).

Finally, my special thanks are due to four ladies who did all the paper work and helped diligently in the organization: Margitta Alter, Edith Rolli, Elsbeth Wiesner and Eva Schröder.

Final Programme

Workshop on
Manipulators, Sensors and Steps towards Mobility

Organizers: Germany and United Kingdom, represented by
Nuclear Research Center Karlsruhe and
Department of Trade and Industry, London

Location: Parkhotel, Ettlinger Straße 23, 7500 Karlsruhe

First Day

Monday, May 11, 1987

8.oo - 9.oo hour		Registration
9.oo		OPENING OF WORKSHOP Workshop Chairman: T. Martin (D) Welcome by Dr. H.-H. Hennies, Member of the Board, Nuclear Research Center Karlsruhe
		Session **OVERVIEWS** Chairman: R. Egginton (UK)
9.15	1	Advanced robotics R&D at KfK D. Smidt (D)
9.45	2	Development of an advanced subsea robot system G.F. Schultheiss (D)
10.15	3	Human scale experiments in mobile autonomous robotics W.R. Hamel (USA)
10.45	4	Trends of automation in space applications U. Kirchhoff (D)
11.oo		BREAK

Attention

The papers are grouped in the eight Workshop sessions, paper numbers being marked on their first page in the upper right hand corner.
The names given indicate the persons who presented the paper; co-authors are mentioned on the papers.
Papers marked with and "S" are Summaries only (no full paper submitted).

The list of participants is appended at the end of the volume.

		Session **MANIPULATORS (1)** Chairman: M.C. Wanner (D)	
11.3o	5	Manipulation system for advanced teleoperation K. Takase (J)	S
12.oo	6	Technical characteristics of electric master-slave manipulator W. Köhler (D)	
12.15	7	Modern servohydraulic drives, inevitable components of advanced robotics P. Saffe (D)	S
12.3o		LUNCH	
		Session **MANIPULATORS (2)** Chairman: D. Walker (UK)	
14.oo	8	Heavy payload servo manipulators in hostile environments D. Walker (UK)	S
14.3o	9	Coilable robot design and applications W.K. Taylor (UK)	S
15.oo	10	Automatic and manual operation modes of the TFTR maintenance manipulator G. Böhme (D)	S
15.3o		BREAK	
16.oo	11	Problems related to the design of a manipulator with a very large reach including an example for a specific application M.C. Wanner (D)	S
16.3o	12	The warrior welding manipulator P.K.J. Smith (UK)	
16.45	13	Application studies and control system design for robots with cooperating limbs H. Bruhm (D)	

Session

LOCOMOTION

Chairman: T. Martin (D)

17.oo	14	On the study of multiple joint biped robots Y.F. Zheng (USA)
17.3o	15	Locomotive vacuum suction disks for wall robots used at nuclear power plants K. Sato (J)
17.45		END OF SESSIONS
20.oo		BANQUET (same location)

S

Second Day Tuesday, May 12, 1987

9.00		START of second day	
		Session **SENSORS (1)** Chairman: T. Martin (D)	
9.00	16	A scanned laser rangefinder system for a cross-country autonomous vehicle J.T. Savage (UK)	
9.30	17	Laser vision sensor for disaster prevention robot K. Yoshida (J)	S
9.45	18	Interpretation of 2 1/2 D images M.J.L. Orr (UK)	S
10.00	19	The new generation of DFVLR robot sensors G. Hirzinger (D)	
10.30	20	Sensor simulation in robot applications J. Raczkowsky (D)	
10.45	21	Simulation tools for the development of autonomous robot vehicles F. Freyberger (D)	
11.00		BREAK	

Session
SENSORS (2)
Chairman: J. Howe (UK)

11.30 22 Low-level vision for advanced mobile robots
K.D. Kuhnert (D)

12.00 23 Airborne ultrasonic array transducer
utilizing silicon micromachining
H. Tanigawa (J)

12.15 24 A real-time modelling, planning, and control
system for assembly-type tasks
D.R. Myers (USA)

12.30 LUNCH

Session
SENSORS (3)
Chairman: J. Howe (UK)

14.00 25 Integrating tactile and visual perception
for robotics
R.A. Browse (CAN) S

14.30 26 Multi-sensor integration for a mobile
robot using concurrent computing
R.C. Mann (USA)

15.00 BREAK

Session

STEPS TOWARDS MOBILITY

Chairman: U. Rembold (D)

15.3o	27	Articulated body mobile robot S. Hirose (J)	S
16.oo	28	Feature-based navigation techniques J. Hallam (UK)	
16.3o	29	Autonomous mobile robots in production P.M. Lutz (D)	S
16.45	30	A rulebased planning system for robots B. Frommherz (D)	
17.oo	31	A behavioural approach to robot task planning and off-line programming T. Smithers / C. Malcolm (UK)	
17.15	32	Planning robotic manipulation strategies in unstructured environments A.C. Sanderson (USA)	S
17.45		FINAL DISCUSSION	
18.3o		END of second day	

Third Day Wednesday, May 13, 1987

EXCURSION TO FRAUNHOFER INSTITUTE FOR MANUFACTURING ENGINEERING AND AUTOMATION (IPA), STUTTGART

(free bus transportation provided)

8.3o Departure from Parkhotel, Karlsruhe

10.oo Arrival at IPA

10.15 Welcome by Prof. H.J. Warnecke

10.2o Introduction to the research work at IPA by Prof. R.D. Schraft

11.oo Tour in groups through the Laboratory
Presentation of following subjects (among others) will probably be given:

- Autonomous mobile vehicle (IPA)
- Advanced mobile system (University of the Armed Forces)
- Inductivly guided vehicle with robot (IPA)
- Advanced sensor systems (IPA)
- Test stand for industrial robots (IPA)
- Robot applications in various fields (machining, assembly, workpiece handling, welding) (IPA)

12.3o Meal at Institute Cafeteria

13.3o FINAL DISCUSSION

14.45 END OF WORKSHOP

15.oo Departure
(The bus will pass and stop at Stuttgart Airport at 15:15, in case participants wish to fly from there.)

16.3o Arrival at Parkhotel, Karlsruhe

Session

OVERVIEWS

CHAIRMAN'S REPORT ON THE OVERVIEW SESSION

The first four papers presented in the Overview Session illustrate the scope of activities and applications embraced by Advanced Robotics (AR).

Professor Dieter Smidt, Director of the Institute of Reactor Development at the Nuclear Research Centre and also professor at the University of Karlsruhe, refers to the particular considerations for teleoperated and very long reach robotic systems. Robotic systems involving long reach referred to by Professor Smidt, include the TFTR maintenance boom developed for the Princeton fusion reactor and future automated cranes and bridge inspection equipment. A project to develop such long reach booms currently involves Putzmeister and the NRC, who will be responsible for developing the collision avoidance algorithms as part of a "computer aided telemanipulation" approach. Problems encountered with operating equipment of this kind remotely were addressed during the recent Chernobyl disaster at which a range of equipment developed by Putzmeister was applied to combat the disaster.

The second paper by the Director of the Engineering Institute of the GKSS, Dr Georg Schultheiss, concerned itself with the use of robots underwater. Constraints imposed by this hostile environment will Dr Schultheiss believes increasingly result in autonomous robots being used for inspection and maintenance operations on subsea structures. One of the most novel features of this project is that it approaches the problem by modifying an existing industrial robot for use underwater. The Monotech R15 robot will be marinised and filled with oil. Mobility will be achieved by mounting the robot on a David submersible equipped with clamps and nozzle thrusters. Some 65 kilowatt of hydraulic power is generated on board with electric power supplied by an umbilical.

In response to questions Dr Schultheiss explained that the control system uses depth and position measuring assisted by TV feedback to the operator; the design is not aiming for automatic positioning. Software developed in the UK is being used to identify the node points for weld inspection.

Some attendees were sceptical of the validity of developing an existing industrial robot for underwater use but, if not successful in its own rights, the project will at least succeed in identifying the limitations of such an approach.

The third paper by Mr Bill Hamel Head of the Telerobotics Systems Section of Oakridge National Laboratory and also associate professor at the University of Tennessee, touched on all of the essential ingredients of AR by referring to human scale Mobile Autonomous Robot Experiments. A basic research programme has been sponsored by the Department of Energy at CESAR (the Centre for Engineering Systems and Advanced Research). The programme addresses a wide range of ingredient enabling technologies such as real time planning, sensors, learning methodologies, machine vision and compliant systems. These technologies have been integrated into a major demonstrator project called HERMESII. Trials with HERMESII have enabled many of the algorithms required to be verified but due to the scale of the computing task involved "off line" programming was used. An upgraded version of HERMESII called HERMESIIb now involves a number of enhanced on board computational facilities to provide for greater autonomy including vision processing.

Future stages of this "state of the art" project will include combining manipulation and mobility functions on HERMESIIb. This development work will constitute the precursor to HERMESIII which will be an electric powered robot initially featuring a single CESAR research manipulator with a second arm added at a later stage. HERMESIII will enable human scale operations to be investigated in a truly autonomous manner and will no doubt be regarded in future as a major milestone in the development of AR. HERMESIII is expected to be operational by late 1988.

As one questioner revealed, a fascinating feature of HERMESIII will be the use of a sonar scanner encoded into neural networks to provide instant call-up of a recorded scene, using feature extraction data, allowing for more rapid observations and navigation processing to be undertaken.

The final paper by Dr Kirchoff reminded the workshop that looking very much to the future one of the most hostile environments for man in which AR will feature prominantly is space. Dr Kirchoff is Head of the Department of Robotics at the Fraunhofer Institute for Production Technology and Product Design in Berlin. Future operations in space would Dr Kirchoff explained contribute towards the demand for equipment able to operate in unstructured environments. Tasks would have to be clarified from a global (high level command) level input through to hierarchical control systems including strategic, tactical and executive levels. Physiological constraints in space would compromise human operators particularly disorientation, nevertheless Dr Kerchoff argued that some structuring of the environment would also be necessary for the effective use of automation and robotics.

The overview session conveyed in my view most of those considerations associated with the subject of AR at present. That is to say a grappling with the problem and issues of how is an industrial robot transformed into an "advanced robot", as illustrated by the underwater project; the benefits that can arise from adopting an alternative approach to existing design principles as suggested by the need for compliance in the long reach construction robots; the need for fundamental research and development and its effective integration into operational systems as most effectively demonstrated by the work at Oakridge and finally the question of where will advanced robots find widest use. Hostile environments will certainly feature strongly in the potential markets and perhaps no environment is more hostile to man than space.

RON EGGINTON

Manipulators, Sensors, and Steps towards Mobility
May 11-13, 1987, Karlsruhe

Advanced Robotics R+D at KfK

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1. Introduction

The Kernforschungszentrum Karlsruhe (KfK, Nuclear Research Center Karlsruhe) has been involved in the research and development in the fields of reactor safety, nuclear reprocessing, nuclear fusion technology and equipment for nuclear emergencies since over two decades.

These tasks call for complex manipulations in a highly hazardous environment. Therefore, we started a program for advanced robotics with the overall target to combine the mobility and flexibility of remotely operated manipulators or vehicles with the speed and reliability of robots, especially for repetitive actions (e.g. building a shielding wall from lead bricks, mounting or dismounting of flanges etc.).

This requires an interface with the human operator allowing him to choose between automatic, semiautomatic or remotely controlled operation and supplies him with the relevant information.

In general the systems consist of

- a carrier for transporting the manipulator to the places of action. The type of carrier depends on the application and may be a vehicle, straight or telescope mast, crane or articulated boom,

- the carrier guiding system. This generally is based on a CAD-model of the environment, including a CAD-collision detector, a model verificator, and redundant collision sensors,

- the manipulator, being a remotely controlled slave arm or a robot,

- the manipulator control and human interface with CAD-assistance, videocamera, vision system, and additional sensors.

The subsequent sections give examples for several applications. It is interesting to note that our nuclear developments have resulted in a nonnuclear offspring as described in /7/, a low cost version of a CAD collision detector for large mobile articulated masts as used in concrete pouring and building maintenance and repair.

2. Carrier Systems

The first carrier systems were manipulator-vehicles and bridge-cranes with telescope mounts for the manipulators.

2.1 Vehicle carriers

Fig. 1 shows as an example the manipulator-vehicle MF3, belonging to a family of similar systems /8/. The vehicle achieves a high mobility by four independent chain drives. Control is by a multithread cable or wireless. As it is known, the Soviet-Union has bought several vehicles of this type for use at the Chernobyl site.

Development on the vehicles started ten years ago and is now completed.

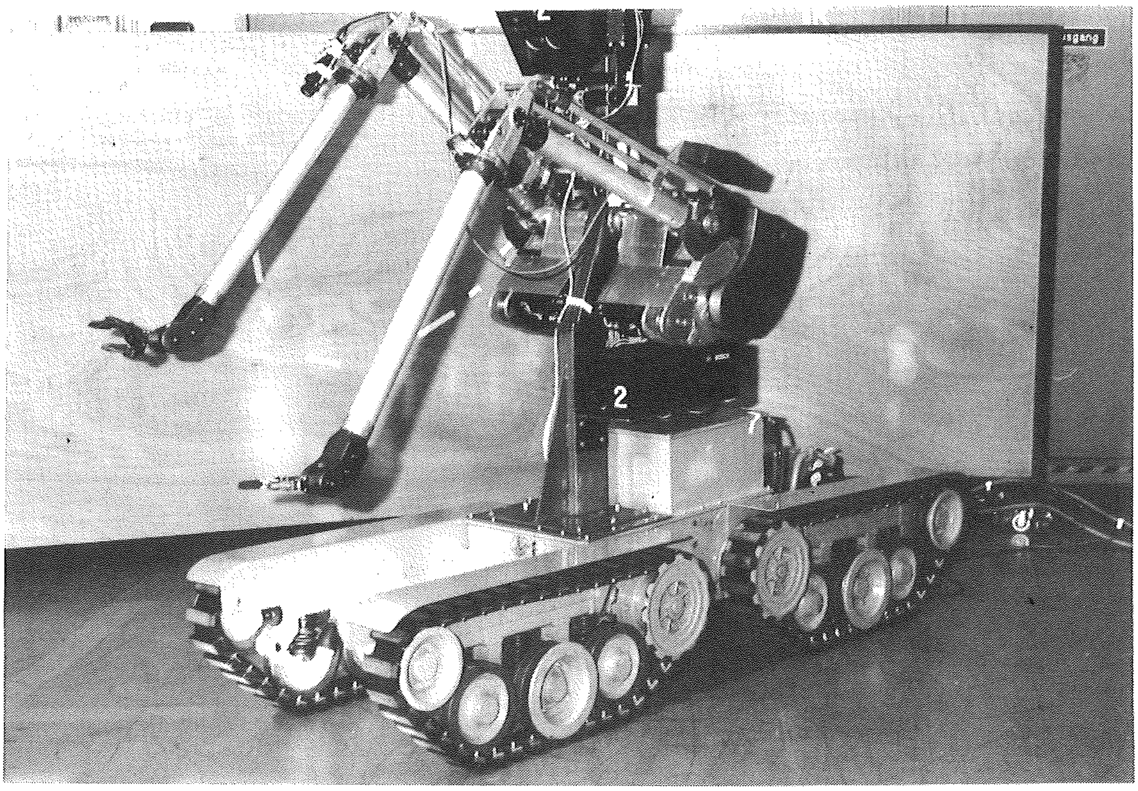


Fig. 1: Manipulator-Vehicle

2.2 Crane and telescope carrier

Especially for use in reprocessing cells and for handling highly radioactive waste a carrier has been developed, consisting of a moveable bridge, carrying a crab with a multipe telescope to hold manipulators, videocameras, tool magazines and other equipment /9/.

2.3 Articulated booms

For in-torus inspection and maintenance of fusion reactors annother type of carrier is in use: the articulated boom, being a combination of a carrier and a manipulator or robot. As an example fig. 2 shows the TFTR-maintenance boom, developed by KfK for the Princeton fusion machine /10/. It can move the manipulator at the front end to the required position in the torus. A similar system is in operation at the JET-machine. A special problem is the movement of the kinematically redundant articulated boom in the very confined operational area.

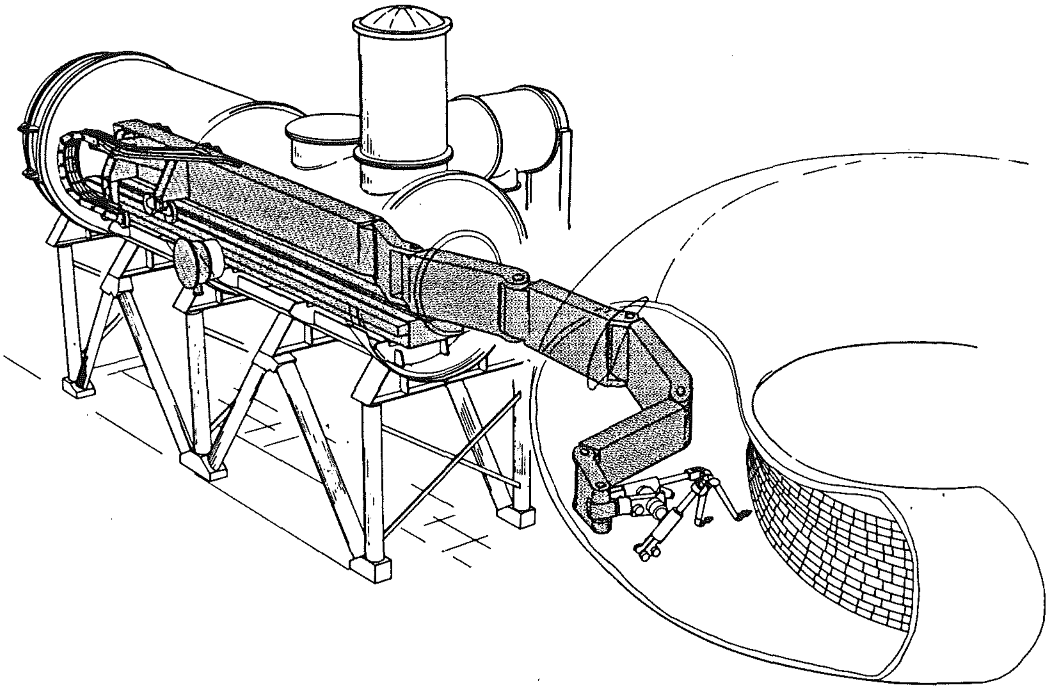
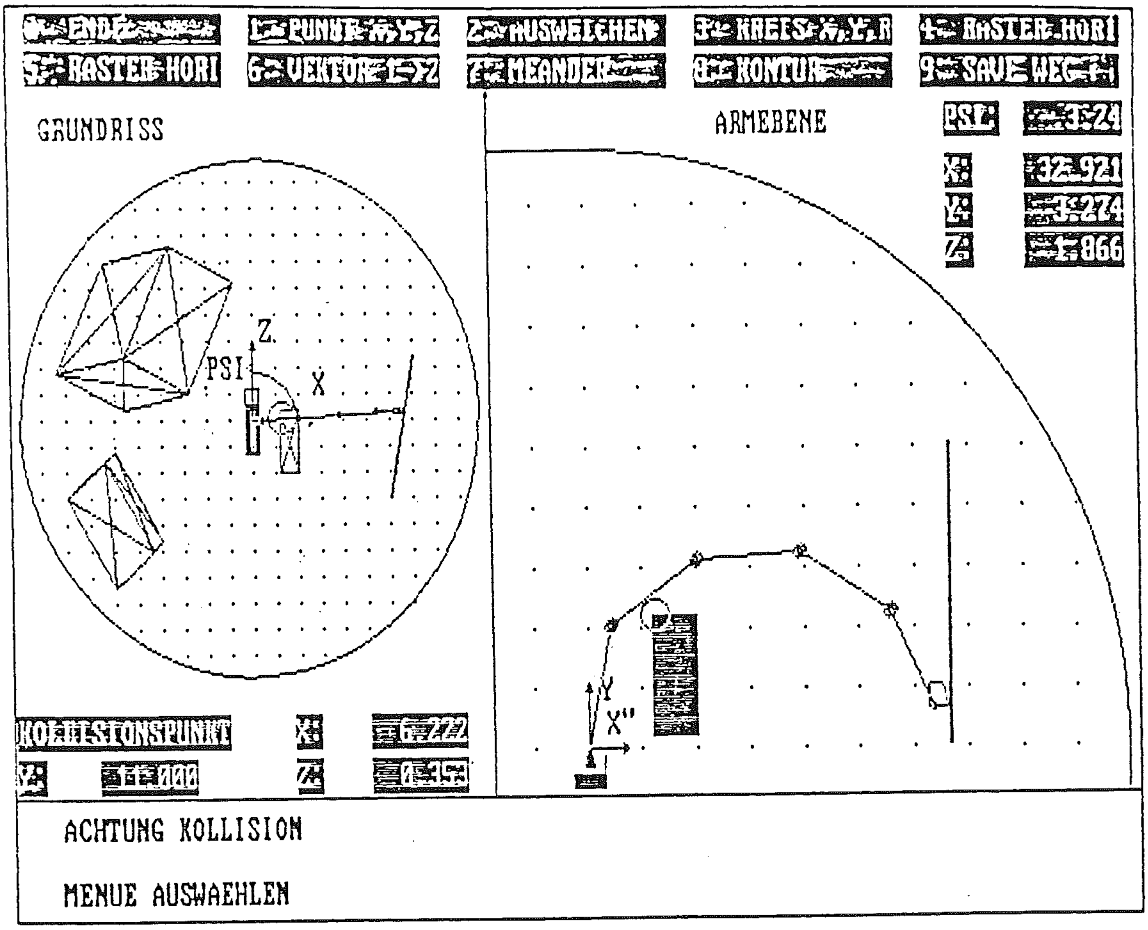


Fig. 2: TFTR Maintenance Manipulator

Recently, a real-time three-dimesional graphical simulation system for the JET articulated boom has been implemented /1 - 4/. The simulator is especially intended to support the remote handling operator during fusion reactor in-vessel manipulation tasks. The simulator produces a real-time synthetical display of the articulated boom, its various end-effectors, its camera arms, together with the working environment. The characteristic features of the system are: geometry and configuration databases of the remote handling equipment and the environment, off-line teach facilities, numerical obstacle avoidance algorithms, solid or wireframe representation of one or more simultaneous operator selectable views, camera tracking and pointing control facilities.

2.4 Other applications of articulated booms

Similar ideas have been applied to non-nuclear applications as inspection, maintenance, and repair of buildings, bridges etc. Here by better control systems large range concrete pouring machines can be converted into very flexible tools. Here KfK develops a CAD-based collision detector. The basic idea is to intersect an internal boom model with an environment model established by an interactive process, where the boom operator uses an electronic theodolit to measure the distances and coordinates of contour points in the scene. For the sake of simplicity and performance speed all simulated obstacles and targets are abstracted to their enveloping parallelepipeds ("box concept"). This strategy requires optimal man-machine-interfaces, where we use a menu controlled dialogue on a graphics monitor. Emphasis is being laid on the design of man and machine collaboration and on low cost of the implementation. Fig. 3 gives an impression of the display of the collision detector, as the operator will see it.



ACHTUNG KOLLISION

MENUE AUSWAEHLEN

Fig. 3: Screen Photograph of CAD-based Collision Detector

3. Manipulators

3.1 Electrical master slave manipulators

The classical tool for remote handling operations is the mechanical master-slave unit. We prefer the electrical master-slave manipulators (EMSM). Fig. 4 shows the EMSM-2 as an example. It allows for remote handling of high quality. According to the principle of bilateral position control it returns force and gives the operator a realistic feeling of his handling.

For simple positioning we use switch-operated electrical power manipulators, having relatively low costs, high load capacity, and large range /12/.

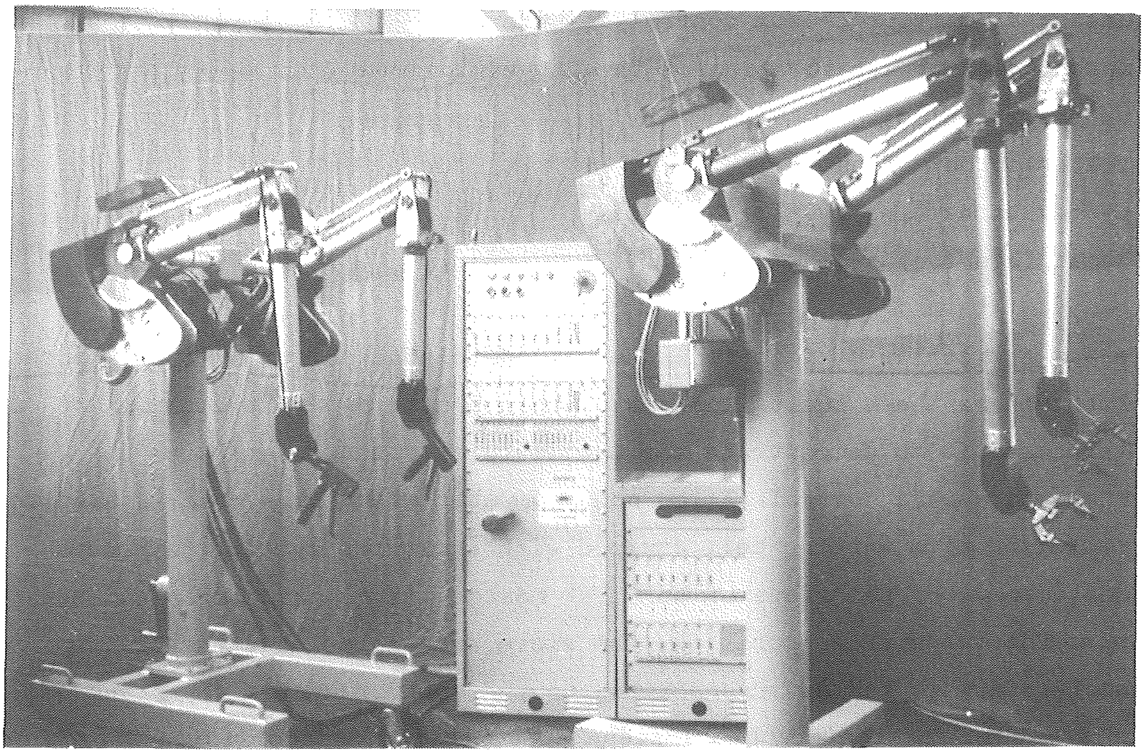


Fig. 4: Master unit, control unit, slave unit (from left to right) of a two-arm electrical master-slave-manipulator, developed by KfK

For operator guided tele-manipulators viewing systems are essential, for automatic operation they are helpful. Operational speed and dexterity can be increased by colour stereo systems.

3.2 Manipulator control

For the more effivient design and use of manipulators, our work includes

- modelling and dynamics simulation for different kinematic systems by CAD methods, /15/, /16/
- investigation and optimization of fast closed loop control algorithms, /17/
- efficient coordinate transformation,
- master compensation with respect to friction, gravitation, and dynamic forces and force-reflection as well, by means of digital control, /18/, /19/
- investigation and integration of sensors,

- design of multiprocessor control-computers,
- measurement or verification of the CAD-environment,
- camera tracking,
- collision detection,
- system connecting by fiber-optics,
- human interface ergonomics.

As a demonstraction of this "computer aided telemanipulation" (CAT)-concept a prototype has been built. The aim of this prototype implementation of our CAT-proposal is to demonstrate the usability of computer graphics in carrier and camera control. A low cost computer graphics system is used for presentation of a working cell equiped with a carrier system (telescope bridge crane) for the slave of an EMSM1 master-slave manipulator and a camera. The transporter position, the slave arm angles, and the camera parameters are sensed and transmitted to the control system where the signals are used for the graphical scene presentation and collision detection.

The system is based on a three-dimensional, hierarchical environment model (each level represented by basic modelling bodies and a surrounding box) and a manipulator model for the description of their kinematic structures with polygon bounded arm geometries. To be able to transfer modelling data from a CAD-system, a special data format closely related to the CAD*I format /5/ was specified. Transporter controlling is supported by a collision detection module using the environment box hierarchy and a special manipulator abstraction by spheres and cylinders. Collision warnings are given by synthetic speech output.

For camera control all camera parameters (viewing angle, focus plane) are graphically displayed. Camera control may be done automatically by tracking the hand point /6/, a room point, or manually by graphics input or speech input. There are no automatic working modules in the sense of our CAT proposal, handling support modules are camera tracking and collision detection during transporter movements.

The system is shown in fig. 5 and may be characterized by:

- Graphical scene presentation based on sensor signals of the transporter, the slave, and the camera (viewing direction, zoom, distance)
- Collision control of the slave, transporter, and camera contra environment; warnings are given by synthetic speech output.
- Camera tracking on the slave hand or a room position while transporter movements
- Graphical input for camera control
- Incremental camera control via speech input or function keys

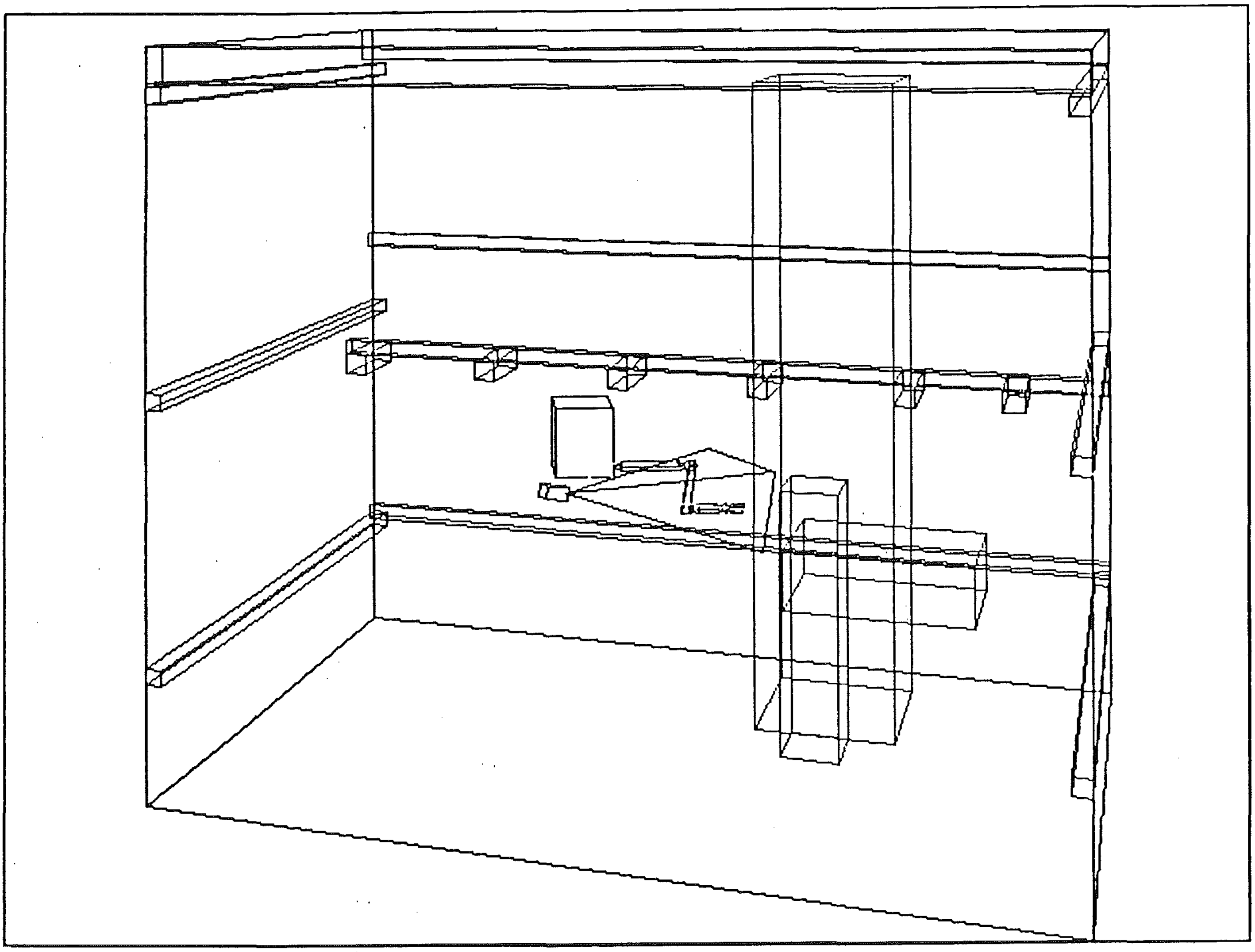


Fig. 5: EMSM1 with Camera and Viewing Volume in a Working Cell

3.3 Use of robots on carrier systems

Using robots instead of master-slave manipulators on carrier system can potentially increase the workspeed for repetitive tasks. An example for repetitive work is the building of a lead shielding wall by the system. Annother task in connection to the insertion and removal of blanket elements of fusion reactors is the closure and reopening of quite a number of flanges. Here also a robot may be applied. It is mounted on a carrier with CAD guided position control. An automatic vision system serves for position fine control. Bolting and unbolting is done by a special spanner with limited momentum and sensors to assist fitting. Fig. 6 shows the robot at work unscrewing.

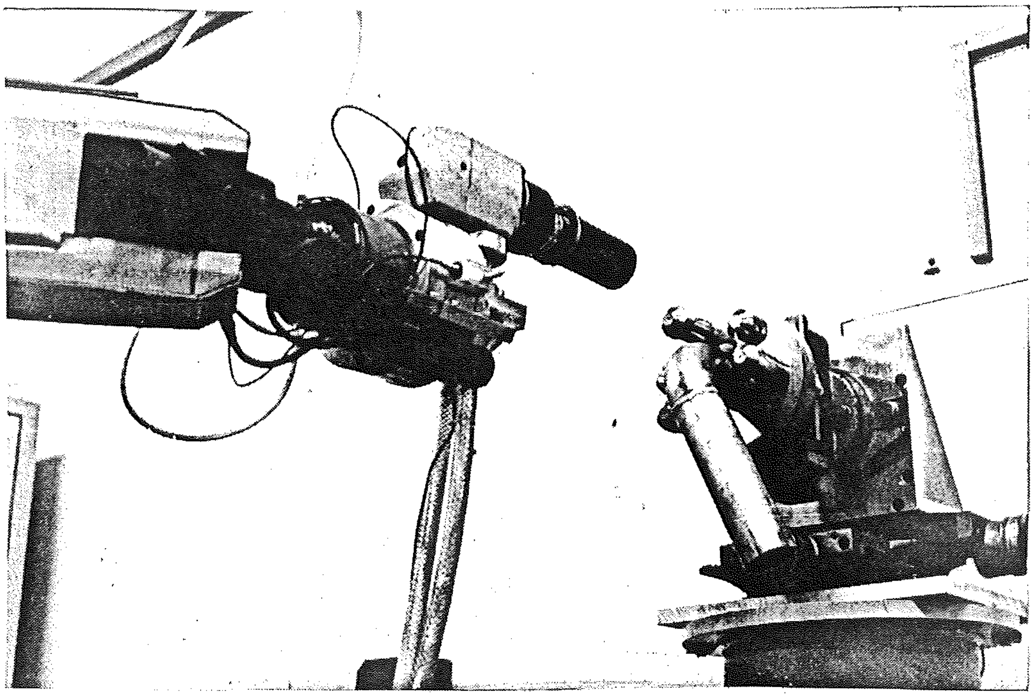


Fig. 6: Robot Holding Percussion Wrench Approaches Flange

The main targets are:

- Integration of autonomous working modules into a tele-manipulation environment
- Tele-teaching of robots

- Manual working with a robot
- Man-machine interface for supervisory work in tele-manipulation
- Automation/semi-automation of general transport tasks in a fusion plant supported by geometric models and collision detection and collision avoidance modules

4. Passive Aspects of Remote Handling

The possibilities of remote handling can be widened by careful design of the objects to be handled. This we call "passive handling design" as for instance better connecting elements (i.e. flanges), modified tools, and better accessibility /13 - 14/.

This bearing in mind we have developed the large reprocessing cells. Modular units are positioned at the walls of a large cell and can remotely be maintained and exchanged, if necessary (FEMO-technology). Fig. 7 shows a mockup at the LAHDE-facility. Exchanging a module typically means opening and closing of 40 to 80 pipes. A proven method is the use of removable pieces of pipe, using an electrical percussion spanner. This method has given good results since it was introduced in 1979.

This technology will be supplemented by methods for remote welding and cutting. These may have special importance for the maintenance of fusion reactors.

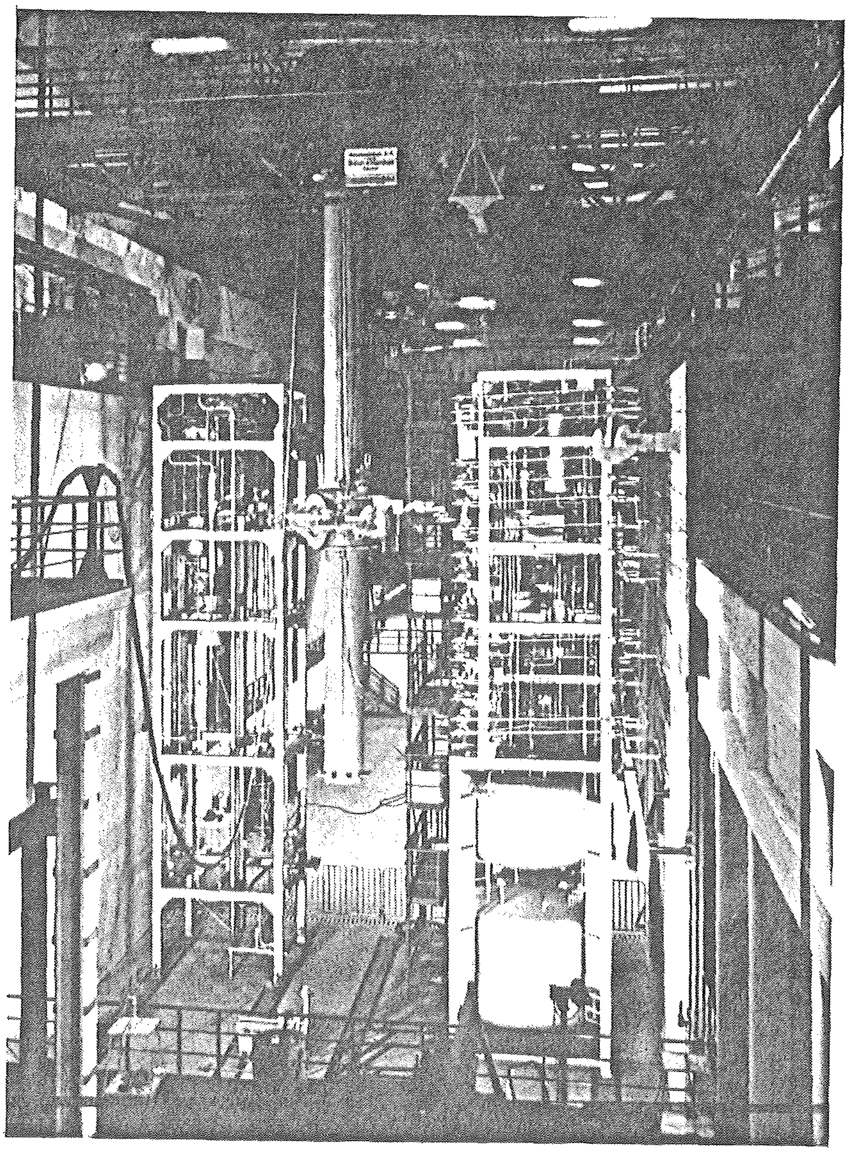


Fig. 7: Prototype Reprocessing Cell, LAHDE Facility

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2

DEVELOPMENT OF AN ADVANCED SUBSEA ROBOT SYSTEM

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1. Problem statements and application area

There are quite a number of underwater steel structures all over the world, which have to withstand unfavorable conditions with respect to dynamic loads and corrosion attack. Thus periodic inspection is an essential part of safety and reliability. Inspection is presently performed by divers and/or remotely operated vehicles, being able to perform simple tasks or carrying tv-cameras. Future developments in inspection and operation of subsea structures will go towards autonomously working robots. The development of an advanced subsea robot in connection with a qualified carrier, performing tasks like cleaning, inspection and coating of underwater structures without diver assistance is the main goal of this R&D-project, called OSIRIS, the Offshore Integrated Robot Inspection System (see Fig. 1).

Fig. 2 shows a block diagram of the advanced subsea robot system and indicates its various components, which have to be developed under a careful consideration of the respective interfaces.

2. Research course and methods used

At GKSS a comprehensive underwater research and development program is in operation, which is conducted also in the GUSI, the GKSS-Underwater Simulator, which allows manned diving tests down to 600 msw and unmanned tests down to 2200 msw. A special subject in this program is the development of programmable handling systems like robots, which will be used to assist and later on to replace divers. As the basis of the handling system the commercially available industrial robot MANUTEC r15 has been selected, which is presently under development to withstand wet underwater conditions down to 1200 msw. Fig. 3 shows this robot and its main design and operation data. The operation under pressure in dry gas atmosphere is already possible.

Major efforts of INTERATOM have been concentrated on technically feasible solutions with respect to quality assurance and inservice inspection under severe boundary conditions. The experience in computer controlled ultrasonic-testing and the development of ultrasonic devices for non normal operating conditions are proven techniques to be modified for inservice inspection of underwater structures at a higher pressure.

At the University of Hannover basic research and qualification of robot components like actuators and electronic systems for hyperbaric dry and wet conditions are performed.

3. Status and results

The specification for the robot module to be developed shows, that the mechanical and control systems have to be adapted to subsea requirements, as far as pressure, pressure transients, temperatures, mechanical loads, operational safety etc. are concerned. Tests with a complete robot in a helium atmosphere up to 110 bar have been successfully performed in the GUSI. In the first project phase the procedures for underwater work are focussed on cleaning of underwater structures, the inspection of weldings in the cleaned area and conservation of the inspected weldings, if necessary. Water jet cleaning and sandblasting for surface treatment, inspection with ultrasonics, eddy current, magfoil and tv-cameras as well as conservation by painting are under test.

The development of underwater tools for these specified procedures as well as tool changing devices and magazines is underway at GKSS. Currently, tests are running with mechanical, pneumatical and electrical devices, in order to find a qualified system under the aspects of energy supply, safe function and effectiveness.

The ongoing work is concentrated on the adaptation of a robot subsystem to wet working conditions. For the selected 6-axes industrial robot the forearm with the axes 4 to 6 is modified by INTERATOM to work independent of outside pressure. Pressure tests will be done in the GUSI facilities.

The subsea robot is planned to be supported e.g. by a remotely operated vehicle like a modified diver assistance vehicle DAVID, which has already shown safe function during pressure tests in the GUSI and in the North Sea. Fig. 4 shows the DAVID, which is equipped with computerized control and has a maximum operational depth of 1000 msw.

The Technical University of Berlin together with GKSS develops a software system, which allows the simulation of robot motions in its specific working environment. This system is planned to assist the operator in optimizing and adapting the robot arm motion to the specific operations like cleaning and testing.

4. Further research

With the test results gained from the robot subsystem of the first part of the project a prototype robot will be built. This prototype of the complete subsea robot module will also undergo extensive test procedures to get a certificate of the Germanischer Lloyd for offshore use.

In the future a software system will also be available for off-line-programming to perform and to optimize complex tasks separated from the real robot system e.g., for reduction of system loads, energy consumption or to preplan collisionfree work finally to reduce operation costs.

The further efforts in this R&D-project can be summarized as follows:

- modification of an industrial robot for wet application down to 1200 msw

- qualification of processes and tools including auxiliary equipment
- adaption of the robot to a remotely operated supporting system
- development of computer controlled task performance
- adaption of adequate sensors for function control and autonomous operation
- graphic simulation for system optimisation and off-line-programming.

The long term program aims in the adaption of adequate sensors for controlled work functions and autonomous operation of the complete system.

5. Interest in cooperation

The development of the subsea robot system is performed in a close cooperation between the institutions shown in Fig. 5. This gives the following combination of special scientific and technical knowledge in this R&D-project of advanced robot technology:

- INTERATOM is involved in the design and construction of the robot system for wet conditions and in NDT-techniques for subsea structures
- the University of Hannover performs basic research on robot actuators, sealings, electrical and electronical systems for subsea application,
- the University of Berlin is involved in the graphically simulation of collisionfree robot motions in specific underwater environments,
- GKSS performs the experimental research work on working procedures and tools in the GUSI and tests the developed systems under realistic subsea conditions. GKSS initiated the project and also coordinates the various activities.

All participating institutions are carefully observing the relevant industrially oriented R&D-work to absorb and integrate useful modules to get the complete system on a more economical basis. Industry interested in collaboration or use of the system is invited to contact Interatom or GKSS.

6. Related Publications

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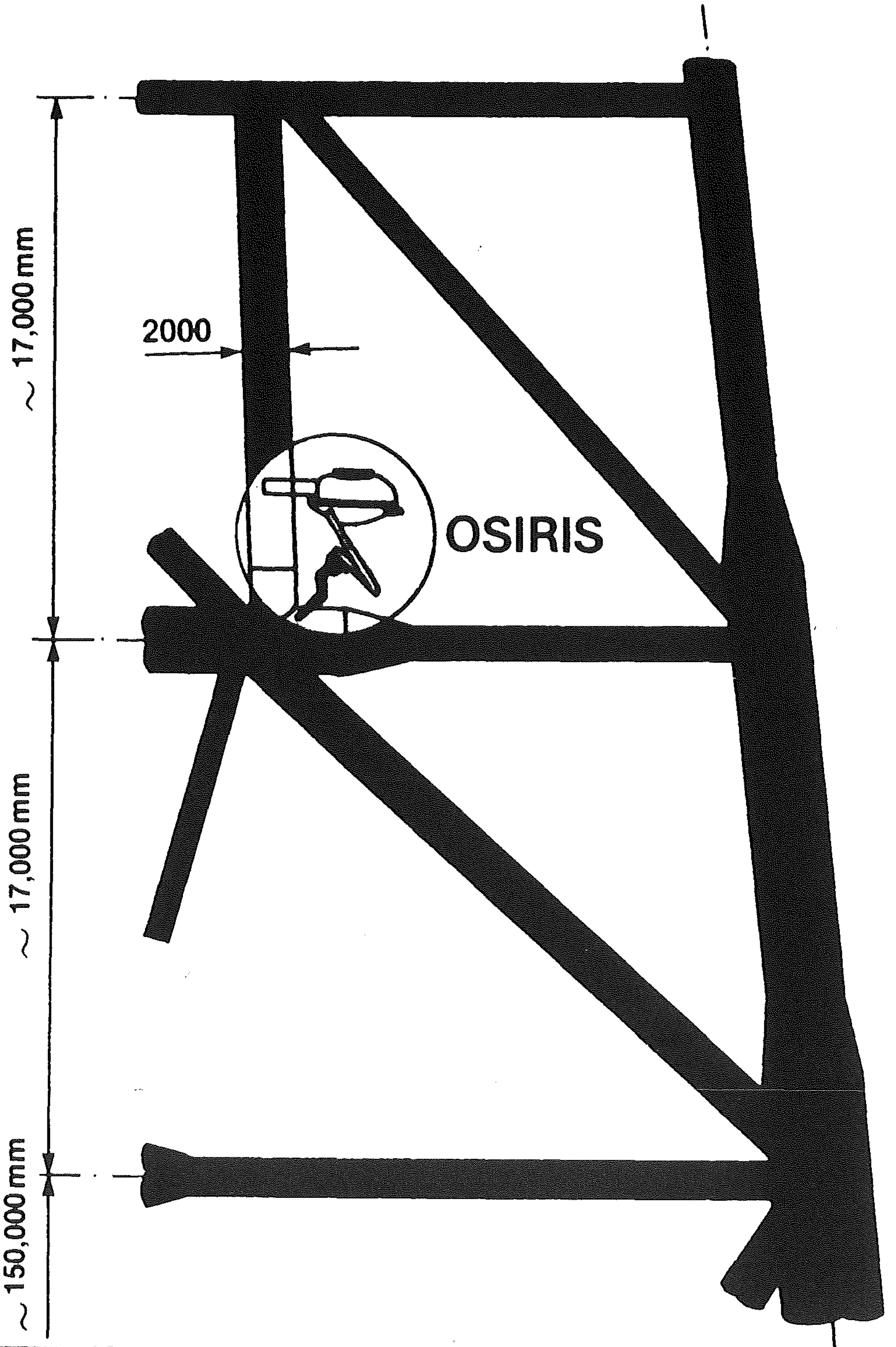
GKSS 85/E/52

Aust, E.:
New developments in robot-technology for subsea application,
Subsea Robotics Workshop in Bergen, Norway, September 17-18, 1986

Markfort, D.:
Advanced NDT- & US-Viewing Techniques, applicable for subsea inspection tasks
Subsea Robotics Workshop in Bergen, Norway, September 17-18, 1986

Aust, E., Bohm, K.-H., Domann, H.:
Robotereinsatz in einer Inertgasatmosphäre bis 50 bar,
GKSS 86/E/47

Objective of the project is making available an underwater working robot in connection with a qualified carrier. Main tasks are cleaning, inspection, and coating of underwater structures without diver assistance.

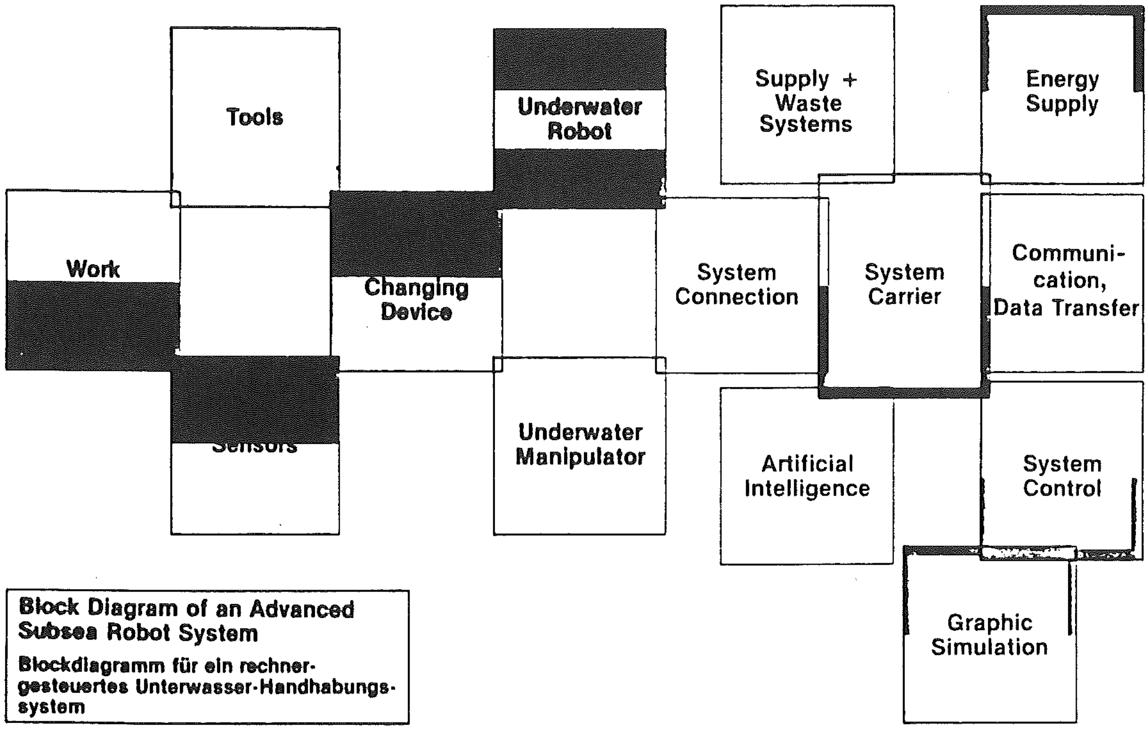


OSIRIS
Off-Shore
Integrated Robot Inspection System

(scaled figure)

Fig. 1

GKSS-FORSCHUNGSZENTRUM GEESTHACHT GMBH

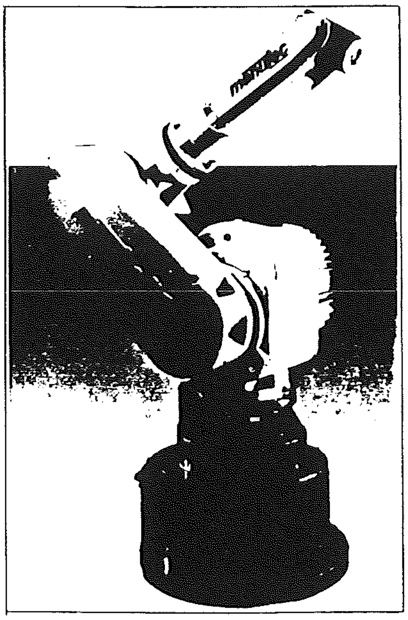


Block Diagram of an Advanced Subsea Robot System

Blockdiagramm für ein rechnergesteuertes Unterwasser-Handhabungssystem

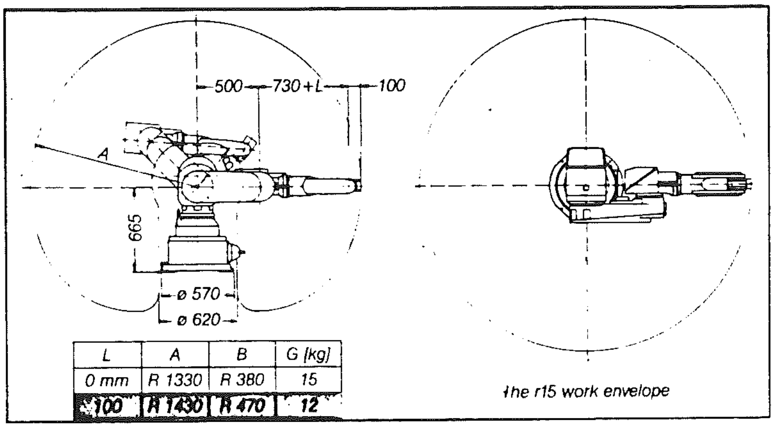
Fig. 2

GKSS-FORSCHUNGSZENTRUM GEESTHACHT GMBH



Industrial Robot MANUTEC r15 Improved for Hyperbaric Operation

MANUTEC r15-Roboter, modifiziert für hyperbaren Einsatz



L	A	B	G [kg]
0 mm	R 1330	R 380	15
100	R 1430	R 470	12

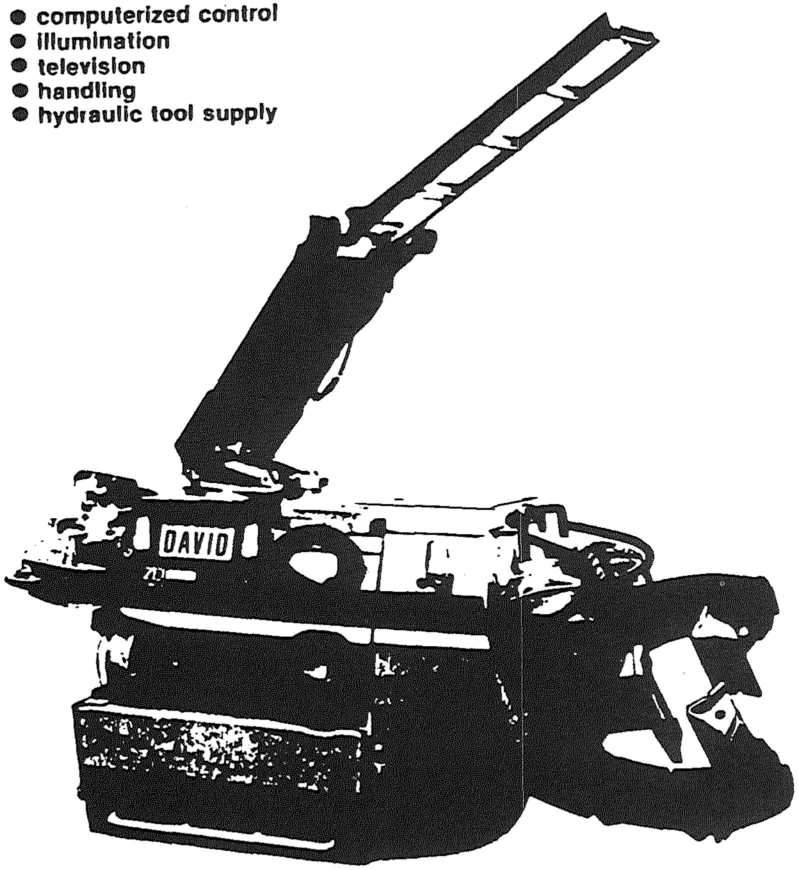
The r15 work envelope

- hyperbaric operation up to 120 bar Helium
- 6 rotating axes
- 120 N lift at max. speed
- speeds: PTP max. 5.9 m/s, LIN ca. 1.5 m/s
- repeatability: ± 0.1 mm
- program types: teaching, mnemonic code in robot-specific, cartesian or tool related coordinates
- program memory: 192 kByte
- interfaces: 32 inputs/outputs
- motion types: PTP (6 axes simultaneous), linear or circular interpolation , tool weaving

Fig. 3

- max. operational depth 1000 msw
- basic vehicle length/width/heigth 2.7 m / 2.1 m / 1.5 m
- electric power via umbilical
- hydraulic power on board 65 kW
- 8 hydraulic thrusters with Kort nozzles
- clamping facility for 0.4 up to 1.37 m dia.
- systems for:

● computerized control
● illumination
● television
● handling
● hydraulic tool supply



The DAVID Submersible
Tauchfahrzeug DAVID (ZF-HERION)

Fig. 4

Participating Institutions on OSIRIS

Off-Shore Integrated Robot Inspection System

GKSS
FORSCHUNGSZENTRUM GEESTHACHT GMBH

INTERATOM

IWF
BERLIN
INSTITUT
FÜR WERKZEUGMASCHINEN UND
FERTIGUNGSTECHNIK DER
TECHNISCHEN UNIVERSITAT BERLIN

IFW
Institut für Fertigungstechnik
und Spanende Werkzeugmaschinen
Universität Hannover (TH)

Germaniſcher Lloyd

Fig. 5

3

CESAR-86/58

HUMAN-SCALE EXPERIMENTS IN MOBILE AUTONOMOUS ROBOTICS*

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Nuclear Research Center Karlshrue
Federal Republic of Germany
May 11-13, 1987
Karlshrue

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HUMAN-SCALE EXPERIMENTS IN MOBILE AUTONOMOUS ROBOTICS*

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INTRODUCTION

The Center for Engineering Systems Advanced Research (CESAR) was established in 1983 as a national center for multidisciplinary, long-range research and development in machine intelligence and advanced control theory for energy-related applications. Intelligent machines are considered operational systems that are capable of autonomous decision making and action. The initial reseach emphasis is in remote operations, with specific application to dexterous manipulation in unstructured dangerous environments. Potential benefits include reduced risk to man, machine replication of scarce expertise, minimization of human error due to monotony and fatigue, and enhanced capabilities through sensors and computers. A CESAR goal is to explore the interface of today's advanced teleoperation with the autonomous machines of the future.

CESAR was created by the Division of Engineering and Geosciences, which is part of the Office of Basic Energy Sciences in the U.S. Department of Energy. The initial CESAR research objectives and approach[1] have evolved with time[2-4] and are currently documented in a five-year plan[5] which is updated annually. Research activities include development of methods for real-time planning with sensor feedback, determination of concurrent algorithms for optimal implementation on advanced parallel computers, formulation of learning methodologies for knowlege acquisition and interpretation, uncertainty modeling and analysis, machine vision based on human ocular processing, and compliant manipulator dynamics and control.

The intial phase of CESAR research has been performed using a small-scale mobile robot which has many of the essential functional attributes of an autonomous robot. This paper describes CESAR's intial work as a foundation leading to more realistic future experimentation and research. Future work will begin to address the challenges of a larger (human-scale) mobile robot system which can perform much more human-like manipulation tasks.

PRELIMINARY RESEARCH

The initial experimental focus of CESAR has been a mobile robot system called HERMIES-II[4] (Hostile Environment Robotic Machine Intelligence Experiments: Series II). This robot is a low-cost system developed for basic experiments in autonomous robot

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*Research sponsored by the Engineering Research Program of the Office of Basic Energy Sciences, of the U.S. Department of Energy, under contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

with dual-arm maniplators, on-board distributed digital processors, and directionally-controlled sensor platform. HERMIES-II, which is shown in Fig. 1, is propelled by a dual set of independent wheels on a common axle alignment and driven by individual dc motors. The on-board IBM-PC and other electronics are located in the enclosure above the drive chassis, and the dual-arm manipulator with shoulder torso are positioned immediately above the electronics. The manipulators are recognizable as Zenith/Heathkit HERO robot arms. The sensor platform has dc servo-controlled pan and tilt mechanisms to position a five-axis sonar ring and a pointable combination of sonar and computer vision CCD cameras. The vision system is an International Robomation/Intelligence P-256 unit which require tethered operations and provides 256 X 256 pixel resolution with 8-bits of gray level. All of the HERMIES-II control software has been written in the FORTH lanquage.

HERMIES-II has now been upgraded to a new form called HERMIES-IIB. This upgrade has involved improvements to the robot's basic mobility chassis and on-board computational resources. These modifications have improved reliability as well as increased the degree of "self-contained" autonomy (i.e., dependence on other immobile replaced with VME and IBM-AT backplances in combination). The VME system provides all control and sensor data interfacing and utilizes a Motorola MC-68020 32-bit microprocessor as the basic robot control engine. The VME system also serves as a data gateway to the AT backplane which houses a 4-th order (16 nodes) hypercube parallel computer based upon the NCUBE Corporation 32-bit node processor chip. The on-board hypercube provides the equivalent processing speed of approximately 16 VAX/11-785 processors. The VME system facilitates the on-board integration of a reasonably high-performance computer vision system using DataCube Corporation expansion boards which provide 512 X 512 X 8 color resolution and traditional image processing functions. It is believed that HERMIES-IIB represents one of the most computationally powerful mobile robots.

Intially, HERMIES-IIB will be used to replicate earlier navigation and path-planning experiments [6,7] with full autonomy. Subsequently, a new set of experiments involving combined manipulation and mobility will be performed. In these experiments, HERMIES-IIB will use on-board vision and an optical guidance/control scheme for manipulator positioning to operate a "simulated" process control panel. The process control panel will consist of two analog readout meters, two slide-type analog input adjustments, and four back-lighted pushbuttons. The discrete logic and continuous dynamic models which interconnect and drive these inputs and outputs will be implemented with an IBM-PC. Upon finding and establishing position reference with respect to the panel, HERMIES-IIB will "operate" the panel to establish the system output states specified in his original task goals. Initial results of these experiments will be presented.

EXPERIMENTAL PARADIGM

CESAR is dedicated to not only theoretical development of advanced autonomous robot concepts, but also the experimental evaluation of such concepts. The HERMIES-II robot series has been used to perform basic experiments in navigation, path-planning, and manipulation/mobility coordination at the functional level. We recognize that many, if not all, of the research challenges in autonomous robotics will derive from real-world constraints and practicalities. Useful robots must be able to perform in some sense what human workers do under typical environmental conditions. This "goal" has many ramifications, but two obvious ones are: (1) the robot's sensors, especially vision, must function under non-ideal (or realistic) conditions (e.g., lighting cannot be overly manipulated or contrived), and (2) the robot manipulators and other resources must be able to manipulate objects and tools which are, at least, in the human-range of force. It is believed that the human-scaling of the experimental environment is a significant research factor (in terms of driving objectives). Because of this, and to give general context to our long-range research planning, the CESAR team established[5] a reference task problem, or paradigm, to organize our goals and objective about. The general problem is the *operation, diagnosis, and maintenance of process control valves.* Our ultimate goal is the development of an autonomous mobile robot which would be capable of repairing, or replacing, typical process valves under off-nominal (perhaps emergencies) conditions. The process valve problem was selected for several reasons: (1) valves are very common in energy-related systems, (2) valve operation, diagnosis, and maintenance tasks cover a very wide range of complexity, load range, and force sensitivity requirements, and (3) typical valve installations in real plants provide difficult mobility, manipulation, and sensing challenges (Refer to Ref. 5 for more detail of the rationale). Actual field and equipment data will presented to further describe the reference problem attributes. It is believed that a robot capable of accomplishing these repesentative tasks would inherently be capable of a wide range to typical human tasks.

HUMAN-SCALE RESEARCH

CESAR is actively pursuing the next phase of research in which the scale of operations will be increased into the realm of human sizes in terms of manipulation geometry and loads. To accomplish this the HERMIES-III robot is being designed and fabricated. HERMIES-III will be an electric-powered robot which incorporates the CESAR research manipulator[9] and a shoulder/torso mechanism mounted on a modified industrial automatic-guided vehicle (AGV) chassis. Initially, only a single manipulator will be installed, but provisions for adding a second arm at a later date are included. The CESAR research manipulator, see Fig. 2, is a human-scale arm with about a 1 m reach, 10-15 Kg load capacity, and no-load tip speeds approaching 200 cm/s. The manipulator was designed from force-refelecting teleoperations principles and as a result it has relatively light weight (on the order of 100 Kg) and very low stiffness. It's very low static friction characteristics make it particularly effective for sensitive force control. The arm has been fabricated and checked out. Presently, advanced position and control algorithms are being developed for its use as an integral mobile robot resource. The arm proper contains six degrees-of-freedom, but an additional degree-of-freedom will be included in the shoulder/torso assembly to provide a redundant joint for obstacle avoidance and optimum configuration control for complex tasks.

HERMIES-III will utilize the combined VME/68020 and hypercube computer assembly discussed above. A new faster and more rigid pan/tilt sensor platform has been developed and the sensor suite includes the five-element sonar ring, a DataCube CCD camera pair, and laser range scanning system. In this configuration, HERMIES-III will be capable of handling relatively large loads from floor level to approximately 2 meters off the floor. HERMIES-III will have 3D optical scanning capability and conventional sonar ranging with additional 2D TV scanning. At this meeting, an update of the HERMIES-III design and fabrication will be given and initial experimental plans reviewed.

CONCLUSIONS

CESAR and many other research organizations have made substantial progress in addressing the fundamental aspects of autonomous robot mobility for the most part with small-scale hardware. We are now beginning to address robot experimental platforms which will be more realistic in terms of physical size and admissable work task range--especially with respect to manipulation functions which are necessary to perform useful work. The HERMIES-III robot will one of the first autonomous robots to combine mobility, manipulation, and advanced sensing on this scale.

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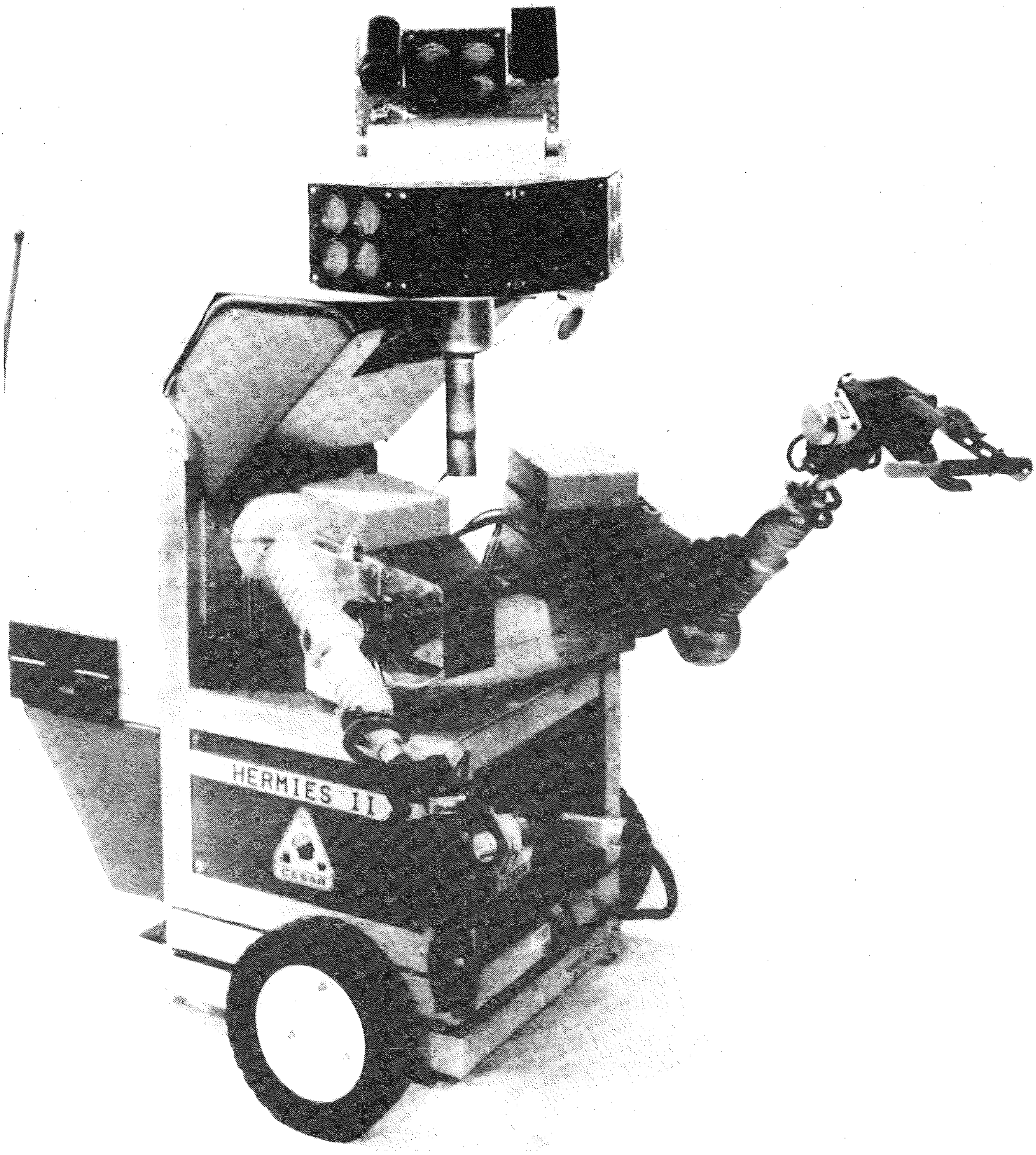

Figure 1, HERMIES-II Mobile Research Robot

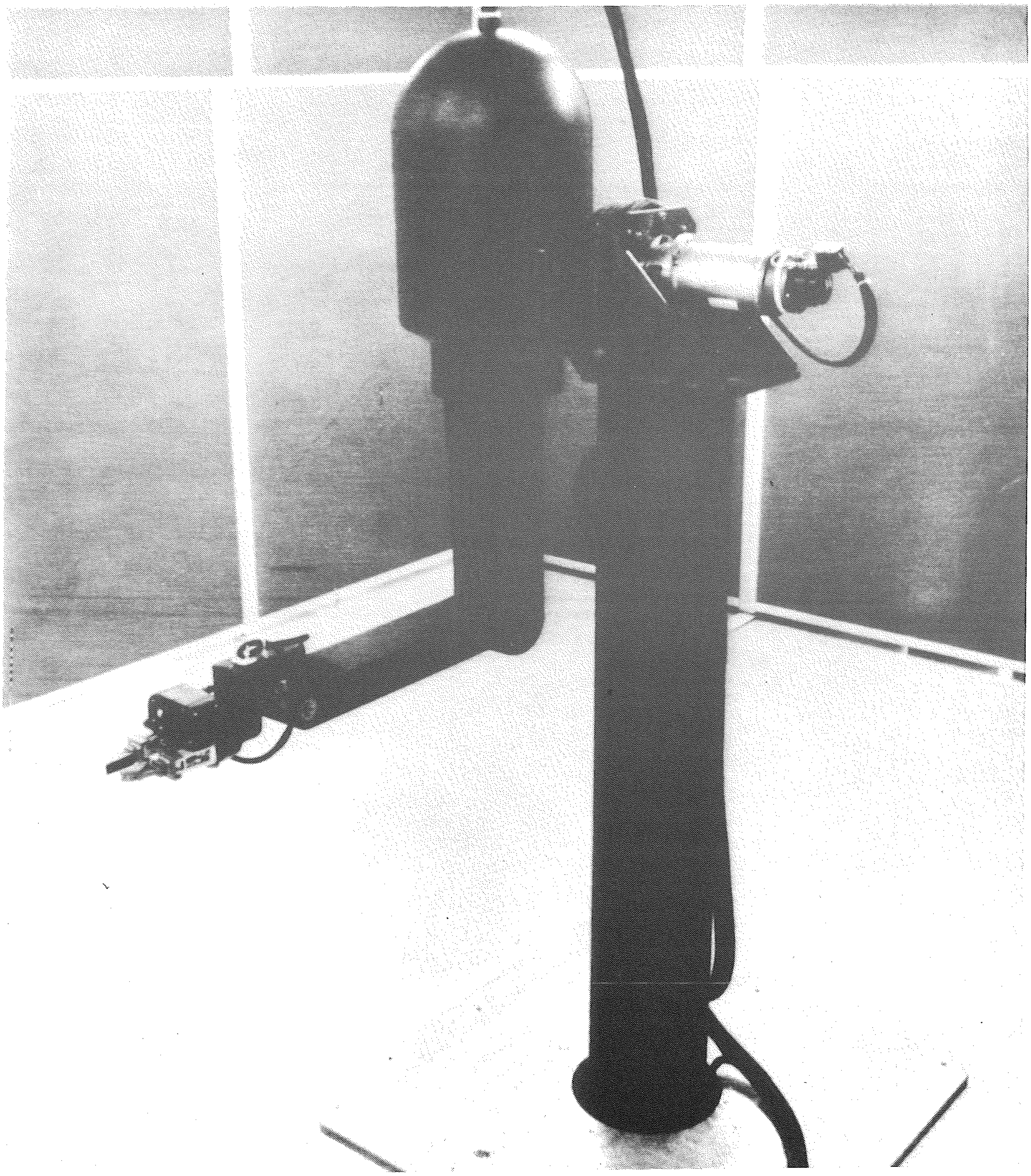

Figure 2, CESAR Research Manipulator

4

Trends of Automation in Space Application

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Abstract

Based on an analysis of realized and planned space missions and system concepts the trend of automation in space application is discussed. In relation to a hierarchical concept for the identification of operational areas of a task execution and a comparison of the characteristics of the human operator and automatic systems a baseline for task allocation is stated. In coherence with this aspect the importance of the automatization oriented system design is mentioned as a fundamental requirement for an efficient and economic use of "Automation and Robotics" in space. Examples of system concepts are presented based on a transfer of technologies from terrestrial manufacturing to space areas.

1. State of the Application of Automation and Robotics in Space

In the last decade in particular in reference to the Remote Manipulator System (RMS) of the Space Shuttle and the planning of space stations Automation and Robotics (A&R) advanced to be a key concept for future space technology. A&R are regarded worldwide as important for future space applications, because A&R offers more flexible and economic execution of space missions. Therefore the availability of this technology will be of great importance for the commercial use of the space.

Independent of this actual discussion A&R had been more or less an integral part of space projects from the beginning of the development of space technology. From the start of the execution of space missions unmanned systems with a high degree of automation and supervised from ground were developed. Projects like Surveyor, Lunochod, Luna and Viking demonstrate an extensive application of A&R technology /1/. This trend of a system philosophy has been true for the development of basic space technologies, unmanned explorations and the commercial use in the field of satellite techniques. These systems were specially designed for the planned missions and had a high level of autonomy for the task execution by the automated systems. Also they have proven to realize an efficient and reliable mission execution over long time periods.

Parallel to this A&R oriented tendency for research and exploration in low altitude orbits and for moon missions manned system concepts have been developed and executed with a low level of automation. For this strong efforts were necessary to develop the transport, life support and security system required for man´s immediate presence in space. In this context the Space Shuttle RMS has to be mentioned which is a manual controlled manipulator by direct sight contact or by a television camera system with a low level of automation.

In the United States and Europe a lot of concepts have been worked out and are in preparation for the use of A&R in future space missions conceptions /2,3,4,5/. Autonomous assembly of space stations up to fully automated production systems in space are mentioned. For near future the system concept being in the planning for realization in context with the execution of scientific experiments for the utilization of microgravity and the assembly and maintenance of orbital systems takes into account manned system concept supported by automated features. Also in the case of remote controlled systems the concepts assume the existence of the human operator in space. The arguments for this elementary form of the integration of the human operator into the mission execution are given by the complexity of the process scenario which does not allow a higher degree of automation in reference to the actual state of technology.

Summarizing it can be stated that for the application of A&R no general philosophy exists. Also the proposed A&R concepts have strongly differing degrees of automation. Dominant for future space missions relevant for A&R will be complex tasks such as assembly of space platforms and maintenance of orbital systems. Due to the fact that the systems itself and the interaction between them are not optimally designed for an automatic task execution from the beginning, universal and high intelligent A&R systems were required which tend to imitate the abilities of the human operator. These requirements are intensified by the general trend to create universal oriented concepts for A&R systems which can be applied to a big variety of mission tasks including the handling of exceptional situations.

Due to these objectives high level automation concepts already successfully applied in specific space mission can not be taken into account for short term projects. With the actual state of technology universal and high intelligent A&R system solutions cannot be realized and therefore are only stated as an objective for the future. In missions to be planned for realization in near future the task execution has to be done in priority by the human operator. Only he offers the general abilities required as a universal controller of high intelligence who can realize the task execution in an unstructured environment inclusive exceptional case handling.

The problems with this task allocation to the human operator are the given restrictions of his control abilities, his physiological constraints, the security problems and the high cost of his presence in space. To reduce the influence of these constraints a support by automated subsystems is adopted which nevertheless leave the tasks of prime execution and prime controlling to the human operator. This leads, e.g. in application areas of robotics, to system solutions of remote controlled manipulator systems. These telemanipulation-concepts are necessary to master exceptional circumstances and task execution in unstructured environments. It will take a long time and fundamental research and development efforts to reach the objective of automated systems which can imitate the overall objectives of the human operator. But in contrast to this approach the increase of and experience with the application of A&R technology in terrestrial areas allow, with the available state of art, to design semiautonomic system solutions with a much higher degree of automation and a more efficient and secure integration of human operator for a variety of mission tasks.

In the following a general concept philosophy for A&R application is outlined which is based on systematics for the task allocation between human operator and automated systems primarily developed and applied in the area of flight guidance and control and the transfer of principles and technologies in the terrestrial manufacturing area.

2. Task Allocation to Human Operator and Automatic Systems

The analysis of the state of A&R application in space shows that the form of the integration of the human operator into the mission execution is strongly dependent on the mission subtasks taken over by automatic subunits. In general it can be stated that independent of any degree of automation especially for complex mission task the human operator will remain integral part of the mission execution. Therefore the task allocation to the human operator and the automated system is an important aspect influencing the design of overall system. On the basis of a hierarchical approach used for structuring the mission task and a comparison of the characteristics of the human operator and the automatic systems fundamental statements for the task allocation can be derived.

Independent of the type of mission task the activities which are by necessity to be performed can be structured into a three level hierarchy (see fig. 1).

The task of the uppermost level is characterized by strategic planning, decision and control functions which have a long-term and general nature. A central activity here is the functional decomposition of the overall task into partial tasks which can be executed on the next level.

In the following "Tactical Level" planning tasks with intermediate and local ranges are included. In addition to these, the process related surveillance and coordination of the functions, to be executed on the lowest level, occur.

All these activities which are executed according to preprogrammed control sequences or simple feedback control principles are contained in the executive level. The output signals of this level control the process to be realized.

From the description of the features of activities in each level of hierarchy and their mutual dependencies the following regularities of the hierarchical structure can be stated.

In the hierarchical levels there occurs a top down decrease in:

- the variability and complexity of the decisions,
- the requirements for the knowledge and
- the demands of comprehension of information and the characteristics of the information processing.

and an increase in:

- the number of the control signals and the amount of information to be processed per unit of time (signal bandwidth) and the demand on the precision and reliability of task execution.

In order to be able to answer the question of the necessary or meaningful degree of automation on the basis of the hierarchical concept, a fundamental comparison of the characteristics of man and the automatic system is represented in the following.

Based on research results from the fields of human engineering /6/ and experimental psychology /7/, the human faculties may be classified into cognitive and sensor-motor areas.

Included in the cognitive faculties of the human operator are his characteristics of an encompassing knowledge of the system behavior, the capability to collect, organize, store and readily retrieve experiences, the ability to enter into a complex exchange of information with his environment and his problem solving capabilities.

Man´s sensor-motor faculties include the completion of movement. Due to his physiological characteristics there are limits to the speed and precision of the execution. Furthermore the human operator has a reaction time which can not be infinitively decreased. Highly repetitive routine tasks lead to a subjectively sensed high degree of stress. The control of complex dynamics require a high standard of training.

In addition to these limited human control characteristics, the marginal physiological constraints for man´s employment in space are to be considered in the decision of task allocation. This concerns the technical expenditures necessary for the transport life-support and rescue systems. Furthermore, there exists a time limit for the employment of man in space /8/.

The area referred to as the "servo loop control level" in automation corresponds to the human sensor-motor activities. Such technical systems may be optimized in a manner which extends beyond the man´s limits. The technologies for the automation of this level of tasks already exist.

The task specific technical imitation of the cognitive capabilities of man, usually called "machine intelligence", are at present still in a state of research and development. According approaches for the area of artificial intelligence are being developed. Up to now the results allow solutions practicably to be used only for limited and specific tasks (e.g. systems diagnosis).

As a summary the following general baseline for task allocation can be stated:

- Due to the fact that automated systems can be optimally designed for the execution of specific tasks they should be applied for subtasks of the mission execution where their use is required for the demands of efficiency of the overall system and where they lead to economically reasonable solutions by guaranteeing the system reliability.
- Most important for automation are the tasks on the executive level to disburden the human operator from repetitive tasks. The technologies to do this are available. Automatization approaches for the higher levels should concentrate on tasks difficult for the execution by the human operator e.g. support for complex task execution planning process and diagnostics by use of KI-technologies.
- Independent of the degree of automation the human operator will retain a central function for the execution of the overall mission task. The task allocation should be

designed in such a manner that predominantly the cognitive abilities of the human operator are used for the execution and supervision of the mission task.

- The operation of human operator and automated system should be designed in such way that a minimum presence of human operators in space is required. The dominant trend should result in automatic working systems in space manually ground controlled due to economic and safety aspects.

3.The Principle of Automatization Oriented System Design

The analysis of the state of A&R application in space demonstrated that in reference to the state of technology a main problem of an extensive use of A&R technology in future projects are the requirements for universal system solutions for task execution in an fairly unstructured environment. The derivation of the system requirements is oriented on existing system structures which are primarily designed in reference to technical and functional constraints. The additional important aspect that the system design has to be automatization oriented is missing. In the area of terrestrial manufacturing it has proven that taking this aspect into account A&R application enables the realization of efficient and economic solutions with a high degree of automation even for complex tasks. An overall system design automatization oriented will also reduce the requirement for application of sensor technology and machine intelligence. By this sooner and in general more economic automated system solutions can be realized in reference to the state of A&R technology.

Terrestrial manufacturing has shown that for the design process of an automated production the overall system has to be taken into account. Applying automatization in existing structures which originally were not automatization oriented designed has proven to be inefficient. Methodologies for this planning procedure are available and computer aided tools with use of KI-technologies are in development /9/.

The system planning process starts with the functional analysis which includes the registration of all tasks to be executed, determination of all constraints and the definition of a profile of requirements. The result is the elaboration of a performance specification which is already independent of an specific equipment. Based on these prerequisites the first step of the layout planning for the system realization can be done which is evaluated and optimized by simulation of the system behavior. After a decision on economic feasibility the final details of the planned system are executed. The last step of the overall process is the planning of the system installation.

The overall system planning process is a highly iterative process because validation activities may require changes in any previously produced result. The objective of this planning process is the determination of suitable manufacturing procedures by means of a technological and economical comparison of solution alternatives. Principles applied for an automatization oriented design are e.g. standardization of mechanical interfaces, reduction of the variation of pieceparts by group technologies, change of production environment from an unstructured to a structured one and the change of the product design.

Finally it should be mentioned that the automatization oriented design does not imply "hard automation" in the sense of inflexible solutions. The objectives of modern manufacturing technology are flexible automatization concepts, so called "soft automation". This implies modular and flexible solutions which are valid for classes of applications and can be easily modified and adapted to specific task of this production class.

A possible transfer of the mentioned technologies existing in the area of terrestrial manufacturing to space applications is possible. Up till now these aspects have consequently not been taken into account in the design of future space concepts.

4. Examples of Automation relevant System Concepts

In the following three conceptional examples of A&R application for an optimized design of semiautomatic systems are given. The first example deals with the automatic execution of experiments under closed lab conditions. In the second example some ideas are presented for an automatization oriented design for the maintenance of satellites. The third example deals with the automatization oriented design for the grasping problem. It will also be used to demonstrate some differences between an automation relevant design compared with the principles of manual task execution.

For the automatic execution of experiments under closed lab conditions (e.g. μg-experiments) a structured environment and a clear defined task is given. Therefore the task execution of handling and assembly can be flexible automated by using the principle of free programmable robots /10/. By this a predefined action sequence represented by the user program is automatically executed in the orbit (see fig.2). Applying off-line programming technologies developed in the manufacturing area a ground based supervisory system can be realized. The simulation system of the programming unit can be used for a presentation of the task execution in the orbit. The graphic representation is based on CAD-technologies and allows a 3-D representation of the task execution with a minimum data rate orbit/ground (see fig. 3). In the case of the required change of the task execution in orbit with the program generation unit of the off-line programming system a new execution program can be created and tested on ground. Then it is sent to the orbit and the new user program will be executed by the automatic system. This is a form of manual control where the human operator only gives global commands to the system and the detailed execution is done by the automatic system. Due to low bandwidth of this control loop time delays in the communication links ground/orbit are irrelevant. This concept is part of the planned Robot Technology Experiment in Space-Lab-D2-Mission (see fig.4) /11/.

The second example presents some ideas for the maintenance of satellites. Due to the variety of the structures of existing satellites the complex requirements for a free flying automatic maintenance system are given. With an overall approach taking the structural design of the satellite and the maintenance system into account an automatic maintenance can be realized. For this purpose a modular structure of the hardware components (ORU-concepts), a standardized module exchange and maintenance interface and a selfdiagnostic system for the module components is required for the satellite. A standardized docking with mechanical centering between the flying maintenance system and the satellite is also necessary. By this a geometrical repeatable geometric configuration for module exchange or refueling situation is given and an automatic maintenance after a preprogrammed execution sequence can be realized. A simplified artistic impression of this szenario is shown in fig. 5.

In the last example an automatization oriented design for the grasping problem for handling and assembly tasks is demonstrated. With the introduction of a standard grasp element a variety of objects can be handled with the same simple grasper (see fig.6). By use of a form closure by the two grasps jaws an exact position of the object can be ensured and a dislocation of the grasped part by disturbance forces is not possible. To avoid unintended movements and dislocations the objects must be secured in position at every time. With the use of simple mechanical centering elements a positioning accuracy in the range of 1/100 mm. can be realized by a required position accuracy of the robot in the range of 1/10mm.

Keeping the geometrical relation for task execution repeatable is a fundamental requirement for an automatic task execution which is only based on the robot internal position measurement systems. Additional sensor systems for the execution are not necessary because the robot has a high repeatability in positioning. This is for instance a fundamental difference of the control characteristic of robots compared with the human operator. His repeatability of position accuracy is worse. To compensate this he uses, e.g. when connecting a plug, his visual system for gross positioning and his extensive force control abilities in his hand system for fine positioning. This is a simple example for the fact that an automatic task execution is not necessarily based on an imitation of the execution by the human operator.

5. Conclusion

Independent of any degree of automation especially for complex mission tasks the human operator will be integral part of the mission execution. Therefore A&R application is not a question of either man or automated systems but the question of a reasonable task allocation to both components of the overall semiautomatic control system.

The analysis of the state of A&R in space demonstrates the actual trend for an imitation of the activities of the human operator by automated systems. These system solutions are necessary for task execution in an unstructured environment and for mastering exceptional circumstances. With the actual state of technology only a low degree of automation can be realized. To improve this long-termed and fundamental research will be of compelling importance.

Based on technologies and experiences in terrestrial manufacturing technology a higher degree of automation can be realized already with the actual state of technology by an automatization oriented design of the overall mission scenario. By this concept for a variety of mission tasks in reference to the performance characteristics of man and automated systems a more efficient task allocation can be realized which will reduce the required presence of the human operator in space.

The more extensive and economic use of A&R technologies is for the presence and for the future not only a question of fundamental research requirements but also a question of an overall automatization oriented system concept for planned mission scenarios.

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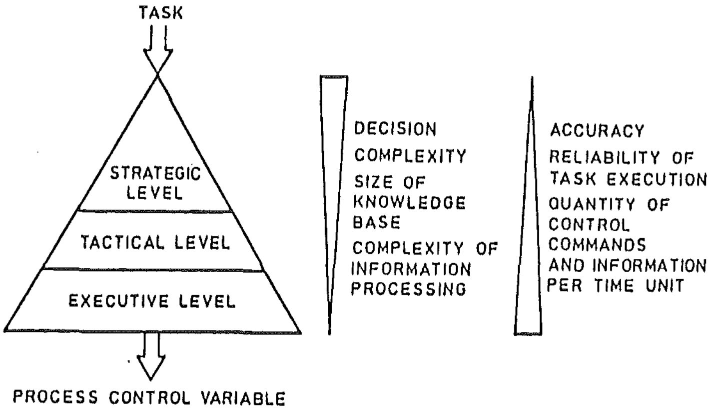


Fig. 1: Task executive hierarchy

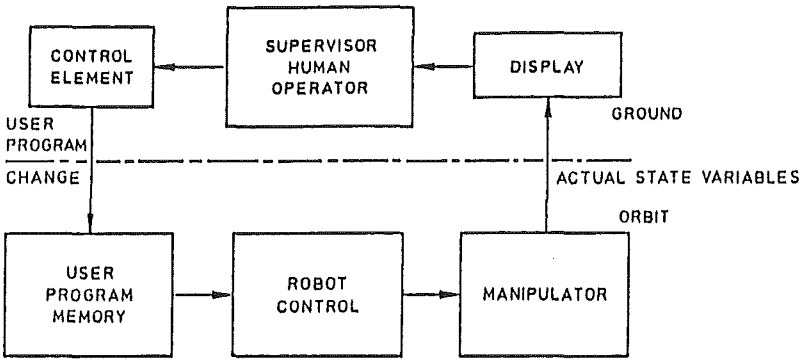


Fig. 2: System structure for combined supervisory and man in the loop on high hierarchical level

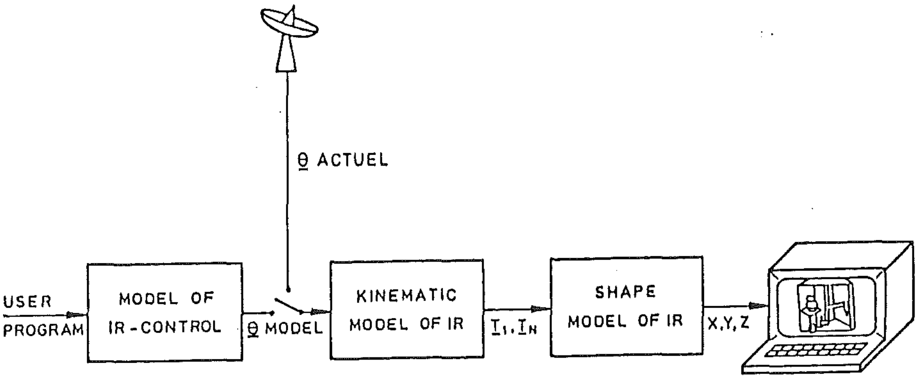


Fig. 3: System structure for supervisory function

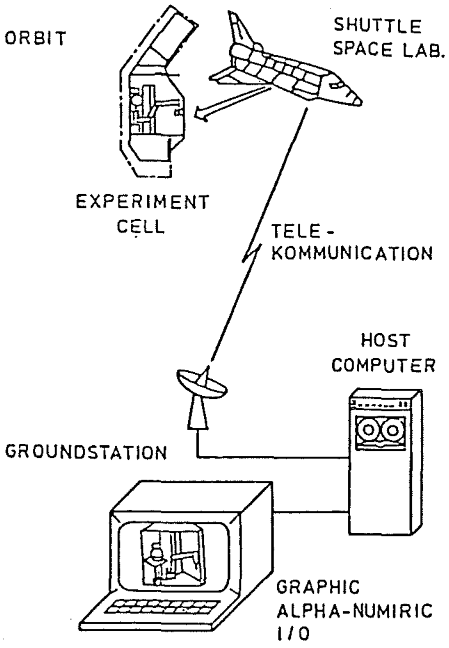


Fig. 4: Concept of groundbased supervisory system and manual control

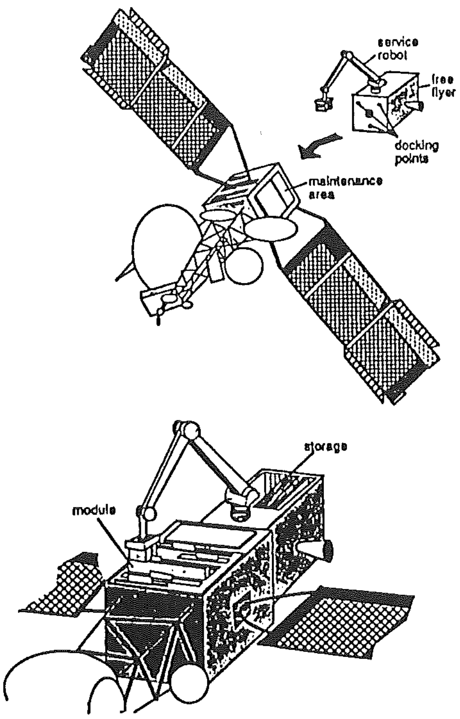
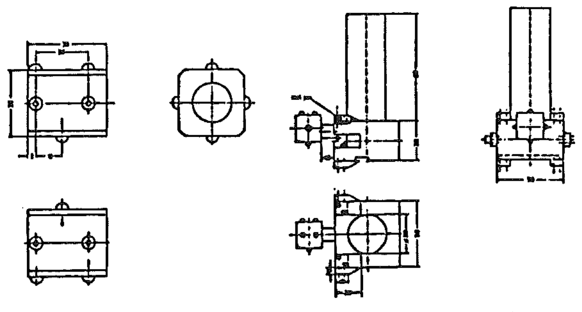
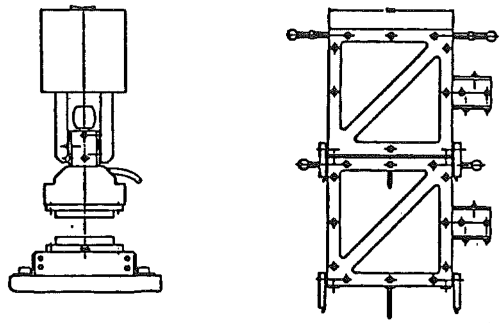


Fig. 5: Automatic maintenance of satellites (artist impression)



Standart grasp element self centring and form closure

Standart sample carrier



Electric connection with zero force plug

Framework with integrated locking bolts

Fig. 6: Automatization oriented design for the grasping problem

Sessions

MANIPULATROS (1)

CHAIRMAN'S REPORT ON THE MANIPULATORS (1) SESSION

In this session overviews of essential components for advanced manipulators were presented:

Dr. Takases paper was dealing with three main topics: new types of manipulators and controllers suited for a hybrid manual/autonomous control, world model for manipulation, path planning and simulation and a new man-robot interface (multimedia display). The questions to Dr. Takase showed great interest from the audience in the man-robot interface where the ETL has entered a new field of development.

The next paper from Mr. Köhler gave a nice overview of the current state of the art of electric master-slave manipulators. The paper showed the great need to think and realize a suitable man-machine interface acceptable to the operator.

Our last paper in this morning session presented by Dr.Saffe gave interesting informations about hydraulic drive systems theory and application. The discussion showed a great potential for hydraulic drives in the field of advanced robotics.

MARTIN C. WANNER

Manipulation System for Advanced Teleoperation

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At the Electrotechnical Laboratory, a new man-robot system (Advanced Teleoperator) is being developed, aiming at efficient execution of remote manipulation tasks. The Advanced Teleoperator can be regarded as a computer-aided teleoperator and/or as a man-assisted robot, where the division of role between man and robot is essential.

In the system, elaborate part is performed by the robot, while the global task monitoring, high-level decision-making or assitance in error recovery are left to the human operator. Several research institutes in the world seem to be engaged in developing such robotic teleoperation systems. Features of our approach are:

(1)we are not using conventional robot arms or teleoperators but developed new types of manipulators and controllers suited for hybrid manual/automonous control,

(2)we utilize a unified world model for manipulation, path planning and simulation,

(3)we introduced new man-robot interfaces such as a multi-media display or a bilateral master controller.

Force control is indispensable for performing delicate tasks such as assembly or tool handling. For controlling force, joint torque controllable manipulators had been developed. The manipulators are direct-drive type, and both position and force can be accurately controlled. However, in practical application, force control is needed in a coordinate system different from the joint coordinate description. This coordinate system is closely related to the task to be executed. Motion components in task- coordinates should be controlled in suitable modes, for example, in position, or in force,or in bilateral teleoperating mode. For the purpose, software task-coordinate servo controllers have been developed. Force vector control is realized by the resolved force control method and position control by the resolved acceleration control method. The controller enables to resolve 6 d.o.f motion into arbitrary 6 components and to apply arbitrary control mode to each of them.

In order to build up a world model, a modeling system composed of a laser pointer and the geometric modeler GEOMAP has been prepared. By using the modeling system, model of objects located in remote working site can easily be produced in an interactive mode. The modeling system and control function for the manipulators are incorporated into a LISP programming environment. The manipulators handle the objects that are specified by the models, if a program written in LISP language is provided.

The motion of the manipulator can be simulated on a multi-media display. The multi-media display can deal with real scene from TV cameras, 3-D graphics and text. It uses multi-window technique. Superimposing differnt items(e.g. graphics and real scenes) is also possible. Graphical display of the manipulator is done in real-time. We also can get stereoscopic image of the manipulator with the background of real scene. It enables easy debugging of the motion program.

By using the geometric model, collision-free path for the manipulator connecting the current position and the goal can be planned. We are studying an efficient algorithm for finding the path, based on characterization of configuration space describing collision-free space.

Geometric path planning is not enough for performing delicate tasks such as assembly, where the relationship between objects must be controlled. It requires the ability of reasoning this relationship between objects on the basis of applying force and resultant motion and vice versa. We proposed a concept of robotic skill yielding an ability of performing tasks dexterously. This may be realized through position/force planning and state monitoring. Currently we are studying 1 d.o.f. skills. For experimental study, we introduced a 1 d.o.f. master controller(knob). It can be assigned to an arbitrary direction in the slave coordinate world (e.g. corresponding to a certain direction as given by task constraint). The master/slave system is working in force reflecting mode. This will be utilized for acquiring skill data or for assisting a robot in operation.

This research is forming a part of the research project "Advanced Robotics" supported by the Ministry of International Trade and Industry.

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Technical Characteristics of the Electric Master-Slave Manipulators

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1. Introduction

Most of future nuclear facilities calling for the use of general purpose remote handling equipment will be production facilities such as the large reprocessing plant for spent nuclear fuels to be erected at Wackersdorf, Federal Republic of Germany. The most important task to be fulfilled will be remote maintenance of the operating components. The dimensions of these future facilities will be great compared with the existing hot cells which serve research, development and demonstration purposes. Consequently, mobile, remotely operated equipment will be required with high performances in terms of plant availability. As these requirements can be met by far best with electric master-slave manipulators, our development work has concentrated for several years on this category of equipment.

2. Design of the Electric Master-Slave Manipulators

The essential features of the electric master-slave manipulators are the motions preset by a master arm and bilateral position controls by which the master and the slave arms are interlinked. Figure 1 shows the components of such a system by the example of type EMSM 1 /1, 2 and 3/ in a laboratory arrangement: from left to right you can see the operator's station with the master arm, the operator, the switchboard cabinet and television monitors as well as the working unit consisting of the slave arm, television cameras and tools.

In a device for practical application the working unit is fixed at a mounting arrangement allowing its displacement to various locations in the working space.

Figure 2 illustrates the basic design features of electric master-slave manipulators. The manipulator arms usually have six motions each so that, in principle, there are no limitations on the mobility. In addition, a grip motion is provided. The drives have been placed in front of the first joint in order to keep small the masses to be moved and to make the arm slim. Figure 3 shows the scheme of functioning of a typical bilateral position control. The most important feature differing from the otherwise employed unilateral position control is that adjustment of control has been provided also for the motors installed at the master arm (right side in the figure). This implies feedback of force to the operator as a pressure feel in his hand. The forces are recorded in an indirect manner. In manipulators with high load-carrying capacities the friction and the mass moment of inertia are partly compensated. In some models, for instance EMSM 1, the deadweight is compensated electrically instead of by counterweights. Most of the recent types are controlled in the digital mode and, in addition, they are capable of fulfilling quite a number of special functions.

3. Properties of the Electric Master-Slave Manipulators

Electric master-slave manipulators are general purpose devices and they are intended to replace the arms and hands of operators in working spaces which are not accessible. They distinguish from other manipulator categories by the great skill and working speed they attain.

These features significantly determine the performance and hence the serviceability of a manipulator. This is possible because the manual capabilities can be better transferred and the operator is provided means of more complete control of the master-slave manipulators.

Figure 4 shows the transferability of the manual capabilities for different categories of manipulators. It can be seen that in the electric master-slave manipulators four parameters can be influenced whereas only one parameter can be influenced in power manipulators with speed controls. The latter is true also for computer aided equipment used to generate Cartesian motions. The working speed is governed by the position which is preset by the master arm. Regarding the skill, the convenient and fast coordination of individual motions into motions of any composition proves to be of paramount importance.

Figure 5 shows the possibilities of control of the operator with different categories of manipulators. It can be noticed that eight controls are available in electric master-slave manipulators; these are matched by only three controls in power manipulators. The reflection of force is fundamental for achieving high skill and a high working speed. Moreover, the capability of coordinating the simultaneous motions of a pair of electric master-slave manipulators is essential in performing complicated operations.

4. Devices Built during the Last Two Years

Figure 6 shows the EMSM 2 type manipulator /4/. It is characterized by a lightweight and compact design and intended above all for use on small, remotely operated vehicles. Each of the two slave arms has a maximum handling capacitiy of 24 kg.

Figure 7 shows an EMSM 2 slave unit mounted by the Nuclear Emergency Brigade (KHG)on the MF3 vehicle with variable chassis geometry /1/. The equipment includes in addition two stereo television cameras and two television cameras used for driving the vehicle which are oriented forward and backward, respectively.

Figure 8 shows an EMSM 2 slave unit mounted on the MF4 vehicle. Two devices of this type have been sold to the Soviet Union. They are used in combination with autocranes.

Figure 9 shows an EMSM 2 slave unit fixed at a bridge mounting system as usually employed in hot cell facilities. On both sides of a power manipulator also two slave arms have been added.

Figure 10 shows an EMSM 2 slave unit suspended on a four - ropes bridge crane. Such a combination of devices is particularly favorable for interventions in facilities.

Figure 11 shows the recently completed type EMSM 2-B intended for use in facilities. The most important improvements include:
- increase of handling capacity to 45 kg,
- three-phase motors with a particularly high specific power,
- independent control of frequency and current,
  Note: This means that the advantages of previously used direct current and three-phase drives are combined.
- control and power units operating in an all digital mode,
- very convenient operation with the master arm,
- automated operation at option.

5. Problems Connected with Automated Operation

Automated operation in this context is understood to mean presetting of motions by a freely programmable control similar to that used in industrial robots for work at plant components. It does not mean automation of secondary operations, auxiliary functions and internal functions of devices.

Most of the new types of electric master-slave manipulators introduced in recent years offer the possibility of presetting motions by programs. Although the repetition of sequences of motions once effected was achieved more than ten years ago by Jean Vertut, nobody has explained convincingly to this day how this feature can be profitably used in nuclear engineering applications.

Regarding automated operation a number of boundary conditions posing serious problems must be observed in maintaining large facilities /5/. The reasons lie in basic differences with respect to the typical situation in fabrication where industrial robots have proved their worth.

These problems include (Fig. 12):

- positioning of mobile handling equipment in a large working space,
- large tolerances of the plant components,
- geometries of the plant components undergoing changes with time,
- on account of their very large sizes, kinematic systems can no longer be designed as rigid structures,
- programmability restricted and difficult, respectively.

Should it be possible to solve these problems satisfactorily, the expenditure required would be extremely high for actually a relatively small number of applications. On the other hand, no reason can be detected why it should not be possible to handle perfectly all operations using operator controlled handling devices combined with tools, including semiautomatic tools.

Other arguments against automatic handling in maintenance work are:

- low frequency of repetitions, if at all, of the operations,
- most of situations unpredictable,
- availability of less expensive, promissory competing methods.

Therefore, a handling equipment optimized for mixed operation or an additional handling equipment for automated operation does not seem reasonable for application in maintenance work.

The new EMSM 2-B type has been supplemented by a freely programmable path control system in order to make a contribution to the ultimate clarification of this open question.

By contrast, developments offering mixed operation suited for applications in industry and in the service sector are promissory according to a study performed under the "Highly Flexible Handling Systems" Project.

6. Current Development Work

The EMSM-WA type is presently being developed. Figure 13 shows how a double-arm slave unit will look like. This type will be tailored to operation in maintenance work to be effected in the large reprocessing plant. The most important goals of development include:

- increased load carrying capacity,
- more robustness,
- high flexibility in application,
- high radiation and corrosion resistances,
- convenient maintenance by master-slave manipulators.

A control system for the EMSM-WA type is being developed at the KfK Institute for Data Processing in Technology (IDT) headed by Prof. Trauboth. It will permit also playback operation and be applicable in highly flexible handling devices for industrial needs.

A variant derived from the EMSM-WA type has been proposed for use in the NET fusion reactor which is presently at the preplanning stage. This new variant will conform to the special requirements imposed by this application.

The electric master-slave manipulators will make a substantial contribution to solving the future tasks in handling technology.

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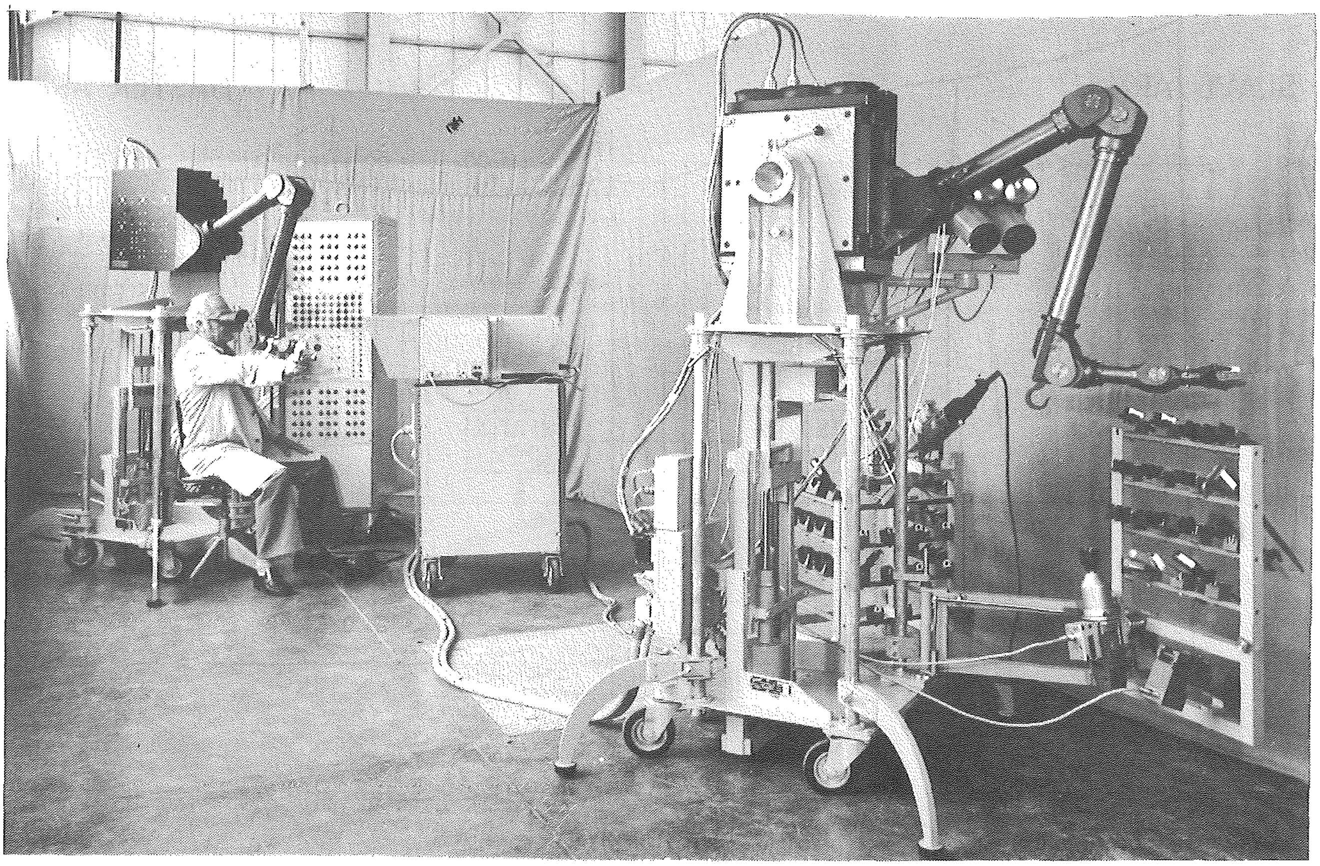

Fig. 1 Electric "EMSM 1" master-slave manipulator

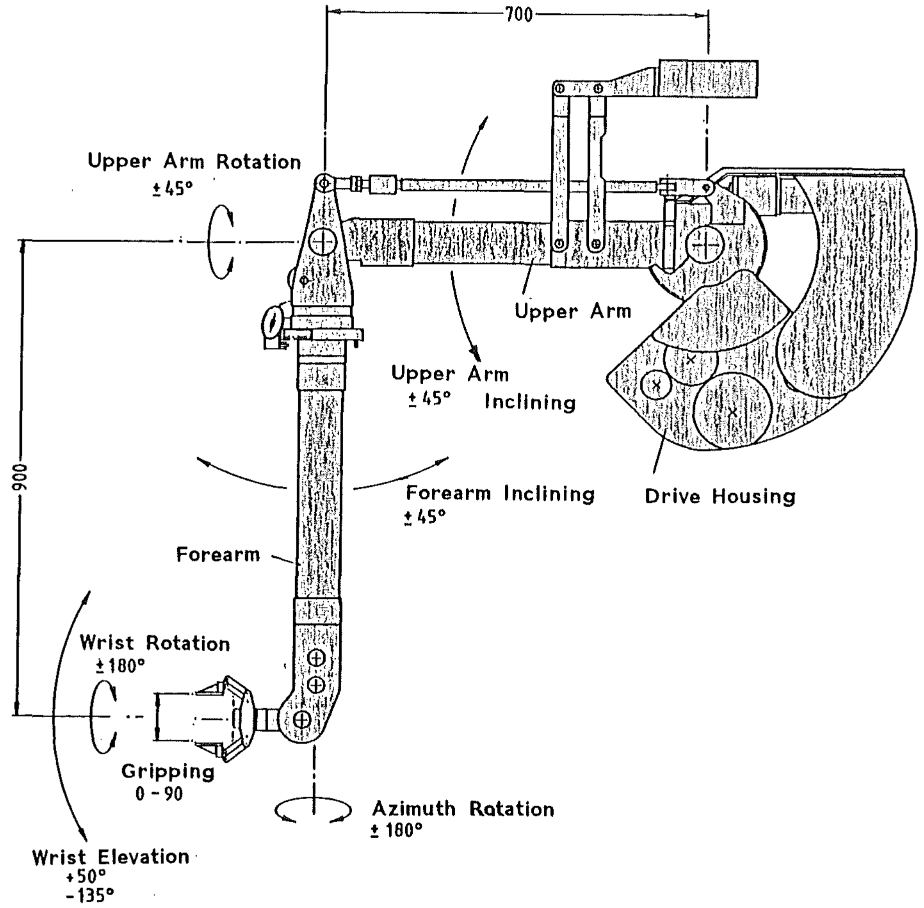

Fig. 2: EMSM 2 - B, Slave Arm

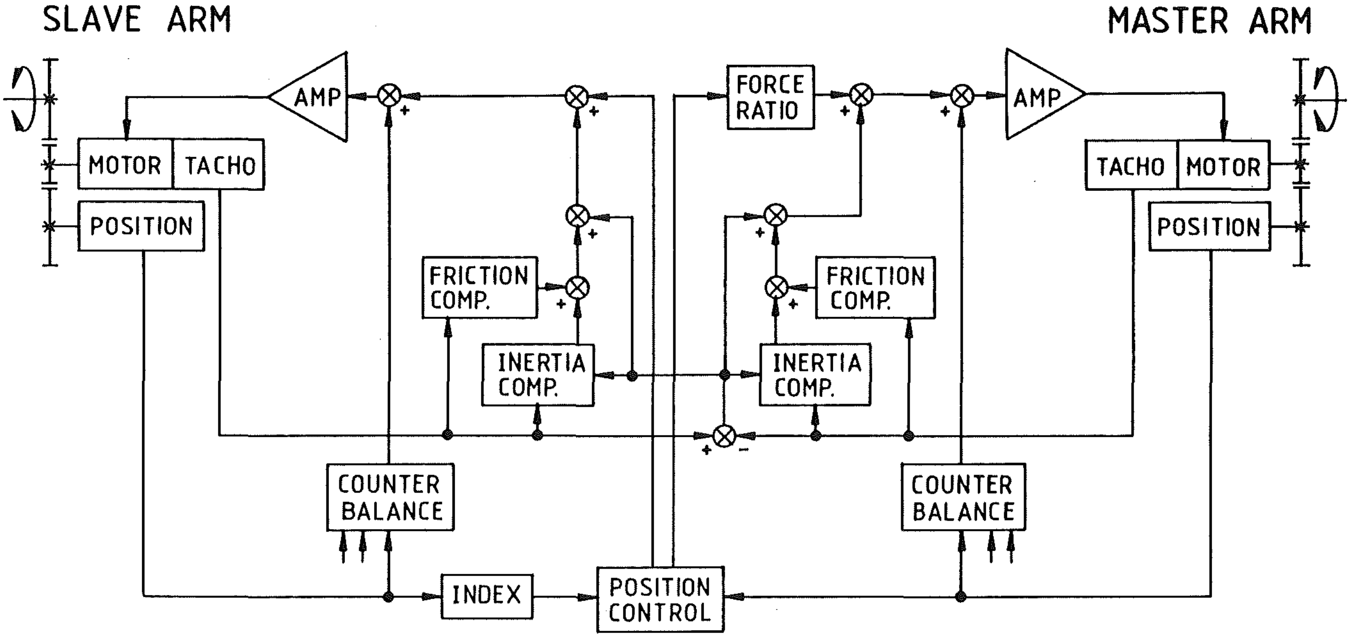

Fig. 3: Block diagram of the typical bilateral position control for electric master-slave manipulators (one positioning motion)

PARAMTER	ELECTRIC MASTER-SLAVE MANIPULATOR	MANIPULATOR WITH POSITION CONTROL	POWER MANIPULATOR
POSITION	ARM POSITION	ARM POSITION	—
VELOCITY	ARM VELOCITY	ARM VELOCITY	SWITCHES
FORCE	FORCE OF HAND	—	—
COORDINATION SINGLE MOTIONS	MASTER ARM	OPERATING ARM	—

Fig. 4: Transferability of manual capabilities with different manipulator categories

PARAMETER	ELECTRIC MASTER-SLAVE MANIPULATOR	MANIPULATOR WITH POSITION CONTROL	POWER MANIPULATOR
POSITION	EYES ARM POSITION	EYES ARM POSITION	EYES ARM POSITION
VELOCITY	EYES TEMPORAL CHANCE ARM POSITION	EYES TEMPORAL CHANCE ARM POSITION	EYES SWITCH POSITION
FORCE REFLEXION	MASTER ARM (WITH MOTORS)	—	—
COUPLING MANIPULATOR AND OPERATING DEVICE	BIL. POS. CONTROL AND MASTER MOTORS	—	—
REVERSIBLE BEHAVIOR	BIL. POS. CONTROL AND MASTER MOTORS	—	—
COORDINATION MOTIONS OF 2 ARMS	MASTER ARMS AND BRAIN	—	—

Fig. 5: Control ability by the operator with different manipulator categories

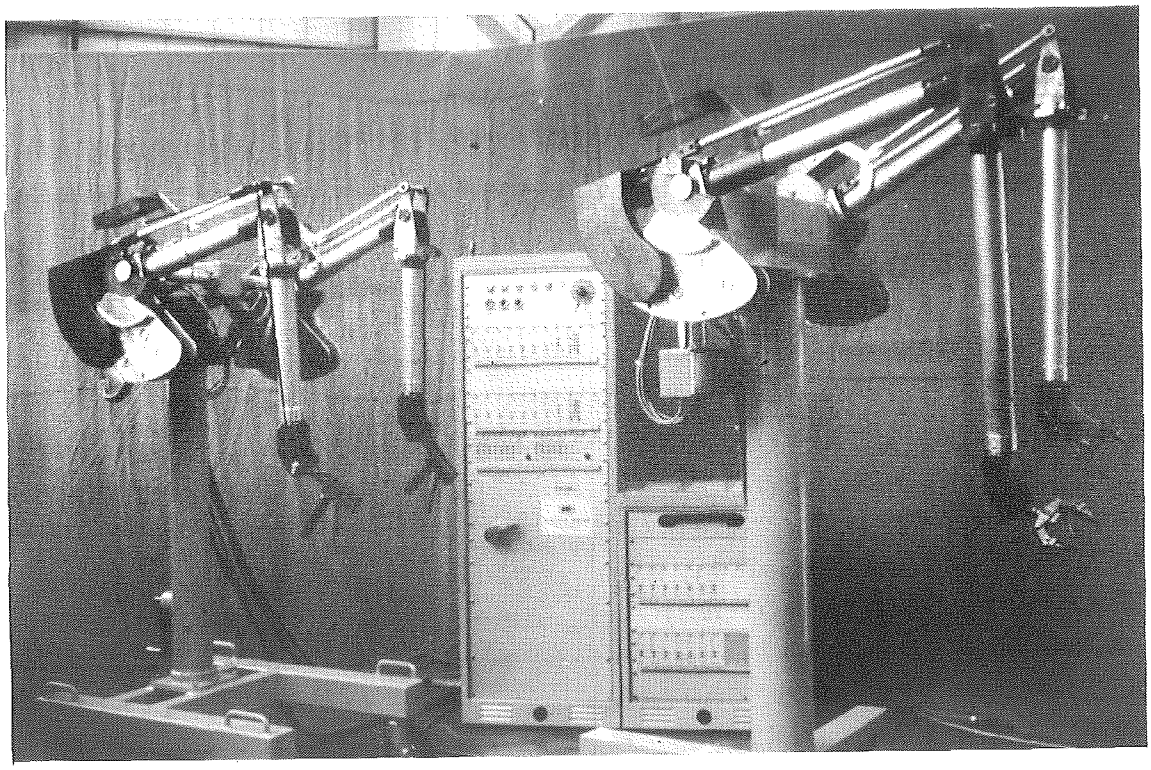

Fig. 6 Electric "EMSM 2" master-slave manipulator

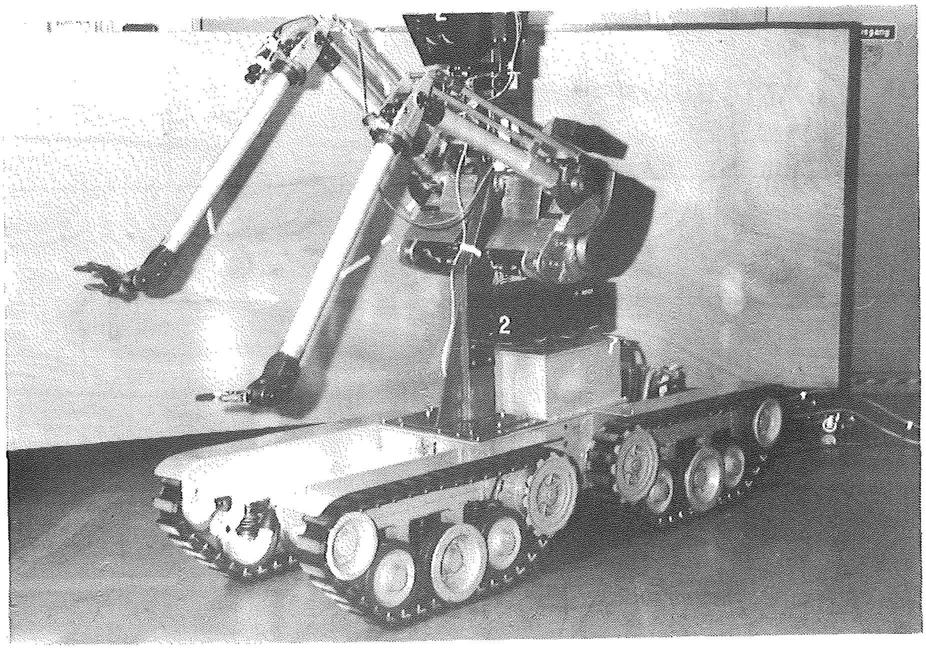

Fig. 7 "EMSM 2" slave unit on "MF3" vehicle

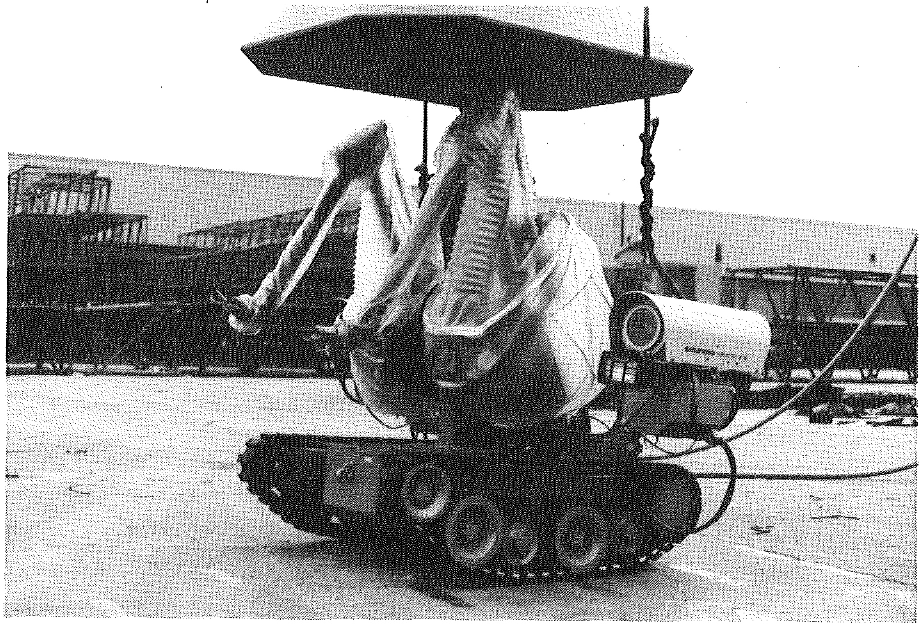

Fig. 8 "EMSM 2" slave unit on "MF4" vehicle

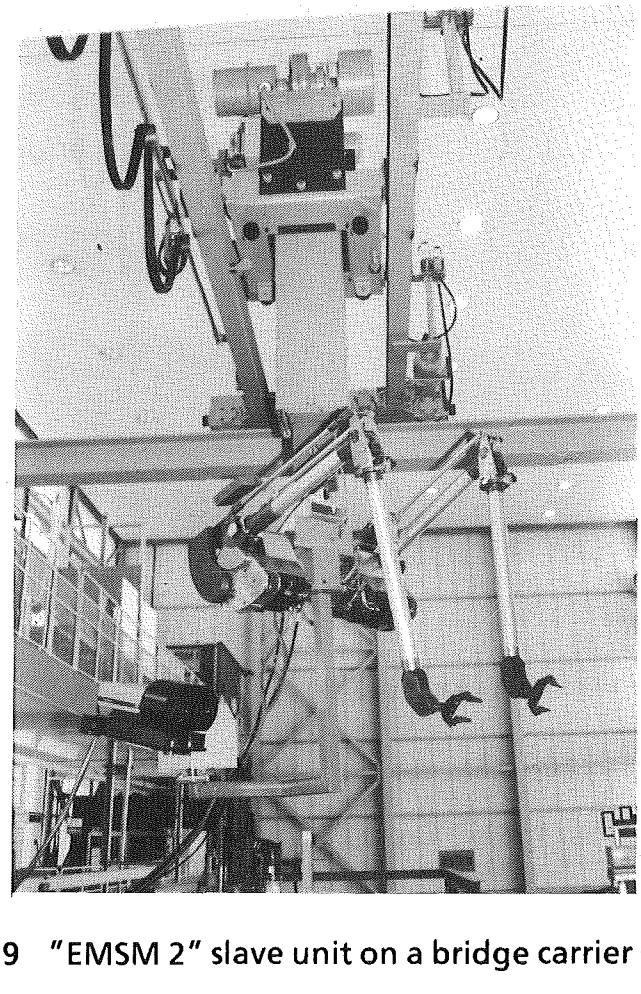

Fig. 9 "EMSM 2" slave unit on a bridge carrier system

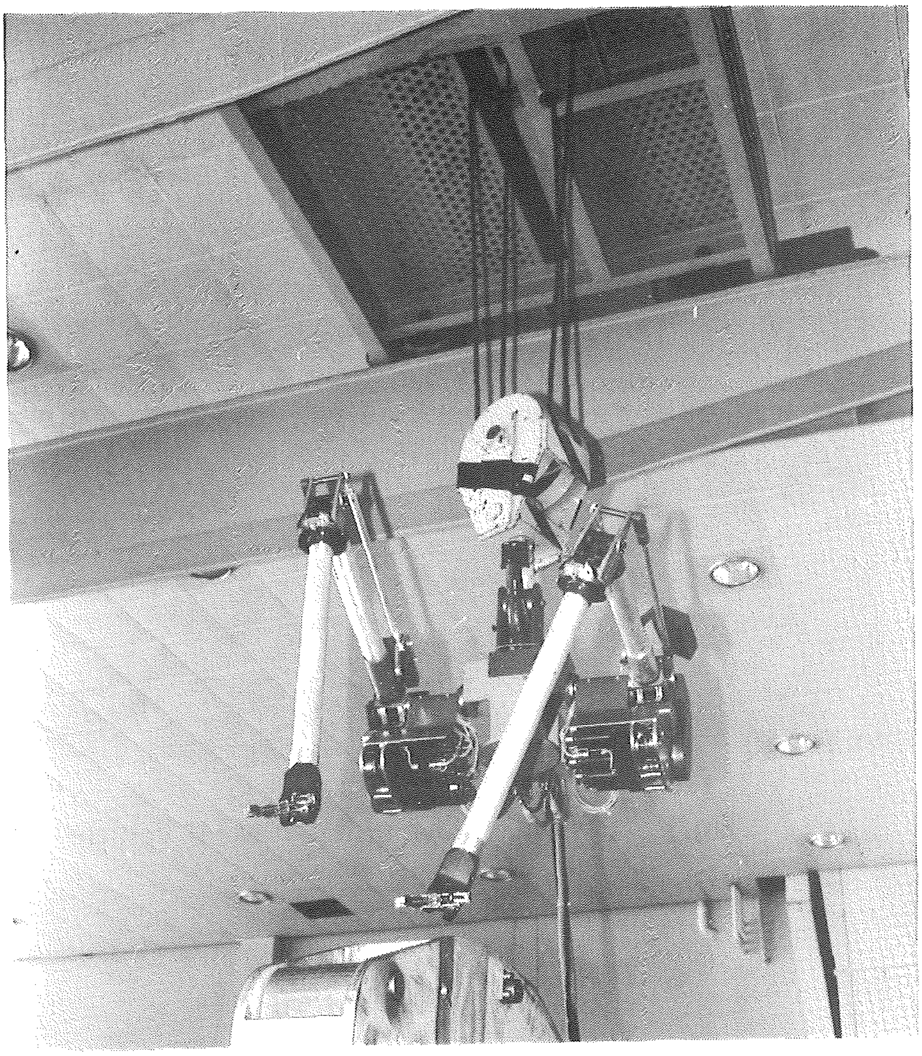

Fig. 10 "EMSM 2" slave unit on a bridge crane

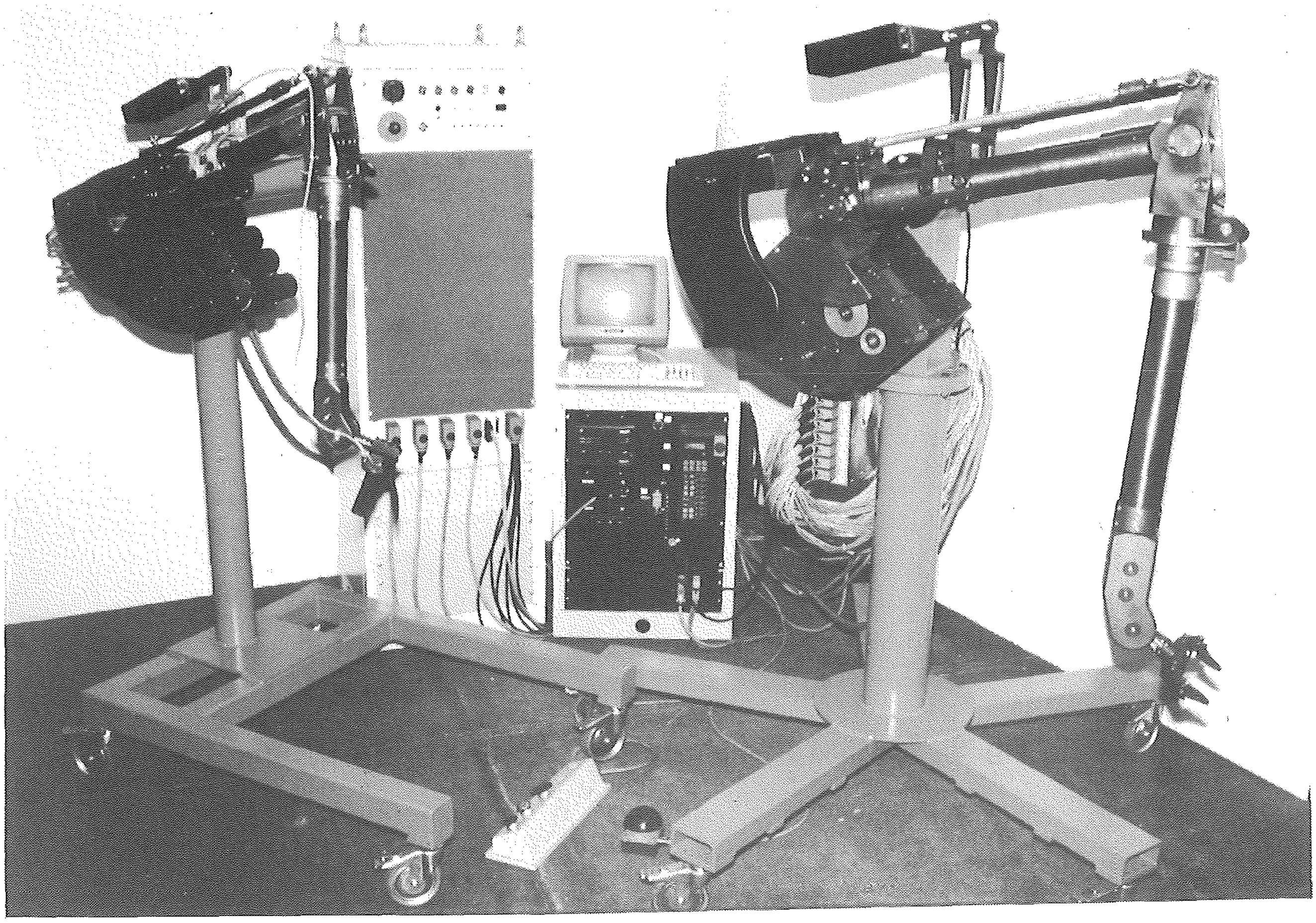

Fig. 11 Electrtic "EMSM 2-B" master-slave manipulator

INDUSTRIAL ROBOT APPLICATIONS	MAINTENACE IN LARGE FACILITIES
WORKPIECES ARE TRANSPORTED TO STATIONARY INDUSTRIAL ROBOTS	POSITIONING OF MOBILE HANDLING EQUIPMENT IN A LARGE WORKING VOLUME
WORKPIECES HAVE SMALL TOLERANCES	LARGE TOLERANCES OF THE PLANT COMPONENTS
KINEMATICS ARE STIFF	KINEMATICS NOT STIFF FEASIBLE BECAUSE OF THEIR DIMENSION
PROGRAMMING AND TEST RUNS WITH WORKPIECES IN WORKING VOLUME	WORKING VOLUME INACCESSIBLE AFTER STARTING OPERATION, OBSERVATION RESTRICTED
HIGH FREQUENCY OF REPETITION OF THE OPERATIONS	LOW FREQUENCY OF REPETITION OF THE OPERATIONS, IF AT ALL
WORKING SEQUENCES ARE COMPLETELY PLANED	MOST OF THE TASKS AND SITUATIONS ARE UNPREDICTABLE
MORE ECONOMICAL THAN OTHER METHODS	LESS EXPENSIVE, PROMISSORY COMPETING METHODS

Fig. 12: Basic differences of the typical situations with industrial robot applications and during maintenance in large nuclear facilities

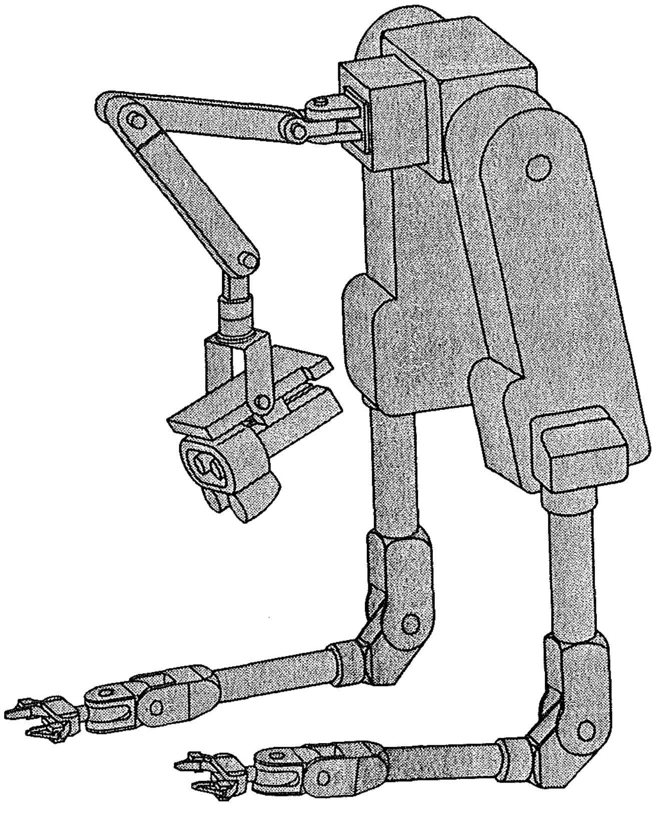

Fig. 13 Electric "EMSM-WA" master-slave manipulator, double-armed slave unit with stereo TV cameras

7

INSTITUT FÜR HYDRAULISCHE UND PNEUMATISCHE
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Modern servohydraulic drives, inevitable components of advanced robotics

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The purpose of developing high flexible, mobile roboters and manipulators is leading to research activities in several fields of technique. The demand for larger and nearly independent working devices causes research projects in kinematics, lightweight construction, sensor technology and signal-processing.

Additional there is a grewing interest in drive technology because high power density and simple connection possibilities are even more important. Therefore a system design without regard to the drive elements cannot give optimal results.

Hydraulic drives have best requirements for the use in high flexible, advanced roboters. As a result of high force density, a simple construction and a high reliability of this drive technique, nowadays nearly all mobil devices are driven by hydraulic power.

Nevertheless the conception has to be adapted to the use in automatical systems. Research results of the last few years have shown that new conceptions, improved components and valves as well as the application of modern, digital control theory can eliminate the problems of hydraulic drives as there are low damping ratio and high power consumption.

In this paper modern hydraulic drives are described. It is worked out how to pay regard to the drive elements even in the design of roboters. New control conceptions are shown as well as software tools for digital simulation and system design. Using these tools the dynamic and static behaviour of the drives can be calculated.

Session

MANIPULATORS (2)

CHAIRMAN'S REPORT ON THE MANIPULATORS (2) SESSION

PAPER 8. Heavy Payload Servo Manipulators in a Hostile Environment

a) The machine shown operated in extremely mechanically hostile environments, with large amounts of airborne contamination in the form of sand, iron dust and water. Questions were asked about the ability of hydraulics to survive in such environment. The speaker said that provided the entire hydraulic system was built properly with neoprene bags in the tank to prevent air exchange, fill filters to ensure clean oil is used to top up the tank, and suitable filtration (including filters to prevent ingress of dirt during pipe change) then the system would work indefinitely in this environment. Machines of this type were expected and did run for complete year between shutdowns without problems.

b) Discussion centred around the difficulty of switching from manual control to automatic control in a position loop. The easy way of combining manual and automatic control was to have the manual control generating a velocity rather than a position reference. But this gives inferior manual control to the force feedback position control system.

c) It was explained that force feedback was done in the majority of cases by hydraulic feedback. This could either be direct for short distances applications through a pressure servoloop with electrical connections through master and slave, or could conceivably be done with a hydraulic slave and an electric master arm utilising pressure differential signals on the hydraulic cylinders.

PAPER 9. Coilable Robot Design and Applications

a) Why did the robot use four wires for position control and not three as the same degrees of freedom could be achieved with only three wires? Answer, using four wires allowed two differential drives to be used and so simplified gearbox design.

b) Question, What was the machines payload? Answer, present machine carried about 10 Kg for about .5M reach.

c) Questions were asked regarding sensors in the grippers. It was explained that vision was used to close the position loop and so compensate for the high degree of compliance in the machine. Questions were asked about the lifetime of cables it was said that in the test machine there had been no problems. Questions were asked about how the links were positioned. The answer was by knowledge of the winch position and the theoretical length of the cables. Compliance could be compensated for in an open loop way by knowledge of the position of the machine but final position accuracy was dependent on vision as part of the loop closure.

PAPER 10. Automatic and Manual Operation Modes of the EFTR Maintenance Manipulator

The motors ran with surface temperatures above 100°C and because of this there was no electronics associated with the motors. It was explained that these motors were especially developed to meet the conditions.

The tribological problems of high vacuum, high temperature applications were discussed. This was solved by the ECR method of coating with Lodum disulphide. Maintenance is carried out in the anti-chamber. The design philosophy assumes that the joint cannot jam.

The only electronics in the area is the other TV sets which are cooled to 150°C.

PAPER 11. Problems Relating To The Design Of A Manipulator With A Very Large Reach Including And Example For A Specific Application

It was stated that to reduce the backlash in the first axis double motors were used.

There was discussion of the problems of damping a structure of this length natural frequency. To achieve this pressure and accelerometer feedback was being considered.

PAPER 12. The Wire Welding Manipulator

Backlash in the joint was stated to be 3 minutes of arc. Questions were asked about the retrieval after failure. It was said that the machine would relax slowly if there was a motor failure and could be pulled out gradually.

General Comments

The papers covered a wide range of machine sizes in terms of reach and inertia handling capability and showed that the majority of work had been done on smaller machines, such as the wire welding manipulator. The area of work being tackled at present tended to be in long reach high payload machines. The paper presented by Moog showed that high payload devices could operate in very arduous environments on a continuous production basis, and was a first step into very large machines. The problems tackled here were being extended, with work being done on Putzmeister type equipment where a major part of the problem would be the control of very flexible structures in terms of closed loop stability and the theoretical correction of position offsets. Another long reach device with similar problems in terms of positioning abilities was the TFTR maintenance manipulator. The impression was given that much of the nuclear industry work had been done on purely manually controlled devices and that the steps taken towards automation in terms of computer control, were to some extent ignoring the work that had already been carried out within the industrial Robot industry. There seemed to be an assumption that programming techniques of industrial robots was not at all applicable to the nuclear application because of the requirement for manual control and the requirement for the adaptability for sensors. There is possible less difference in reality and effort can be saved by taking standard industrial robot controllers and automation controllers, and various centre controls to give programmability as an option to manual controlled machines. Industrially the robot controller is a well accepted building block, not only for robots in terms of machines with multijointed limbs, but in terms of flexible manufacturing lines involving a large number of machines co-ordinated, position controlled. I believe the nuclear industry could use such controllers as a basic building block around which to interface their specialised requirements. This possibility I believe is being ignored.

DEREK WALKER

draft

heavy payload servo manipulators in hostile environments

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servo manipulators are usually highly sophisticated small payload devices designed for use, at limited work rates in relatively clean environments. larger manipulators have tended not to have the sophistication of the force feedback and closed loop position control of the smaller devices. a major reason for this is the difficulty of stabilising the control system, and producing a precise response at high payloads. these problems have been overcome, and the paper describes a range of industrially robust closed position loop force feedback manipulators, capable of handling payloads of many hundreds of kilograms, at reaches extending to several metres. these machines have been developed independently of the work being done in the nuclear and underwater industries, and were initially built to meet the needs of heavy industries, such as foundry and forging. the demand for these developments stemmed from the dangerous working conditions and high manning level requirements, prevelent in these industries. these are not places where one would expect to find highly sophisticated servo controlled devices, operating on a three shift basis, six days a week. to survive, the control electronics and servodrives have to withstand airborne silica dust, severe vibration, heat and high overloads, on a continuous basis. although designed for extreme environments, the same technology can be applied to any manipulator.

to date, manually controlled manipulator and computer controlled robots have tended to follow separate development routes. the requirements of each type of machine in terms of performances, controls and drive characteristics have been quite different, with the result that a robot does not make a good manipulator, and vice versa. this divergence becomes more marked at higher payloads.

the differences are discussed, firstly, against the author's background in developing robots and manipulators (which are between 10 and 200 times greater in inertia handling capacity than the larger material handling robots common to industry), and secondly, against his present involvement in specialised hydraulics and electric servo-drives and control systems.,

these differing requirements and solutions become increasingly important as sensor technology advances, leading to hybrid devices with manual and computer control capabilities. the ability to convert human movements and computer references into physical movements becomes even more critical as ai technologies develop, leading uultimately to highly autonomous machine behaviour.

the paper summarises the work done, the techniques employed, and looks at how these techniques can be developed for hybrid robot/manipulators.

COILABLE ROBOT DESIGN AND APPLICATIONS

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Problems of access to confined spaces can occur with conventional six degree of freedom robot configurations, particularly in nuclear plant, fire fighting and emergency rescue operations. The ability of a robot to avoid obstacles and find routes through narrow passages can abviously be improved by adding more degrees of freedom. This technique is limited however by the lengths of any rigid links between joints, since they cannot negotiate sharp turns encountered on the route. Efforts to improve obstacle avoidance by making all rigid links as short as possible leads to a multijointed robot with a chain of revolute joints alternating in direction by 90^o from one joint to the next. If motors are incorporated in the increased number of joints the weight of the robot relative to its payload at full horizontal extension is also increased. This problem can be overcome by taking all the joint actuating motors back to the base of the robot but there remains a limitation with revolute joints in that only sharp bends for which the plane of the bend happens to correspond with the plane of the joint movement can be negotiated. The solution has been to eliminate all revolute joints and to replace them by bendable links that can be bent in any direction through a right angle. Thus a single bendable link, positioned vertically when unbent, can be bent to have any elevation or tilt from 0 to 90^o and any azimuth or pan from 0^o to 360^o under the influence of four control cables working in differential pairs and hence providing the equivalent of two revolute degrees of freedom in a single bendable link. When bent by the maximum amount of 90^o the link central axis of length ℓ forms a quarter of a circle of diameter

$D = 4\ell/\pi$ and hence four such links in the same plane would form the complete circle of minimum diameter D. With zero bending the four connected links uncoil to form a straight link of length $4\ell = \pi D$. By slightly altering the angles of the four links they can be made to form one turn of a closely wound solenoid coil and in general 4n links can form a "Coibot" or coiled robot of n turns capable of uncoiling to reach almost any point within a sphere of radius $4n\ell$ metres or of passing through $4n\ell$ metres of a three dimensional maze of pipes only slightly larger in diameter than the Coibot, providing the minimum radius of pipe bend is not less than $\frac{D}{2}$. The minimum radius of curvature of the Coibot determines its outside diameter which also fixes the smallest circular access hole through which it can all pass to perform inspection, welding and fire fighting etc. The distance from the Coibot central axis to the centre of the coil is D/2 and hence the maximum diameter is D, assuming a constant circular cross section throughout the length, although a tapering Coibot is feasible. In the tightly coiled solenoid configuration the Coibot fits inside a cylinder of length Dn, diameter 2D and volume $n\pi D^3$. The volume of the fully uncoiled straight Coibot is $\frac{\pi D^2}{4} 4n\ell = \frac{\pi}{4} n\pi D^3$. A small eight DOF Coibot has been constructed to give n = 1 (1) and this has been equipped with a gripper and vision system employing an image guide that passes through the hollow centres of the links. Image analysis(2) enables objects to be recognised and tracked by the robot gripper.

Further research will be directed to developing a larger Coibot with more coils, a greater payload and the facility for teleoperation through a small hand held master containing radius of curvature sensors for each link so that any shpae is reproduced on a larger scale and with considerable power amplification in the slave Coibot. Collision avoidance will be through tactile or proximity sensors on the slave feeding back to the controlling computer and end effector manipulation will be through video monitor feedback from the in-hand camera on the final link.

Co-operation with organisation envisaging applications and control strategies for Coibots of appropriate size, degrees of freedom and power would be welcomed.

Related Publications

Taylor W.K., Lavie D. and Esat I.I. "A Curvilinear Snake Arm Robot with Gripper-Axis Fibre-Optic Image-Processor Feedback." Robotica Vol 1, pp 33-39, (1983).

Taylor W.K., Lavie D. "A Microprocessor-Controlled Real-Time Image Processor". Proc IEE, Vol 130, Pt E, no 5. September 1983.

ADVANCED ROBOTICS WORKSHOP, MAY 11 - 13, 1987, KARLSRUHE 10

Automatic and Manual Operation Modes of the TFTR Maintenance Manipulator

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Summary

The remote in-vessel operations scheduled to maintain the Tokamak Fusion Test Reactor at Princeton, NJ, USA, comprise inspection, calibration, cleaning and protective tile replacement. The environmental conditions inside the torus vessel are ultra high vacuum, moderate γ-radiation and 150°C temperature of the vessel structure.
The Princeton Plasma Physics Laboratory (PPPL) and KfK are jointly developing a maintenance manipulator (MM) which can perform these tasks.

The manipulator system as shown in fig. 1 consists of a non articulated cantilever arm which is mounted on a carriage, an articulated arm consisting of 6 links and exchangeable end effectors which may be a general inspection arm (GIA) with TV cameras and inspection devices or a pair of electrical master slave manipulators (TOS M/S). The carriage runs on a 6 m long rail system in an ante-chamber which is permanently attached to the toroidal TFTR vacuum vessel. Fig. 2 is a top view of the TFTR and the ante-chamber with the MM in retracted, partly extended and fully extended positions.
The p ayload of the system is 5 kN at the end effector interface, the total extension more than 10 m and the maximum permitted cross section for all parts passing through the TFTR entry port is about 0.75 m high and 0.33 m wide.
The environmental conditions have largely influenced the design concept. The operational requirements (automatic and manual control, retrievebility in the case of failures) have contributed to that.
As far as possible a modular composition was chosen for the whole system. The modules can be easily and quickly dis- and reconnected.

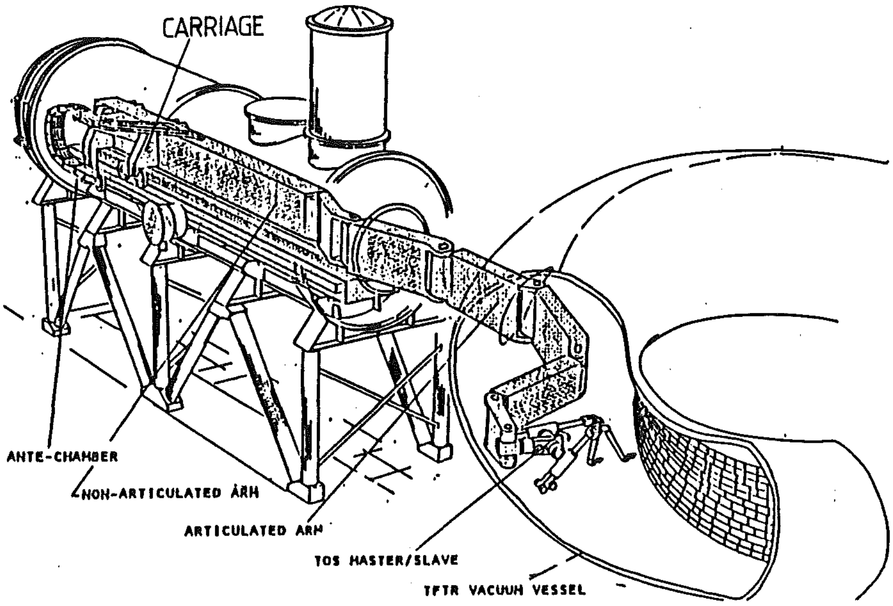

Fig. 1. TFTR maintenance manipulator system

The life time of the components should be sufficient for about 500 maintenance missions inside the TFTR torus.

Automatic or manual control for all motions is optional. The automatic control is of the point to point type. 500 points are defined along the torus center line for the interface position. Their distance from each other is about 5 cm. Another 600 points are defined for the interface orientation. The manual control allows continuous actuation of all motions with a resolution in the 1 mm range.

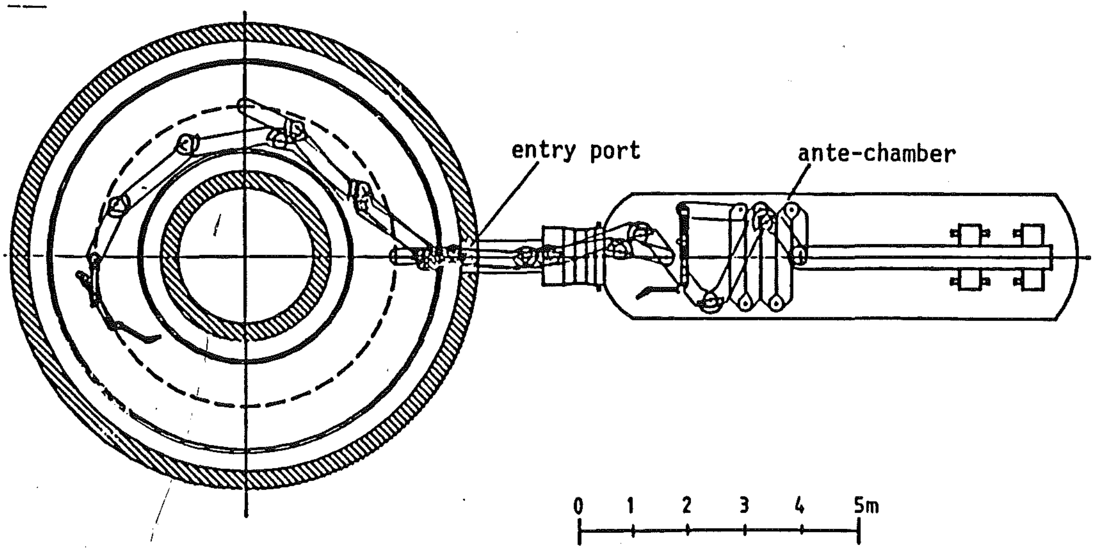

Fig. 2 Top view of TFTR with MM in various positions

The components of the control system which are located inside the elevated temperature boundary of the ante-chamber have to withstand more than 200°C because electric motors and cables can heat up to this level during operation.

Therefore no electronic components are admitted in this part of the system. For that reason and in order to reduce the number of electrical conductors a new high vacuum and temperature resistant incremental position encoder for the drive was developed using rotating permanent magnets and encapsulated REED switches.

During operation the control system continuously compares the number of pulses for the stepper motors in the drive units with those fed back from the encoders. This results a reliable position control because both motors for one joint are supplied by the same pulse generator.

Moreover this redundant pulse couting principle renders a simple hardware control technique possible which can be easily operated in the modes foreseen.

As a later extension for a free programmable MM operation the connection to a computer control system is intended.

In contrary to the MM arm the TOS M/S end effector can only be manually operated. Force feed back for all seven movements of each of both arms, power amplification and positioning ratio selection render a variety of operator controlled working modes possible.

11

Problems related to the design of a manipulator with a very large reach including an example for a specific application

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1. Problem analysis

Robots for application in an industrial environment are restricted in the following important features:
- o Reach (less than 5 meters)
- o Payload (less than 1000 kg)
- o Degree of mobility
- o Flexibility of the armstructure

The aim of a joint project currently under progress with AEG, Dornier, Putzmeister as partners from the industry is directed to overcome those problems.

2. Application of robots with a very laarge reach

There is a wide range of possible applications for manipulators with a large reach:
- positioning of platforms for machines (e.g. robots) and workers
- positioning of process equipment (nozzle for concrete pumping, fire fighting)
- handling of heavy workpieces

A large number of applications are presented in /1/. For safety reasons the machine should only be operated with a 'man in the loop' system. Such hybrid control systems are proposed in /2/.

3. Area of research and results

Fundamental problems, current research and results are secribed below:
- o Relationship between joint angle and movement of the hybrid cylinder.
  Here we have to consider several closed kinematic chains in order to achieve one mathematic solution also for movements with more than 180 degrees minimum forces at the

cylinder. A computer programme was developed to optimize those parameters. No further research is needed.

o Inverse kinematic solution for the redundant kinematic chain.

For the manipulator described above we have up to six rotatory axis to realize the positioning problem. In this case we have three redundant axis. Different solutions were tested with the following results:

- Start configuration and end configuration is given by the teach-in procedure. Linear interpolation of axis 2,3 and 4, direct computation of the remaining axis.
  This very simple solution worked in certain areas of the workspace for the positioning problem. Path planning with constant speed at the platform is not possible.
- Optimum configuration is a pitch circle. This method is only possible to realize with very simple obstacles. Another drawback is the need to bring the manipulator in the optimum configuration before starting the movement.
- Method of weighted cartesian movements related to the axis. The approach can be described as a closed solution for two axis computed four times in sequence for one step. With this simple approach good results could be realized.
- Method of related proportions of movements related to the local axis. We use the Jacobian J matrix as a 6xN matrix. If a solution exists for q_i the equation is not unique. It is possible to select one particular solution for q_i. The selection is done on a basis of satisfying a specified optimal criterion - in this case related proportions of movements. The method itself produces very good results but is time consuming.

- Flexibility of the arm structure
  The methods to compute the displacements for quasistatic conditions are state of the art - a special programme was developed to cope with this specific manipulator. Procedures to measure the displacement in each axis under different load conditions and configurations turned out to be quite complicated due to the large size of the measured structure (reach 32 m).
  In addition the finite element analysis was used to determine the frequencies of the mechanical system.

4. Further research

Currently under development at the IPA are methods for path planning considering obstacles in the workspace. First results show the advantages of the selected methods for the inverse kinematic solution for this specific task. CAD-modelling of the environment (simple models with known coordinates in space) and collision detection can be already aquired from the industry. The automatic or manual data aquisition of the coordinates from the obstacle has to be developed for the future.
A topic for further development is the dynamic control of the flexible arm structure.

5. Specific application

A video and slides are shown from power manipulators with a very large reach for concrete pumping in a difficult environment. Experience has shown that more sophisticated machinery should be developed for future accidents.

6. References

/1/ Prospekt der Fa. Putzmeister, Aichtal; PM 891-1

/2/ Wanner, M.C., Baumeister, K., Köhler, G.W., Walze, H.:
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THE "WARRIOR" WELDING MANIPULATOR

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ABSTRACT

The Warrior project (Welding and Repair Robot in Oldbury Reactors) instigated by the United Kingdom Central Electricity Generating Board (CEGB) has been initiated to carry out a continuous Metal Inert Gas (MIG) weld inside the pressure vessel of a gas cooled nuclear reactor. A vital element in the programme has been the design and development of a unique six axis manipulator arm. This machine has the dexterity, stiffness, precision and control necessary to carry out remote MIG welding in hostile and confined locations. Its extremely smooth and slim profile is particularly suited for introduction to the working zone through restricted apertures, which may be as small as 200mm in diameter.

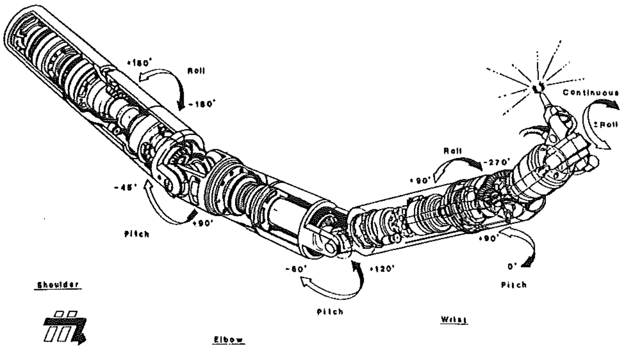
INTRODUCTION

With the advancing age of Britain's gas cooled Magnox reactors, and the increasingly strict operating requirements of the licensing authorities, it has become necessary to undertake regular inspections of critical areas of the reactor structure. Occasionally it has also been necessary to effect repairs to the reactor internals, and this work has been carried out by deploying purpose designed "work packages" via manipulators inserted down the refuelling standpipes during reactor shutdown periods. However, the scope for remote work using current manipulators is limited by constraints inherent in their mechanical designs and also in their control systems.

Tasks such as profile grinding, or arc welding may be considered to typify the more advanced maintenance jobs, and these operations require a standard of precision and control which the essentially point to point, open loop systems used in existing designs of manipulator are incapable of. The CEGB consequently wished to develop techniques to advance their capability for reactor maintenance and have carried out a programme of work to advance the enabling technologies. The details of this generic work are described by Perratt[1]. As a part of this work a specification was issued for a Prototype Advanced Manipulator (PAM). This machine was designed and built by Taylor Hitec and has been used by the CEGB to develop remote MIG welding and associated control software. Fig 1 shows a cutaway view of this 35kg payload, six degrees of freedom arm. This arm has met all expectations, and achieves a tip repeatability of better than 0.5mm.

Experience gained with this prototype proved invaluable when a specific application arose to carry out a remote weld repair at CEGB Oldbury. Whilst the PAM arm had been designed to be fully suitable for operation in the reactor environment, the specification was general in nature and it was decided that a Smaller Advanced Manipulator (SAM) would be built to optimise the design with a reduced payload requirement of 10 kgs. Thompson and Jerram[2] trace the development of the Warrior project, of which SAM is a fundamental and critical element.

Fig 1. Prototype Advanced Manipulator (35kg payload)



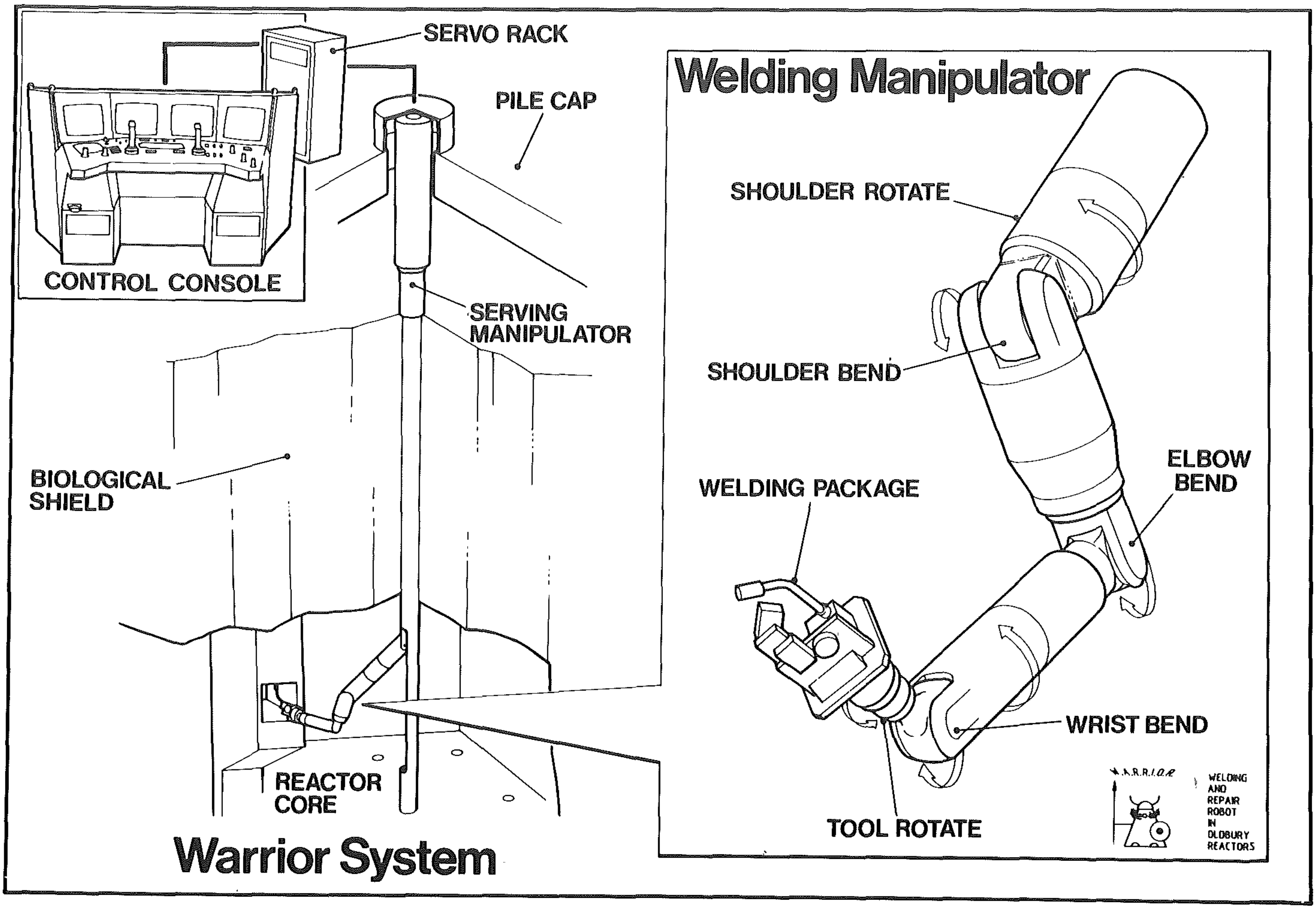
WARRIOR WELDING ARM SPECIFICATION

The essential requirement for a remote MIG welding manipulator is the ability to precisely control the welding torch electrode position and velocity, and to ensure that it is in the correct location with respect to the workpiece. The design problem is considerably complicated when the workpiece is situated many meters away from the operator, in a dark, hostile, inaccessible, hot and confined environment. Such an environment exists inside a gas cooled nuclear reactor and even during shutdown periods when maintenance is carried out, ambient temperatures of 70-80°C may be expected, with radiation levels of 10^3 rads/hr (gamma) being typical.

The difficulties are further compounded by the access route available for introducing the welding manipulator to the repair site. The refuelling standpipe at CEGB Oldbury, which is used for access, has a minimum internal diameter of 225mm, and this dictates that the profile of the welding manipulator must not project beyond the boundary of a 190mm diameter circle. The welding arm is itself delivered to its working area by a separate serving manipulator, which forms a relatively stable "base plate" from which the arm articulates. The concept is shown in Fig.2. During insertion into and withdrawal from the reactor the welding arm is folded away inside the tubular section of the serving manipulator mast. Because the machine is operating in an environment which is totally inaccessible to humans, it is essential that the equipment has very high reliability, and that in the event of a malfunction it must still be possible to withdraw the machine from the reactor. The operating zone has numerous obstructions around which the arm must reach, and consequently the design must have the maximum achievable articulation. It must have an external profile which is free from snagging points and a smooth exterior to minimise radioactive contamination pickup. In particular at Oldbury it is necessary for the wrist section to be no greater than 112mm in diameter, in order to reach one of the envisaged weld sites.

It was recognised that to carry out a remote weld in the environment and with the restrictions described above, the operator would require assistance from a remote sensing system (in addition to closed circuit television) and would need sophisticated resolved motion tip control facilities. Mechanical deflections of the manipulator system and uncertainty in the exact location of the workpiece, together with the difficulty of precise

Fig. 2 Warrior Manipulator System Concept



remote observation of the welding gun tip mean that it is not practical to teach the manipulator the welding trajectory in the usual teach/repeat manner common in industrial robotic systems. Consequently a laser range-finding device has been developed and is used to map the local weld area site, the final manipulator trajectory being calculated following an initial scan.

The manipulator control system must, therefore, have the ability to carry out complex mathematical transformations, as well as real time servo control, interlocking and operator information processing and display functions. In order to maintain the correct orientation and vector tip speed during welding, the manipulator must be capable of achieving joint speeds within a tolerance of 5% of the commanded joint speed. For MIG welding the manipulator tip speed must be continuously variable up to 100mm per second, and a position repeatability of 0.5mm is necessary. To attain a good quality weld the torch must be positioned in a smooth path free from vibration or oscillation.

The final element in the specification is the provision of inert gas, a welding cable and instrumentation wiring to the end effector.

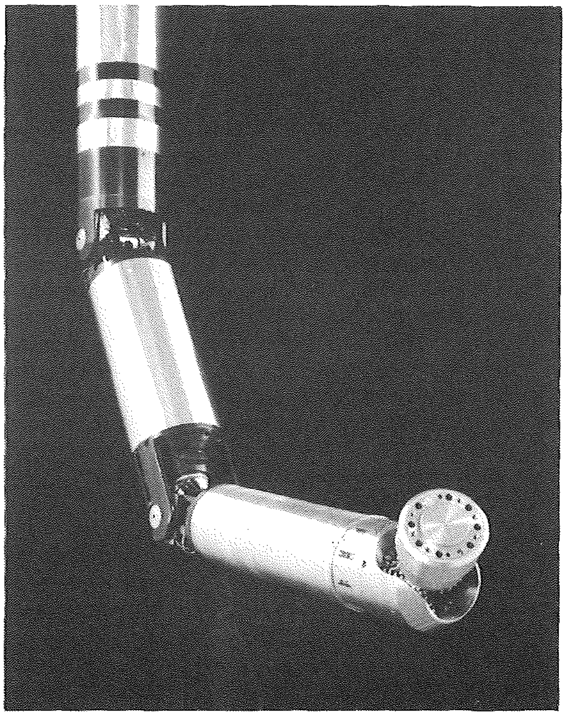
A summary of the main parameters is given in Table 1 below.

- Maximum equipment diameter 190mm
- Maximum wrist diameter 112mm
- Maximum coverage within a 1200mm radius hemisphere
- Deployment in any attitude
- Payload up to 10Kgs
- Overall repeatability of tip positioning ± 0.5mm
- Six degrees of freedom
- Speed range 0 to 0.1 m/sec vector tip speed, loaded
- 70°C ambient gas temperature
- Reactor compatible materials
- Retrievability in the event of a malfunction
- Control capability required to position a MIG welding torch for a continuous path weld

MANIPULATOR DESIGN

The limited size of the access hole into the reactor dictates the maximum sizes of joint drive component, eg motors, gearing and bearings. A traditional arm configuration has been selected, with shoulder, elbow and wrist movements, as this layout with its revolute joints is well suited to working in confined spaces, and the difficulties of routing service lines along linear axes are avoided. A total of six degrees of freedom are necessary and sufficient to position and orientate the welding torch and sensor.

Fig. 3 P.A.M



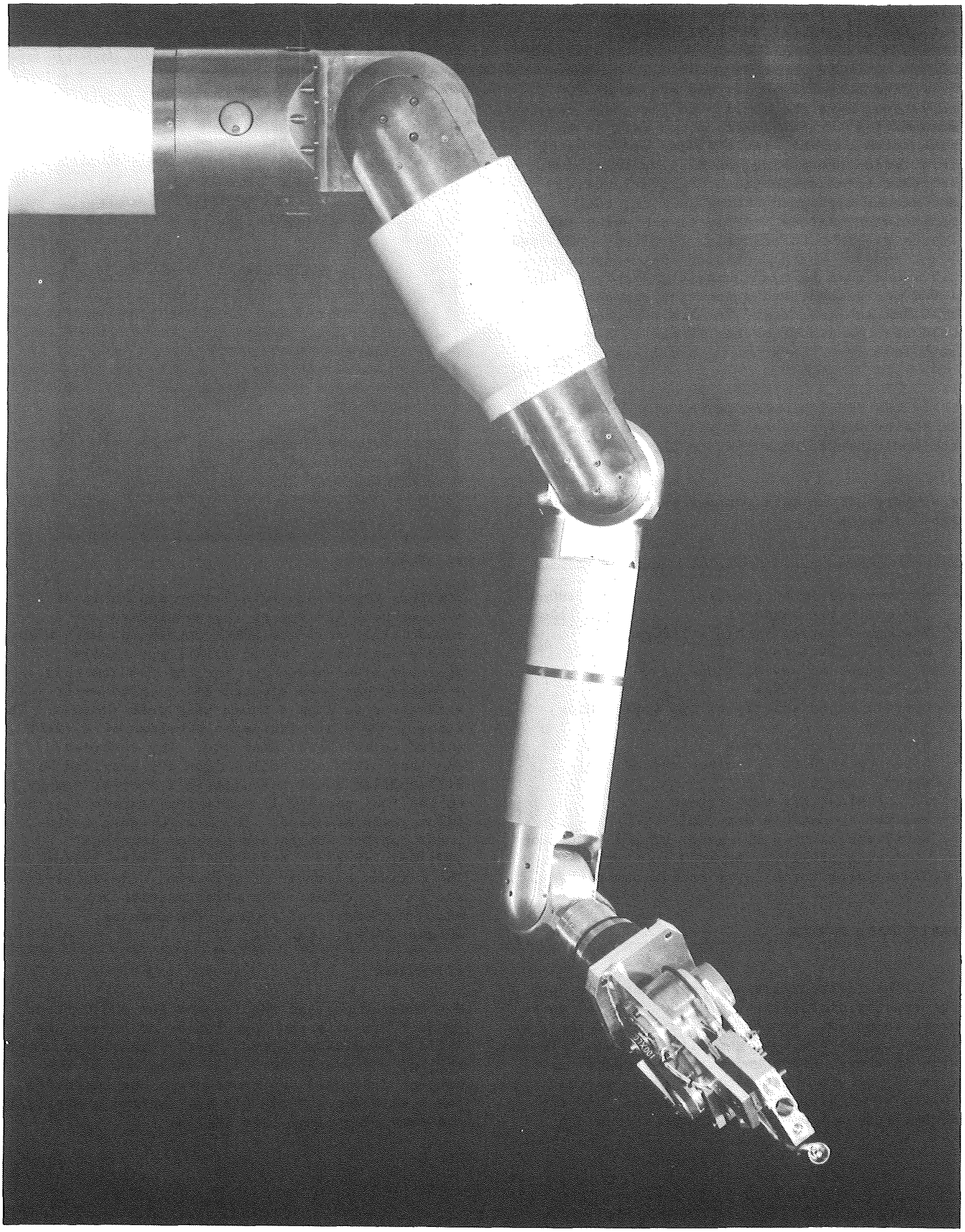
i) P.A.M.

Previous experience with remote manipulators for nuclear work had led to the development of a compact tool roll and pitch mechanism, with high torque capability, based on differentially operated bevel gearing. For the PAM arm this mechanism has been adopted and a third wrist roll axis added to form a three axis wrist module. The elbow joint articulation is provided by a right angled spiral bevel gear set. The combined shoulder pitch and roll joints are provided by a differential bevel gear set in a similar manner to the tool pitch/roll mechanism, except that no idler gears are used. In this way gear tooth loads can be reduced and gearbox loadings similarly shared between the two drive trains. The maximum diameter of this arm, (the shoulder section) is 205mm. The wrist section has a maximum diameter of 150mm. The machine weighs 230 kg. See Fig. 3.

ii) S.A.M.

The reduced payload requirement for the Warrior project arm gave the opportunity to design and build a machine with even greater precision than that of the prototype. Full advantage of the concept developed and tested with the prototype has been taken and the SAM arm employs essentially the same technology, see Fig. 4.

Fig. 4 "WARRIOR" WELDING MANIPULATOR (S.A.M.)



In particular, the use of DC permanent magnet torque motors driving Harmonic Drive reduction units is the basis of the design. A fundamental difference between the prototype and the Warrior SAM arm is in the overall layout of drive motors and speed reducers, and the means of generating rotary motion at the joints. Whereas the PAM has the drive equipment "in-line" and co-axial with the centre line of the arm sections (with bevel gears at each joint to produce the required motions), the SAM arm has the pitch motion drive components arranged so that they lie in a transverse position relative to the arm centreline. Torque is transferred from the motors to the Harmonic Drives via spur gear trains, the Harmonic Drive being located in the centre of each joint served. This results in a lighter more compact arm. Roll motion drives are arranged co-axial with the arm section centrelines. This concept reduces manufacturing and assembly complexity, eliminates the intricate gear shimming required with bevel gearing, increases the drive train stiffness and minimises joint backlash. The joint drives have been designed to backdrive when power is removed, so that in the event of a malfunction resulting in complete loss of joint control it is possible to withdraw the machine from the reactor by straightening the joints against the bottom of the standpipe. The general kinematic configuration is identical to the prototype, except that shorter limb lengths have been used. It has also been possible to increase the range of joint articulation, the following movements being obtained:-

Shoulder pitch	± 90°
Shoulder roll	± 180°
Elbow pitch	± 120°
Wrist pitch	± 120°
Wrist roll	± 185°
Tool roll	± 180°

The mechanisms are contained in four sections, shoulder, upper arm, wrist and a separate tool roll package which may be detached. Wiring for the manipulator equipment and for the tooling packages is taken through internal ducts. The welding cable is taken through the elbow section only and is loosely clipped to the wrist section. Argon for the welding gun is ported internally through drillings and rotary seal units at the joints, as are other low pressure gas services for force cooling the motors (for in reactor use) and for actuation of tooling (if required).

Lubrication of all moving parts is with radiation resistant grease. All seals, motor windings and wiring insulation have been specified with radiation tolerance of 10^7 Rads minimum.

The maximum diameter of this arm (the shoulder) is 190mm. The wrist section has a maximum diameter of 112mm. The machine weighs 140 kg.

JOINT SERVO DRIVES

To position the six manipulator joints accurately and repeatably, with fine resolution, high performance servo drives are provided. Each drive is operated under closed loop control. The computer generated position demand signal is compared in a software discriminator with the actual joint angle measured by a feedback resolver to 16 bit resolution. Any error between the two is amplified and used to provide a correcting signal to the joint actuator. A minor hard-wired velocity loop is also incorporated, the velocity signal being provided by a tachogenerator mounted on each drive motor shaft.

Each of the six drives is continuously controlled, and the servo systems 'lock' the joints in position when they are required to be stationary.

The choice of joint drive actuator is usually a complicated matter when high performance is required, and the relative merits of pneumatic, hydraulic or electric prime movers were assessed. The coupling of a DC frameless torque motor to a precision Harmonic Drive speed reduction unit offered the prospect of a very compact high torque, low backlash 'backdriveable' servo drive, and this approach was adopted. The decision was made to utilise brushed rather than brushless motors, as it was felt that the additional wires required for electrical commutation of a brushless motor could present additional routing problems in the confined cross section area available. It was also decided to provide the velocity feedback signal by direct measurement using frameless tachogenerators closely coupled to the motor. It was considered that this method of rate feedback would provide the most assured method for smooth control of the manipulator tip, essential for remote welding, and this approach has proved to be very satisfactory.

Resolvers were selected as being the most appropriate device for providing the joint position feedback signal. They were selected primarily for their radiation and temperature resistance, accuracy, resolution and relative immunity to interference from electromagnetic influences.

In the prototype arm, housed, brushless units are used. In the Warrior arm, pancake (slab) resolvers have been installed as they are extremely compact.

Following discussion with the motor manufacturers, and as a result of detailed calculations, special motors were built with the best torque/speed characteristic achievable in the space available. High temperature motor windings were also specified. In order to improve heat dissipation from the motor windings and the surrounding housings, cooling air passageways are provided.

The servos are driven by pulsed width modulated servo amplifiers with a switching frequency of 20K Hz. Resolver to digital converters provide the resolver signal in a 16 bit digital form. The position loop is closed via software, whereas the velocity loop is hard-wired directly into the servo amplifier. The proprietary servo amplifier contains features for open circuit protection, and the maximum current delivered to each joint can also be limited by an external adjustment (so limiting the joint torques). Other features available are velocity gain control and dynamic performance adjustment networks.

CONTROL SYSTEM

The control system for the Warrior manipulator arm also incorporates the hardware and software required to control the serving manipulator. In total, nine degrees of freedom are available to the operator, plus other controls for associated television viewing cameras. The serving manipulator has a vertical movement, an azimuth rotation and a pitch axis movement. A separate control system is provided for welding process control. During operation the serving manipulator is used to deploy the SAM arm into position, and its joints are then "locked". The co-ordinates of the welding manipulator attachment point are referenced and used as the datum for the welding manipulator movements.

1. Hardware Overview

The operator controls are mounted in a desk, which contains joysticks, push buttons, visual display units and television monitor screens. As well as the operator controls, the control desk contains 16 bit Intel multibus computer hardware, with 512 Kbyte multibus RAM plus 512 Kbyte on-board RAM.

Three processors are used, the control processor (8086) the display processor (8086) and the resolved motion processor (8086). The multibus system is also used to communicate with the welding system processor (8086). The system has a 20 Mbyte Winchester disc unit for program storage. Other electronic hardware comprises resolver to digital converters, a resolver oscillator card (400 HZ), a watchdog card, a desk interface card and the associated power supplies.

A separate servo control cabinet is provided which houses the servo amplifiers, interface modules, a master card, isolator, fuses and the power supplies. This servo cabinet is positioned on the reactor pile cap in order to minimise the length of connecting cable between the manipulator and the servo control electronics. It has local controls which provide a very basic control capability. The servo cabinet is linked to the operator's control desk, which is 50 metres away from the pile cap, by deck cables.

2. Control Overview

The 16 bit multi-processor computer system is used to control the arm and serving manipulator in their normal mode of operation. The control processor performs the main control functions of the manipulator drives. It closes the position feedback loops by reading the output of the joint angle resolvers, and uses algorithms to compute a velocity demand for each joint servo drive. Interlocking and fault conditions are also dealt with by this processor.

The display processor is concerned with the display of data on the operator's visual display unit (VDU), and with the processing of commands received from the operator's keyboard. A table of position data can be displayed for each joint, together with the limits of operation (which are adjustable by the operator) for confined area working. A second VDU is also driven by this processor which displays the serving manipulator axes and alarm conditions.

The resolved motion processor performs the co-ordinate transforms required to position the manipulator tip in the desired attitude and velocity, and outputs joint velocity demands to the control processor. This processor can receive commands from two 3-axis joysticks, or from the welding computer.

There are three levels of control available.

Level 1 is a backup control which does not use the computer system and is for emergency use in the event of failure of higher modes. It is selected and operated at the servo control cabinet. In level 1 there is no closed loop position control or software fault interlocking. However, if the computers are running the joint positions are displayed.

Level 2 is a normal manual control. Using four joysticks (two 3 axis joysticks for SAM, one 2 axis and one single axis for the serving manipulator) the operator can position 9 manipulator joints at speeds proportional to the joystick angles.

Level 3 is the resolved tip motion mode.

3. Software Overview

The control processor is the main functional processor. The program is looped around until 20 milliseconds have elapsed, which provides a fixed sampling time. The manipulator joint servo commands are then updated.

The first part of the program checks for possible faults and determines what action (if any) is required, which can range from no action at all to complete de-energisation of the system dependent on the fault priority.

It also reads the joystick inputs and determines what demand velocity (if any) is required for each joint, as well as reading the target position to which the joint is to be driven. Finally, information is transmitted and received via a common area of memory to and from the other processors.

The second part of the program may take one of two forms depending on the level of control selected. In level 1 control the computer only reads the joint angles and converts these readings for display by the display processor. The program executed for the level 2 and level 3 control is the same, except that a subroutine is called which implements a closed loop position control strategy based on single joints. The position of a joint is held stationary unless a velocity demand is received, either from a joystick movement or from the resolved motion computer.

The display processor displays the manipulator information to the operator, and carries out the interactions required for changing certain parameters of the manipulator. Six independent routines are used which communicate with each other by means of flags. These routines receive data from the operator via a keyboard, and transmit information to the relevant VDU. Other functions include interprocessor communication and status checking.

The operator has two VDU displays, the Operator VDU and the Alarm VDU. On the Operator VDU (with a keyboard) he may select either joint angular positions or a level 3 display showing the position of the SAM tip in a co-ordinate frame system.

On the Alarm VDU (without keyboard) the serving manipulator and camera joint angles are always displayed.

In addition to these displays, warning messages may appear on either VDU.

The resolved motion control processor inputs velocity demands, communicating with the control processor and display processor. A discussion of the software structure is beyond the scope of this paper.

TESTING AND PERFORMANCE

Both the prototype and the Warrior arm have been subjected to a sustained and rigorous series of tests. These include full payload endurance tests of 30 hours continuous running, both at ambient room temperature (20°C) and at 75°C in a warm box. Other tests have evaluated the velocity and position control capabilities. The prototype has been in constant laboratory use for over two years and in September 1986 was used to demonstrate a fully automatic multi-run remote MIG weld, for the first time. This weld was of excellent quality. The Warrior arm has recently been fully commissioned and integrated with the serving manipulator. It has demonstrated extremely smooth velocity and position control and has amply met the specification requirements. Tip position repeatabilities of 0.25mm have been measured, at full reach.

FUTURE PROGRAMME

It is intended to couple the welding equipment to the Warrior system in the immediate future. The manipulator is to be put into the Oldbury reactor in December 1986, and the system evaluated in the reactor environment.

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APPLICATION STUDIES AND CONTROL SYSTEM DESIGN FOR ROBOTS WITH COOPERATING LIMBS

Present status of research activities at the Technical University of Darmstadt

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Abstract: The paper gives a survey of a research project on robots with multiple cooperating limbs, which was started in 1985, covering the analysis of performance features and possible applications of such advanced manipulation systems, and the development of a new, non-master/slave strategy for coordination of cooperating arms. Some results of the application-oriented studies are presented, the main elements of the new coordination strategy are introduced, and simulation and hardware test facilities being created for the project are described.

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1. Introduction

At the Technical University of Darmstadt, research in the area of advanced manipulation systems featuring cooperative use of multiple limbs (arms or legs) is being pursued under the following topics:

- evaluation of performance features
- identification of application areas

- development of coordination strategies
- development of a multi-arm simulation system
- realisation of an experimental bi-arm robot system
- collision avoidance

This paper presents the research project under these various aspects, discusses present status and future plans and gives some highlights of the results obtained so far.

2. Evaluation of Performance Features

In view of the different methods used for their evaluation, we have made a distinction between qualitative and quantitative performance features. Qualitative performance features can be evaluated simply by comparing lists of classes of operations that the robots can perform, whereas the evaluation of quantitative performance features (i.e. of features which are characterized by a numerical value) requires more sophisticated methods of analysis or measurement. In both cases the results may be weighted by the relative importance of the performance features in a particular application.

2.1. Qualitative Performance Features

This section gives a brief survey of the most important qualitative performance features which are distinctive of multi-limbed robots:

- A robot with multiple limbs possesses a high degree of functional redundancy which can be used to increase the reliability or the speed with which a task can be performed.
- The gain in reliability is particularly high in cases where a robot is not accessible for manual repair, because with multiple arms a mutual repair capability can be built into the system.
- A multi-limbed robot is capable of multiple simultaneous actions. Many tasks can only be achieved if such a capability is provided.
- Multiple arms can control shape and vibrations of an object. This is due to the ability to apply internal forces and torques to the object (i.e. pairs of forces/torques whose external effects cancel each other).
- The work envelopes of the individual arms can be combined if the manipulated object is passed from one arm to another.

- A possibility to <u>optimize dexterity</u> is present when there is overlap between individual arm workspaces. The object can then be passed to the arm having optimum access to the target location.

2.2. <u>Quantitative Performance Features</u>

The quantitative performance features that have been evaluated in our studies are of particular importance in connection with precise handling of large objects. Up to nw we have looked at the following features:

- positioning accuracy/repeatability

- positioning stiffness
  (= external disturbance force rejection) and

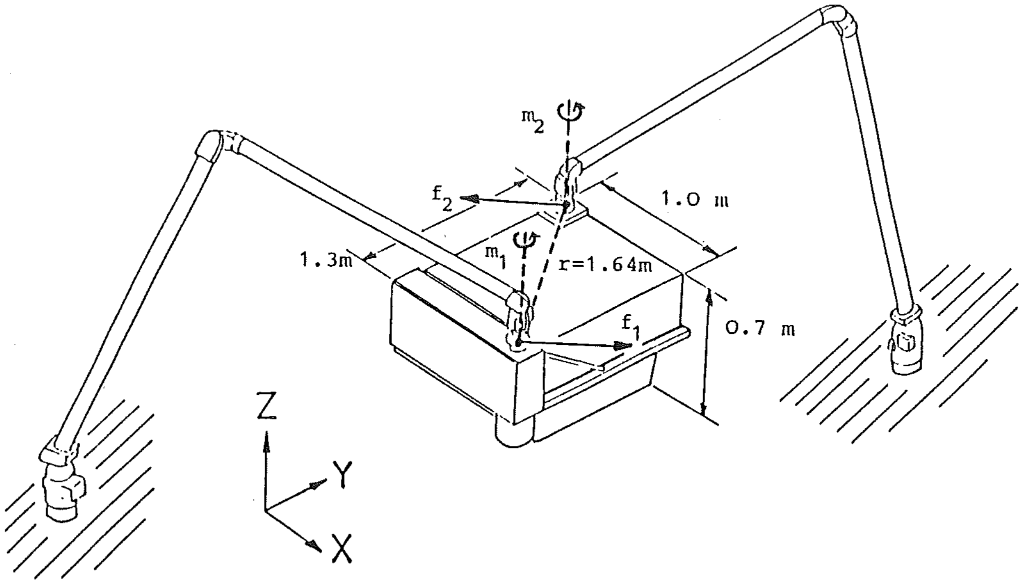
- maximum force/torque capability

In contrast to the common definition of these values for a single arm, which is related to the end-effector, we were interested in performance features related to a reference point on the object being held by one or more arms.

It was not the primary goal of our studies to determine these performance features for a particular application; we rather wanted to identify the general relationship between the end-effector-related values for the individual arms (which we assumed to be known) and the corresponding payload-related performance feature values. We found that, as far as positioning accuracy, repeatability and stiffness are concerned, the payload-related values are a linear function of the end-effector-related values, which can be expressed in form of structurally simple matrix equations. We have derived these equations (to be published in /1/) and verified them by comparison with the results of finite element analyses which were performed for a number of test cases. The maximum force/torque capability at a reference point on the payload may be obtained as the solution of a constrained optimization problem, using standard numerical algorithms (e.g.E04VAF.from the NAG library /2/).

We consider our methods for the determination of payload-related performance feature values in single- and multi-arm configurations as important tools for system design and concept trade-off (single- or multi-arm solution?), because they permit the performance of a very complex system to be estimated on the basis of performance feature values for the system components, which are much more easily obtained. The possibility to predict payload-related performance feature values is also very useful in the planning of operations where certain critical values of such features have to be guaranteed. The methods can be used, for example, to determine the best of several possible grasp configuratins for exerting a torque about a given axis.

For an example of the superior performance of multi-armed robots consider the scenario of fig.1, where two space manipulator arms handle cooperatively an in-Orbit Replaceable Unit (ORU). With a force/torque capability of 100 N and 50 Nm for each arm, and with the given dimensions of the payload, a torque of 264 Nm can be produced about the global Z-axis. This is achieved by combination of the maximum torques of each arm and another torque component of 164 Nm, which is produced by a pair of forces applied by the arms, using the distance between the two grapple interfaces as a lever arm. A full record of the results of our comparative evaluation of performance features of single- and multi-limbed robots will be given in /1/.



<u>Fig.1:</u> Cooperative handling of an in-Orbit Replaceable Unit (ORU) by two space manipulator arms: Exerting a torque about the global Z-axis.

3. Identification of Application Areas

Our interest in robots with cooperating arms has been roused by the problems of automatic servicing, maintenance and repair, which will very likely be required in future large scale space projects (Space Station with Columbus, space industrialization, etc.). Such tasks will require a broad spectrum of manipulative skills even for nominal operations, and it must be kept in mind that there will inevitably be contingency situations where the task elements and the environment will be much less cooperative than in the nominal case. The required level of versatility and dexterity can probably only be provided by a servicing system with at least two arms. Additional limbs may be required if the system is to be able to walk on legs and/or berth itself to the various work-sites.

We think that simular requirements as in the sketched space scenarios may come up also in other hostile environments. We expect applications of multi-limbed robots in high radiation areas and at under-water work-sites, where they will perform tasks that would, under more favourable environmental conditions, be done by human workers with their two ams.

4. Development of Coordination Strategies

The use of multi-armed robots requires some kind of inter-arm coordination, which may be more or less tight, depending on the type of cooperation between the arms. Cooperative handling of large objects, as introduced above in this paper and exemplified by fig.1, poses the most severe requirements concerning speed and accuracy of the inter-arm coordination strategy. Bad coordination may lead to high internal forces in the closed kinematic chains, which may cause damage to the arms or the load. Our work on coordination strategies is focused on this worst case situation. We have studied several strategies proposed in the literature and developed a new one of our own.

4.1. Master/Slave Strategies

In a rough classification of the coordination strategies, one can distinguish between master/slave and non-master/slave approaches. The master/slave method is mentioned in the literature /3, 4/ only in connection with robots whith no more than two arms. It is characterized by strictly fixed and rather different roles of the two arms:

One (the master) is the leader, with pure position control, and the other one (the slave) is the follower, being force controlled, usually about a nominal motion trajectory. In other words, the motion of the master has priority over the slave motion. An extension of the master/slave strategy for more than two arms will be difficult, if not impossible, because the basic concept leaves the priority relations between multiple slaves open. It would be necessary to go from binary to multi-valued priority relations, and one would have to find a possibility to reflect the different priorities in the control laws of the corresponding arms. This is still an open problem. Another disadvantage of the master/slave strategy lies in the fact that the fixed allocation of "leader" and "follower" roles prohibits optimization of operations. Finally, if only the slave is equipped with a force/torque sensor, there is no way to distinguish between internal and external forces and torques, the consequence being that any contact of the payload with surrounding objects will severely disrupt the control.

Our conclusions from this theoretical argument about the limitations of the master/slave strategies are supported by the results of the experiment shown in fig.2. The task for the two arms, which were controlled in a master/slave fashion, was to grasp and handle a large object by pinching it in between the "flat hands". It turned out that it was difficult to correct for speed differences between master and slave if the motion was in the plane of the hand surfaces, and the detection of payload touch-down at the (unknown) final position was not very reliable, due to the problems with the determination of external forces.

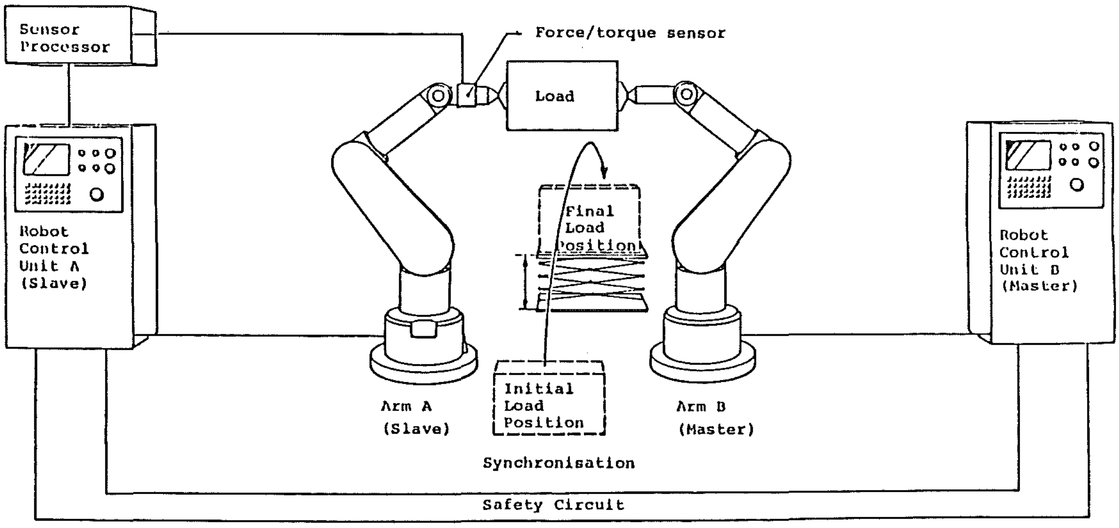


Fig.2: Bi-arm handling of an object without a suitable grapple interface, using a master/slave coordination strategy

4.2. Non-Master/Slave Strategies

As we have not yet found a sharp definition of a non-master/slave coordination strategy, we shall begin this section with an attempt to formulate one. In our opinion, a non-master/slave method should fulfil the following criteria:

a) The basic principle must be applicable for the coordination of an arbitrary number of arms.

b) The control of each individual arm must be concerned with both of the two principal aspects of mechanical manipulation: motion and force. This implies that the arms must be equipped with the respective sensors, i.e. each one must have a force/torque sensor as well as position encoders and (optionally) tachos.

c) The coordination system must provide explicit or implicit mechanisms to control the use of the redundancy inherent in a multi-arm system, i.e. to specify <u>how</u> the arms should cooperate. A possibility for the user or an intelligent planning system to exercise explicit control over the way of cooperation would be a very desirable feature. As a limit case, it should be possible to set the redundancy control parameter(s) so as to realize cooperation of two arms in a master/slave fashion.

d) The coordination system must be able to identify and control forces and torques resulting from a contact of the payload with an external object (external forces/ torques).

e) The coordination system must be able to identify and control (i.e. usually eliminate) counter-active forces exchanged between the arms via their common payload (internal forces).

It is clear, by this definition, that a non-master/slave system requires a more complex sensory and control hardware than a comparable master/slave system. On the other hand, the definition makes sure that the drawbacks and limitations of the master/slave approach, as discussed at the end of the previous section, are avoided.

The earliest example of an non-master/slave method we could find in the literature is the one of Fuji and Kurono /5/. Another example is presented by Ishida /6/ in connection with a "rotational transfer task". Also Mason /7/ outlines a non-master/slave coordination strategy as a special application of his theory of compliance and force control. We have classified these strategies as belonging to the non-master/-slave type, although they have only been presented in bi-arm settings, and although it is not always clear how they fulfil the other criteria included in the above definition. We think, however, that the authors would be able to show how their approaches fit into this a posteriori definition.

We consider our own coordination strategy /8,9/ as a rather generic specimen within the class delineated by the above definition of non-master/slave strategies. Its main elements are shown in the global control block-diagramm of fig.3: feed-forward coordination of motion and force/torque, and feed-back coordination by means of special internal and external compliance laws. Fig.4 is an expansion of the "active compliance" block in fig.3.

At the end of this discussion of non-master/slave coordination strategies, we will briefly explain how our strategy fulfils the criteria included in the above definition:

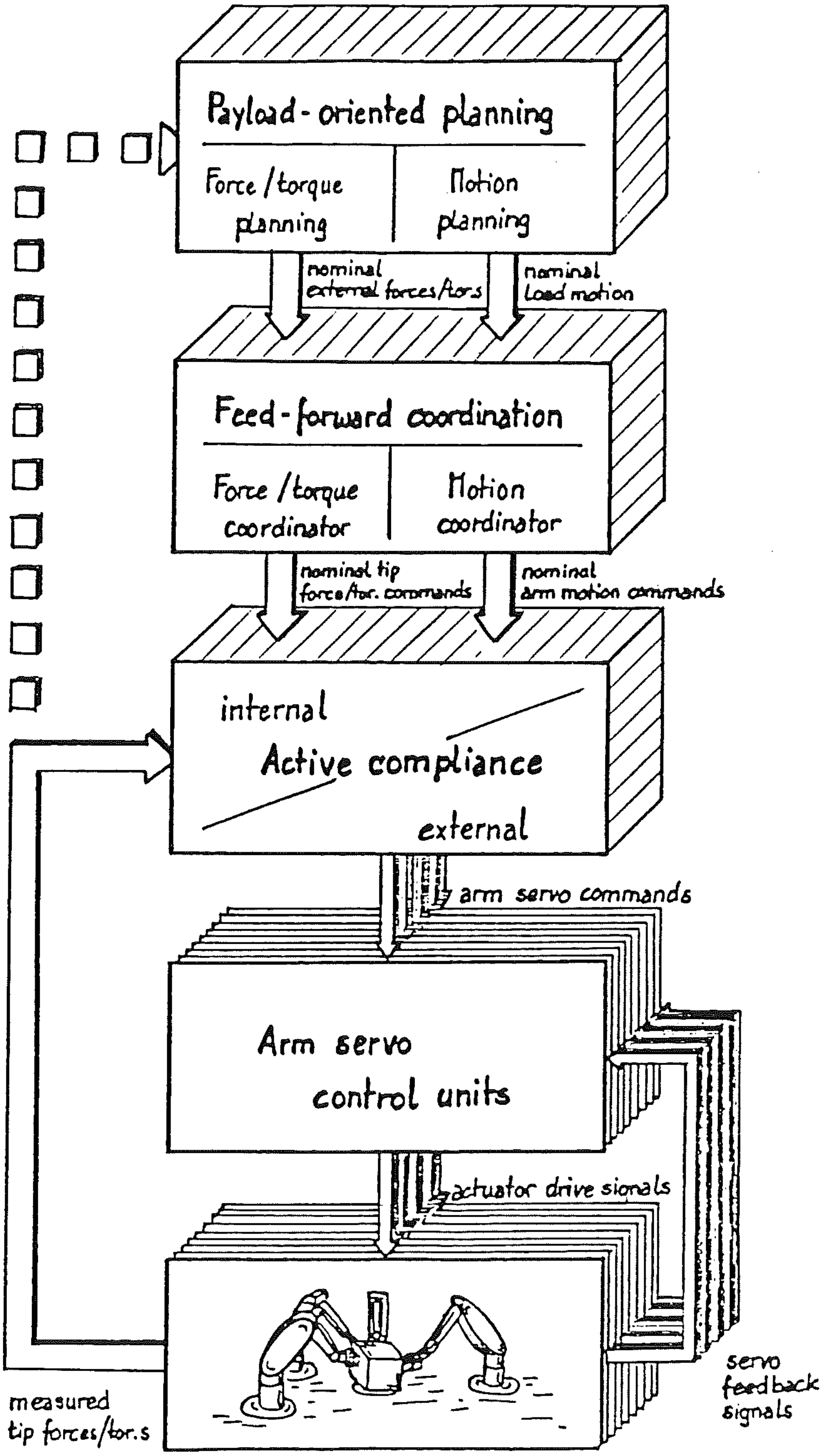


Fig. 3: Global functional structure of our control system for robots with cooperating arms

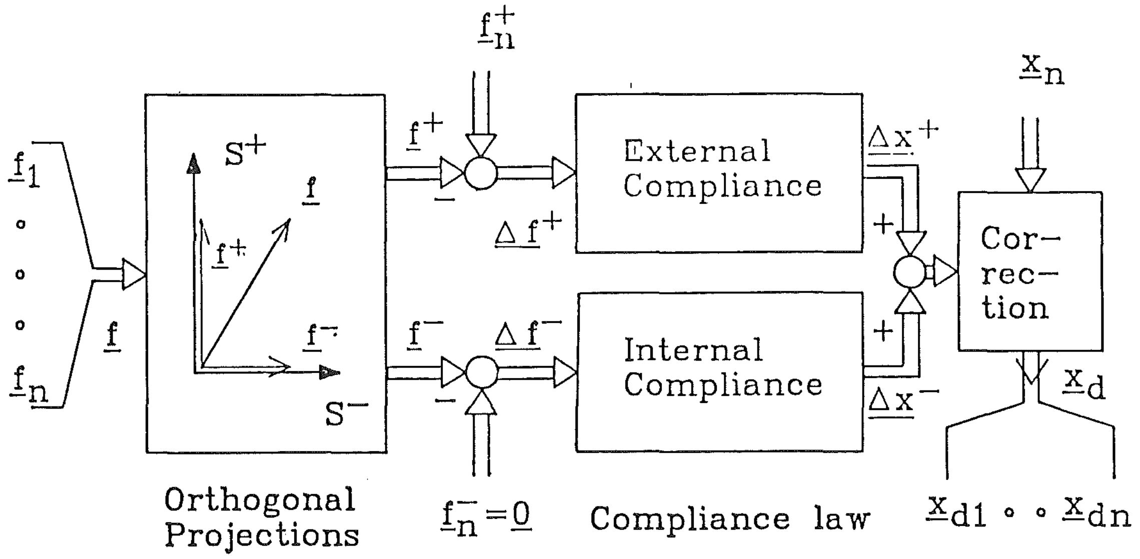


Fig.4: Feed-back coordination by means of internal and external active compliance

a) The formulation of the control strategy (as presented in /8,9/) leaves the number of arms open. A change in the number of arms is possible simply by an adjustment of the dimensions of matrices and vectors and by specification of the appropriate number of control parameters, while the basic structure of the equations remains unchanged.

b) The feed-forward coordinator plans motion and force/torque trajectories for all arms. Each arm is assumed to be equipped with a wrist force/torque sensor. The combined output vector of these sensors is processed by the active compliance algorithm which, in the general case, applies corrections to the nominal motion commands for every arm.

c) A linear force distribution law specifies how the cooperating arms are to share the forces and torques required to accomplish a given task. The force distribution law can be adjusted by direct input of a force distribution matrix, by the assignment of cost coefficients to components of force and torque exerted by the individual arms, and by specification of the coordinate frame in which the force distribution law is to be evaluated.

d) and e) External and internal components of force and torque are determined by projection of the combined measurement vector $\underline{f}$ onto orthogonal vector spaces S^+ and

S^{-} . The external compliance law controls the interaction of the payload with objects of the environment, while the internal compliance law reduces the level of counteractive forces in the closed kinematic chains.

5. Development of a Multi-Arm Simulation System

By the extension of an existing program /10/ for dynamic simulation of a single manipulator arm we have created a tool to study the behaviour of our coordination strategy and to optimize its parameter settings for various combinations of manipulator arms and arm servo control systems. Requirements concerning modularity and user-friendliness were major design drivers for this simulation system. Its main features are:

- Interactive simulation model configuration from a library of modules corresponding to functional units of the physical system to be modelled.

- Flexible hierarchical configuration scheme, comprising a global configuration description and an appropriate number of arm configuration descriptions.

- Interactive input and editing functions for module parameter sets, configuration data sets and simulation run control parameter sets.

- Automatic storage, retrieval and documentation of module parameters sets, configuration data sets and simulation run control parameter sets.

- Recording of a configurable set of process variables during a simulation run.

- Interactive retrieval of recorded process variable traces and presentation in graphical or tabular form.

The library from which the simulation model may be configured includes the following modules:

- Command modules: choice between joint space motion planning (for use with a single arm only) and load-related cartesian motion planning (for a single or several cooperating arms).

- Coordination module.

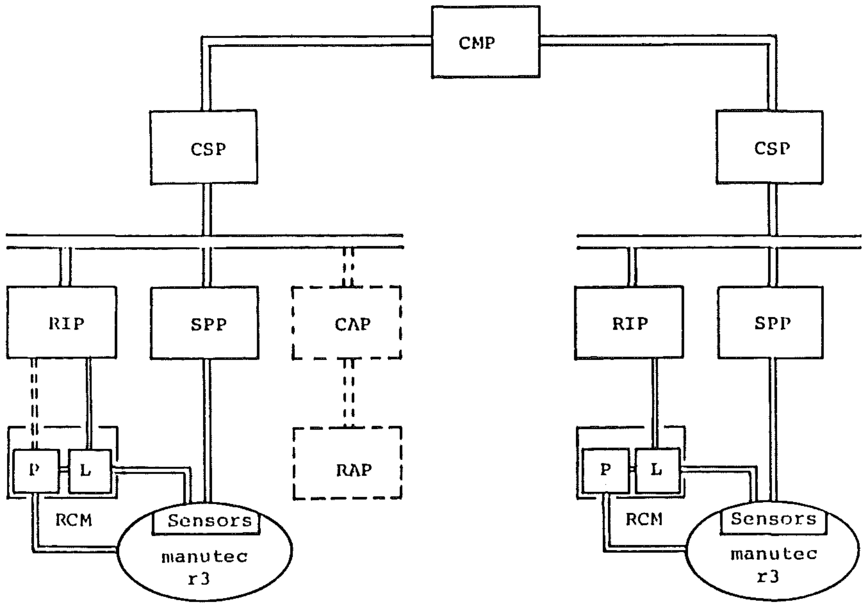
- Cartesian control module.

- Joint control modules: several centralized, decentralized and adaptive control schemes.

- Drive train modules: motors, gear stages.
- Arm dynamics module: arbitrary chain-structured kinematical configurations.
- Sensor modules: tachos, angular encoders, wrist force/torque sensors
- Load dynamics module: choice between user-supplied model and standard rigid body model with rigid or elastic mechanical interface to the arms.

The dynamics of an arm together with its servo control system may also be represented by a so-called "virtual robot model" with a prescribed linear, decoupled behavior in cartesian coordinates. This feature allows the application of model reduction techniques in the first steps of the design of a coordination controller.

6. Realisation of an Experimental Bi-Arm Robot System



CMP: Coordination master processor
CSP: Coordination sub-processor
RIP: Robot interface processor
SPP: Sensor pre-processor

RCM: Siemens Robot Control M
P - Power conditioning unit
L - Logic unit
CAP: Cartesian arithmetic processor
RAP: Robot arithmetic processor
(RAP and CAP not used in this context)

Fig.5: Configuration of the experimental bi-arm system ARC2 (Advanced Robot Control system for 2 arms).

The next major step in our research project on robots with cooperating arms will be the realisation of an experimental bi-arm system on the basis of two normal industrial robot arms. We will use this system as a hardware test-bed for the validation of our coordination strategy and the predicted performance features. The system configuration as shown in fig.5 includes the following hardware components:

- 2 manutec r 3 arms
- 2 Siemens RCM2 control units
- 2 robot interface processors (8086)
- 2 sensor pre-processors (8086)
- 1 coordination master processor (Intel 310)
- 2 coordination sub-processors (8086)

This configuration was arrived at partly for reasons of compatibility with other research projects using the same hardware. (The path with the CAP and RAP processors is used in those other projects and not needed for the bi-arm control system). Apart from that, a modular, hierarchical system architecture and convenient margins in processing power and memory capacity were important objectives in the concept definition phase.

7. Collision Avoidance

The development of new collision avoidance algorithms is outside the scope of our present research project. Being aware of the importance of collision avoidance in multi-arm mperations, however, we have screened the related literature for a method that would be suitable for an off-line collision check of preplanned trajectories of our experimental bi-arm robot. We decided to use the method of Lumelsky /11/ for this purpose. Our implementation of the method is embedded into a program for graphical simulation of coorperating robot arms and can be interfaced to a path planning system.

The speed of our collision checker has been considerably improved by the exploitation of a priori knowledge about "impossible collisions". An "impossible collision" is, in our laboratory set-up, for example a collision of an arm with the pedestal of the other arm, because it is out of reach.

8. Prospects of Cooperation

We envisage possibilities for joint research projects oriented towards a number of topics related to our present studies (but not covered by them) such as:

- intelligent planning of mult-arm operations including mixed parallel and sequential cooperation
- on-line predictive collision detection
- pilot applications of cooperating robot arms
- application of our coordination strategy to multi-finger hands and legged locomotion systems

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Session

LOCOMOTION

CHAIRMAN'S REPORT ON THE LOCOMOTION SESSION

The session contained two papers only dealing with very different types of movement, namely biped walking and vacuum suction on walls.

Mr. Zheng and co-authors from Clemson University, South Carolina, work on a two-leg robot project sponsored by the Savannah River Nuclear Power Plant. Their goal is a usable robot for which they have human kind tasks in mind. Unlike other places, they do not wish to do locomotion research, but use the work of others (e.g., in dynamic modelling, gait stability and control theory) to start with. So far, they justified the general structure of their SD-2 biped robot with static standing and first dynamic walking experiments. No load test has been performed yet, and the topple problem has not been solved. Their program for the next three years comprises walking on uneven surface with a compliant ankle and using sensors for detecting abrupt terrain.

Mr. Sato from JGC Corporation reported on a project to develop a wall climbing robot to be used in nuclear power plants, as part of MITI's large scale project in Advanced Robotics. Its envisaged tasks are inspection and decontamination works while travelling on the walls of containment vessels and other nuclear power plant equipment. The robot can retain itself on a wall with its two vacuum suction disks. It moves unto walls from floors and strides over wall obstacles by moving its two jointed members. Demonstration of a prototype robot is being planned for 1990.
The robot is supplied via cable. A failsafe concept against air pressure drop is not being considered.

TOM MARTIN

14

ON THE STUDY OF THE MULTIPLE JOINT BIPED ROBOTS

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ABSTRACT

Static standing and dynamic walking capabilities of a practical biped robot are studied in this paper. In order to measure the static standing performance of the biped in terms of its stability, two parameters, stable margin and stable index, are introduced. For dynamic walking, a mathematical treatment is first described. The analysis is based on the impact theory previously proposed by Zheng and Hemami [15,16]. The conclusion is reached that by proper positioning of the landing foot, stable dynamic walking can be realized. The design of two biped robots, SD-1 and SD-2, are described in the paper as well. SD-1 is a biped robot with no ankle joints, and SD-2 is a refined model of SD-1 with ankle joints added. Experimental results of static standing and dynamic walking of the biped robots are presented.

Keywords: practical biped robots, static standing, dynamic walking

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1. Introduction

Research on biped locomotion and biped robots has been conducted for a number of years. Unfortunately, due to the complicated motion control algorithms, most studies have been concentrated on the theoretical aspects [1-8]. Practical biped robots have been built by only a handful of scientists [9-14].

Kato and his colleagues built one of the earliest biped robots, which started to walk in 1973 [9]. It is statically stable at all times, relying on keeping its center of gravity above at least one of its large feet. Later, Kato and co-workers developed a locomotion gait for bipeds which was called quasi-dynamic walking [10,11]. Its main feature was that the transition of support from one foot to the other was very quick without an obvious two foot supporting phase. More recently, Miura and Shimoyama built a biped that employed a dynamic walking gait [12]. Their biped had no ankle torque and each foot contacted the ground at a point. Thus, the biped would collapse if both feet were kept in stationary contact with the ground. As a result, continuous stepping was required for walking or to maintain an upright balanced posture.

Physical biped robots were also built and studied by Katoh and Mori [13]. The robot was similar to the one built by Miura and Shimoyama; however, the emphasis was put on a control method of dynamic biped locomotion that gave asymptotic stability of the trajectory. A biped robot was also constructed and studied by Miyazaki and Arimoto [14]. They noticed that in some cases the degrees of freedom for a biped robot became larger than the number of actuators during dynamic locomotion. In order to stabilize the biped robot when this happened, a control method called the singular perturbation technique was proposed. This control mechanism was applied to a biped robot with seven degrees of freedom.

In the previous studies of biped robots, the emphasis was always on locomotion, and never considered practical applications of the robots in industrial environments. In fact, a biped robot has two legs, and appears like a human being. Since many industrial environments were originally created for human operators, biped robots could be used to replace human beings in many applications without any modification to the original set up. This makes the biped robot very attractive for use in future automated manufacturing. To realize the goal, a biped robot should be practically useful. By "practically useful", we mean that the biped robot should have a mobile platform and a pair of legs. The function of the platform is to carry a load or a robot arm for executing manipulating tasks. The function of the legs is to provide platform mobility.

In order to provide a mobile as well as a stable platform, one may find that standing is as important as walking for a practically useful biped robot. It is clear that to accomplish a manipulation task, the biped robot must be able to firmly stand such that the platform can provide the manipulator with a stable base. To measure the stability of a biped robot, we need to define related parameters which can be used for design and control.

The second problem is the walking gait. For a practically useful robot, the walking gait should be efficient and stable. In this regard, a dynamic walking gait, instead of static walking, is required. Thus a practically useful biped robot should have both static standing and dynamic walking capability.

In this paper, we will study the above two problems and present some theoretical and experimental results for practical biped robots. In the next section of this paper, we will first study static standing of a biped robot. To describe the static standing stability of the robot, two parameters, stable margin and stable index, will be defined. The study will also develop a means to optimize the two parameters.

In the third section, the study will concentrate on walking. The gait of static walking will be briefly described; however, the emphasis will be on dynamic walking. The dynamic behavior of the robot in dynamic walking will be analyzed based on the impact theory proposed in our earlier works.

In the fourth section, the design and construction of two biped robots at Clemson University will be discussed. The theoretical results discussed in the preceding sections will be applied to the robots, and the experimental results for both static standing and dynamic walking will be presented.

2. Stability Measure of the Biped Robot Static Standing

In practical applications, the main body of the biped robot serves as a mobile platform on which a robot manipulator may be installed (Fig.1). The mobility of the platform can enlarge the work space of the manipulator. When the manipulator is executing a task, however, the platform must provide a firm and stable support, which in turn requires a stable standing configuration. The stable standing must be realized by proper positioning of joint angles without continuous motion of any robot links. This kind of standing is called static standing. Dynamic standing, which keeps the biped from collapsing by continuous motion of links, is not suitable for practical purposes since it is impossible to keep the platform from deviating from a preplanned position and orientation.

Biped feet are used to support the weight of the robot. In order to have a stable standing, each foot must have a flat surface used for contacting the ground and supporting the robot. The contact surface may have any shape, but a practical foot is often designed to have a rectangular shape [9-14]. For the purpose of simplicity, we assume a rectangular contact surface of the foot. We further introduce two parameters to define the size of the contact surface: the distance from the center of area of the surface to the front boundary, f_{xd}, and the distance from the same center to the left boundary, f_{yd} (Fig.2). The values of f_{xd} and f_{yd} play an important role in the study of the stability problem. The detailed relationship will be discussed as follows.

When the robot is standing on its right foot, the weight of the robot is totally supported by the contact surface of the foot as defined in the last section. In order to have static standing, the vertical projection of the robot center-of-gravity must be within the supporting surface of the foot. We define a parameter called stable margin (SM) for the biped robot when it is in a static standing status. The stable margin is the shortest distance from the vertical projection of the robot center-of-gravity to the boundary of the supporting surface. It is clear that if the vertical projection of the center-of-gravity is outside of the supporting surface, the biped robot will fall. Therefore, the value of the stable margin is to provide a measure of the degree of stability of a biped robot; the larger the value of the stable margin the greater is its stability. Actually, there is a maximum stable margin for a specified foot. For a rectangular foot, the least of the two parameters, f_{xd} and f_{yd}, is the maximum stable margin (SMm) that the robot can achieve. This conclusion is true because the center of a rectangle has the maximum distance to the boundary. Any other point will have a shorter distance to the boundary in one direction or another.

Another important factor, which plays an important role in stabilizing the system, is the height of the robot center of gravity. Consider that a biped robot is standing on the right foot (Fig.1), and all the joints are adjusted in such a way that the vertical projection of the robot center of gravity is at the center of the supporting surface. If the stable margin is the only criterion, then the robot has an optimal stance. In actual practice, the stability of the system is also related to the height of the center of gravity. To study this, one must examine how a biped robot could be forced out of a stable status, and how it can improve its ability to maintain its stability. We consider a robot to be stable if its center-of-gravity remains within the supporting surface after an impact by any external object. An impact on a robotic system will cause an abrupt velocity increment [15,16]. The more severe the impact, the higher the velocity the robot acquires immediately after the impact. Therefore, the stability of a biped robot can be measured by its ability to withstand a horizontal velocity increment without losing the static standing status (note that the vertical component of the velocity does not affect the robot status). The following study develops mathematically how the height of the center of gravity above the supporting surface affects the robot ability to withstand a horizontal velocity increment.

Suppose that the horizontal velocity of the center of gravity after an impact is v and the vertical component of the velocity is zero. Then the kinetic energy acquired by the robot is $(1/2)mv^2$ where m is the total mass of the robot. The center-of-gravity projection tends to move out of the supporting surface, due to the instantaneous horizontal velocity. Meanwhile the center of gravity also rises. (Here we have assumed that the friction force between the biped robot and the ground prevents the biped from sliding on the ground. Otherwise, the biped may slide under an impact and never fall.) Let the height of the center of gravity before the motion be denoted as h. Then the highest possible height of the center of gravity is (Fig.3)

$$h_m=(SM^2+h^2)^{1/2} \qquad (1)$$

The maximum increment of potential energy because of the rising of the center of gravity will be

$$mg(h_m-h) \qquad (2)$$

For the center of gravity projection to go across the boundary of the supporting surface, the kinetic energy must be at least equal to the maximum increment of potential energy, i.e.

$$(1/2)mv^2=mg(h_m-h)=mg[(SM^2+h^2)^{1/2}-h] \qquad (3)$$

From equation (3), one can see that if stable margin, SM, is increased, the instantaneous velocity that the robot can withstand is also increased, which means that the system is more stable. However, equation (3) indicates that the height of the center of gravity also affects the stability of the biped robot, which means that the right side is monotonically decreasing with respect to h. Therefore, in order to increase stability, the height of the center-of-gravity should be reduced. To consider the effect of the height of the center-of-gravity in determining stability of the robot in static standing, we define a new parameter called stable index, SI=SM/h. Thus, to optimize static standing with respect to stability, one must make the two parameters, stable margin and stable index as large as possible. Given stable margin and stable index one may derive from (3) the upper bound of the instantaneous speed that a biped robot can withstand:

$$v_m=\{2gSM[(1+(1/SI)^2)^{1/2}-1/SI]\}^{1/2} \qquad (4)$$

It is clear that stable margin and stable index can be used to measure the stability of a static stance. To optimize the stability of a static standing, one must reduce the height of the body center-of-gravity as much as possible. Meanwhile, the vertical projection of the center-of-gravity should fall on the center of the supporting surface area.

When the biped robot is supported by two feet, the supporting area is greatly increased compared with the supporting surface area of a single foot. This area is not just twice the area of one supporting surface, but the entire area of the convex hull formed by the two feet and the area between the the two feet. Clearly, the same stability concept as studied in the single-foot-supporting case can be applied in two-foot-supporting case.

3. Pattern Analysis of Biped Dynamic Walking

In general, there are two kinds of walking patterns available for biped robots. One is called static walking and the other is called dynamic walking. In static walking, the vertical projection of the center-of-gravity is always contained within the supporting area of the feet. The center of gravity does not move until the swinging foot firmly touches the ground. Thus the motion profile of the center-of-gravity experiences an alternately moving-and-resting pattern. As a result, static walking is slow and inefficient.

In comparison to static walking, dynamic walking can offer a higher speed of motion. However, this is realized by a relatively complicated walking gait. Basically, the gait of dynamic walking can be divided into the following four phases, which are further illustrated in Fig.4.

Phase 1: The robot is supported by one foot and the other foot swings forward. Meanwhile, the center of gravity moves forward as well.

Phase 2: The projection of the center-of-gravity moves out of the supporting area and the platform starts to fall down. Meanwhile, the center of gravity keeps moving forward.

Phase 3: The swinging foot touches the ground, and the falling velocity instantly reduces to zero.

Phase 4: The biped is supported by two legs, and the projection of the the center-of-gravity moves toward the supporting area of the newly landed foot.

Mathematical analysis of dynamic stability of a biped locomotion was previously conducted by Gubna, Hemami and McGhee [5]. The same treatment will be used here. The difference is that in [5], the biped model was based on a human being and the emphasis was put on finding a control law; in this paper, however, the study is based on a practical robot and the goal is to find a kinematic control algorithm, i.e., a proper positioning of robot links.

In Phase 2 of the robot gait described above, the biped robot center-of-gravity is falling out of the supporting area. The joint motions of the supporting leg are very limited, which may be considered zero. We may, therefore, consider the biped robot as an inverted pendulum at any point of time in Phase 2. As a result, the dynamic behavior of the biped robot is governed by the following equations

$$m\ddot{x}=F_x \qquad (5)$$

$$m\ddot{y}=F_y-mg \qquad (6)$$

$$I(q)\ddot{\theta}=-F_xL(q)\sin\theta-F_yL(q)\cos\theta+T \qquad (7)$$

where m is the total mass of the robot; I(q) is the equivalent inertia, which is a function of the joint angles, q; and L(q) is the distance from the center of gravity to the ankle joint, which is also a function of the joint angles. In addition to the fact that $I(q)>0$ and $L(q)>0$, their exact expressions are not important in our study. Further, T denotes the torque generated by the joint which connects the supporting foot. If the joint is not in the sagittal plane, which is a possible design for a practical robot, T should be set to zero. Other parameters appearing in (5), (6) and (7) are all self-explanatory in Fig.4.

At the instant that the projection of the center of gravity moves out of the supporting area, it acquires a velocity $\dot{x}$ with no or very small acceleration. This can be achieved by controlling the joint velocities in Phase 1. Since $\ddot{x}$ is approximately zero, F_x may be regarded as zero. As a result, the first term of (7), $-F_xL(q)\sin\theta$, is equal to zero. The second term of (7), $-F_yL(q)\cos\theta$, is greater than zero. This is because F_y is always greater than zero as the ground cannot hold the robot if the foot intends to leave the ground, and $\cos\theta$ is less than zero. Finally, T is greater than or equal to zero because T is used to accelerate θ when the biped starts to move, and is reduced to zero when a desired velocity is achieved. Note that T is the effective torque generated by the joint actuator and the joint friction. "T is equal to zero" does not mean that the actuator torque is null. From the above analysis, we can conclude that the right side of (7) is greater than zero. Thus, one has the condition that

$$I(q)\ddot{\theta}>0 \tag{8}$$

when the biped goes into Phase 2. Equation (8) reveals that the angular velocity $\dot{\theta}$ is monotonically increased, which results in monotonically increasing $\dot{x}$ and monotonically decreasing $\dot{y}$. The latter will make the system eventually fall. However, this problem can be solved by proper positioning of the swinging foot.

At the instant that the swinging foot contacts the ground, the biped robot receives an impulsive force. The effect of an impact on a robotic system was previously studied by Zheng and Hemami [15,16]. The method of treatment is as follows. Because of the impulsive force, for a short duration of the impact, equations (5) and (6) should be written as

$$m\ddot{x}=F_x-F_{x\delta} \tag{9}$$

$$m\ddot{y}=F_y-mg+F_{y\delta} \tag{10}$$

where $F_{x\delta}$ and $F_{y\delta}$ are two impulses acting on the biped robot by the ground through the landing foot. Integrating (9) and (10) in an infinitesimal period of time Δt one gets

$$\int_{t_0}^{t_0+\Delta t} m\ddot{x}d\tau=\int_{t_0}^{t_0+\Delta t} F_x d\tau-\int_{t_0}^{t_0+\Delta t} F_{x\delta}d\tau \tag{11}$$

and

$$\int_{t_0}^{t_0+\Delta t} m\ddot{y}d\tau=\int_{t_0}^{t_0+\Delta t} (F_y-mg)d\tau+\int_{t_0}^{t_0+\Delta t} F_{y\delta}d\tau \tag{12}$$

the first term of the right sides of (11) and (12) vanish because F_x and (F_y-mg) are limited quantities and the integration of a limited quantaty in a infinitesimal period of time is null. As a result, one has

$$\dot{x}(t_0+\Delta t)=\dot{x}(t_0)-\Delta F_x/m \qquad (13)$$

and

$$\dot{y}(t_0+\Delta t)=\dot{y}(t_0)-\Delta F_y/m \qquad (14)$$

where

$$\Delta F_x= \int_{t_0}^{t_0+\Delta t} F_{x\delta}d\tau$$

and

$$\Delta F_y= \int_{t_0}^{t_0+\Delta t} F_{y\delta}d\tau$$

In [15,16], it is shown that the magnitudes of ΔF_x and ΔF_y are determined by the robot joint positions and the velocity increment of the landing foot immediately before and after the foot contacts the ground, ΔV_f, i.e.,

$$[\Delta F_x \ \Delta F_y]^T=J(q)(J(q)D^{-1}(q)J^T(q))^{-1}\Delta V_f \qquad (15)$$

where J(q) is the 2xm Jacobian matrix relating the linear and·angular velocities of the landing foot to the speeds of robot joints (note that m is the number of robot joints), D(q) is the mxm inertia matrix of the robot, and

$$\Delta V_f=V_f(t_0+\Delta t)-V_f(t_0) \qquad (16)$$

If the velocity of the landing foot immediately after the contact, $V_f(t_0+\Delta t)$, is equal to zero, ΔV_f in (16) should be replaced by $(0-V_f(t_0))$ which is related only to the velocity of the foot immediately before the contact. This can be realized by selecting suitable material for the foot or ground such that the relative velocity between the foot and the ground immediately after the contact is zero [16]. Then by controlling the joint positions of the biped robot and the landing velocity of the swinging foot, one can get desired magnitudes of ΔF_x and ΔF_y, and further get the desired $\dot{x}(t_0+\Delta t)$ and $\dot{y}(t_0+\Delta t)$.

The relation between the impulsive forces, ΔF_x and ΔF_y, and the joint positions, q, is very complicated as can be seen from (15). Using (15) to calculate the required joint positions is very time consuming, if not impossible.

Furthermore, because of the modelling errors involved in the estimation of the system parameters, the calculated results may be considerably different from the actual required value. For the above two reasons, we recommand experimental techniques to determine an optimal set of joint positions. This topic is discussed in the next section.

4. The Design of Two Practical Biped Robots

Two practical biped robots were designed and constructed at Clemson University. The first biped is a prototype model named SD-1. It was designed and constructed in 1985 and started to walk in 1986 (Fig.5). The second biped robot, named SD-2, was constructed in 1986 and started to walk in 1987 (Fig.6). The detail structure and experimental results of SD-1 and SD-2 are discussed in the next sub-section.

4.1 The SD-1 Biped Robot

(A). General Structure of the SD-1 Biped Robot

The SD-1 biped robot has a platform and two legs; each leg has two links with two degrees of freedom. Joints q_3^r and q_3^l, which connect the platform to the two legs, are used to swing the leg; joints q_2^r and q_2^l are used to lift the platform when a leg is standing so that the other leg can clear the ground and make a swing. The platform is made up of a two-beam structure (surface area=160 sq.cms) connecting the speed reducers for the swinging joints of two legs. Each leg consists of two links, and is terminated by a flat rectangular foot as in Fig.5., with f_{xd}=2.5cms and f_{yd}=3.5 cms.

Each robot joint has a speed reducer with a 100:1 gear reduction ratio and the speed reducer is driven by a 72 g-cm DC servo-motor. The weights of the speed reducer and the DC servo-motor are considerably heavier than the links of the legs and the beams of the platform. Furthermore, the platform has two drivers installed on and each leg has one. Therefore, the platform is about twice as heavy as each leg. As a result, for the SD-1 Biped Robot the center-of-gravity of the platform is not same as the center-of-gravity of the robot. In fact, when a leg swings forward, the center-of-gravity shifts forward as well. This procedure will actually be utilized in dynamic walking.

(B). Dynamic Walking of the SD-1 biped Robot

Since there is no ankle joint in the direction of walking for the SD-1 biped robot (i.e., T=0 in (7)), dynamic walking is realized by proper positioning of the landing foot. The optimal gait of dynamic walking by the SD-1 is realized as follows. During the first walking phase the platform, supported by the right leg, is lifted by 10 degrees. This is accomplished by rotating joint angle q_2^r from 95 degrees in the static standing case, to 105 degrees. As a result, the left leg is raised 2.5cms and the left foot clears the ground. The left leg is now swung forward 20 degrees by simultaneously rotating joint angle q_3^l from 90 to 100 degrees and joint angle q_3^r from 100 to 90 degrees. In the second phase, as soon as the left leg reaches the desired position, the center-of-gravity projection moves out of the supporting area of the right foot and the platform begins to fall down. We found 20 degrees as the minimum angle through which the leg has to swing for the platform to loose its balance by having the center-of-gravity projection moving out of the supporting area of the right foot. During this phase the center of gravity is supported by neither foot. The forward velocity of the swinging leg is selected to be 12 degrees per second.

To stop the platform from falling, the platform joint is lowered by 10 degrees in the third phase. This allows the swinging foot to touch the ground and the falling velocity of the center of gravity instantaneously becomes zero. In the forward direction, however, the center of gravity continues to move. It should be made clear that the zero velocity of the landing foot immediately after contact is achieved by a soft contact accomplished covering the ground with a rubber mat, for example. During the fourth phase, the platform is supported by both the legs and because of the continuous motion of the center-of-gravity, it moves into the supporting area of the newly landed foot. The movement due to the inertia of the platform is now balanced by the reaction forces of the foot and hence the biped achieves a static stance on the new foot. This completes the first dynamic walking step of the SD-1 robot.

The same procedure is now repeated for the other leg for the next step.

4.2 The SD-2 Biped Robot

(A) The Function of the Ankle Joints

The SD-1 biped robot does not have ankle joints, however, the ankle joints have proved to be very important for both static standing and dynamic walking. This can be understood by examining the standing and walking aspects of biped motion.

First let us consider the biped standing. For SD-1 biped robot, the stable stance of the biped is guaranteed by the accurate positioning of the hip joints such that the projection of the center of gravity of the platform falls on the supporting surface of the feet. However, the biped cannot detect the relative position and orientation of its legs with respect to the ground. Therefore, if the hip-joint positions are not accurately servoed for any reason, the platform may be out of balance and start to fall. However, the biped cannot detect this falling situation. With the sensors installed on the ankles, the robot will be able to detect the falling platform by sensing the changing ankle-joint positions, and a prompt response could be taken by the biped to prevent it from collapsing.

Not only can the ankle joints help stabilize standing, but also they make dynamic walking more flexible. Consider the walking pattern used by the SD-1 biped. It was discussed in the previous section that the center-of-gravity of the robot is moving out the supporting area in Phase 2 of dymanic walking. Since no ankle joint is installed, this can only be accomplished by swinging the non-standing leg forward. The magnitude of the swing, as was discussed in the previous section, affects the landing velocity of the foot. As a result, one does not have any freedom to select a different gait, other than by experimentally choosing the optimal swing angle. With the ankle joint installed, the biped can employ the torque generated at the ankle joint to move the center-of-gravity, and use the swinging leg to select different walking gaits. Robot will thus be more flexible to choose walking patterns.

(B) The Structure of SD-2 Biped Robot

From the above description, it can be seen that the ankle joints play a very important role in generating sophisticated locomotion. They must be installed in any advanced biped robot. Based on this consideration, we designed the SD-2 biped robot (Fig. 6). In comparison to the SD-1 biped robot, four more joints are added. Pairs of joints are used to form a two-degree-of-freedom ankle. Thus the SD-2 biped robot has a total of eight degrees of freedom. With the ankle joints installed, the SD-2 biped robot demonstrates a more flexible and stable walking gait.

5. Conclusions

In this paper, motion control and design of two practical biped robots have been discussed. Both theoretical and practical results were presented in the discussion. First, we have studied static standing of a biped robot. Two parameters, stable margin and stable index, were defined for performance analysis of static standing. In order to increase the degree of stability of static standing, both parameters must be optimized. Secondly, we analyzed dynamic walking of a biped robot and concluded that as long as a biped robot can properly position its landing foot, stable dynamic walking can be realized. Finally, the design of two practical biped robots, SD-1 and SD-2, were discussed. Experiments have been performed using both robots, and the results have confirmed the validity of the theoretical studies. The importance of the ankle joints were discussed for the SD-2 biped robot. The discussion has justified the general structure of the SD-2 biped robot, which has a two-degrees-of-freedom ankle joint installed in each leg.

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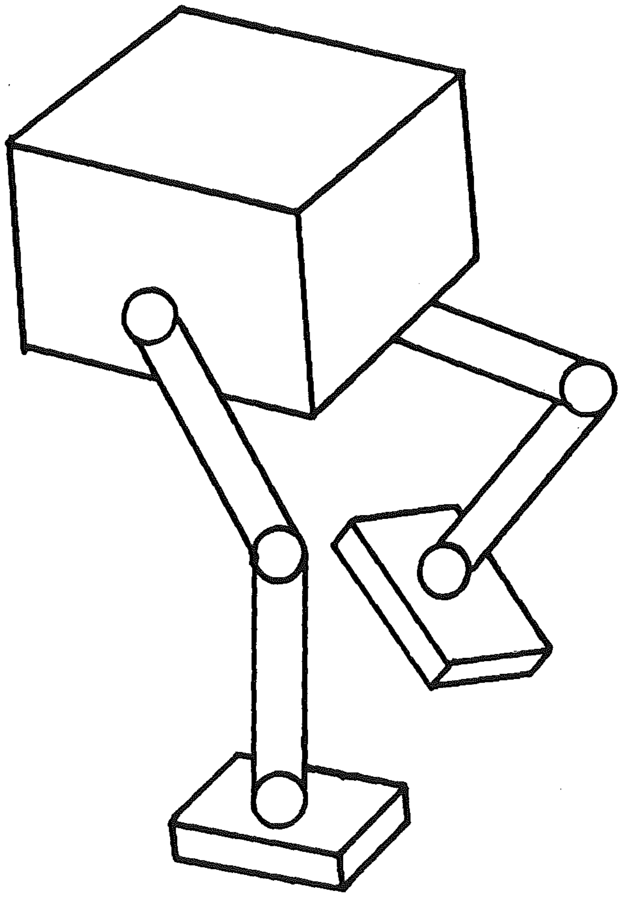


Fig.1 A Practical Biped Robot

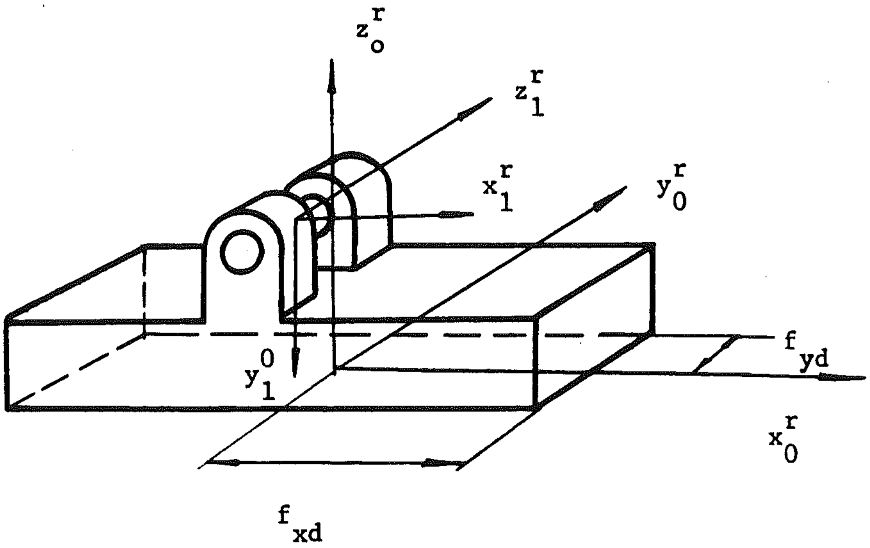
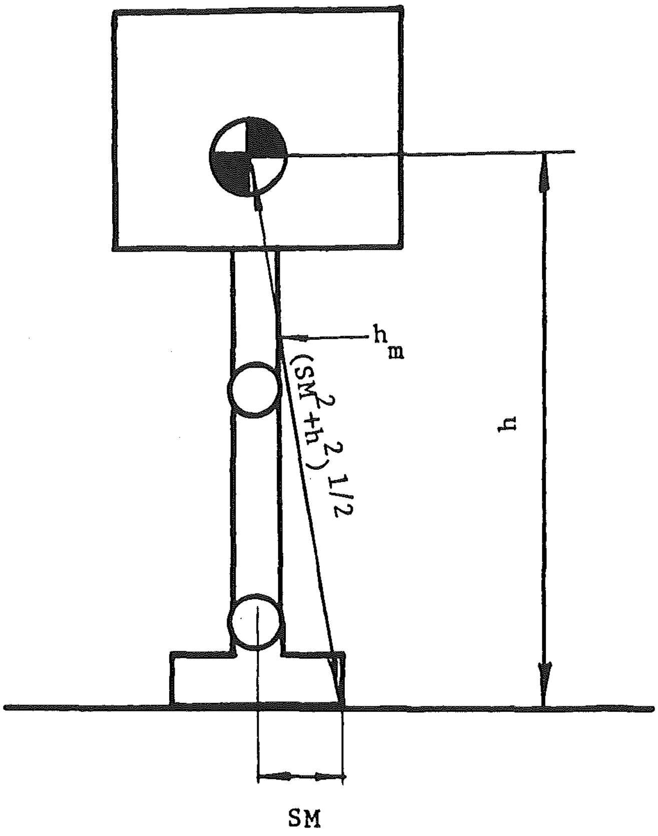


Fig.2 Two Parameters f_{xd} and f_{yd} with the Foot



Stable Margin: SM
Stable Index: SI=SM/h

Fig.3 Stable Margin and Stable Index of Static Standing

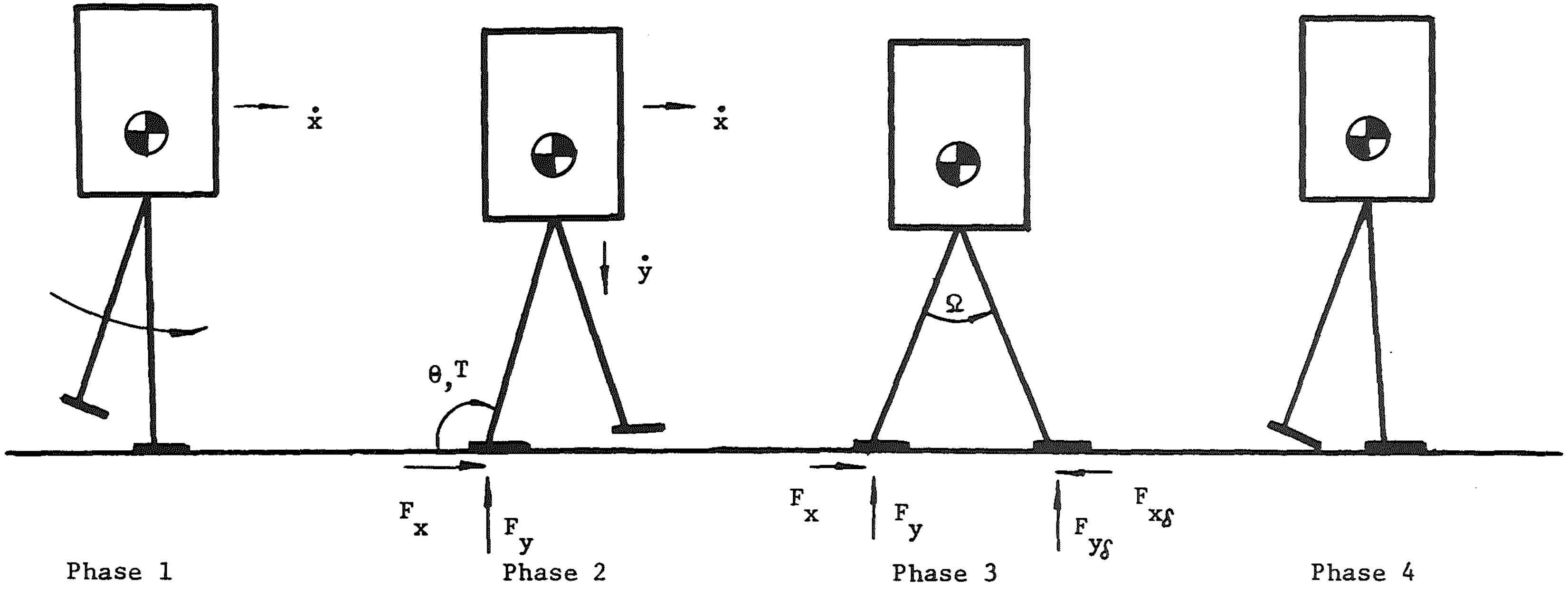


Fig.4 Four Phases of Biped Dynamic Walking

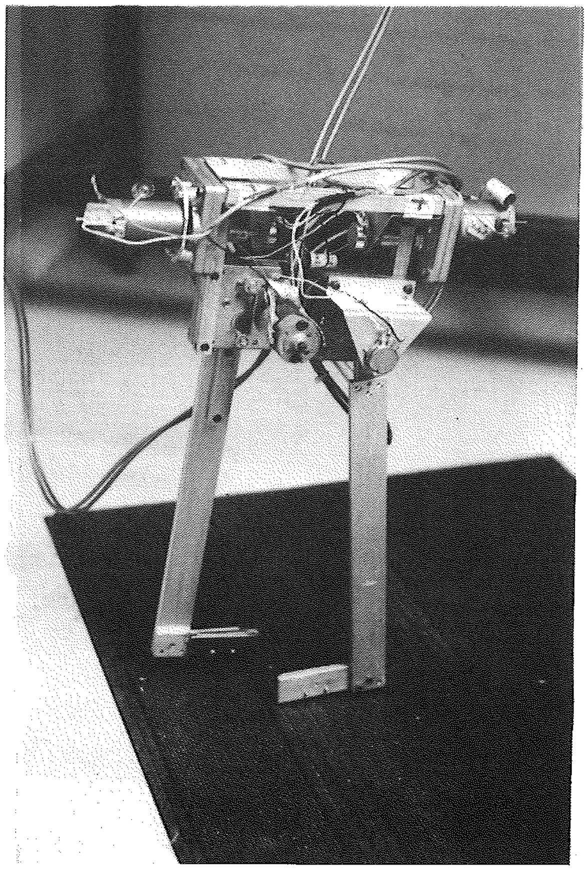


Fig.5 The SD-1 Biped Robot

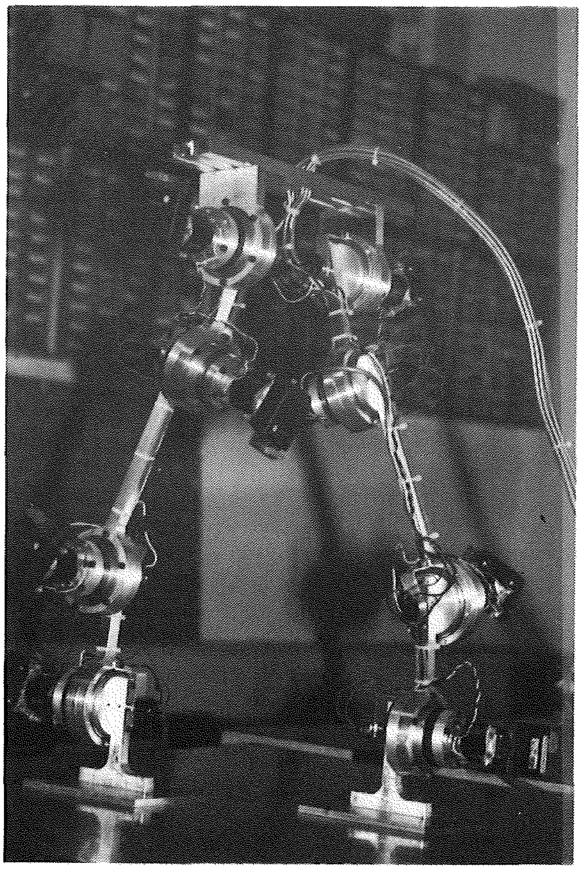


Fig.6 The SD-2 Biped Robot

LOCOMOTIVE VACUUM SUCTION DISKES FOR WALL ROBOTS USED AT NUCLEAR POWER PLANTS

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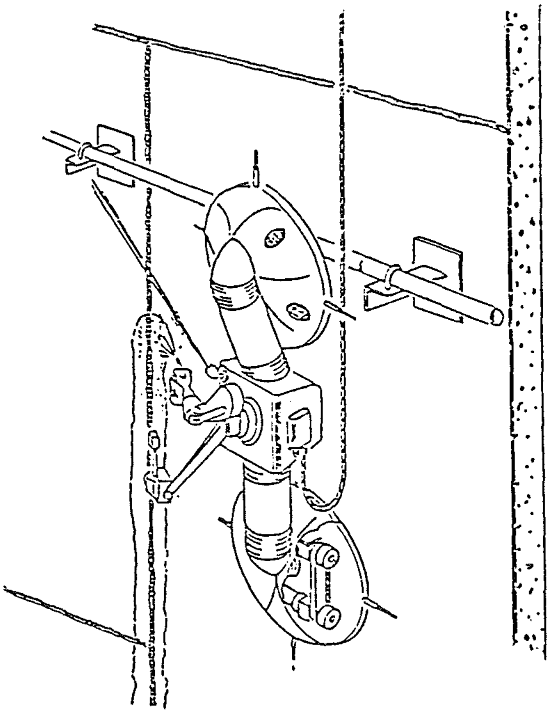
Research and development of work robots use in hostile environments (e.g. nuclear power plants, under water, disaster arrest) are being carried out in a large - scale national R & D project on " Advanced Robot Technology" which is being promoted until 1990 by the Agency of Industrial Science and Technology of the Japanese Ministry of International Trade and Industry.

The robot presently under development is an on - wall locomotive robot shown in the figure.



This robot performs inspection, decontamination and other work while travelling on the walls of container vessels, large - size tanks, metal lining pools, and other equipment installed it nuclear power plants.

Target travelling speed is 2 km / hr, respectively. This robot can stride over wall obstacles and move onto walls from floors.

The robot travels on the wall with two locomotive suction disks. There are equipped with a driving mechanism using high - friction tires' wheels with an electric servomotor and a vacuum maintaining mechanism using sealings and exhaust fans. The robot can retain itself on the wall and stride over wall obstacles by moving its jointed positions connected to each suction disk.

Such a robot requires all materials and parts used to be light and compact to ensure high performance. Therefore, important goals of this R & D work are development of a compact actuator, high - efficiency exhaust fan, vacuum sealing mechanism ensuring less air leakage, high - friction wheels and other parts. The actuator is being developed by Fanuc Co., Ltd. and its weight - to - power ratio is expected to be smaller than that of commercially available servomotors with a decelerator.

In recent test, the specified pressure difference of the vacuum sealing mechanism was maintained even when the robot travelled on a cylindrical wall having weld beads and the frictional force of the seal was satisfactorily small.
The coefficient of friction of the driving wheel was larger than that of commercially available wheels with respect to dry strip stainless steel plates.
This coefficient, however, will decrease on wet or dusty surfaces.
Surface conditions of walls, such as the height of weld beads, curvature of the wall surfaces and so one effect suction disk shape and sealing mechanism design.
However, fluctuations in air leakage from the sealing surface can be maintained within a small range by adopting a mechanism to maintain the specified sealing surface pressure, even when the shape of the suction disk or the surface conditions of the wall has changed.

Research on a subassembly is presently being conducted based on the results and data obtained from this basic research. Tests on the travelling mechanism will be conducted in 1988 and demonstration of a prototype robot in 1990.

Session

SENSORS (1)

CHAIRMAN'S REPORT ON SENSORS (1) SESSION

Six papers were presented during this first of three sessions on sensors. They fall into three areas with two papers each, namely development of new sensors, vision image interpretation and simulation.

Development of new sensors

Mr. Yoshida from Matsushita Research reported on a laser vision sensor envisaged for a disaster prevention robot that gives information on objects in the disaster environment, especially in smoke, water vapour and flame. This project is part of MITI's large scale project on Advanced Robotics. A CO_2 laser beam is chosen, because it is expected to penetrate well through fine particles of 1 micrometer or less in diameter. So far, laser visioned pictures of objects placed in the clear atmosphere were demonstrated.

Mr. Hirzinger and his co-workers demonstrated their new generation of DFVLR robot sensors and their integration in the robot control feedback loop, the latter aspect being their real specialty. The six component force-torque sensors have been made smaller and smaller and can easily be integrated in grippers. So can their laser range finder being less in size than a match box.
They teach a robot in a novel approach operating a 'sensor ball'. This functions, loosely speaking, as follows. If the robot moves in free space, the ball forces are transformed into translational commands, however, if the robot senses contact with the environment, it takes the ball inputs as nominal force values to be used during tactile tasks.
Their work is planned to be used in the Robot Technology Experiment in Spacelab D2 Mission.

Vision image interpretation

Mr. Savage from RARDE, UK Ministry of Defence, described the application of a scanned, pulsed GaAs laser rangefinder system to the problem of terrain mapping the path ahead of an autonomous vehicle in arbitrary surrounding. To date the sensor has been operated independently of a vehicle, with data collected off-line. Work is in progress to integrate the sensor system with the navigation and position fixing sub-system in an on-vehicle 8086 based computer system.
The approximate cost for customers of such a system would be 150.000 pound sterling. In the USA, DARPA performs similiar developments for the D.O.D..

Mr. Orr from University of Edinburgh works within a consortium whose goal it is to interpret 2 1/2 D images (representing depth and surface orientation) determining what objects are present and what their scene locations are. So far, his group has coped with test scenes containing one or two target objects which the program (written in 'C' and running on a SUN 2) knows about. They are currently involved in extending the object models. They would be interested in collaboration with other groups dealing with geometric reasoning and with people who have experience in parallel computer architectures (to make the program run faster; so far, it takes about two hours per picture).

Simulation

Two contributions dealt with simulation of mobile robot for industrial automation in production. The design of such robots can be facilitated with the aid of a simulation system allowing to navigate the robot through the manufacturing system on a CRT screen.

Mr. Raczkowsky and co-authors develop a concept for simulating sensors as part of the Simulation System for Robots known as ROSI developed at the University of Karlsruhe. For off-line testing of robot programs controlled by sensors, they use a sensor emulator to emulate the sensing and the sensor preprocessing. The system is supposed to work as follows: The sensor is specified and activated by a command language. These commands are recognized and interpreted by the run-time system.
The run-time system invokes the sensor emulator when it has to interpret a sensor command.
In the discussion it was stressed that this concept depends strongly on the accuracy in which the sensor and the environment can be described.

Mr. Freyberger and co-workers take part in an interdisciplinary research project entitled Information-Processing in Autonomous Mobile Robots at the University of München. They specifically deal with simulation tools for the development of mobile vehicles. Since the distribution of software and hardware of the various subsystems involved are not known in the early phases of development, a flexible system architecture is mandatory. Processes communicate by sending and receiving messages via the knowledge base using a 'software bus' (comparable to a LAN). Concerning sensors, a model of a range imaging sensor system simulating the perception of obstacles was implemented, as discussed in the paper in detail. One asset of the system is that components can be exchanged simply, and real components can be replaced by simulated ones and vice versa.

TOM MARTIN

A SCANNED LASER RANGEFINDER SYSTEM FOR A CROSS-COUNTRY AUTONOMOUS VEHICLE.

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1. Introduction.

This paper describes the application of a scanned, pulsed GaAs laser rangefinder system to the problem of terrain mapping the path ahead of an autonomous vehicle in arbitrary surroundings, such as may be encountered in cross-country driving.

In comparison with television based systems scanned laser rangefinders for autonomous vehicle applications generally have the following characteristics,

(i) Moderate angular resolution; typically a few milliradians.
(ii) Moderate ranging rate data; generally some 10 's of kilohertz.
(iii) A limited maximum range depending on the signal to noise which may be achieved.

Laser sensor heads also tend to be relatively large and of high cost compared to modern television sensors. However laser sensors have the strong advantage that they provide the direct measurement of depth in arbitrary scenes thus simplifying the data processing problem.

2. Sensor System.

Figure 1 shows a schematic of the overall vehicle system and illustrates the position of the laser sensor subsystem in the overall vehicle system. The sensor subsystem hardware comprises the sensor head, an interface unit and an 8086 based processor. Sensor software running in this processor will extract the location of obstacles ahead of the vehicle

3.1 Sensor Head.

A scanned GaAs laser rangefinder has been constructed using a Thorn-EMI laser altimeter and Lettington co-axial scanner as shown in figure 2. The rangefinder, seen at the upper left, is scanned in a raster over a 40 X 30 degree field of view by two rotating polygons. The laser is fired in synchronism with the scan and measures the range to points in the scene at equal angular intervals. The range data is digitised to 12 bits, associated with a pixel number and stored. Table 1 summarises the characteristics of the sensor.

3.2 Data Processing.

The range image measured by the sensor is processed to extract the location of obstacles relative to the sensor. To date the sensor has been operated independently of the autonomous vehicle computer system, with data collected off-line and processed in laboratory based machines. The processing steps applied to the data are illustrated in figure 3 and described below.

(i) Scan conversion.

Look-up table re-ordering of pixel number from the scanner and frame averaging if required.

(ii) First derivative edge detection followed by thresholding.

$| \text{Grad } Z | \leqslant \text{Threshold.}$

where in Cartesian co-ordinates the surface of the terrain is represented by $z = z(x,y)$ with z aligned with the local vertical. This operation is currently carried out on the raw data with no filtering.

(iii) Region growing to detect clusters of edge points corresponding to obstacles.

Neighbouring edge pixels are clustered together if their range separation is less than a pre-set value.

(iv) Simple obstacle description by enclosure of obstacle clusters in boxes.

(v) Computation of path length to nearest box-obstacle along a given bearing from the sensor.

4. Results.

Data from typical outdoor scenes has been measured by the sensor system and the processing scheme outlined above applied to the data. Figure 5 shows a perspective plot of the raw data measured by the sensor viewing the typical track scene shown in figure 4. In the right handed co-ordinate system shown in figure 5, if the z axis is vertical, then the x, y and z axes are marked at intervals of 3.75m, 1.125m and 0.5m respectively.

Figure 6 shows a 3 grey-level thresholded gradient image corresponding to this scene. Light and mid-grey regions correspond to pixels above and below the gradient threshold respectively, dark pixels are those for which a range measurement was unsucessful, either because insufficient reflected energy was returned to the rangefinder or because foreground points in the scene were within the 6 metre minimum range of the rangefinder.

Figure 7 shows the obstacle boxes assigned to the original scene indicating the clear path ahead of the sensor. The total CPU time for this scene was 7.5 seconds on a VAX 11/785.

5. Further Work.

Work is in progress to integrate the sensor system with the navigation and position fixing sub-system in an on-vehicle 8086 based computer system.

Limitations imposed by 'image' flow during the sensor scan and by the computer processing speed will only currently permit a stop/go mode of operation. Future enhancements will be directed at achieving continuous motion, using an improved sensor head and by the provision of an appropriate data processing rate.

There is activity at RARDE and elsewhere to apply television sensors to autonomous vehicle control, and methods of data fusion may be particularly relevant for sensors which to some extent have complementary performance.

6. Applications.

The work described here is part of a programme directed towards the movement of military autonomous vehicles. Clearly there may be a number of mobile robot applications for which suitably developed active ranging systems represent appropriate technical solutions to measurement or 'vision' problems.

7. Collaboration.

The UK Ministry of Defence is interested in collaboration in this area and work has already been undertaken to define collaborative programmes with other European Ministries of Defence under the Inter European Programme Group (IEPG), Technology Area 8, covering Computer Vision for Robot Applications, which includes techniques appropriate to autonomous land vehicle control.

Within the UK a recently initiated, Ministry Of Defence / Department of Trade and Industry, Civil Industrial Attachments Scheme is directed at encouraging Civil Industry / MOD co-operation in areas of mutual benefit. Robotics is clearly one such area.

Laser Rangefinder.	Thorn EMI type RR28F001
Transmitter	GaAs SH Laser Diode.
Receiver	Avalanche photodiode.
Peak Output Power	10 W
Output beam divergence.	10 mrad approx.
Operating range.	6 m to 50 m.
Range resolution	2.5 cm SD (approx.), normal target.
Maximum ranging rate.	25 kHz.
Scanner	Lettington co-axial scanner.
Scan pattern.	56 line raster.
Angular sampling interval.	12 mrad.
Number of pixels/frame.	3080
Field of View.	40°X 30°
Frame rate.	1 Hz (nominal).

Table 1. Parameters of the Scanned Laser Rangefinder.

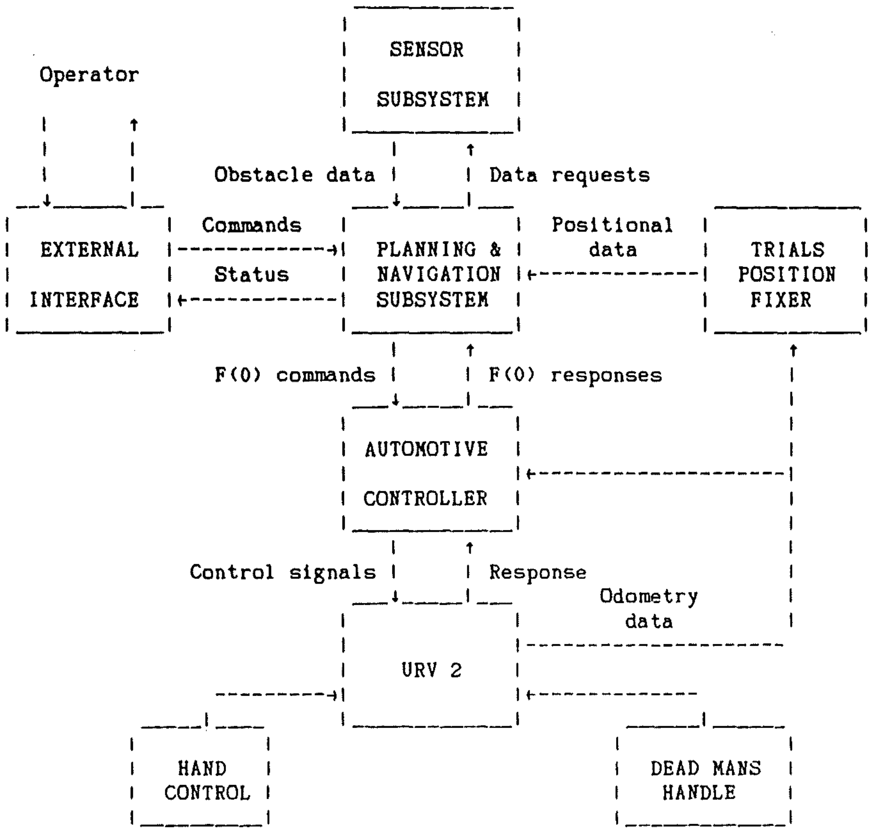

Figure 1. Overall autonomous vehicle system.

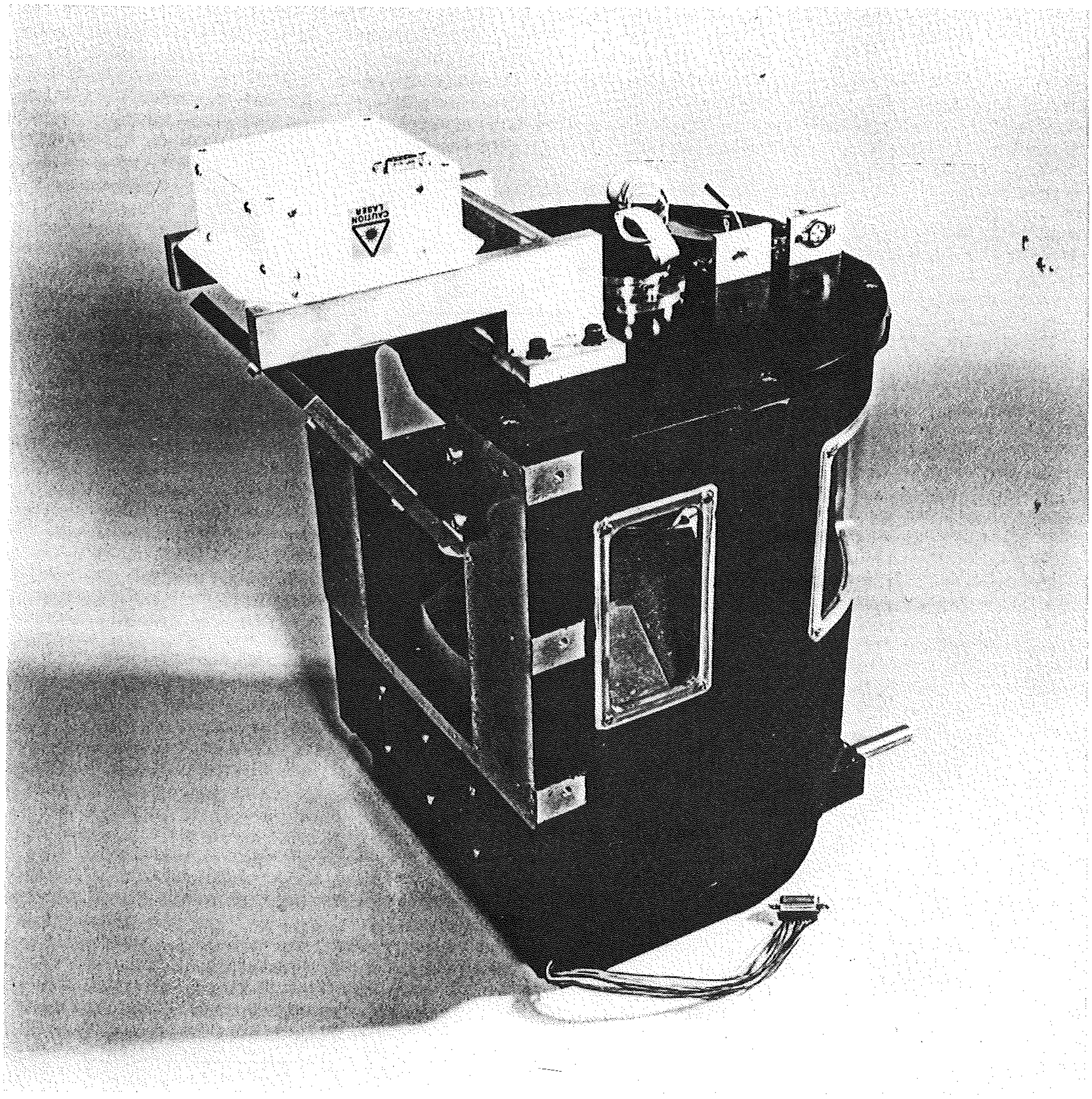

Figure 2. The sensor head. The rangefinder is to the upper left. One of the scanning polygons is partly visible inside the scanner housing.

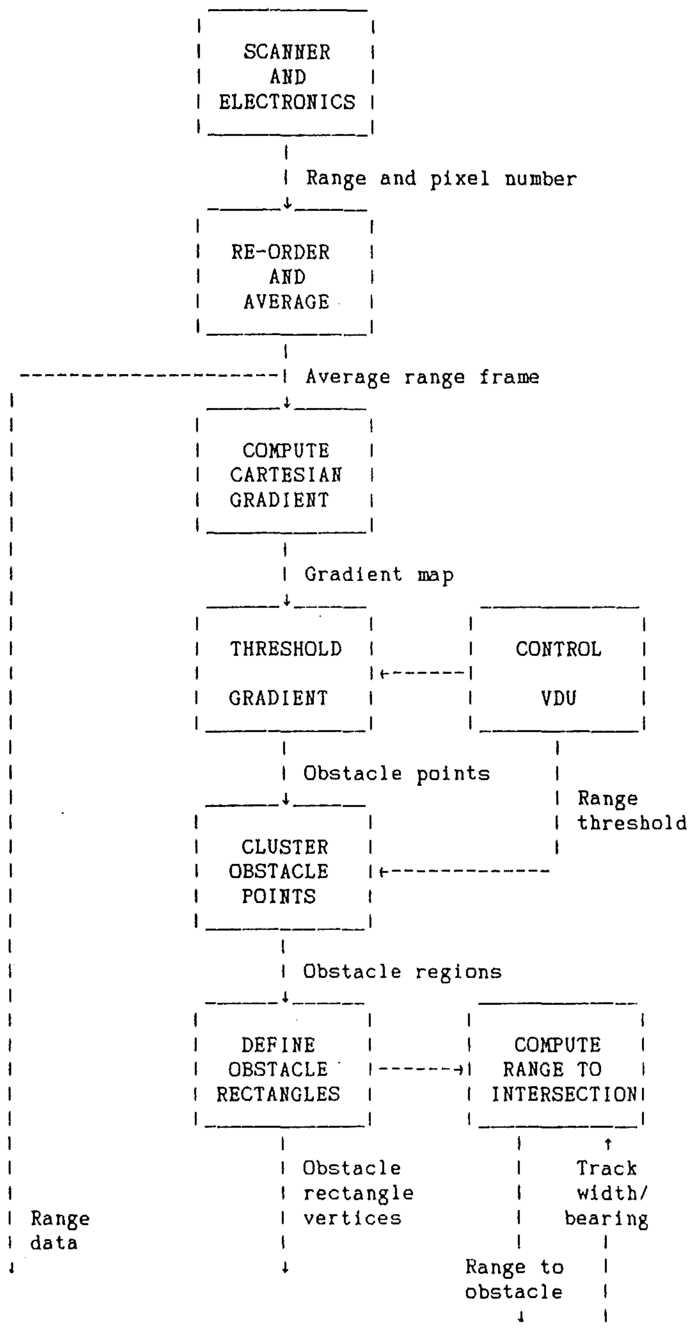

Figure 3. Data processing steps in the sensor subsystem.

Figure 4, Track scene, The track surface is of sandy soil,

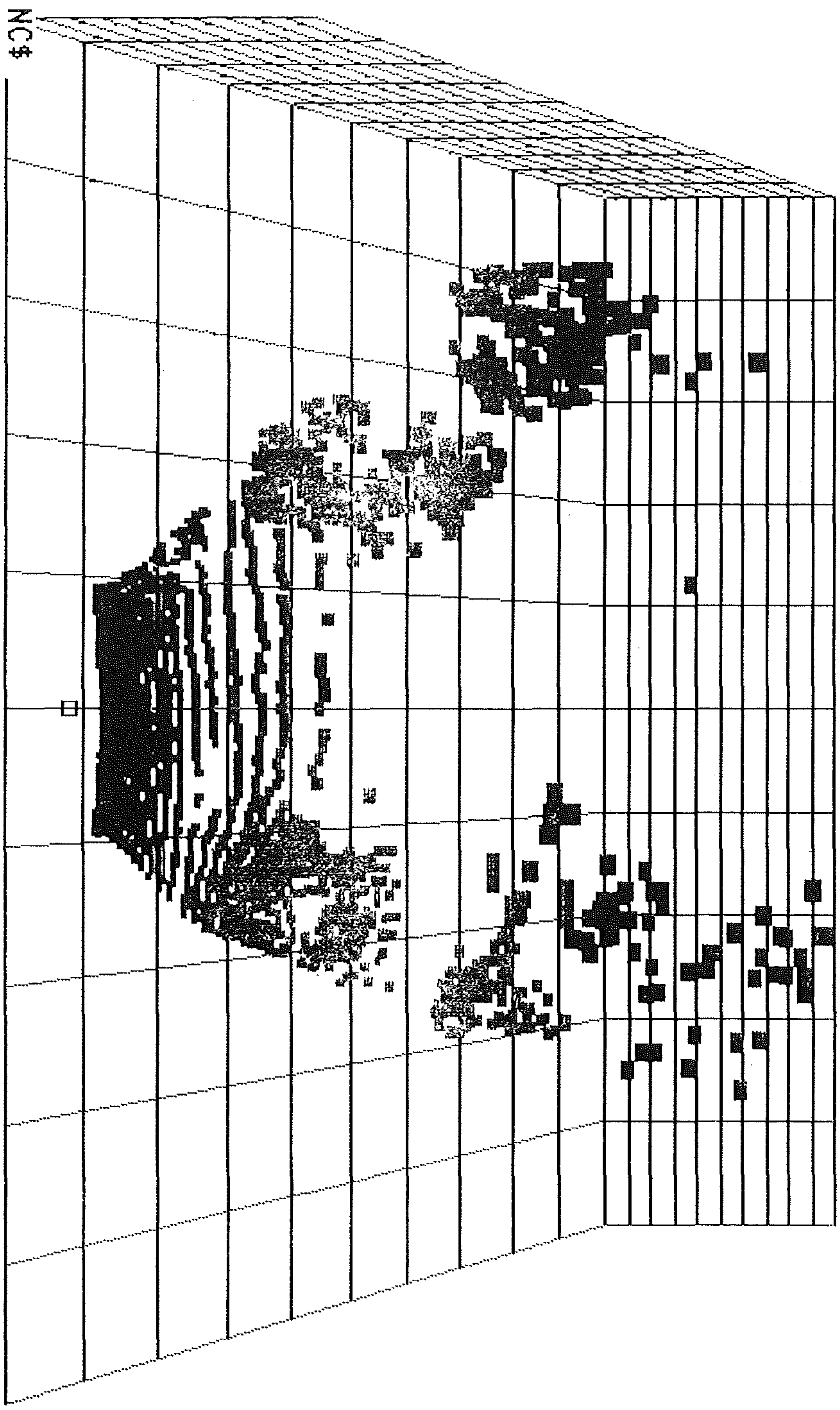

Figure 5. A perspective plot of the range measurements on the track shown in figure 4. The sensor was located 1 m above the ground in the position marked by the box in the foreground.

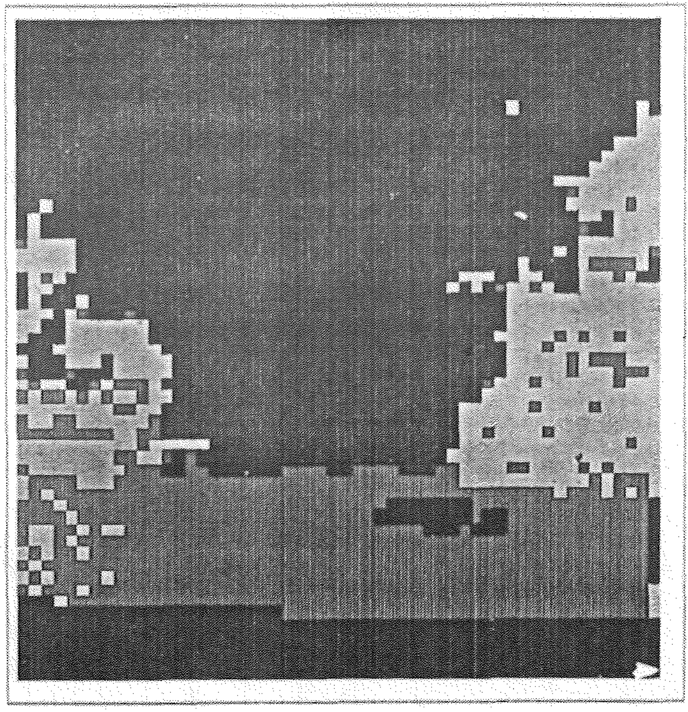

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Figure 6. Three level gradient image corresponding to figure 4.

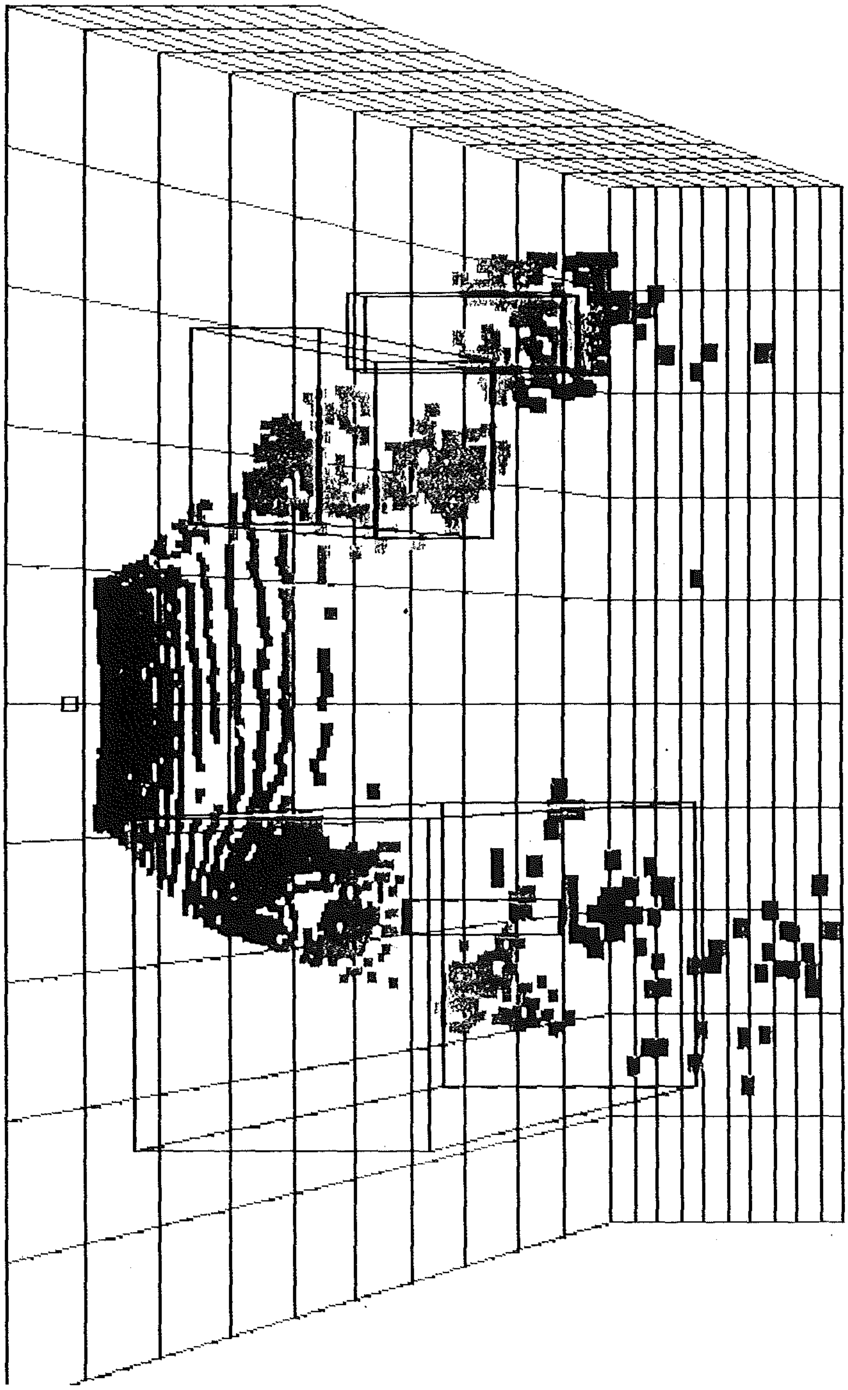

Figure 7. Obstacle boxes, aligned with the sensor axes, placed around high gradient regions. All boxes are extended to the minimum value of z measured in the data.

Laser Vision Sensor For Disaster Prevention Robot

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What kind of vision sensor should a disaster prevention robot (DPRobot) be equipped with ? The answer will be dependent on what kind of DPRobot we are going to develop. If we expect the DPRobot to work at petroleum tanks and/or oil refinig plants and to extinguish a fire during the period of early burning stage, we should provide with the robot a sensor which can give us information on the objects placed in the disaster environment, especially in smoke, water vapour and flame. It is exactly this kind of sensor that we are now developing under the national R&D project "Advanced Robot Technology".

Our conceptionally designed DPRobot, being operated by remote control, has two types of new visual sensors in addition to conventional ITV cameras. The one is an ultrasonic sensor now being developed by NEC and the other is a laser sensor.

Our laser sensor is functionally composed of five parts; CO_2 laser oscillator, high speed laser scanner, phase detector and signal processor, image processor, and CRT display. (In the conceptional DPRobot system, the former three parts will be mounted in the DPRobot itself and the latter two in an operator room, so signals will be transmitted from the DP Robot to the operator, and vice versa, via an optical fiber.)

The reason why to chose CO_2 laser as a light source of the active sensor is as follows : The beam of CO_2 laser goes through the atmosphere. The wave length of this laser is in the far infrared region (10.6 μm), so scattering loss due to fine particles of 1 μm or less in diameter is fairly low in comparison with cases of near infrared beam or visible beam. The CO_2 laser beam is, therefore, expected to penetrate through the environment involving smoke and water vapour. The laser beam, coherent and directional, is also expected to be separable from thermal radiation field, an incoherent noisy background.

The laser beam amplitude-modulated at 15 MHz and emitted from the robot will irradiate an object in the disaster place. Certain portion of the irradiated beam will be reflected on the surface of the object, while detectable portion of the reflected beam will return to the oscillator. Phase retardation of the hetrodyne received beam to the reference one is equivalent to the distance between the oscillator and the irradiated point of the object. By scanning the laser beam in the way similar to raster scanning of TV, a distance map will be obtained on the whole surface of the object facing to the robot.

The disaster environment is considered to disturb beam propagation remarkably, so a process to reduce the noise effets and to pick up signals bedded in the disturbance field is essential to have a clear map of distance. The most preferable interface to an operator is a display of an object on the CRT screen in front of the operator as if it were to exist really just in front of him. Conversion of distance to brightness, for instance, will produce a quasi three dimensional vision of the object on the CRT screen.

The specification goal of our laser vision sensor is as follows: measurable range of distance is 3-30 m, resolution of distance is within 10 cm, picture elements of a frame are 100 x 100 and the maximum frame rate is 10 Hz.

Laser visioned pictures of objects placed in the clear atmosphere will be demonstrated at the present workshop.

INTERPRETATION OF 2½D IMAGES

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Problem statements

Our problem, which is in the area of machine vision, is to interpret 2½D images (representing depth and surface orientation rather than light intensity) determining what objects are present and what their scene locations are. Although we ourselves are not concerned with the aquisition of the data (but only its interpretation) we are part of a consortium in which other groups are working on this problem (e.g. from stereo). The goal of the consortium is to produce a complete system from scene to interpretation.

Application area

The target application is any autonomous system which needs to interpret a visual scene in order to identify and locate objects which it already knows about. Objects which are composed of well defined surface patches (most man made objects) can be represented and recognised, but the system cannot handle objects which are difficult to characterise geometrically (i.e. natural objects).

Methods used

In the course of our research we have developed techniques for the following sub-problems:

i) The description of segmented 2½D images in a way which facilitates their comparison with object models.

ii) The description of object models in a way which facilitates their comparison with image data.

iii) The model invocation process. This process is designed to speed up recognition when there is a large data base of possible object models to check through. A few models only (typically 1 - 5) out of possibly thousands will be invoked for each image entity and only these will go through the constraint reasoning process.

iv) Finding constraints on the translation and orientation of object models and expressing them in numerical or symbolic forms.

v) Reasoning with constraints to discover inconsistencies and therefore mis-identifications, to find the locations of correctly identified objects and to deduce allowed values for variable quantities occurring in model definitions.

vi) The verification of hypotheses which have successfully passed the invocation and reasoning stages.

Status

We have a working program written in 'C' and running on a SUN 2 which, starting from segmented 2½D images, has correctly recognised and located objects in several test scenes. The test scenes typically contain one or two target objects which the program knows about (e.g. a chair, a robot arm, a trashcan) plus some spurious objects which might be obscuring parts of the targets.

Results

The program is slow on our equipment, typically taking about two hours computing per picture. However, we have designed the key program components (model invocation and geometric reasoning) to be implemented on a parallel network and run much faster.

The positional accuracy with which objects can be located is roughly 5cm at a camera-scene separation of about 5m. Orientation is good to about 10 degrees.

Further research

We are currently involved in extending the object models to include curve features, volumetric features and viewer dependent features as well as surface patches. This will enable the program to gather useful information from a greater variety of image features. We are also changing from reasoning based on a numerical representation for geometric constraints to reasoning based on a symbolic representation. This will enable a richer set of constraint types to be represented and provide a more accurate way of handling data errors.

Our future plans include investigations into viewpoint dependent scene understanding, visibility, appearance and location prediction, 3D geometric descriptions and alternative evidence matching.

Interest in cooperation

We would be interested in future collaboration with anyone working in 3D image data, its aquisition and interpretation. Also with workers who have experience in parallel architectures involving large networks of simple computing nodes.

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THE NEW GENERATION OF DFVLR ROBOT SENSORS

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I. Problem Statement

There are a number of reasons why sensorcontrolled robots are so rare in real applications. The probably most important of them are

- sensors very often are too expensive and too big for an elegant integration into grippers, they come with an extra black box and are difficult to integrate into robot control systems from the viewpoint of fast data transmission.

- powerful techniques are missing that allow to automatically generate feedback structures and algorithms dependent on sensor data and task specification, and that allow the human operator to interfere with the robot any time he wants via very "natural" man-machine-interfaces.

We tried to make a few steps into resolving these problems as outlined in the sequel.

II. Application Areas

Sensory feedback is the basis for future intelligent robots and manipulators. The techniques we are emphasizing involve the human operator´s experience via new man-machine interfaces as are six-axis-hand-controllers; thus an advanced manipulator type or telerobot with learning capabilities is envisioned that is particularly useful in space, subsea, nuclear power plants or any type of construction.

III. Research Course

For more than 10 years now DFVLR has been working towards the goal of making robots more intelligent via sensors and sensory feedback. Main features of the present state of work are:

A new generation of force-torque-sensors and optical range-finders for the end-efector, having the following characteristics in common:

* small size and leight weight

* all signal processing (including digital computation) is inside the sensor or at least inside the end-effector (SMD-technique)

* sensors are connected to the robot control system via a fast serial bus system (375 kBaud), so that even in case of a multisensory gripper only two data-lines are requested.

* Each sensor derives the dc-voltages it needs via a tiny transformer from a 20 kHz ac-power supply; thus all sensors are galvanically decoupled.

The new sensors are briefly characterized as follows:

a) Stiff force-torque sensors based on strain gauge measurements

In addition to the well-known DFVLR-"standard" sensor a new arrangement in form of a double-maltese-cross has been designed (fig. 1). Forces and torques generate symmetric deformations in the two crosses rigidly connected in their center.

20 strain gauges are arranged in a perfectly symmetric way into 8 fullbridges assuring redundancy in case of gauge failures. The analog electronics and 12 Bit digital evaluation are mounted inside the sensor. The standard version

with a height of 4,5 cm and a diameter of 7 cm is easily configurable up to a force load of 100 kp.

b) Compliant force-torque-sensors on an optical basis

We call these sensors "instrumented compliance" - in contrast to the very stiff strain-gauge sensors - with stiffness selectable via springs connecting a center basis and an outer ring (fig. 2). The deflections corresponding to forces/torques are measured optically, i.e. the light beams as emitted by 6 LED´s in the center basis of the sensor are projected via slits onto linear position sensitive detectors inside the outer ring of the sensor, which is mobile against the center basis. Slits and PSD´s are alternatingly orthogonal. Compliant sensors of this type are of advantage especially in assembly tasks. Resolution is 10 Bit here.

c) New combinations and special arrangements

Force-torque-sensors should occupy as little space as possible in a robot gripper. Therefore e.g. a new version of the instrumented compliance is realized in form of a ring around the gripper drive (fig. 3). Furthermore it depends on the application or the section of a task, whether a stiff or a compliant force-torque-sensor is better suited. Thus for example a ring compliance - as in fig. 3 but without instrumentation - in combination with a stiff strain-gauge-sensor inside allows to generate a fully switchable system; in case of free motion the compliance is locked pneumatically, while in case of contact it is released.

d) Triangulation-based range finders

The principle of triangulation (fig. 4 and 5) as a range finding technique has been known for a long time, yet it was difficult to develop range finders for robots that are small and precise and yet cover a large measuring range.

The DFVLR sensors work with a laser diode, the transmitted power of which depends on the reflected light spot´s intensity and is controllable within about 10 µsec in a range of 1 to 10000. Thereby quickly changing, smooth and slant surfaces are measurable satisfactorily. The reflected light spot is focussed onto a linear position sensitive detector and the two voltages measured (U_1 and U_2) allow to determine its position via the equation

$$U = \frac{U_1 - U_2}{U_1 + U_2}$$

For avoiding quantization errors this division is performed in new logarithmic circuits in analog form thus guaranteeing a denominator range of 1 to 1000.

Fig. 6 outlines the basic structure of our recent grippers, which in addition to a force-torque sensor contain an array of 9 range finders. The "long range finder" (for distances e.g. 5 to 50 cm) in the wrist has approximately the size of half a match box (fig. 5). Due to its small weight ($<$ 16 g) it may be used for scanning without mirrors. The four range finders in each finger are even smaller by a factor of 3-4, but of course they measure smaller ranges of e.g. 0 to 3 cm.

IV. Telerobotic Concepts

IV.1. Basic Elements

* The DFVLR-steering balls ("sensor ball")

They are based on the idea of integrating a 6-component-sensor into the center of a plastic hollow ball, so that the forces or torques exerted by a human hand are transformed into translational and rotational commands for real robots or simulated 3D-computergraphic objects. The first sensor balls had a stiff strain-gauge sensor inside, the balls shown here however use the compliant optical system as shown in fig. 2. All the analog electronics is integrated inside the ball. Fig. 7 shows a commercial design of the ball.

* 3D-computergraphics

For visualization of robot position, working cell, path distortion, sensory information and joint load in real time. The graphic display (wire frame presently, but shaded solid models in the very near future) runs either passively parallel to the robot, or the operator steers the graphically simulated robot via the sensor ball; the thus generated commands may be sent to a far-distant real robot e.g. in a space-craft with considerable transmission delay.

* Stereo-image display

In all the cases where the working area is remote (nuclear plants, underwater sites, space) it makes sense to telecommand the robot via the sensor ball by hand of a stereo-image, if delay times are small. A fairly simple technique we are using is to connect the left camera (or the left fiber-optic bundle in the gripper) with say the green channel of a colour monitor, and the right camera (fiber bundle) with the red channel and look at the mixed image with red-green glasses. A long-term goal especially for space robotic applications is to take stereo-image and range finder information just as an information source for updating a 3D-computer graphics model of the robot´s environment.

* Voice-input-output

Voice-input-output systems are available today on the board-level and in our concept serve for menue control and for Parameter input, but not for motion control. Thus the operator may concentrate himself in the programming phase completely onto the (real or graphically simulated) robot without operating a terminal.

trolled subspace ($\underline{f}_{T,cf}$); there they are either neglected in case nominal sensors values have to be kept constant autonomously or they are counterbalanced with the wrist sensor data as mentioned above yielding a robot that is fully under human control. We treat the range finders as pseudo-force-sensors too, thus arriving at a unified treatment of completely different sensors. For the generation of subspaces we use kind of a simple knowledge-base, which depending on the present task together with the actual sensor data generates these subspaces automatically.

Now fig. 10 may also help to unterstand our predictive control approach usig advanced 3D-computergraphics in case of teleoperating a space robot from ground with overall delay times of 2 and more seconds. This is the case in our space robot technology experiment ROTEX which we have proposed to fly in the next spacelab-mission D2 (fig.9). The operator handles the ball by looking e.g. at a predicted wire frame graphics model of the robot which may be superimposed to the stereo image of the real scene. We assume a linearized cartesian state space model $\underline{x}_{k+1} = \underline{A}\ \underline{x}_k + \underline{b}\ \underline{u}_k$.

This model in standard form of digital control theory does not only describe the cartesian robot dynamics, but also the disturbances. That is to say, if the robot as shown in fig. 10 does not fully execute the rudimentary commands due to sensory contact with the environment, the missing motion in the sensorcontrolled subspace may be interpreted as a constant disturbance which is very easy to model. Of course if an environment model is contained in the graphics simulation, this model knowledge can be used to set initial estimates for these disturbances at the approximate "first contact" instants.

Thus the left part of fig. 11 is just a prediction of the robot´s present estimated state $\hat{\underline{x}}_k$ robot to the future state $\hat{\underline{x}}_{k+n_u}$; n_u is the uplink-delay-time expressed as a multiple of the sampling period, that makes up one delay d. This predicted state is just the state to which the presently issued ball command has to refer. But the more interesting part is the estimator on the right half of fig. 11. It compares the measured, but downlink-delayed output data $\underline{y}_{k-n_d}$ (the robot's positions and orientations) to the output data $\hat{\underline{y}}_{k-n_d}$ from the robot model running through the downlink-delay computer model (n_d is the number of sampling periods in the downlink-delay).

The estimator's structure has been shown by the author to be very efficient in digital control systems with large measurement delays /9/. The observer or Kalman filter gain matrix $\underline{K}$ is designed with the low order system matrix $\underline{A}$, i.e. without any delays. Then the structure as depicted in fig. 11 is applied, assuring that after a disturbance has occurred and the delay time ($n_d \cdot d$ here) has elapsed, the observer behaves as if the delay line were no longer present.

V. Further Research

One of our main concerns in the future will be to derive 3D-graphic models of a robot's environment by using sensory and vision data as input. Furthermore the application of associative memories to the learning of sensory behaviour is of mayor interest.

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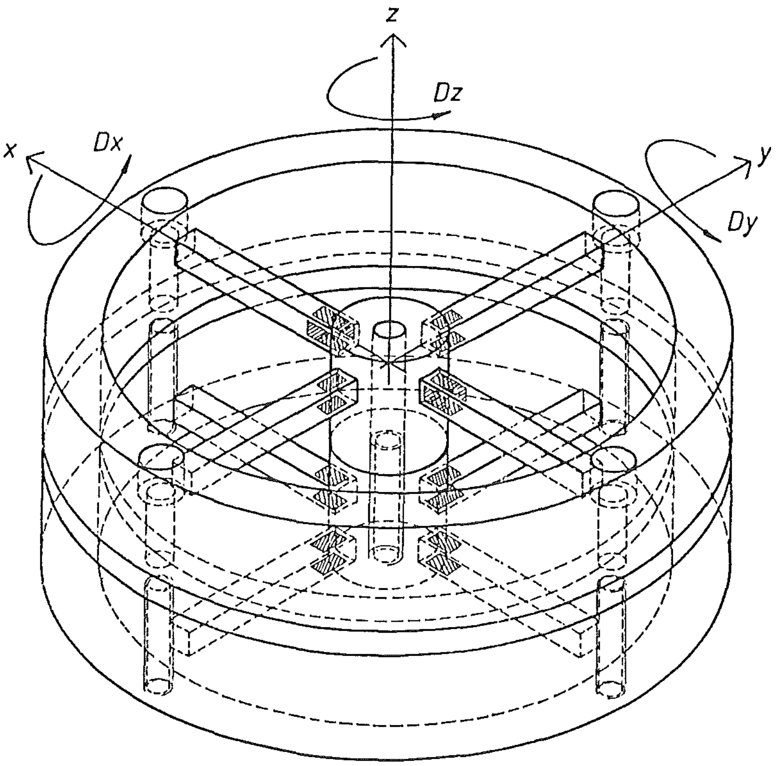

fig. 1 New strain-gauge-force-torque sensor

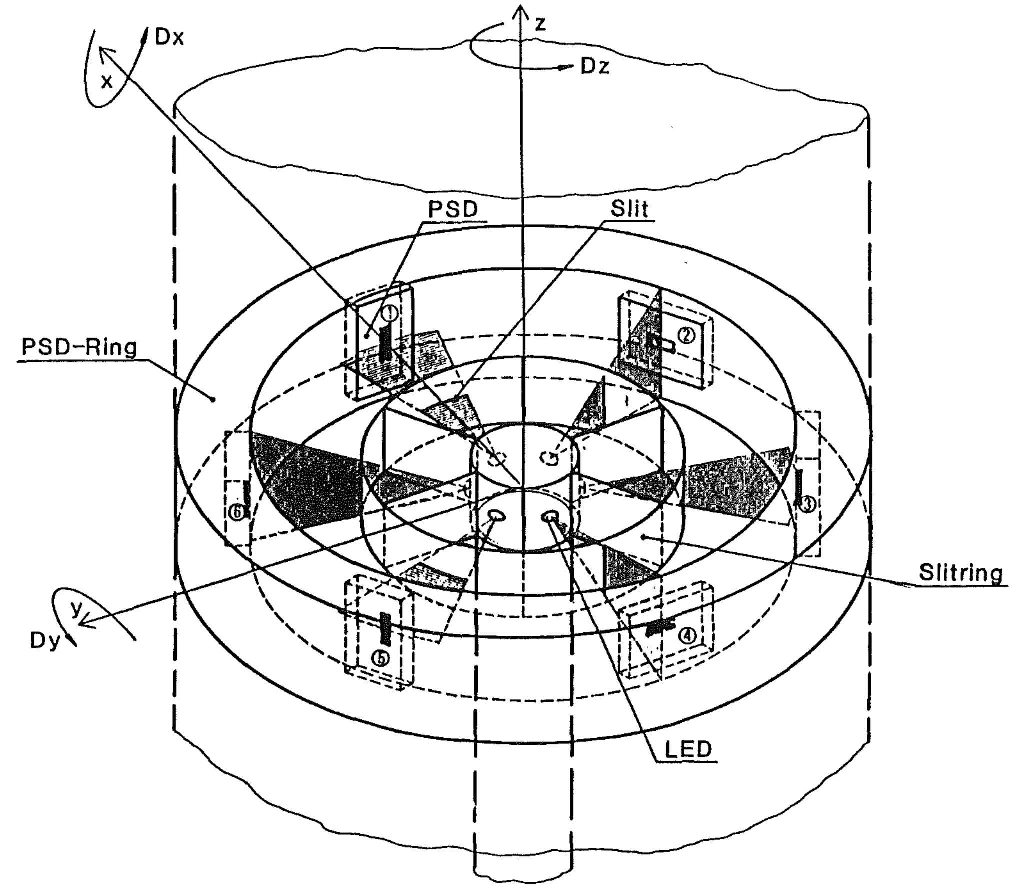

fig. 2 "Instrumented compliance"

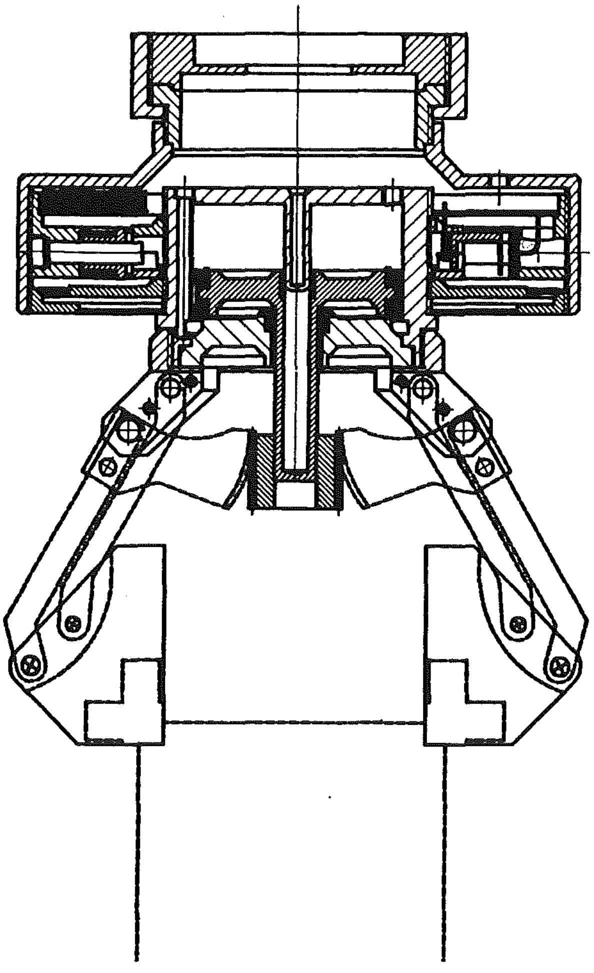

fig. 3 Compliant force-torque sensor shaped as ring around the gripper

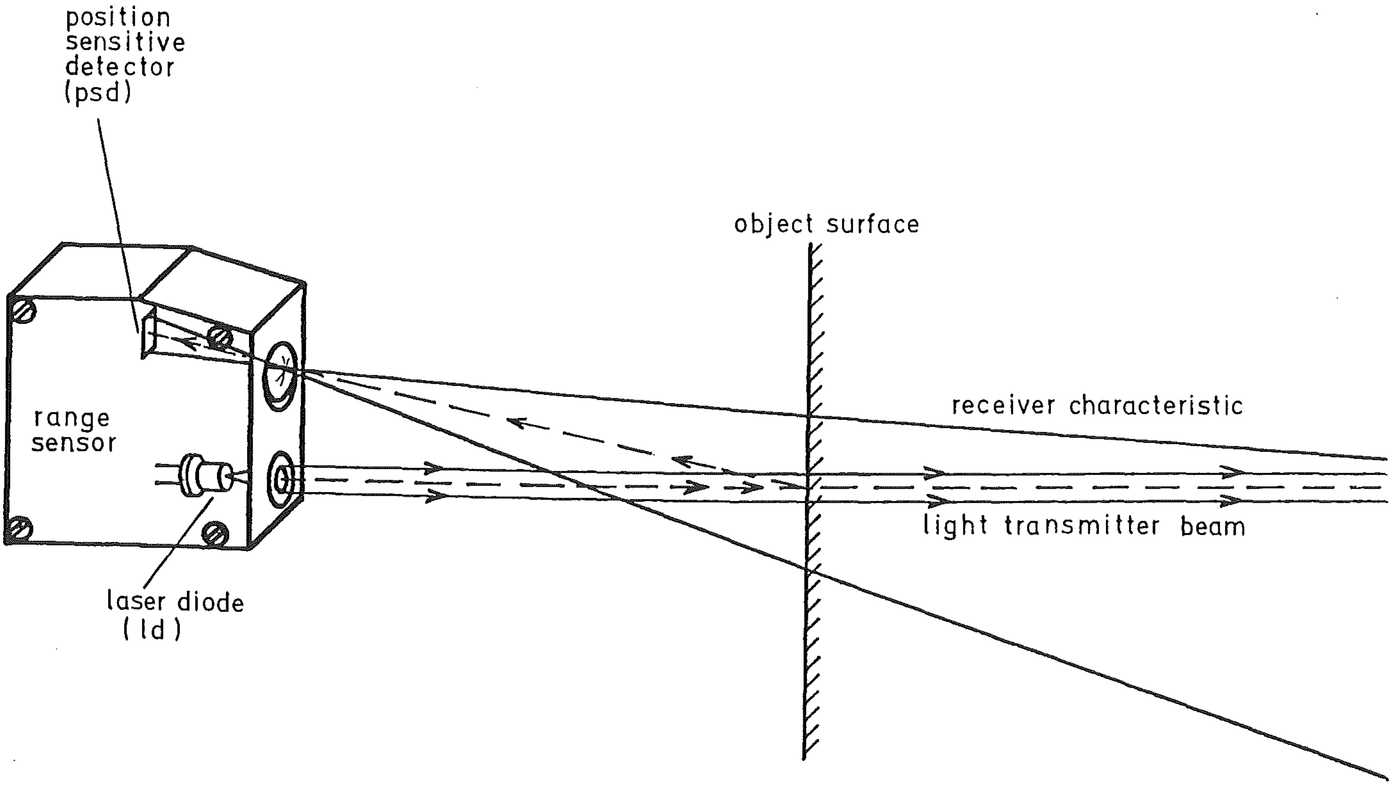

fig. 4 Range finder based on triangulation

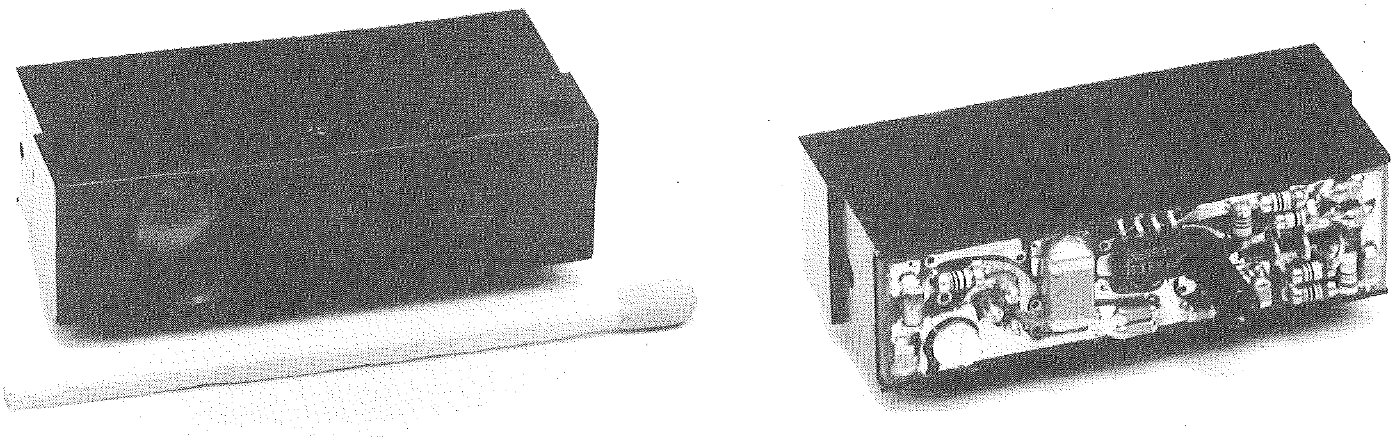

fig. 5 A DFVLR-range finder for the measuring range of 5-50 cm, probably the smallest one that has been built so far.

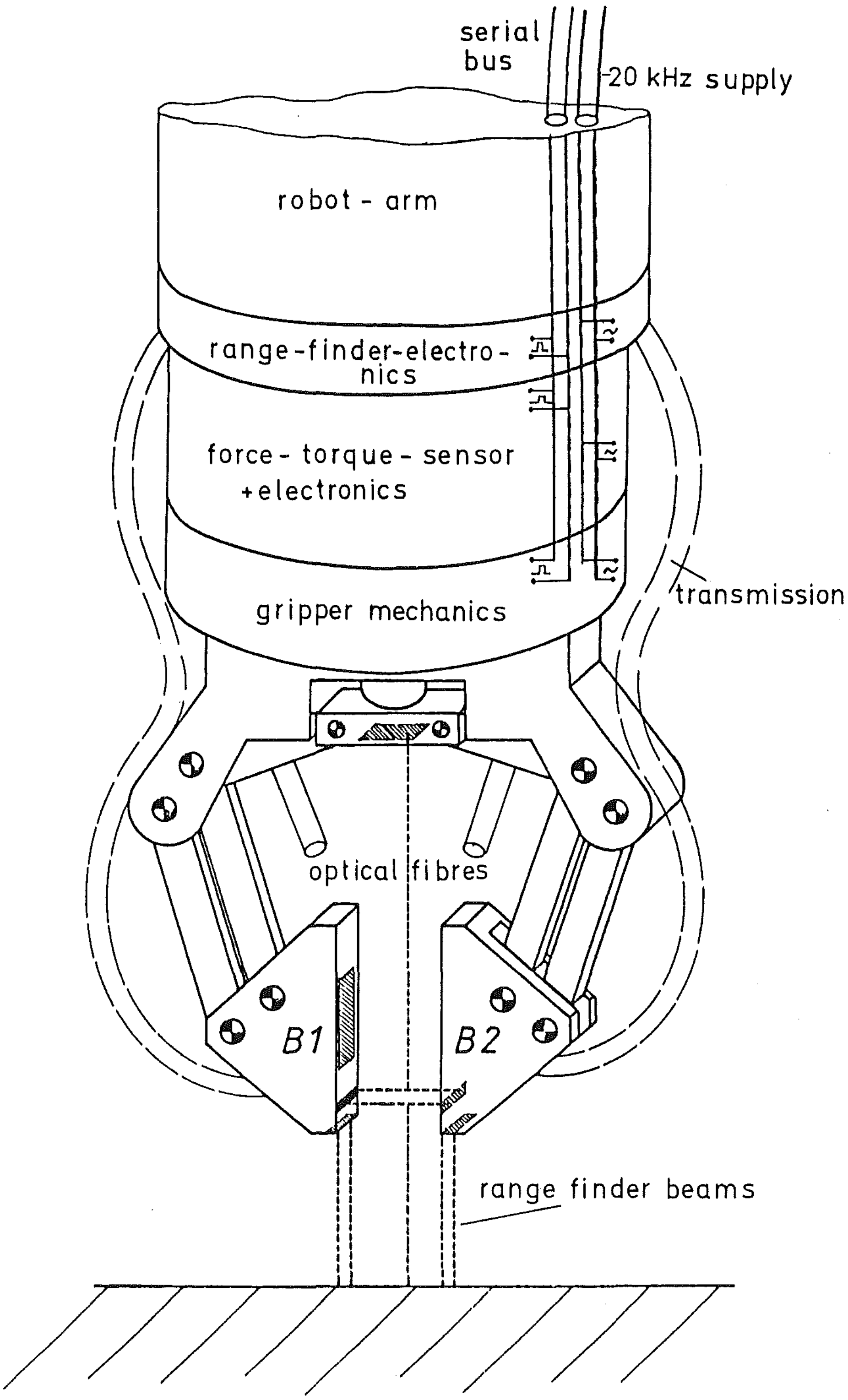

fig. 6 Schematic structure of our grippers with a force-torque-sensor and 9 range-finders

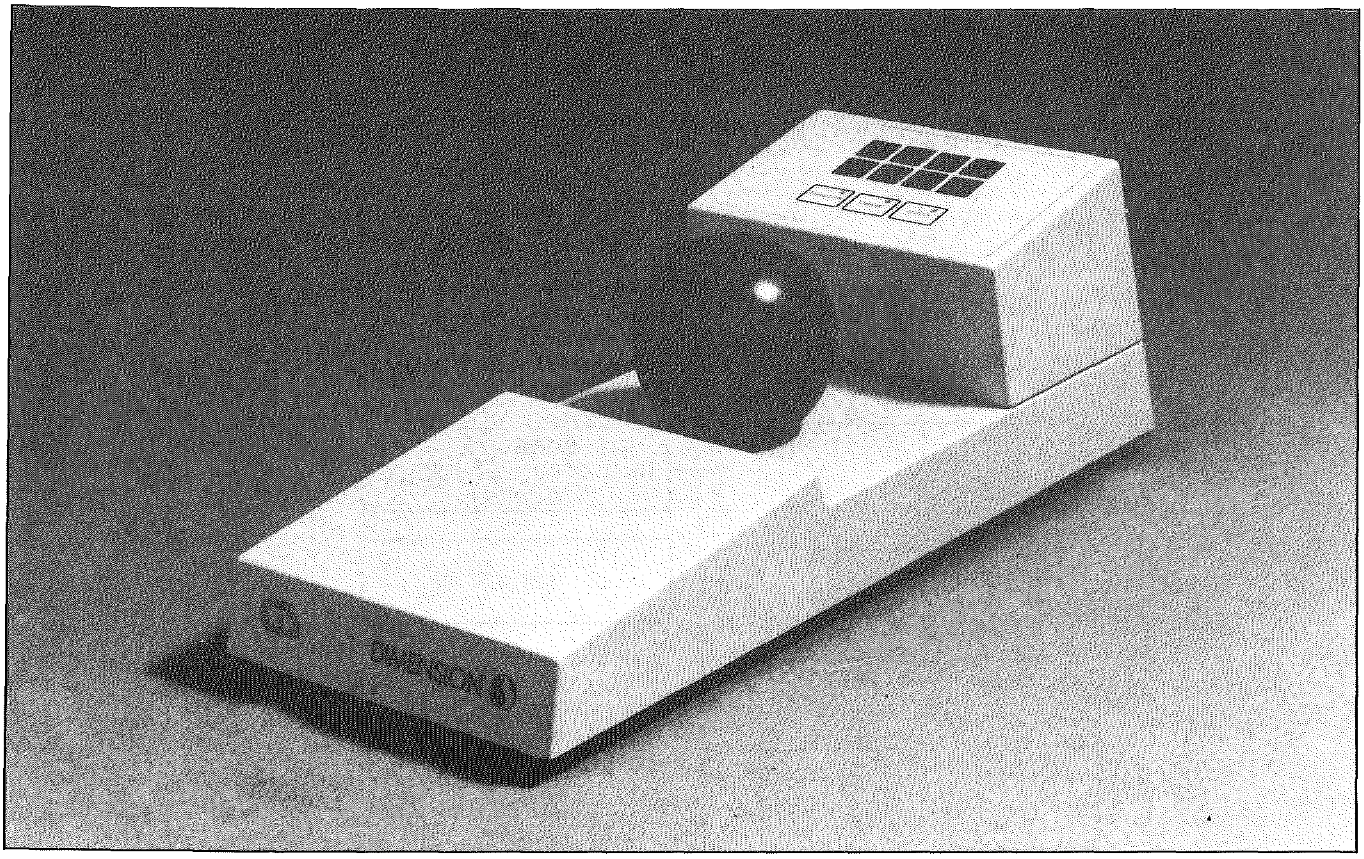

fig. 7 Commercial version of our 6 axis steering ball

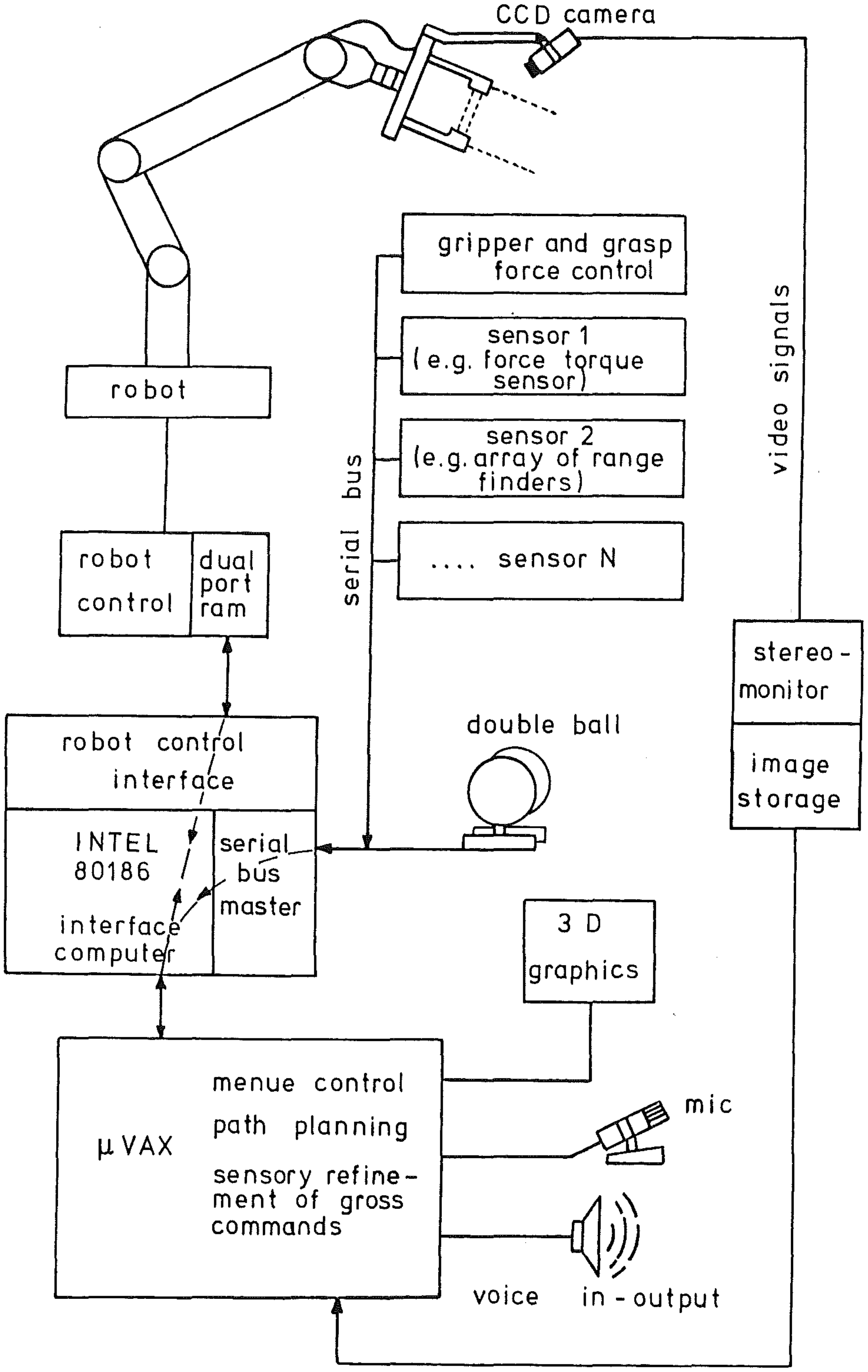

fig. 8 Bus and blockstructure of our sensorbased telerobotic system

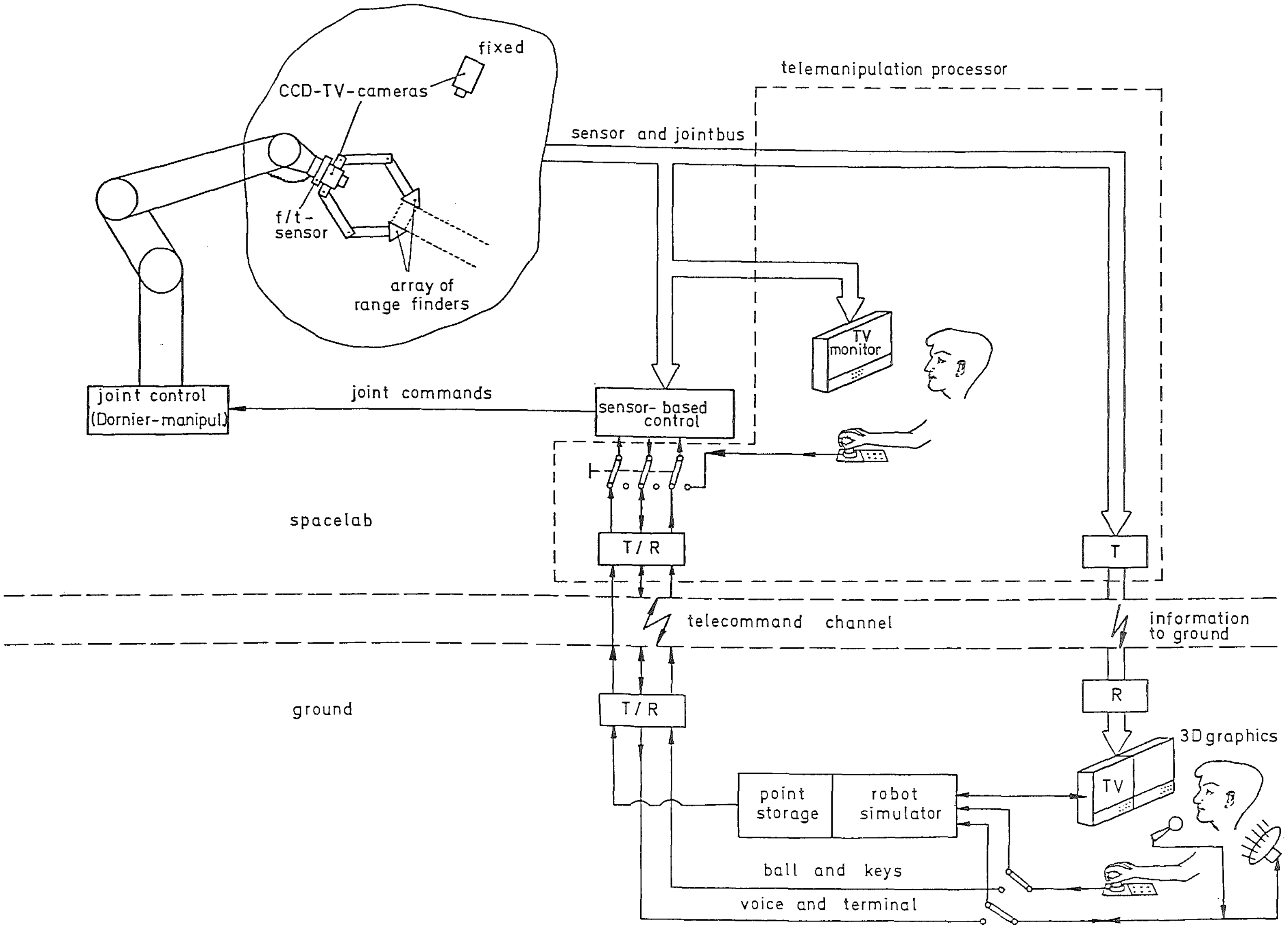

fig. 9 Schematic representation of ROTEX, a robot technology experiment for the next spacelab mission D2

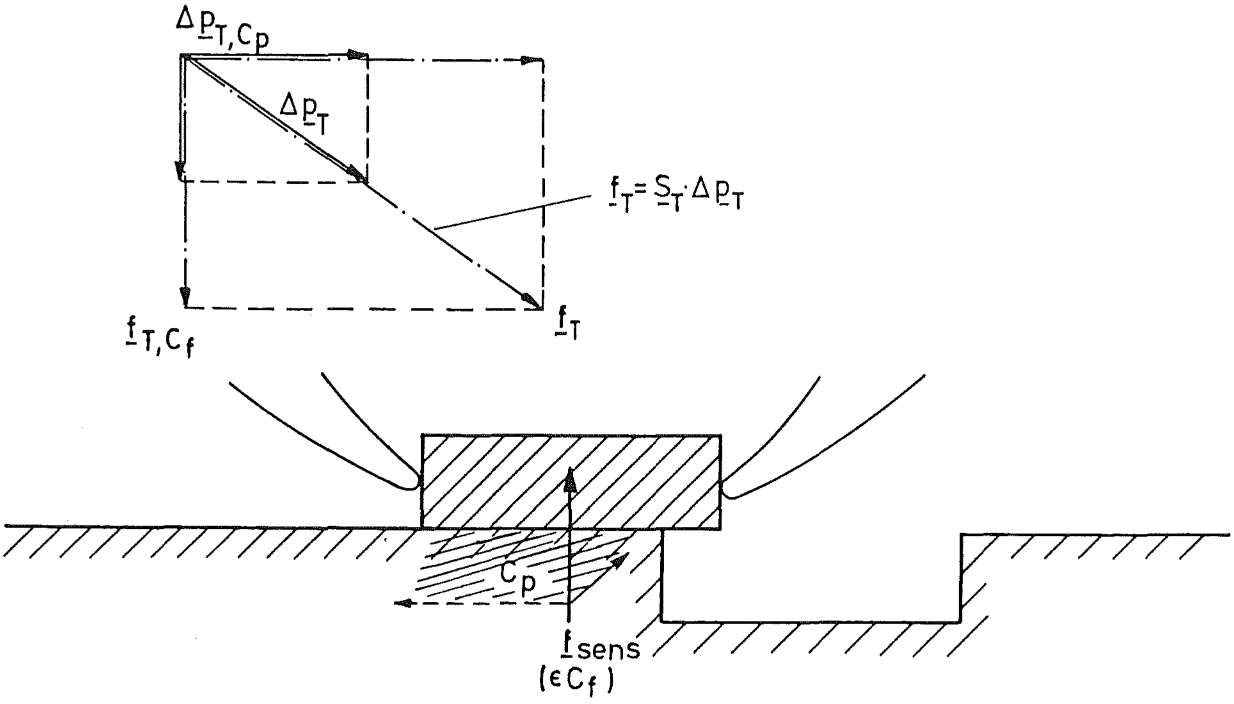

fig. 10 Projection of rudimentary commands into position and sensor-controlled subspaces

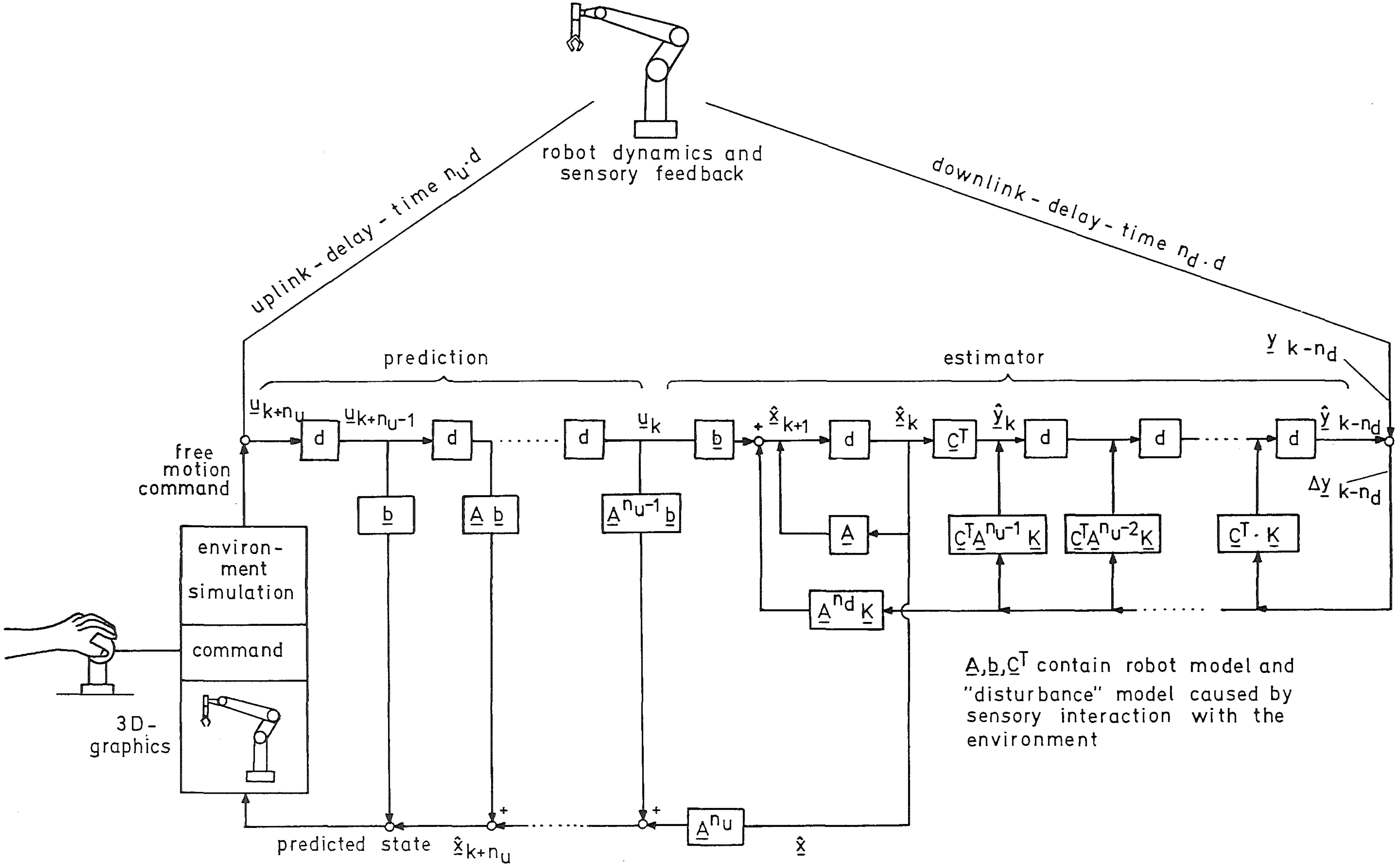

fig. 11 Predictive estimation scheme for the graphic simulation of a teleoperated robot that has sensory feedback on board and a large time delay in the transmission links.

SENSOR SIMULATION IN ROBOT APPLICATIONS

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Abstract

This paper describes a concept for sensor simulation in the area of robotics. Our approach shows how geometric modelling based on a boundary representation can be used for such a system. On the next level physical modeling will be integrated into the system. An example shows the implementation of the used data structures and how to operate with them.

Introduction

The growing complexity of systems for industrial automation necessisates the use of powerful tools to test new installations and modifications in automation systems. Graphic visualisation helps the human planner to simulate the difficult processes of planning and testifying during implementation phases. Specially when robots are used as a part of the automation system, serveral tools for testing [LAU84] [TSU83] [HEG77] have been developed on the basis of simulation. These tools may be employed to model complete working cells with manipulators and workpieces.

The main application of simulation is to validate the developed software with a corresponding visualisation on a graphic station. Several robot simulation systems [MEY81] [AND] have introduced sensor modules in their simulation processes. But all these systems have several restrictions. Therefore it is not easy to simulate physical effects in the model and only simple sensors eg. distance and contact sensors, have as yet been modeled.

A Simulation System for Robots [DIL86] known as ROSI has been developed at the Institute of Informatic III, University of Karlsruhe. This paper describes the special concept of the simulation of sensors used in ROSI.

The first step is to use the geometric data of the working cell components (ie. robot arms, workpieces, feeders, fixtures,...) to calculate the geometric relation among them. Based on these relations physical effects can be emulated, for example reflections.

In the second step the physical description of various classes of sensors is presented. The embedding of various classes of sensors enables the development of simulation of robot systems of the next generation. Due to the introduction of sensor data the validation of the behaviour of future robot systems will be much more complex than it used to be. Therefore more powerful tools are needed to support the development of these new systems. The integration of sensors in robot simulation systems is a step in this direction.

2 The robot simulation system ROSI

ROSI is an interactive system for off-line planning and programming of robot applications in automatic manufacturing. The basic off-line programming tasks carried out by ROSI with the aid of graphical simulation are:

- planning of the layout of manufacturing cells,
- selection of robots, end-effectors, sensors, peripherals,
- generation of programs for handling devices,
- graphical simulation of the executed program,
- detailed debugging of grasp and compliance tasks.

ROSI is an independent system with interfaces to different programming methods, CAD-systems and to the devices of the real manufacturing cell. The overall system structure consists of the main components and their arrangement and interconnection links (figure 2.1).

The main components are:

- a user interface to model and to program manufacturing cells,
- a modeling module for generation of a realistic computer internal model of the manufacturing cell,
- a set of emulators to imitate the behavior of real devices,
- a programming module to program robots and handling devices,
- a simulation module for graphical and analytical verification of generated programs,
- a run-time system that controls the interpretative execution of programs,
- a data management system to manage the computer internal model.

ROSI runs on a VAX 750 under the operating system VMS. A PS300 vector graphic system improves the graphical representation by a set of locally computed transformations like rotation, translation, zooming, etc. A more detailed description of the structure of ROSI is given in [DIL86].

2.1 Integration of the sensor emulator and interfaces to other modules

For generation and testing of robot programs controlled by sensors, a sensor emulator is needed to emulate the sensing and the sensor preprocessing. For that reason a sensor emulator module is integrated into the simulation system. The sensor emulator is an independant component of the emulator module, which has interfaces to the run-time system, the programming module and also to the data management system.
To specify a sensor measuring as an action of the program, the internal command language includes sensor activation commands. These commands are recognized by the run-time

system that interpretes the internal command language. The run-time system invokes the sensor emulator when it has to interprete a sensor command. For an activation of a sensor operation it is neccessary to pass the name of the sensor and an appropriate data buffer for repassing the emulated sensor signal value.

The practical use of sensor emulation in the area of robot off- line programming depends essentially on the information about the manufacturing cell and the used sensor which is stored in the computer internal model. The accuracy in which the internal model corresponds the reality, determines mainly the adaptability of an emulated sensor operation.

For that reason the data base has to offer detailed information about the cell conditions, the cell objects, as well as detailed description of the properties of sensors. Therefore information about the geometry of objects, the kinematic structure of handling devices, technological and physical properties of workpieces, devices and sensors are required. From the point of view of sensor emulation, the internal model is divided into an environment model and a sensor model.

2.2 Model of the environment

Irrespective of sensors, a computer internal model stores detailed information about:

- the conditions in the manufacturing cell (light, dust),
- the layout of the cell (arrangement of the handling devices, material buffers, workpieces),
- the mechanical und kinematical structure of handling devices,
- the geometrical description of devices and workpieces,
- the physical and technological properties of devices and workpieces.

For geometric description of the cell objects a data structure according to the boundary representation scheme is implemented. It is a hierarchical structure consisting of 3 layers. The single layers comprise nodes for description of faces surrounding the body, of edges bordering the face and of points closing edges. Compared to other geometric data structures, the BR-scheme allows to add further information to each node (face, edge, point) of the tree. Consequently a wide variety of analytic definitions for the geometric items, face and edge are possible. For the requirements of sensor emulation the easy extensibility is an important fact. Addition of technologic parameters to the face nodes of the geometrical models of workpieces provide the sensor emulator with properties which influence the real sensing to an considerable extend. The inclusion of physical effects in sensor emulation requires information about surface quality, colour of surface, reflection properties, etc.

2.3 Sensor model

In the context of sensor emulation sensor modeling means description of all properties of a sensor required for the process of emulation. This presumes a geometric model of the sensor, the description of the functionality of the sensor together with all physical parameter that influences the sensor measurement.

The data base in ROSI provides a set of relations to design a specific data structure for sensor modeling. The comprehensive sensor model established by different relations and references between them is outlined in figure 2.2. The sensor model as part of the computer internal model consists of data to describe the elementary properties of the sensor (sensor description), of data buffers to store intermediate states of the sensor during the process of emulation (sensor measuring) and references to other relations. The scheme in figure 2.3 shows some attributes of single data blocks of the sensor model. The significance of these attributes is described briefly as follows:

The data which describes the sensor identify it as part of the data base. In case the sensor is a component of a sensor system, the description identifies it as part of that system. Successor is a reference to the following sensor component in case of a sensor system. The attribute measuring result specifies the kind of the sensor result. Physical properties describe the function of a real sensor by attributes like physical principle or measuring area. The physical principle describes the physical phenomenon responsible for the function of the sensor. This attribute determines the method of emulation. According to the physical principle and the geometry of the sensor a measuring geometry provides a useful representation of the sensor signal for emulation (figure 2.4). The measuring point defines the starting point of the measuring signal which in this case is the reference point for the measuring geometry. The measuring plane is defined by this point and the orientation of the sensor. All geometrical properties are referenced according to the measuring frame of the local coordinate system of the sensor. Measuring geometries are point, straight line, cylinder, cone and sphere.

The sequences of actions in the manufacturing cell and the sensor measuring produce many dynamic changes in the cell and intermediate results. From the point of view of a sensor the position and orientation of a sensor can be changed because of a robot motion or a motion of an independent attached sensor, for example a camera system. References describe information about the arrangement of a sensor attached to a handling device with the frame that stores the relation to the reference coordinate system.

3 The structure of the sensor simulation module

3.1 Interface with the geometric model

The interaction between the two models — the geometric and the sensor — is based on a series of geometric operations. They are adapted to the concept of the sensor emulation, but they can also be used for other purposes, specially for the operations computing the intersection of bodies, distance calculation and recognition of geometric pattern.

When a sensor is activated, it should first check the surrounding of the objects to be measured and reduce the number of possible objects (Figure 3.1 shows the algorithm used at an activation of a sensor). The physical aspects are to be checked thereafter.

The first phase in a measuring sequence is the recognition of objects located inside the measuring area of the sensor. For this purpose geometric bodies are approximated by spheres. The centres of these spheres are defined by the centres of gravity of the objects. The radius of the sphere is the maximum distance between points case on the shape and the centre of the circle. This simple approximation is easy to obtain and can be used for other purposes (for example detection of collision free spaces etc.) in a later stage.

The algorithm used for recognition of possible objects is called measuring plane projection. The first step for this is to project the centre of gravity into the measuring plane. Thereafter the vector difference form the centre of the body and its projection is calculated. If the orientation of this vector is negative with respect to the normal of the measuring plane, the object is located in front of the measuring plane and may be used for measuring purposes (see Figure 3.2).
A special case is identified if the centre of gravity is behind the measuring plane and the distance to the plane is smaller than the approximate radius of the sphere. In this it is necessary to check whether any part of the object is lying in the measuring geometry of the sensor.

All recognized objects can be sorted in a measuring chain according to the relation of the approximated sphere and the measuring centre of the sensor. This measuring chain defines the objects to be inspected. With the given data of the measuring geometry, the position of the object and accordingthe measuring distance (i.e. the distance of the centre of gravity and its projection into the measuring plane) the decision can be made which parts of the object are placed in this given measuring geometry of the sensor.
Figure 3.3 shows the relations in the geometry when this decision is made. This example has a cylindrical measuring geometry. After computing the projection into the measuring plane of the sensor, the radius of the approximated sphere added to the radius of the cylinder of the measuring geometry must be greater than the measuring plane distance — i.e. the distance of the projection of the centre of gravity into the measuring plane. If this condition is true, some parts of the object can be placed within the measuring geometry.
According to the measuring distance the object can be placed in the measuring chain.

For every complex object the number of considering faces can be reduced by marking the visible faces for the sensor. Depending on the specified type of the sensor it is sufficient to calculate the range of the vectors of the face, but in some special cases hidden faces must allready be detected, specially for emulation of cameras.

When the measuring chain is defined and the number of geometric objects is reduced, the sensor emulator run in a phase, where geometric values according the geometric attribute of a sensor are calculated. This is done by the basic, geometric operations called *contact* and *distance*. They are offered at the interface of the geometric model. Other operation computing the projection of objects into the measuring plane and intersection of different geometries are in progress.
The *contact* operation determines any contact of measuring geometry and an object. In the most simple case of a micro switch with a point as measuring geometry, only the relation of a point has to be checked. A much more complex example would be a finger of a robot with a tactile sensor arranged as a matrix contacting an object (see figure 3.4).
The *distance* operation calculates the distance of object and sensor according to its measuring geometry. The straight line is the most simple case here. The first point of intersection defines the distance. In all other cases of measuring geometry the minimum of intersection has to be determined (see figure 3.5).

3.2 Physical use of geometric data

After the geometric emulation of the sensor its physical meaning must defined. For this pupose the data received from the geometric algorithm must be transformed into physical signals to simulate the physical mode of action of the sensor and physical phenomenons, like reflexion, interference etc.

At the modeling phase a *measuring range* must be defined. This variable fixes the frame of physical or geometrical use of the described sensor. The frame contains the information about: minimum, maximum, resolution and threshold (figure 2.3). No direct information is given at the stage about physical use. It depends on the physical attributes of the specified sensor. This range describes the geometric as well as physical range (intensity for example). This attribute therefore specifies only the value and not the meaning.

At the modelling phase for every sensor in the system a result must be defined. This result specifies the 'intelligence' or capability of a sensor. A simple micro switch or a light barrier may have a *binary* result, a more complex sensor — a camera, for example, will have a *scene* as result. Possible results are alarm, binary, value as physical signal, moving as value and direction, object as position and size and scene as list of different information. With this result a set of data types is fixed. The data types consist of boolean, integer, real, vectors, matrix and a dynamic list of any combination.
The geometric operation is choosen according to this result and the physical attribute. Some examples may explain the mode of working of this feature:

A *binary* result will choose a boolean data type and the operation *contact* or *distance*. A *value* a *real* and a *dynamic* result will choose a matrix and the operation *distance* or the planned operation *projection*. Dynamic lists generated by the result *scene* use only the operation *projection*.

The physical attribute of a sensor describes its physical mode of action. It is the base of the interpretation of any geometric data and possibly existing disturbances. This can be explained with a simple example:

A sensor with the physical attribute ***passive magnetic*** detects a magnetic field. The output of this sensor depends on the incomming field intensity. The distance-operation calculates the distance to any object. A general description of the object in ROSI describes the origin field intensity and the measuring range must be interpreted as field intensity.
With these variables the signal can be generated.

4 Realisation of a simple example

The mode of working and the values in the sensor model may be presented in a simple realisation. The modelled sensor is a infrared distance switch. It detects the light reflected by objects in front of the sensor. The sensor should be placed in the gripper of a robot.

The geometric situation for this realisation is shown in figure 4.1. Let us assume **S** as the sensor and **LS** as the source of infrared light. Objects O_i with their centre of gravity S_i are placed in front of the sensors. The circles with dotted lines show the approximated spheres.

Figure 4.2 shows the datastructure representing the sensor in the model. The first group of data define the configuration and is presented in figure 4.2a. This contains the name of the sensor (light distance switch) and a file containing the geometric description of the sensor. This file is generated by the geometric modeler ROMULUS at the modeling phase of the working cell. It should now be integrated into the internal geometric model. The name of this file in this paper is *lds.xmt*.
The sensor is not integrated into a sensor system, so that no other surrounding sensor system must be named. For that reason the field of the successor is empty. The result is defined as binary one.

The second group of data consists the physical properties and measuring data. For the light distance sensor they have the values 0 for hysteresis, because there is no hysteresis, and a minimal frequency of 0 and maximal working frequency of 100. The physical principle must defined as 'opto-electrical'. A working coefficient specifies the physical value of the principle. In this case it means the wave length of the infrared light and has the value 950 10^{-9}.
The measuring area describes the sensitivity of the sensor and contains the maximal and minimal detectable intensity, number of steps (here 0, because there is only on/off) and the threshold between two steps. This value is here 0. This means that the threshold lies in the middle of two steps.
For the measuring geometry for such a sensor a straight line or a cylinder would be the right choice. In this case a straight line is chosen. It is defined by the measuring point and a vector given relative to the local coordinate system of the sensor. This vector also defines the normal of the measuring plane. An overview about these data group is shown in figure 4.2b.

Runtime changes of this sensors are not possible, so that in this part of the model no other values may be integrated. Referenced objects are the mounting device and the light source, required for correct working.

In runtime the recognition of possible objects will determine all objects as possible. All vectors from the centres of gravity to the measuring plane are negative oriented to the normal of the plane, during definition of measuring geometry, so that the measuring chain contains object O_1 and O_2. O_1 will always be before O_2, because the measuring distance of O_1 is smaller than the distance of O_2.
The distance operation chosen in the present case determines an intersection with O_2 and calculates the geometric distance.

The sensor emulator knows the light source by references in the model of the sensors and can compute its distance from the object O_2. In the description of the sensor the emulator finds the physical principle *opto-electrical* and the wave length of the light, so that any disturbance in the object desciption of the databasis of ROSI can be found. With the light source and the physical principle of the sensor the emulator needs the property of the intersected plane. These properties can be obtained from the world model, so that this information along with the path of the light can be transformed into the resulting intensity. The description of the measuring range supplies the information about the resolution and the threshold. The decision about the resulting output is made by comparing both values.

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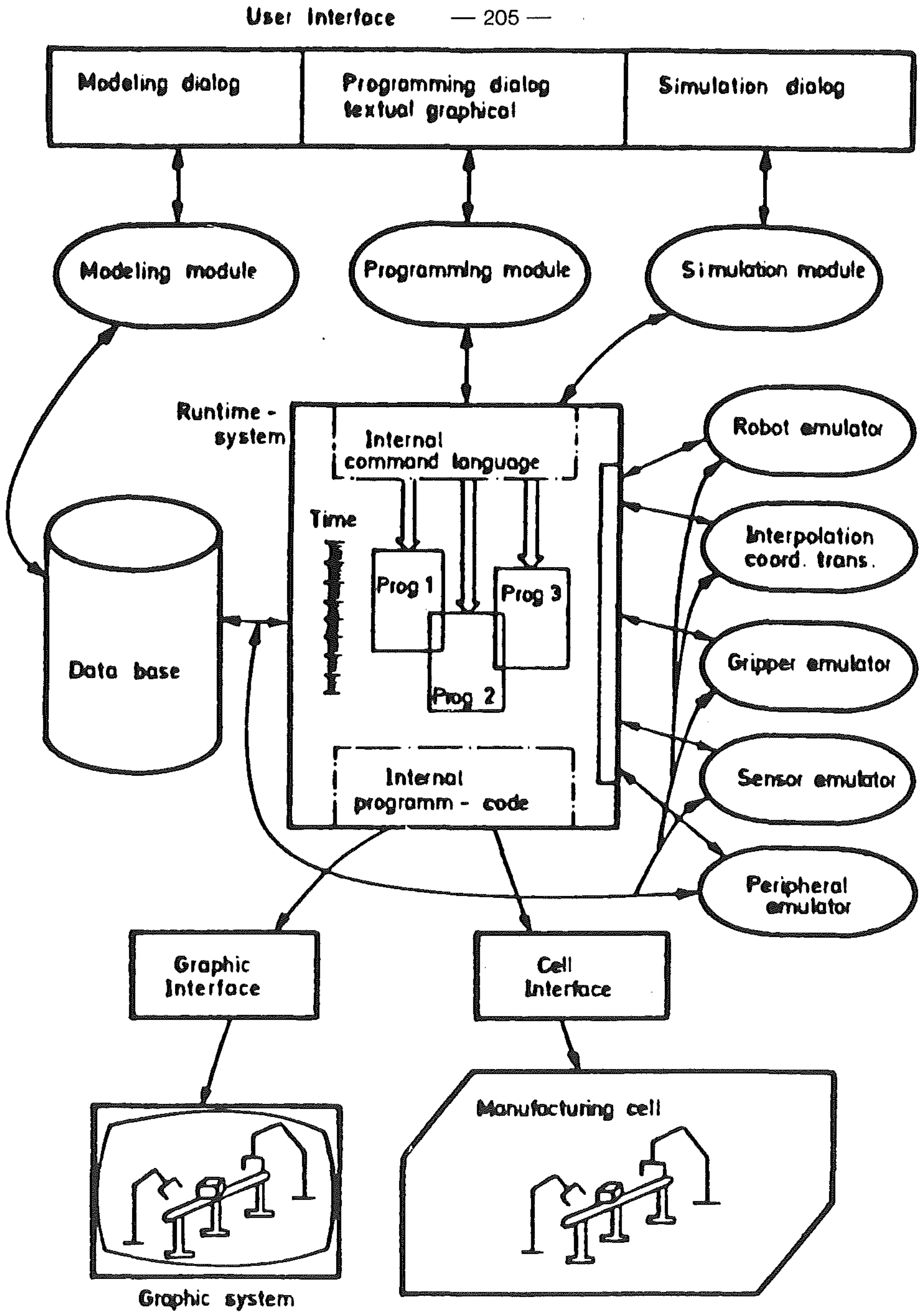


Figure 2.1

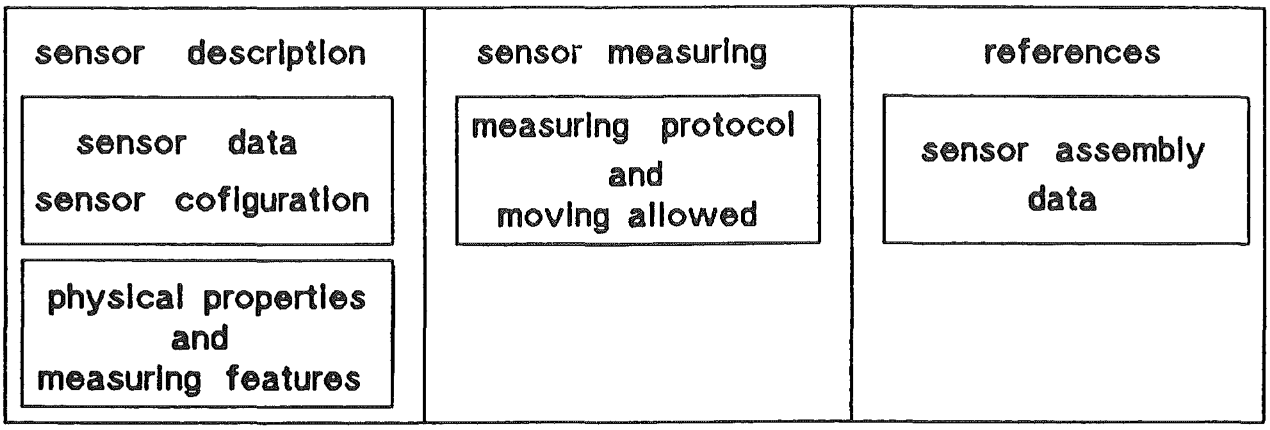


Figure 2.2

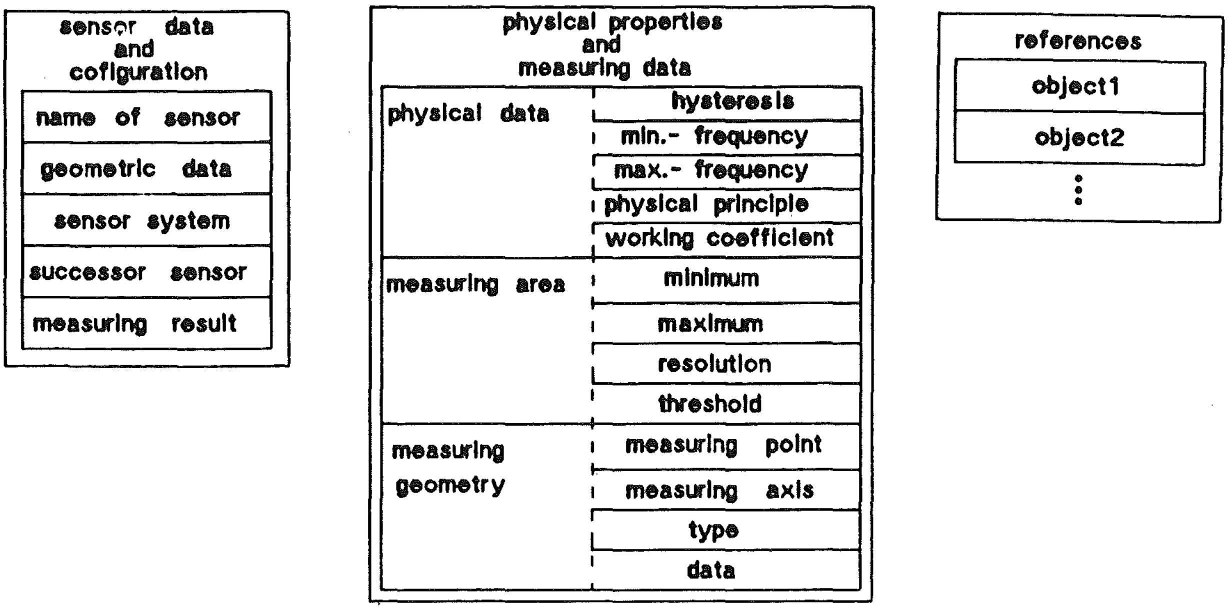
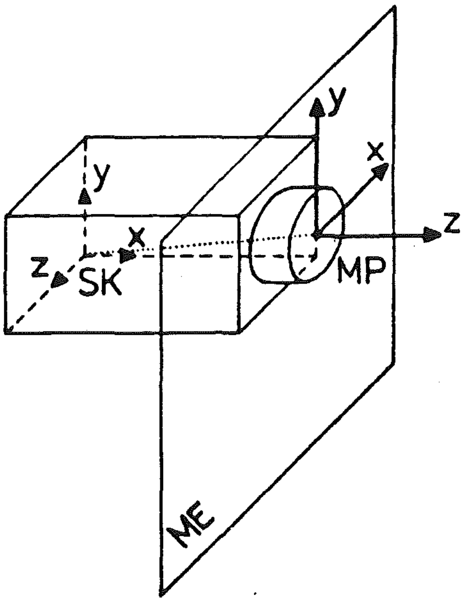


Figure 2.3



SK: sensor coordinate-system
MP: measuring point
ME: measuring level
: measuring frame

Figure 2.4

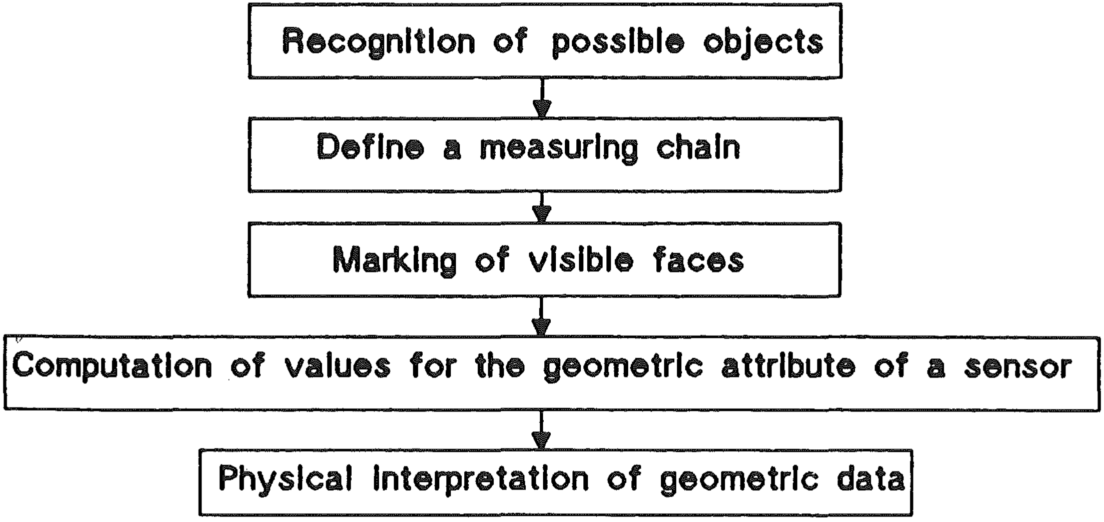


Figure 3.1

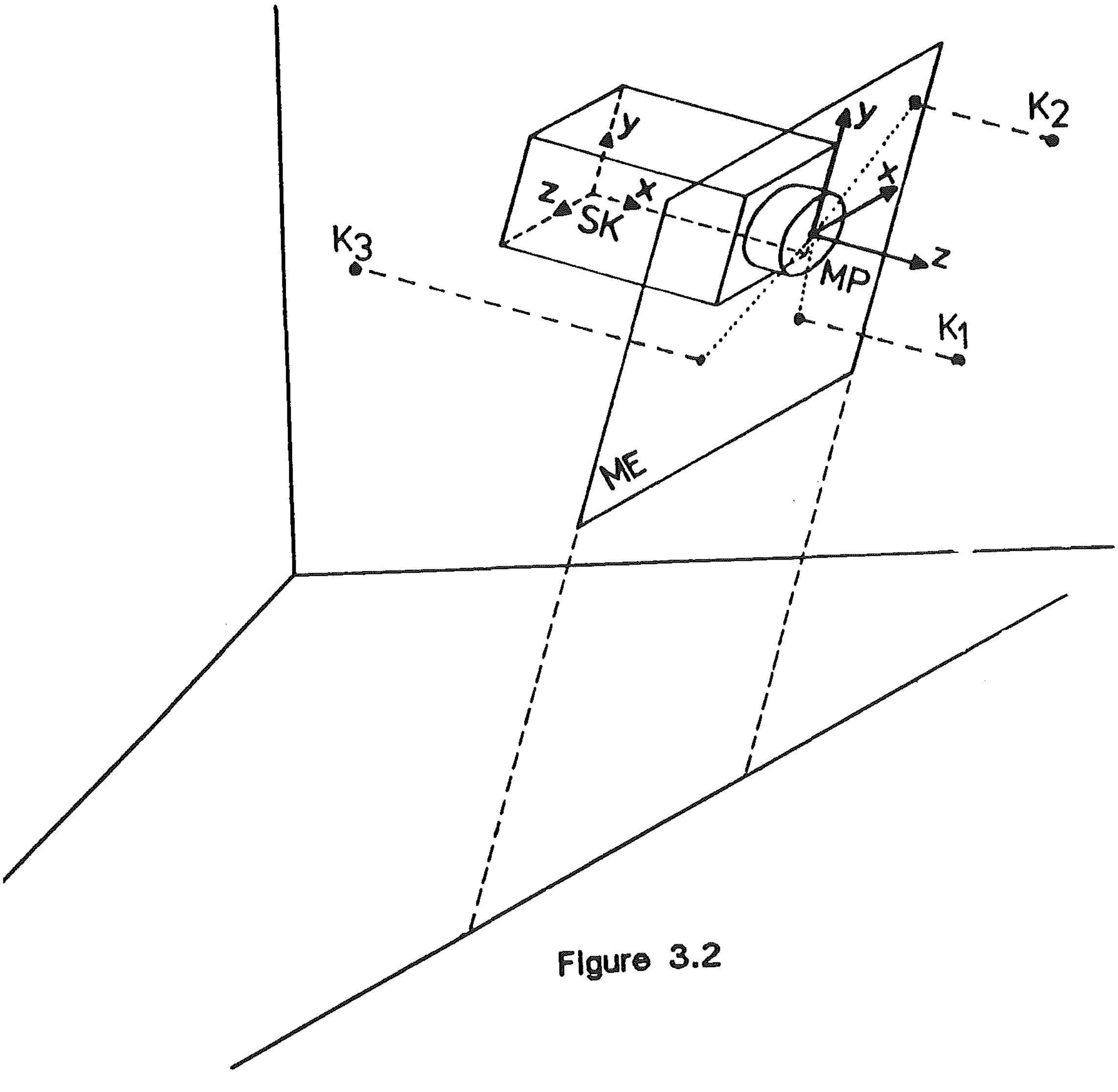


Figure 3.2

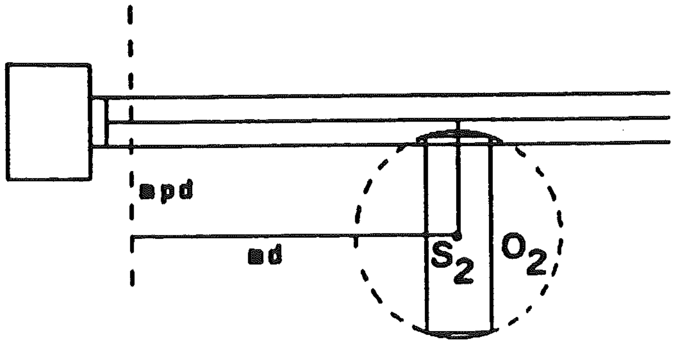


Figure 3.3

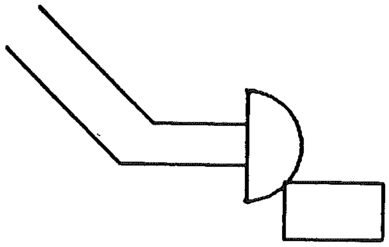


Figure 3.4

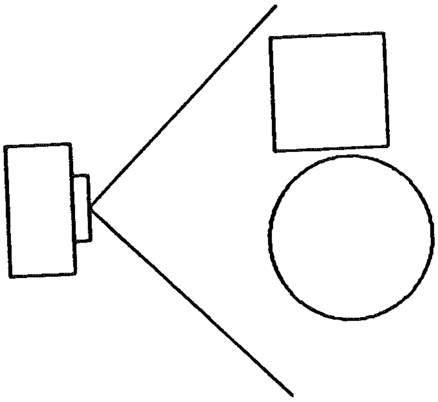


Figure 3.5

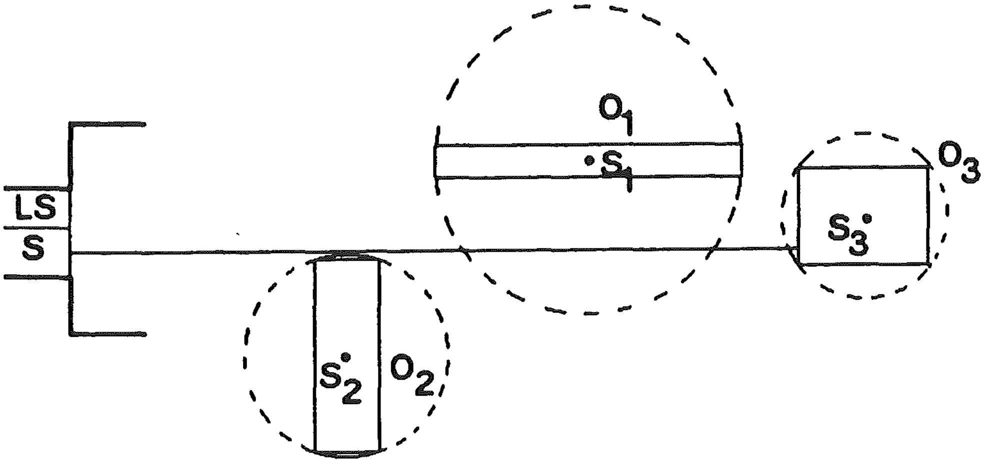


Figure 4.1

sensor data and cofiguration
light distance switch
lds.xmt
light distance switch
———
binary

a

physical properties and measuring data	
physical data	0
	0
	100
	opto-electronical
	$950 \cdot 10^{-9}$
measuring area	minimum
	maximum
	0
	0
measuring geometry	measuring point
	measuring axis
	straight line
	———

b

sensor changing
no moving
———

references
gripper
light source

c

Figure 4.2

SIMULATION TOOLS FOR THE DEVELOPMENT OF AUTONOMOUS MOBILE VEHICLES

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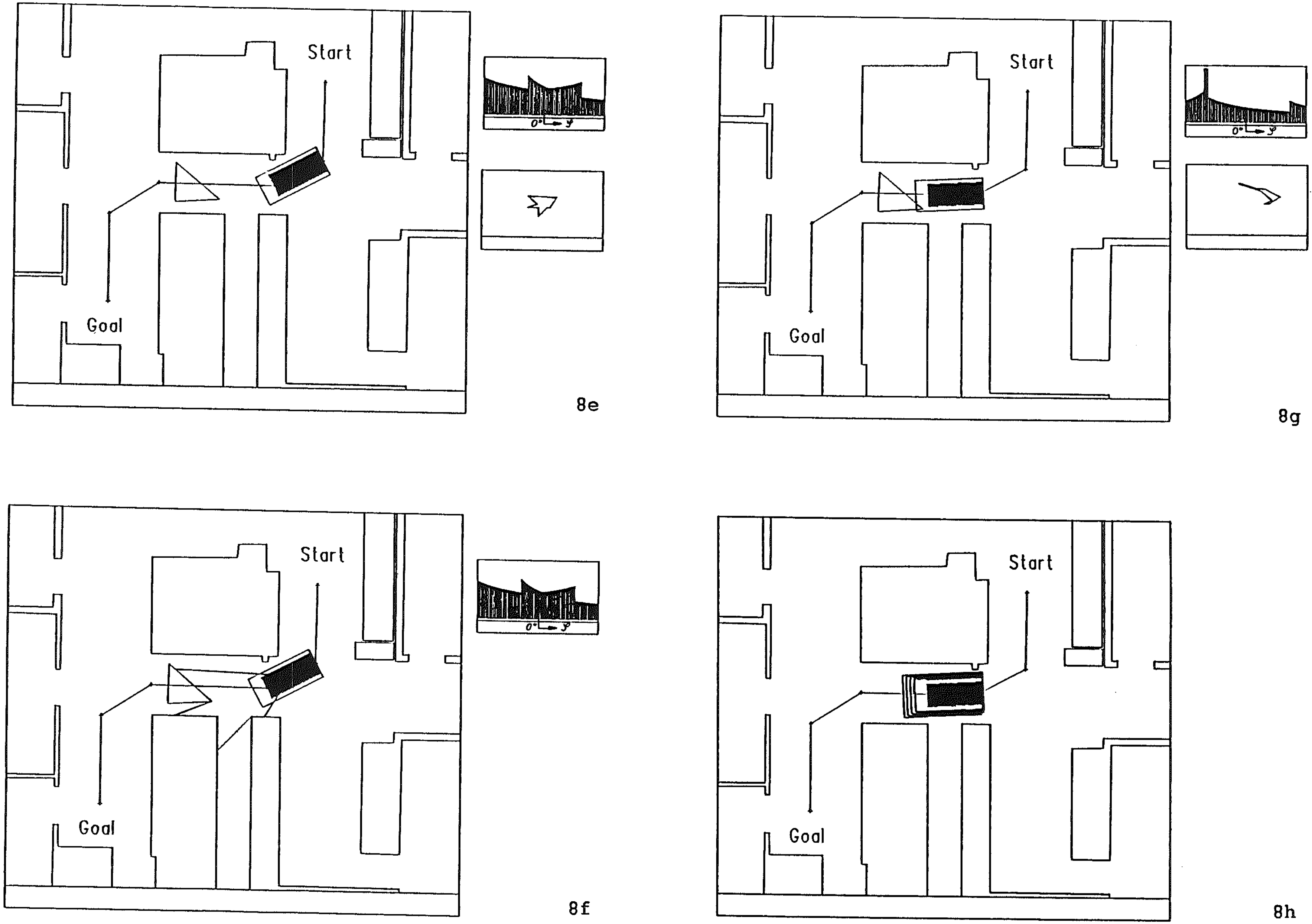
Abstract

This report gives an overview of the planned architecture and communication mechanisms for the control of an autonomous mobile robot. Both support flexible system development and smooth system integration. The usefulness of a sophisticated window managing system is discussed in some detail. It serves as a skeleton for application-specific graphical debuggers and an intelligent system configuration unit. Finally, the implementation of one functional unit simulating a range finder system and an example of a test run are presented.

1 Introduction

Autonomous robot vehicles are becoming more and more important for industrial as well as non industrial applications. In our context autonomy means a robot vehicle's ability to operate in a partly known or completely unknown environment solely by the use of on board systems. The increased flexibility of an autonomous



8e

8g

8f

8h

Figure 8 Example of a Test Run

vehicle in performing advanced transportation tasks becomes evident when compared to the modest abilities of a state-of-the-art AGV. Many examples for other advantageous applications of autonomous vehicles are shown in Table 1.

kinds of application	examples
transportation	materials, parts, tools between machines and/or storages; shop-floor tasks; disabled persons in buildings;
manipulation	arc welding, glueing, paint-spraying of extended objects; maintenance work; vacuum cleaning; harvesting in greenhouses;
exploration	inspection; disaster prevention; rescueing; mining work.

Table 1: Application fields for autonomous mobile robots

Experiments conducted in our laboratory over the last five years with a small scale autonomous vehicle called MICROBE [1] have shown that information processing becomes more and more complex with increasing autonomy. This led to the conclusion that the future development of a large scale autonomous mobile robot called MACROBE will require a comprehensive, flexible, computer based testbed.

2 System Architecture and Information Processing

Intelligent navigation of autonomous mobile robots requires management of several subsystems which cooperate in achieving common goals. Since the distribution of software and hardware is not exactly known in the early phases of development, a flexible system architecture is mandatory.

It has to support:
- modular, more or less incremental system development,
- easy exchange of components,
- smooth system integration,
- extensibility in software and hardware,
- different communication features,
- easy debugging.

2.1 Modular System Development

Modularizing means decomposition of a transportation mission such as "drive from starting point S to goal G" into basic operations which the vehicle has to execute during its mission. For this purpose we decided to subdivide the information processing problem into several layers of competence, each holding a certain degree of autonomy. Fig. 1 shows the mutual relations of the information processing layers with other system units.

The **Planner** establishes a rough route for reaching the goal based on a map of the vehicle's environment. The output of this layer is a list of subgoals leading to the major goal G.

The **Navigator** performs the task of path planning between subgoals. While driving, range images are interpreted, evasive maneuvers are planned, if required, and the local environmental map is updated.

The Pilot translates the motion commands coming from the Navigator (e.g. "go straight ahead 5 meters") into steering commands for the motors. The execution of the steering commands is monitored by internal sensors and corrections are made, if necessary.

Autonomy is achieved through feedback of sensor information, then interpretation and reaction based on this information. In the same manner, the Pilot is an autonomous operating layer which is able to execute a motion command within a known degree of accuracy using signals from internal sensors. Although these layers form a hierarchical structure, each layer may be developed and tested independently. Temporal horizon (interval of supervision), response time and range of view differ between various layers (Table 2).

layers	interval of supervision, response time		range of view	
Planner	long	>= 10s	wide	> 10m
Navigator	medium	0.5 ... 2s	medium	1...10m
Pilot	short	< 0.5s	short	< 1m

Table 2: Features of control layers

Since the scope of each layer is still rather broad, layers must be subdivided into independent limited sections. The separation of functionally differing parts produces meaningful components or so-called functional units.

For example, functional units are required to:
- plan point-to-point connections leading to the goal point based on the environmental map,
- plan trajectories which the vehicle is able to perform,

- control the motion of the vehicle,
- produce visual information, range imaging data,
- monitor the paths to be traveled (short range collision detection and avoidance),
- detect obstacles (wide range),
- plan evasive maneuvers,
- update the environmental map.

Each functional unit consists of a core that solves the partial problem concerned and an interface to other functional units. The core of each functional unit may either be software or hardware.

A serious problem is the availability of information about the status of the system. This is especially important for supplying debugging and monitoring units with the necessary information. To verify the reasons for unexpected behavior of a planning unit, the underlying data leading to this wrong decision must still be available. Since the location of the complete set of actual valid data in the memory must be known, knowledge bases are used.

Data needed for program execution and data needed only for monitoring and debugging tasks (protocol data) must be strictly distinguished from one another, i.e. mixing of data should be avoided. Furthermore, static data should be separated from dynamic data. Static data are, for example, geometrical and kinematical parameters of the vehicle or range imaging specification data. Dynamic data are local goals, driving commands, the local map of the environment, etc . A knowledge base for storing configuration data and rules is necessary as well. For this reason, four main knowledge bases are used containing:

- static data,
- dynamic data,
- protocol data,
- configuration data.

If all of the actual data can be found in one known place, consistency checking is facilitated.

Data access is allowed only by use of uniform write and read procedures that belong to the knowledge base interface. This protects the data from incorrect access and helps keep the data consistent. It is called the "data capsule principle".

2.2. Advantageous System Implementation

The objective of this implementation is to maintain the independencies of the functional units in spite of their integration. For this reason, we decided to combine only those functional units which require sequential operation and a great amount of data exchange to one process. Based on this principle, a couple of parallel processes communicating with each other via a message oriented "software-bus" (comparable to a LAN) are created (Fig. 2).

Parallelity gives the advantage of running the programm in two separate manners. It is possible to run the complete program on one processor quasi-parallel (this may be easier in the first steps of system development) or on several processors in parallel. Control often needs to be done in realtime, therefore parallel processing enables considerable speedup in execution time by application of special hardware (e.g. signal processors, LISP machines).

2.3 Communication Features

Processes communicate by sending and receiving messages. The functionality of this interprocess-communication is comparable to that of a Local Area Network (LAN). Using this principle, communication participants need not know the location of other processes and it is not important for them whether the receiving process is running on the same or on another processor. The message management is performed by interprocess-communication.

Two principles of message flow will be implemented in this project:

(i) Process / Knowledge-Base / Process Communication

Processes communicate by sending messages to the knowledge base and by requesting and receiving messages from the knowledge base. This mechanism supports debugging and monitoring as described above. Two necessary communication principles are discussed below.

- Messages Based on Special Events (Fig. 3a)

Data fields within the knowledge bases are supervised. If data within a certain field changes (through the message of a process), a certain action corresponding to this field is executed. In our case, other processes will be informed if data concerning these processes changes (i.e. a special event has occurred). These processes are not waiting explicitly for this information, but are occupied with their normal operation ("passive message request").
Information about the processes concerned and their state - running or inactive - can be demanded from the configuration knowledge base.

- Messages Based on Actual Requests (Fig. 3b)

The process using this kind of message exchange sends a request ("active message request") to the knowledge base to indicate what it needs to know. The knowledge base is searched for this information and a response is sent to the requesting process.

(ii) Process / Process Communication (Fig. 4)

This type of communication is used for time-critical processes. Messages are sent directly to another process (Fig. 4). For example, in case of collision detection, no time may be wasted in reacting on this information. This message must reach the destination process as fast as possible. Processes that use this type of communication build the lowest layer of the system.
However, during the development of these processes data is also sent to the knowledge base for debugging purposes. Later on, data is sent to the knowledge base only when an unexpected event is detected. This principle helps to reduce data exchange.

3 Simulation and Development Tools

Some components, for example the range imaging system or the motion base of the vehicle, are still under development. Therefore they are not available for testing the planning and control units developed in parallel. Furthermore, adequate debugging tools are not available on the market.

For these reasons we implemented functional units simulating:
- perception mechanisms and sensor operation,
- vehicle motion and motor operation,
- geometrical features of the environment,

and a window manager which supports graphical debugging.

The specific architecture used in our system (Fig. 2) allows configuration similar to the building block principle. This means components can simply be exchanged and real components replaced by simulated components as soon as they are available.

3.1 Simulation of Sensors

Sensor units supply the autonomous mobile robot with information about its environment, i.e. simulation models of the environment and the sensors are required.

For this purpose a graphical editor was developed that allows easy construction of a 2D-model of the environment. Three-dimensional objects in the environment are so-called obstacles. Their 2D-projections are approximated by polygons. The graphical editor has the following features:

- interactive, menu-driven graphical input,
- functions supporting modification and manipulation of obstacles and sets of obstacles,
- long-term storage possibilities of the map,
- operator support through instructions and error messages.

A model of a range imaging sensor system simulating the perception of obstacles in the vicinity of the vehicle was implemented. Parameters such as maximum range, distance resolution, errors, scanning rate, scanning angle etc. may be modified to enable tests under various conditions.

3.2 Simulation of Vehicle Motion

Another functional unit simulates the vehicle and allows variation of driving inaccuracy, which means that errors in angle and length referring the distance covered are simulated as well.

Functional units, such as the simulation of the range imaging system, generate a great amount of data. The examination of the correctness of this data would be tedious without graphic support. With a graphic display of the results, it is possible to recognize at a glance whether a simulation unit is operating satisfactorily.

3.3 Window Managing System

A tool that allows examination and deposition of data with the aid of graphics is called a graphical debugger. The window manager mentioned above is a comfortable tool and can be regarded as the skeleton of the graphical debugger.

Main features of the window manager are:

- management of several virtual displays (windows),
- flexible arrangement of several windows,
- manipulation of the window display (zooming, panning),
- documentation (hardcopy),
- extensible menu-driven operation.

An application interface permits easy inclusion of user-written, application-specific input and output functions. Several predefined input functions (text, values, graphic input) and the menu-driven selection of user-written subfunctions facilitate the application of the graphic system. Fig. 5 shows the sotfware structure of the window managing system consisting of the window manager, the interface and the user programs.

High-level functions simplifying the use of this graphic system are made available by the module "UserFcts" (Fig 5). Different users are allowed to write their graphic functions irrespective of each other. For inclusion of the user-written functions in the window managing system, the module "InitUsers" which introduces these functions to the window manager must be provided.

Keeping in mind the system architecture described above, the complete data of the static, dynamic and protocol type can be found in the knowledge bases. User-written procedures are able to access this data by message exchange with the knowledge base concerned. With the aid of user-written display procedures, data can be monitored during program execution.

Fig. 6a illustrates data flow during data examination. The window manager calls up the user-written display functions at selected time intervals or in the case of an actual user interaction. Under control of the window manager (1) the user function "get_list_of_subgoals" sends a request for data to the knowledge base (2). The respective knowledge is extracted from the knowledge base (list of subgoals) and returned to the calling function (3). Based on this data and the result of preparations made by the window manager (e.g. activation of the concerned window), the user-written function invokes visualization of the data (4) on the workstation screen.

Data flow in the opposite direction corresponding to the debugging function "deposit" is shown in Fig. 6b. The menu controlled by the window manager offers a function that allows activation of the user-written input functions. In our example the function "write_list_of_subgoals" was chosen for determination of an arbitrary path. The window manager calls the user function (1) which requests user input from the workstation (2). At this point the user locates the subgoals by use of the graphical input devices. The coordinates of the marked points are transferred to the user-written input function (3) which stores this data in the knowledge base (4). The following program execution, e.g. a simulation run, is based on this data.

Through this cycle data can be monitored and changed. These features combined with the possibilities of flexible window management (e.g. superposition of windows on the screen) and window manipulation are fundamental for a sophisticated, application-specific graphical debugger.

So far, the mechanisms for supporting the framework of graphical debugging have been described. Next the display and input procedures which complete the graphical debugger and belong to the different data fields in the knowledge bases are implemented. If new sections are added to the knowledge bases which should possess debugging possibilities, new display and input procedures have to be written to keep the debugger in an actual state.

4 System Configuration

To obtain the flexibility of testing different system configurations, a unit supporting configuration must be available. To correspond to our system structure, the configuration must be executed in two steps. First, the layers and the processes within these layers which participate in a specific test run have to be selected. In the second step, the functional units which are active within a process must be determined.

Functional units exist which cannot run without the support of other units. For example, the unit responsible for collision detection needs data from the simulation unit of the range imaging system or from the real range imaging system. Units which are not necessary for the desired configuration may be switched off. The configuration knowledge base contains basic rules for verifying the correct construction of configurations.

When the configuration phase is completed, the processes concerned are started. During the initialization phase each process requests information from the configuration knowledge base as to which functional units should be active.

In addition, changes in the configuration during the test run should be possible. This concept allows gradually developed processes and functions to be integrated and tested within different configurations.

5 Example of a Functional Unit

As an example we will discuss the simulation of a range imaging system in more detail. This simulation unit is based on information resulting from a model of the environment and the position of the vehicle.

5.1 Measurement Principle

The range imaging system developed for the previously mentioned vehicle called MACROBE consists primarily of two parts: a laser rangefinder and a scanning mechanism. The system produces polar range images of 100 x 60 range data (corresponding to 60 degrees azimuth and 40 degrees elevation angle) with a frame rate of 5 images/second and a maximum measurement distance up to 10m.

5.2 Simulation

In the simulation model of the range imaging system, the emitted and received signals are approximated by polar oriented rays. The rays of a 2D cross section from a complete range image are examined for possible intersections along the edges of the obstacle polygons in the environmental model. Based on these intersections, the measured values of the range imaging systems are evaluated in polar coordinates.

To save computing time, two "pre-selection" methods are applied. Both attempt to isolate the obstacle polygons and their edges located inside the visual range. This method decreases the number of edges which have to be examined for possible intersections with sensor rays.

Fig. 7 illustrates the operation of the "pre-selection" methods. The obstacle polygons as well as the range image of the robot are approximated by rectangles. Only those obstacle polygons belonging to rectangles overlapping with the rectangle of the range image are further used. Similarly, the edges of the remaining polygons are approximated by rectangles and examined for overlapping with the range image rectangle. Fig. 7c shows the isolated edges which are sufficient to evaluate the range values.

5.3 Measuring Errors

According to the real range imaging system, various measurment errors may occur. The simulation model allows variation of the parameters denoting the influence of range value errors. Thus, the operation of the control and decision units can be tested under different conditions.

6 Example of a Test Run

In the following example a complete test run simulating the motion of the vehicle from start to goal position with the occurrence of an unexpected collision situation is discussed. First, the simulation system will be configured comprised of the following functional units to be tested:

- simulated environment model,
- simulation of range imaging system (azimuth angle of 60 degrees),
- simulation of the motion base of the vehicle,
- collision detection unit,
- unit for path-smoothing.

For this example, only processes in the Navigator and Pilot layer are configured. Therefore, subgoals must be stored in the system before the start of the test run as described in section 3.
Fig. 8a shows the model of the environmental map, a layout of our laboratory and the connecting lines of the subgoals.

The functional unit for path-smoothing evaluates trajectories based on the list of subgoals and the kinematic features of the vehicle (Fig. 8b). The resulting drive commands are stored in the dynamic knowledge base. The simulation model of the vehicle's motion base requests these commands and translates them into the simulated motion of the vehicle. Fig. 8c shows the vehicle at its starting place. The rectangle surrounding the vehicle indicates the area supervised by the collision detection unit. On the right side of Fig. 8c two windows are displayed showing the simulated distance values of the range finder. In the upper representation the measured values are plotted against the azimuth angle, while the lower representation shows the distance values related to the position of the vehicle.

To verify the simulation of the measured values, their representation is projected into the environmental map. With the aid of Fig. 8d the correct function of this unit can be recognized very quickly.

Fig. 8e represents the test run at an advanced phase where an additional unexpected obstacle has appeared in front of the vehicle. In Fig. 8f the range image information is overlaid to the vehicle's area of operation.

Fig. 8g represents the point of time where the collision detection unit becomes active. The overlapping of the obstacle and the safety zone of the vehicle is visible. The boundaries of this zone depend on the shape, the kinematics and the velocity of the vehicle and are varied online (Fig. 8h).

Acknowledgement

This research is partly sponsored by the Deutsche Forschungsgemeinschaft within a special research program entitled "Information Processing by Autonomuos Mobile Robots" (SFB 331) at the Technische Universität München.

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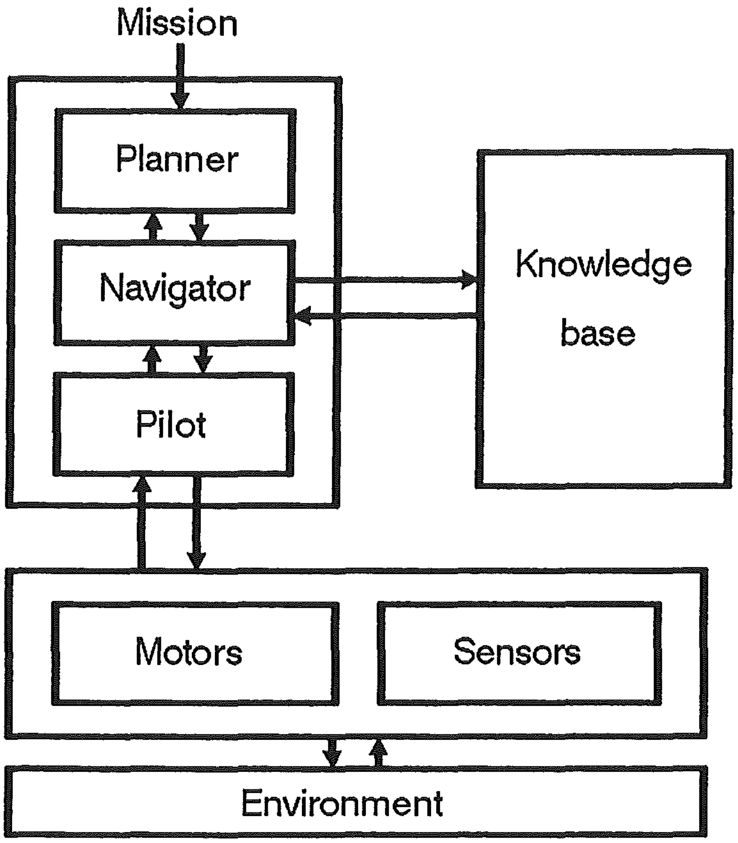


Figure 1 Information processing scheme

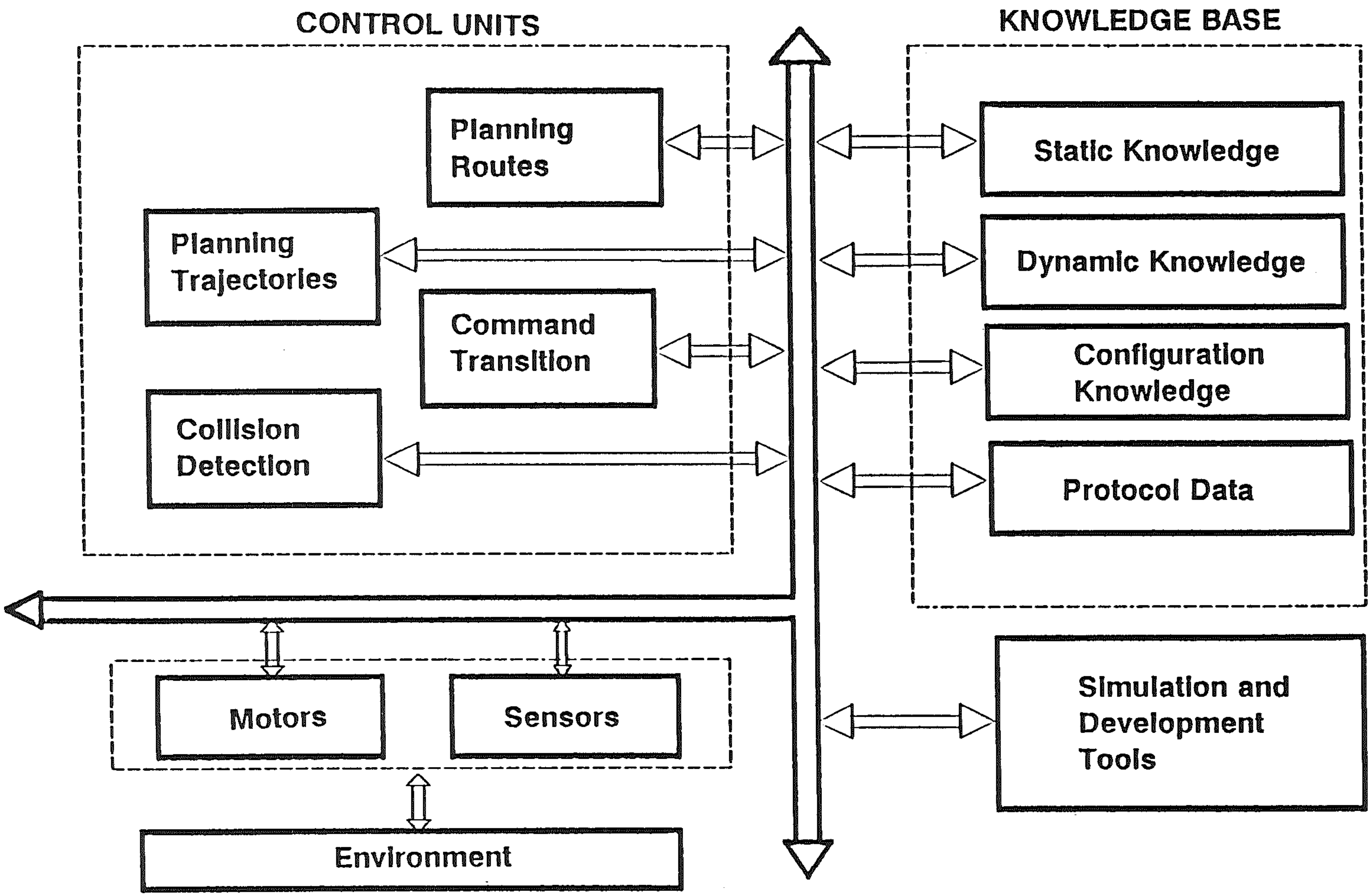


Figure 2 System architecture

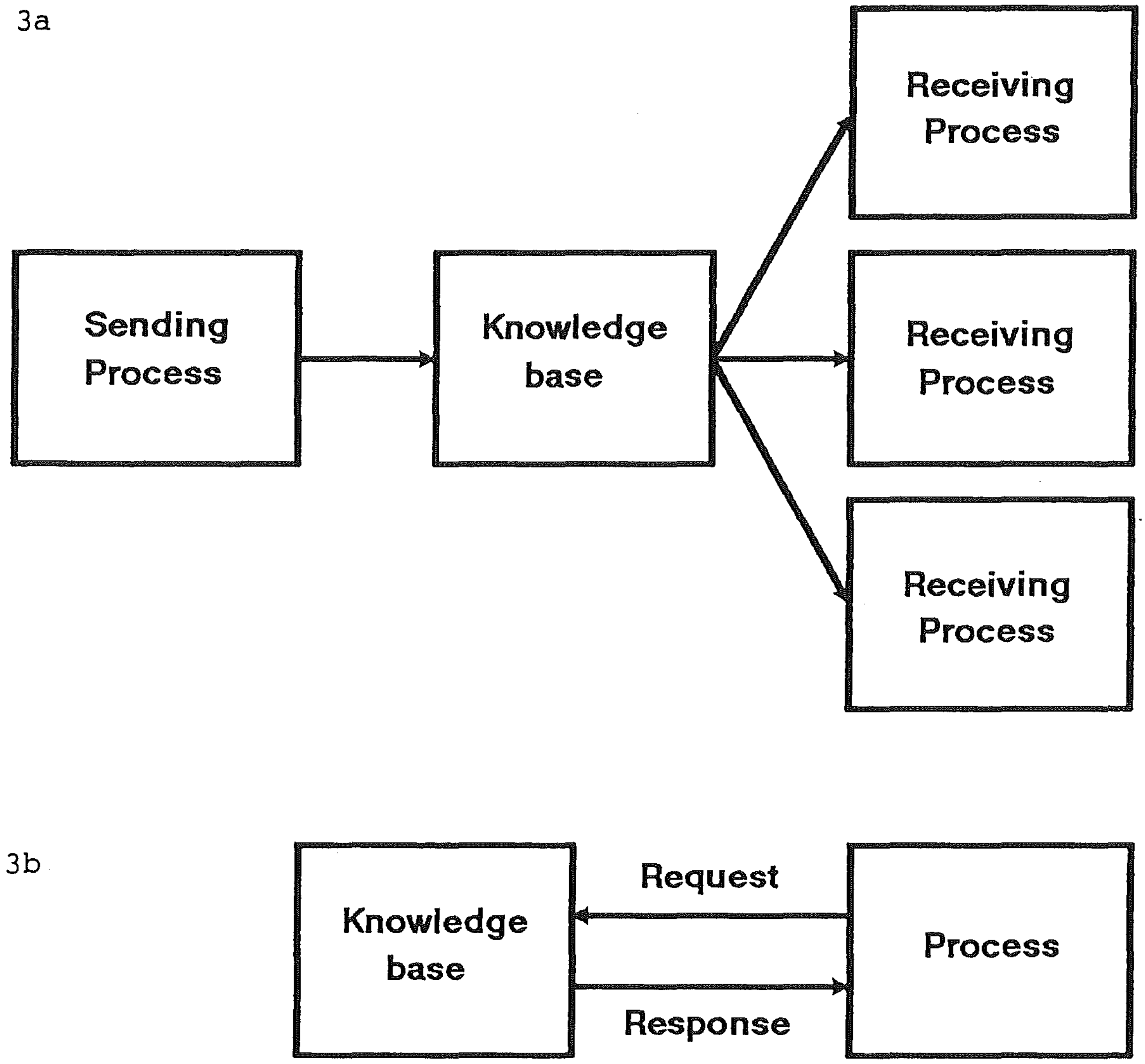


Figure 3 Process / knowledge base / process communication
3a Passive message request
3b Active message request

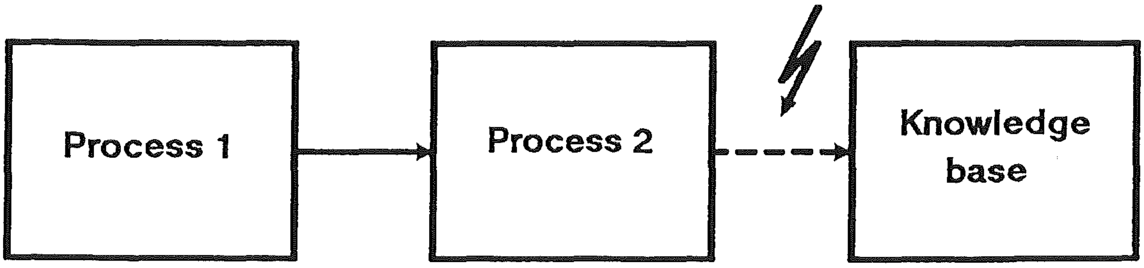


Figure 4 Process / process communication

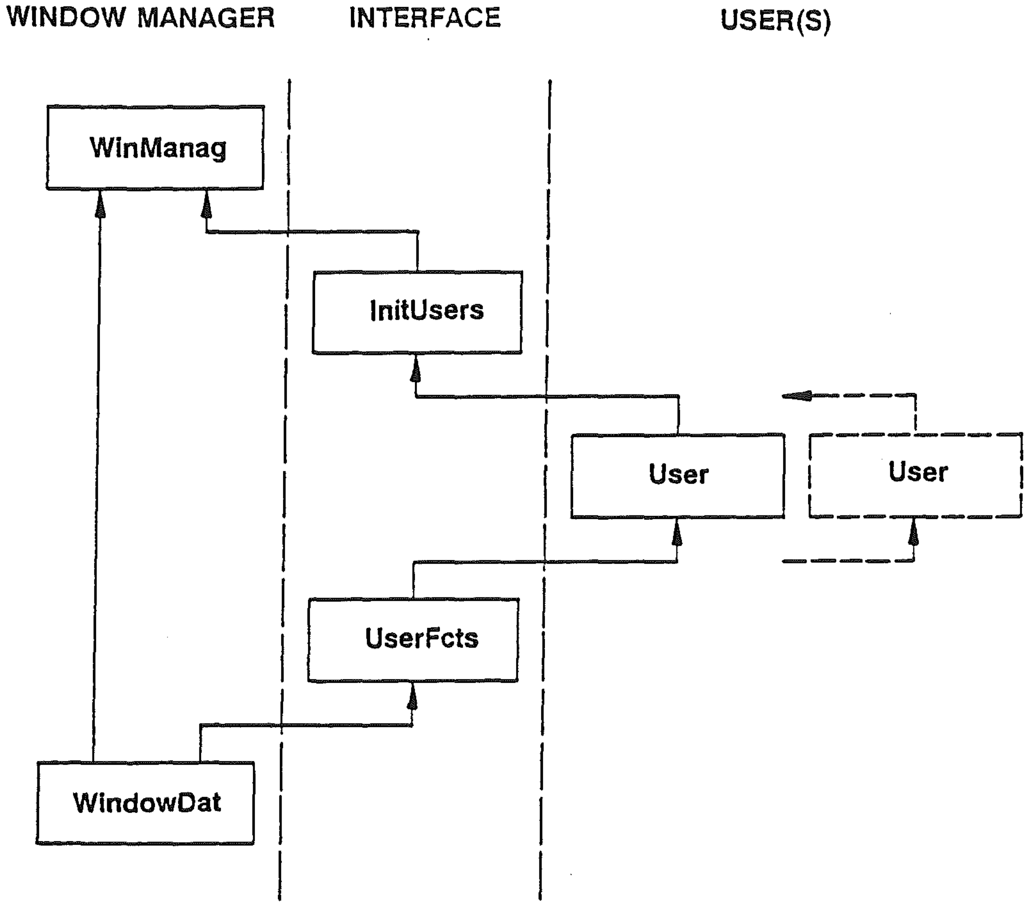


Figure 5 Software structure of the window managinig system

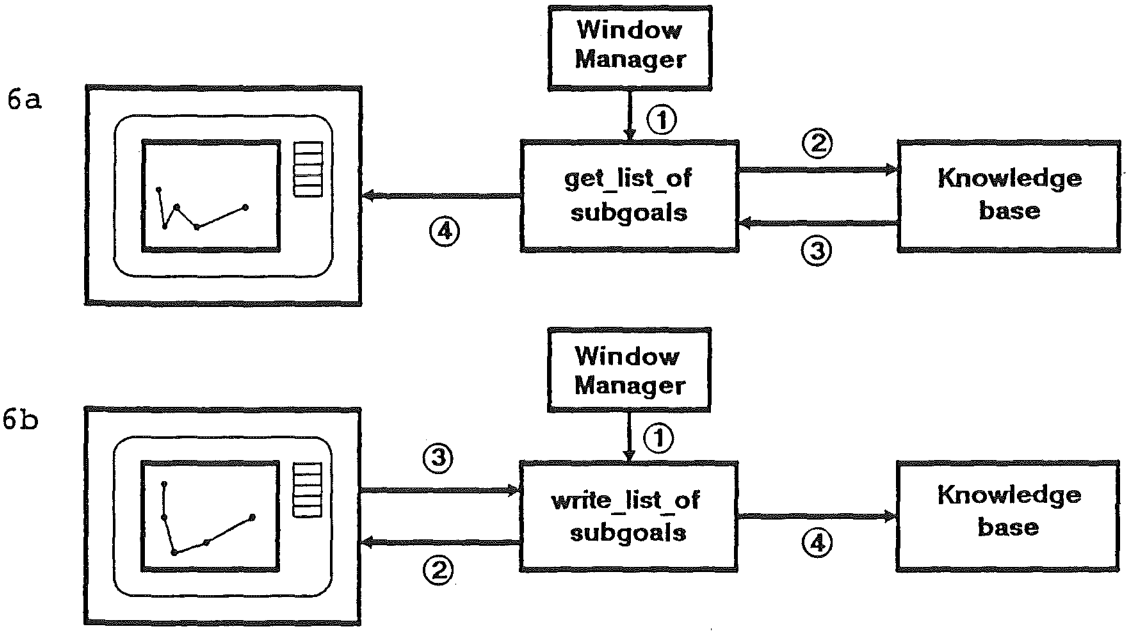
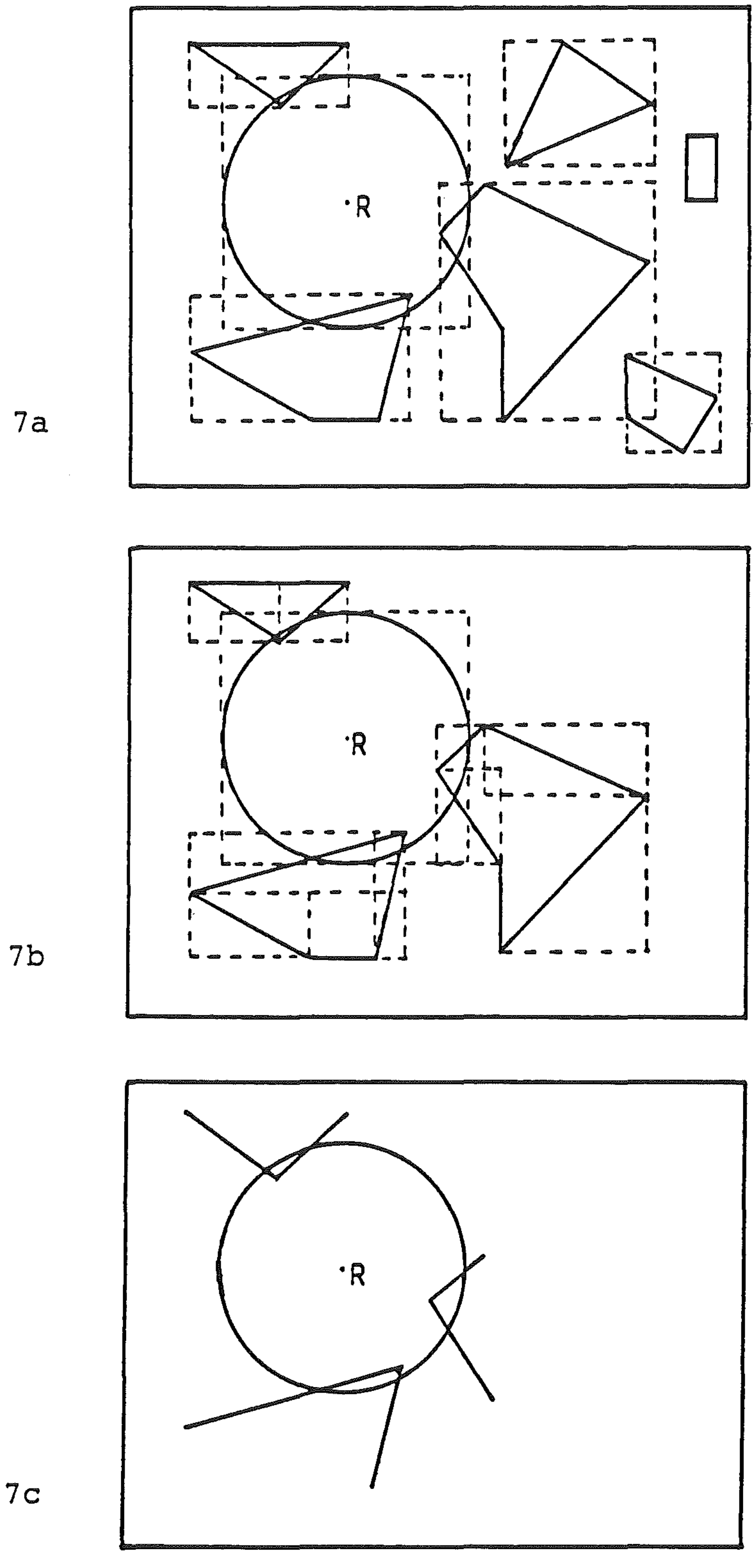
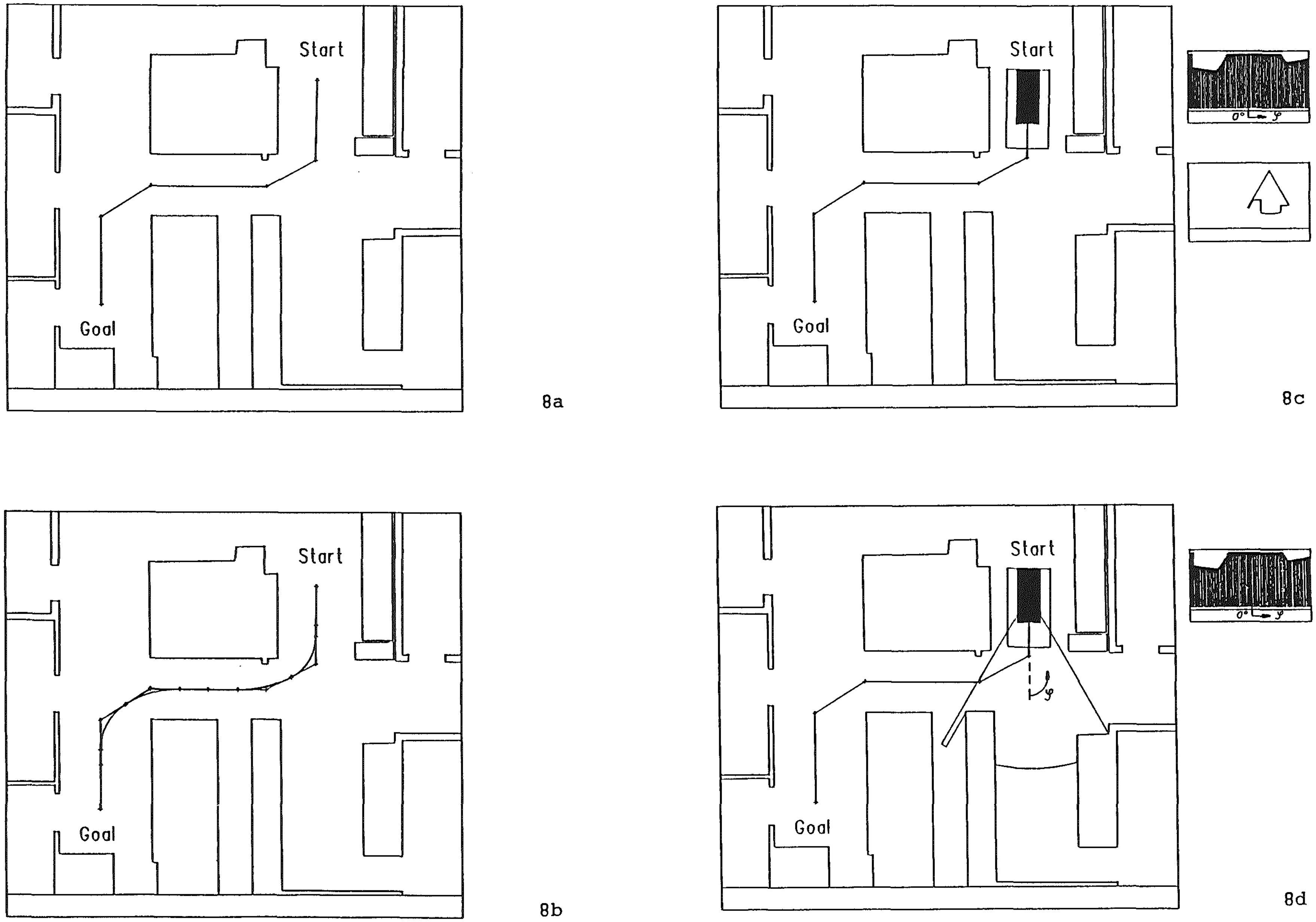


Figure 6 Data flow within the graphical debugger



R: Vehicle Position

Figure 7 Principle of "Pre-Selection"



8a

8b

8c

8d

Figure 8 Example of a Test Run

Session

SENSORS (2)

CHAIRMAN'S REPORT ON THE SENSORS (2) AND (3) SESSIONS

Five papers were presented during the sessions on Sensors which I chaired. They fall naturally into two quite different application areas, namely mobile robots (three papers) and automated assembly of objects from parts (two papers).

Mobile robots.

Dr Kuhnert presented a most impressive video of a vehicle driving along an autobahn at speeds of up to 40-50 kph, under automatic control. It illustrated the vision system described in his talk which detects the presence of edge segments within sub-sets of image points (dynamic windows), where these edge segments represent edge of road markings. Fast processing of the images is achieved by using a multi-processor system, with one processor per window. Edge segments are detected by means of intelligently controlled correlation techniques. Since the programming is tedious and slow, the next step is to build an improved software support system, based on interactive program generation, and to use it to detect non-linear features.

Whereas Dr Kuhnert's project deals with automated control in a lightly structured environment, Dr Mann is concerned with more highly structured situations, as inside nuclear power station structures. His task was to combine information from different, partly redundant sensors. This is treated as a consistent labelling problem, in which labels are assigned to sensory features and labelling conflicts are resolved using posterior Baysian probabilities. This can be cast as a stochastic relaxation problem and handled concurrently using simulated annealing. While the approach appears to be viable, like all Baysian methods it requires good prior information which might limit its generality.

The third presentation, relevant to mobile robots, was the paper presented by Dr Tanigawa in which he described an interesting phased array ultrasonic proximity detector. It generated a 64 pixel image covering ± 45° aperture, with 0-2m range at each pixel. The polar plots of beam amplitude/sensitivity against angle contain many side bands, only 3dB down. Their presence is a matter for concern and suggests that further work is required to improve the sensor's performance.

Assembly Robotics.

In his presentation Mr Myers described experiments being undertaken at Lord Corporate Research to develop a general purpose two fingered parallel jaw gripper, with tactile and force sensing. By and large, the approach appeared to be pragmatic. Much of the talk centered on the use made of known techniques to interpret feature information from a 10x16 pixel tactile array. Methods of increasing dexterity, such as providing a third finger, or providing each with a second joint, were discussed briefly.

The final presentation by Professor Browse focussed on the problem of defining and extracting tactile features, to characterise sets of unknown laminar objects, as input to a recognition process which makes use of *a priori* models of these objects. Since the type and position of each tactile feature constrains the model selection process, recognition is efficient. The approach is restricted, however, to only single objects, of uniform cross section.

JIM HOWE

Low-Level Vision for Advanced Mobile Robots

Volker Graefe and Klaus-D. Kuhnert[1]

Contribution to the Advanced Robotics Workshop on
Manipulators, Sensors and Steps towards Mobility
Karlsruhe, May 11 - 13, 1986

Problem Statement

Advanced robots of the future will require a human-like sense of vision to drive vehicles fast and safely, to maintain and repair equipment, to perform complicated high precision assembly tasks with non-perfect arms and hands, and to survive and continue to function autonomously in an unpredictable and changing environment.

Vision systems of human-like flexibility and generality are far beyond our present technology. It is, however, possible today to build computer vision systems which perform at human-like speed in limited domains of scenes to which they have been adapted. Such systems can be very useful for special applications, but most importantly, they enable us to study the problems of computer vision experimentally. Real-world and real-time experiments are an absolute necessity to bring about the truly general vision systems of the future.

A computer vision system can be assumed to consist of several levels or layers of processing. The so-called lower levels process image data to build and update a symbolic description of the presence, location and motion of relevant scene elements (so-called features), while the so-called higher levels combine these feature

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descriptions with stored knowledge to update an internal dynamic world model. Feedback from the higher levels can assist the lower levels and focus the attention of the lower levels on the most critical elements of the scene.

Low-level vision is computationally very expensive. Performing this task with a general-purpose computer in real time usually is not practical, and even large commercially available image processors are too slow and too inflexible for all but the slowest autonomous robots. Davis et al. (1986) report that in the American ALV[2]-project a VICOM image processing system required 6 - 7 seconds per image to track the clearly visible boundaries of the road, limiting the speed of the autonomous vehicle to about 3 km/hour and forcing it to move in a stop-and-go mode.

The problem we address is the development of better tools and better methods for low-level vision, necessary to enable, for instance, autonomous mobile systems to travel reasonably fast and smoothly through a natural environment.

Application Areas

Vision is either a necessity or of great advantage for any autonomous robot working in space, nuclear plants, agriculture, civil engineering and construction, plant operation, fire fighting and emergency rescue operations and services, including domestic ones.

Research Course

We are firmly convinced, that to understand vision and to build powerful computer vision systems, there is no substitute for practical experiments. To make such experiments possible we have designed multi-microcomputer systems "BVV" which, in spite of their relative simplicity, are powerful enough to support low-level vision in real time (Haas, 1982; Graefe, 1983 a, 1983 b, 1984). We have then developed software for feature extraction in a variety of scenes. The performance of both, the hardware and the software, has been verified in cooperation with the Institute of Systems Dynamics and Flight Mechanics of our university (prof. Dickmannns) in a number of demonstration experiments. In these experiments the vision system was part of a

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[2] Autonomous Land Vehicle;
part of the Strategic Computing Program

control loop operating in real time and was the only or the main sensor used to control a mechanical system.

Methods Used

- In the image processing systems "BVV" several standard microcomputers have been combined in a way that each of them has simultaneous access to the digitized image sequence.

- Each microcomputer has its own task which it can perform independently; this simplifies programming and increases the efficiency of the system by minimizing the need for communication.

- To use the available resources efficiently, the computing power of the system is concentrated on those parts of the image where the relevant features are located.

- A special correlation method is used to locate linear features; correlation is a very good method in noisy images (Kuhnert, 1984).

- Correlation masks are shifted along a search path that iscontrolled by a task specific search strategy. Several different maximum detection techniques are used to detect feature candidates, which are combined into complex features; e.g. line elements. Figure 1 shows a sketch of road border-detection using intelligently controlled correlation. This scheme can be implemented in efficient ways, allowing cycle times for the entire feature extraction of 17 to 33 ms per image on an Intel 8086 microprocessor (Kuhnert, 1986 a, 1986 b).

- Programming such algorithms in conventional high level languages is an error prone and tiring job. So we have developed a special support software that is able to generate programs dealing with specific plane geometrical relations. Figure 2 shows the user's view of this software package.

Status and Results

A computer architecture has been developed that has made it possible to build real-time vision systems (figure 3) using relatively slow standard-microcomputers. To track features in dynamic scenes, the temporal coherence of the scene should be exploited.

Therefore every image delivered by the camera should be analyzed, even if this limits the available computing time to 17 - 33 ms per image (Haas and Graefe, 1983; Graefe 1983 c). Data controlled correlation is a good and efficient method to detect and track features in noisy images (Kuhnert, 1986 a). Other methods can be more powerful in certain situations, but require substantially more computation (Kuhnert, 1986 c).

The demonstration experiments in which the system has been used, and their results, have been described in detail by Meißner (1982), Meißner and Dickmanns (1983), Dickmanns and Zapp (1985, 1986), Kuhnert and Zapp (1985), Mysliwetz and Dickmanns (1986) and by Wünsche (1986). The experiments have demonstrated the validity of our concepts. A particularly important result is, that even systems moving at high speed can be controlled by computer vision. In several experiments the low-level vision system has located and tracked the borders of the road correctly and in real time while an experimental road vehicle with the vision system (figure 4) was moving at speeds up to about 100 km/hour. In other experiments the vision system has determined the location and state of motion of a fast-moving inverted pendulum, enabling it to be stabilized, with the vision system being the only sensor in the control loop.

Further Research

Research is under way to improve the computing power of the low-level vision system by two orders of magnitude by adding coprocessors which are currently designed. The increased computing power will be used to develop algorithms for locating more general features in images under less favorable viewing conditions and in more complex scenes, but still in real time.

Interest in cooperation

We are interested in cooperating with partners who are willing to apply the described methods and results to control advanced robots.

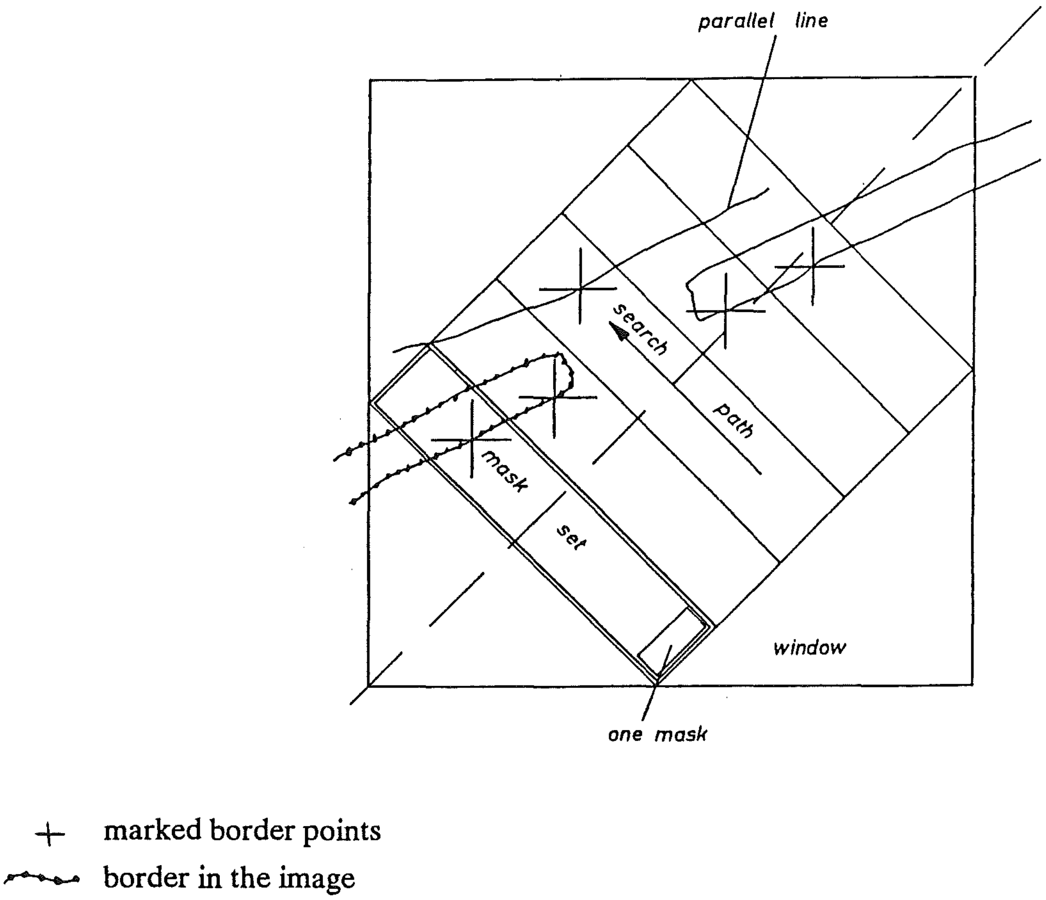

Figure 1: Example of intelligently controlled correlation

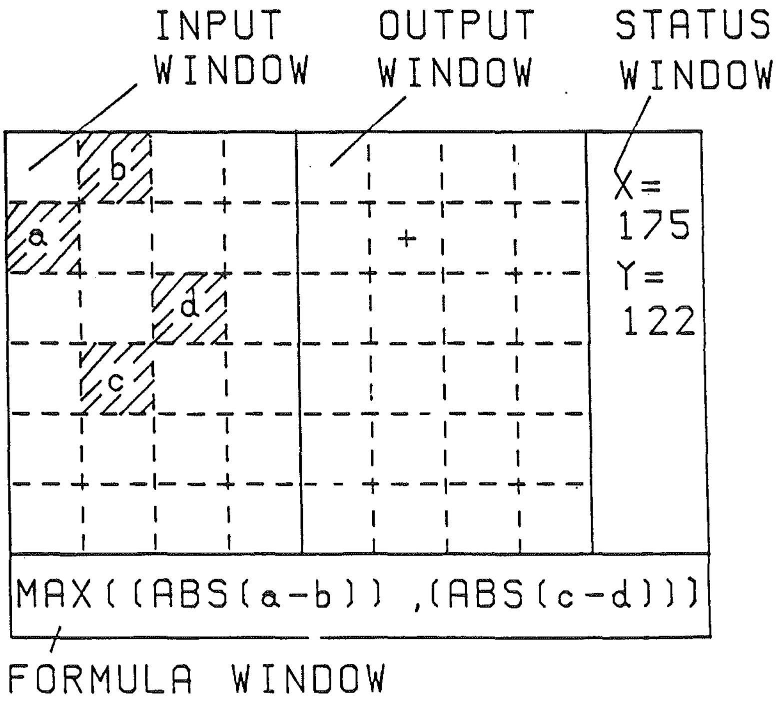

Figure 2: Typical screen of the interactive program generator

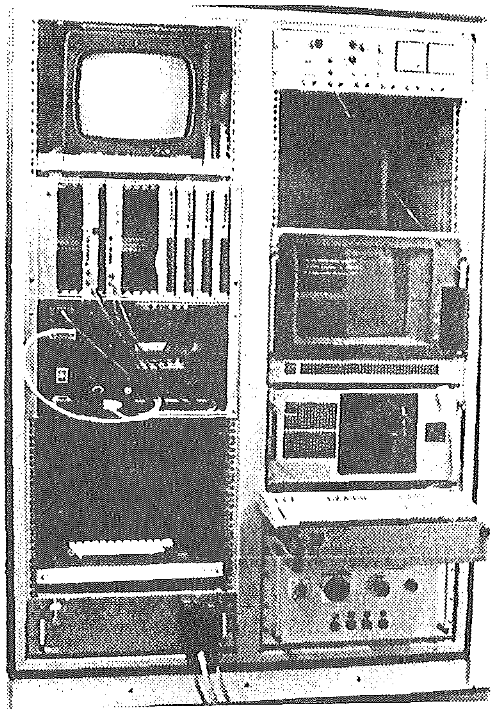

Figure 3: The computers in the experimental vehicle. On the left side the BVV 2, together with a TV-monitor and a terminal, on the right side an IBM IC, acting as a main computer in the vehicle.

Figure 4: The experimental vehicle of the UniBw (Institute of System Dynamics and Flight Mechanics, prof. Dickmanns) used for research in computer vision and autonomous mobility. The camera platform with two cameras can be seen behind the center of the windshield.

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Airborne Ultrasonic Array Transducer Utilizing Silicon Micromachining *

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A proximity sensor is required to give a robot such capability as collision free movement and correct approach to an object. Among some previously reported sensors, the ultrasonic proximity sensor, consisting of a transducer array combined with electronic circuits for beam scanning, has the most attractive advantage of being operable under conditions of darkness and having no mechanical scanning equipment. Though conventional piezoelectric ceramic transducers are widely used in range finders, they have some disadvantages as array transducers: poor time response and large sensitivity variations due to their sharp (high-Q) resonant characteristics. In place of piezoelectric transducers, an electrostatic ultrasonic transducer has been developed to be applicable to proximity sensors which use electronic beam scanning.

The transducer was fabricated, as shown in Fig.1, using modern silicon micromachining technology: (1) Starting material was a silicon wafer with (100) surface orientation. Small square windows (80 $\mu m^{\square}$) were opened through a thermally grown SiO_2 layer. (2) Square orifices were made on a silicon surface by using $N_2H_4 \cdot H_2O$ etchant. This anisotropic etchant produces pyramidal-shaped orifices (57 μm depth), limited at the side-walls by [111] surfaces. The etch is "self-stopping" at the point where the [111] planes intersect. Orifice shapes are subsequently easily reproduced by this technique. (3) After oxidizing the whole surface, an evaporated aluminum layer was patterned into back electrodes. (4) A thin polyester foil (12 μm thickness), with a coated electrode (500 Å thickness) on a top surface, was stretched over the back electrodes.

The fabricated device, before stretching the foil over the back electrodes, is shown in Fig.2. In a single silicon die, 32 back electrodes are arranged in a linear array with a 1 mm pitch. Each electrode has a 0.6 mm width and 18 mm length. Connecting the 4 electrodes together results in an 8-element array transducer.

The operating functions are as follows: the polyester foil acts as a vibrating membrane to transmit/receive sonic waves. Arrayed air cavities, between the back electrodes and the foil, serve as miniature acoustic resonators. When transmitting waves, an ac signal with dc bias voltage is applied between the back and common electrodes to drive the membrane, whereas received acoustic waves vibrate the membrane and then modulate capacitance values between the two electrodes. In a range find application, distance can be measured using the ordinary time-of-flight method.

Sensitivity-frequency characteristics for a single element transducer are shown in Fig.3. In the transmitter mode [Fig.3(a)], emitted acoustic pressure is proportional to the square of the signal frequency and reaches its maximum value at around 140 kHz. It was found that the characteristics depend on the orifice size; the smaller the size, the higher the frequency for the maximum response. In the receiver mode [Fig.3(b)], the smaller the orifice size, the smaller the acousto-electric conversion efficiency. Flat responses, however, are obtained over a wide frequency range. For a device with 80 $\mu m^{\square}$ orifices, ultrasonic waves up to 140 kHz can be transmitted/received with reasonable sensitivity. Figure 4 shows the transient characteristics. An envelope period is less than 30 µsec for 100 kHz transmitter operation, which corresponds to the minimum detectable range of 1 cm in air.

When operating the array transducer under beam scanning, each back electrode are sequentially driven on a time axis in a transmitter mode. For the receiver mode, voltage signals due to capacitance change at each element are summed through a set of delay lines. The scanning direction depends on the delay time differences between adjacent back electrodes (Fig.5 for transmitter mode).

The directional characteristics were measured using fabricated test driver circuits. The delay line for each channel consists of a fast A/D converter and a 16 Kb RAM followed by a D/A converter. Delay time difference was achieved by controlling the read access time after writing the input signal to the RAM. The experimentally obtained directional characteristics are shown in Fig.6. When emitting a 100 kHz continuous sine wave, the half band widths for the main lobe were 7.5 and 9.0 degrees at perpendicular and 45 degree directions, respectively. For a large sector scanning angle, unwanted side lobes in the inverse direction, due to continuous waves, were obtained. They can be diminished by applying burst waves. The scanning angular area was as wide as ± 45 degrees.

In this transducer, electric/acoustic characteristics in each element can be made uniform because of the precisely controlled orifice size. Moreover, such peripheral circuits as drivers, delay lines, and analog signal processors can be integrated on the same die because the proposed transducer is based on silicon technology. The integrated sensor will be available in small sizes as well as at low cost. This feature is attractive for multi sensor systems in advanced robots.

* The present research effort is part of the National Research and Development Program's "Advanced Robot Project," which program has been established by the Agency of Industrial Science and Technology, MITI.

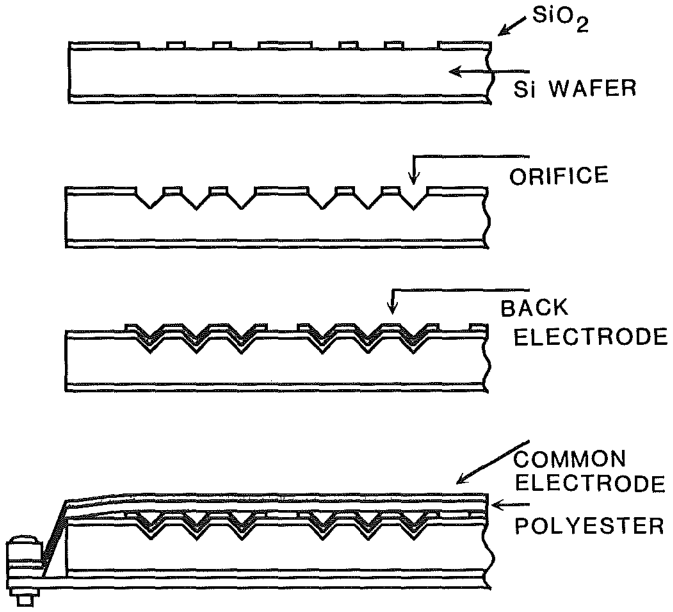

Fig.1. Ultrasonic transducer fabrication processing.

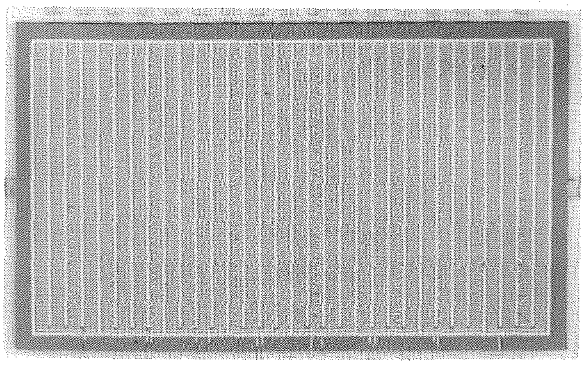

Fig.2. Top view of the fabricated array transducer before stretching the vibrating membrane. 32 back electrodes are linearly arranged on a single silicon die. More than 1000 small orifices are formed on each electrode.

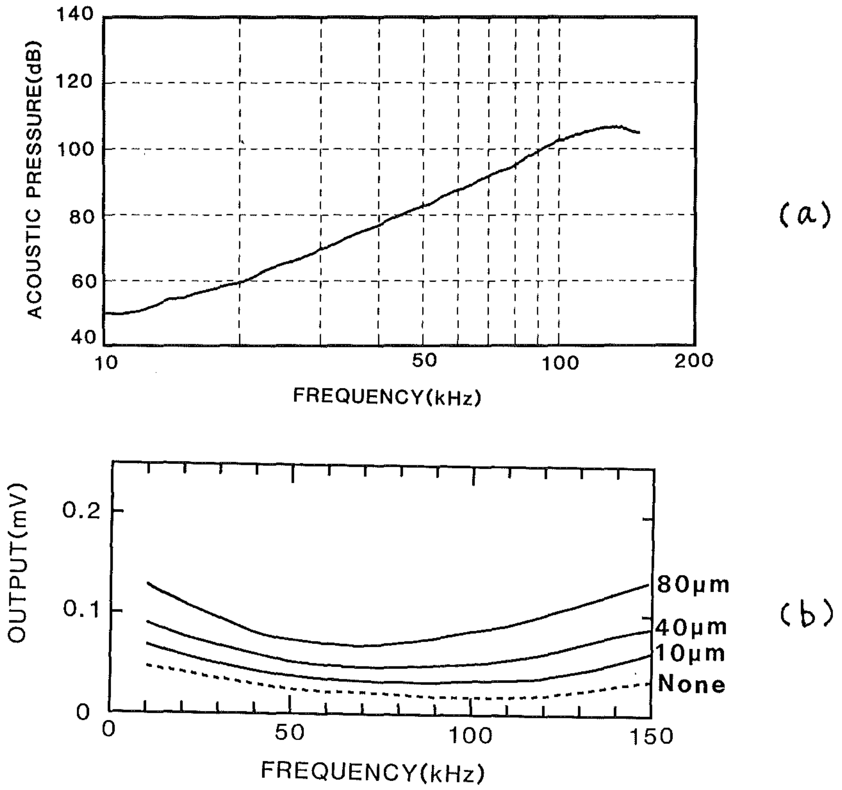

Fig.3. Sensitivity-frequency characteristics for a single element transducer in a transmitter mode (a) and in a receiver mode (b).

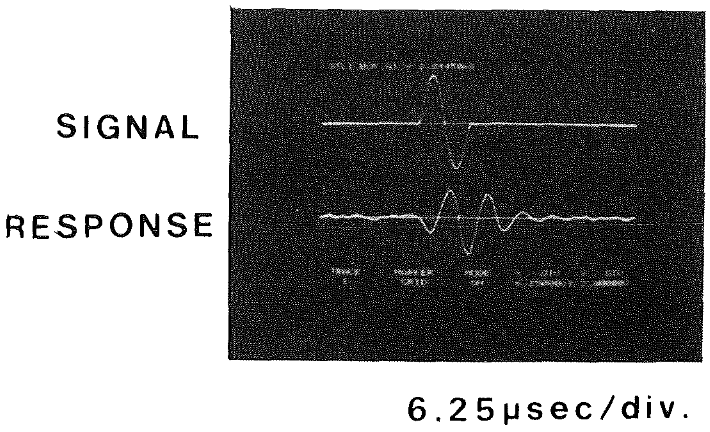

Fig.4. Transient characteristics. For the excited 100 kHz burst pulse, the transducer emits about 3 pulses.

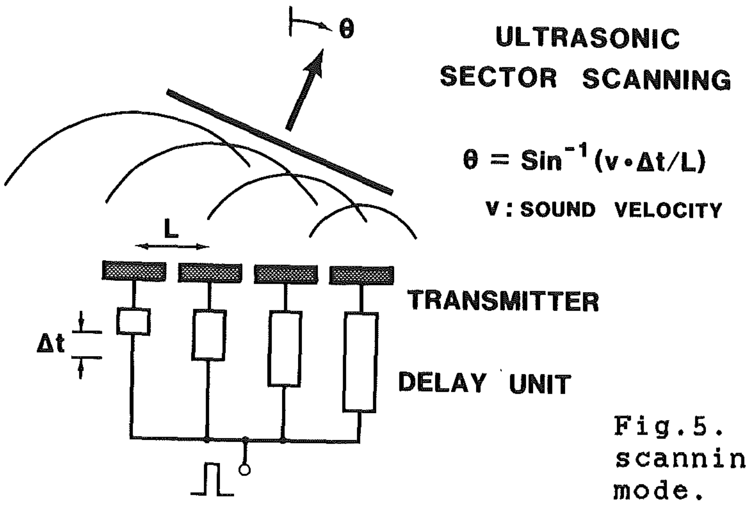

Fig.5. Electronic sector scanning in a transmitter mode.

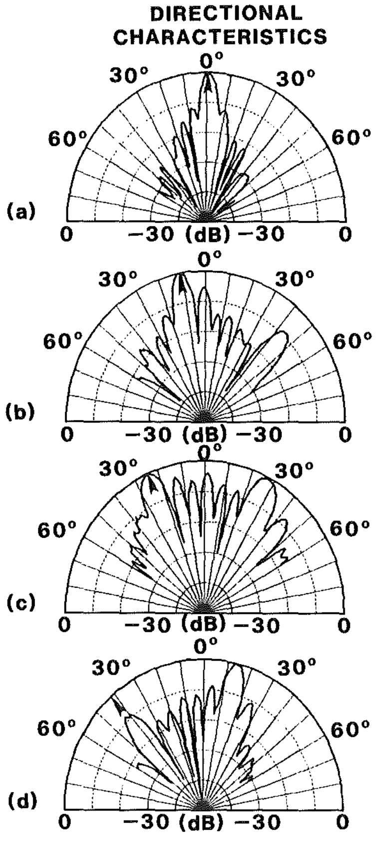

Fig.6. Experimentally obtained array transducer directional characteristics. Delay time differences between adjacent back electrodes were set at (a) 0 µsec, (b) 2.5 µsec, (c) 5.0 µsec and (d) 7.5 µsec. Ultrasonic waves were transmitted to the front, 12 degrees, 25 degrees, and 42 degrees, respectively, as shown by arrow heads.

24

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ABSTRACT

A real-time modelling, planning, and control system has been designed to facilitate the integration of a variety of sensory modalities for use in assembly-type tasks. Manipulation functions were developed based on a pseudo-force control scheme which integrated both force/ torque and tactile array into the control loop. The system employing selected manipulation primitives was used to develop an object recognition demonstration based on edge tracking. The demonstration included detection and recognition of edge defined objects using force/torque and tactile array sensing.

I. INTRODUCTION

For applications involving contact of a manipulator with its environment, such as in assembly-type operations, slight inaccuracies in the positional control of that manipulator can result in large reaction forces between the arm and the environment. As a reult, much research over the past ten years has been devoted to developing stategies to control end effector force and torque, as opposed to end effector position and orientation. Prominent examples of such work include Khatib's operational space approach [1], Salisbury's active stiffness control [2], Mason's compliance control [3], and Raibert and Craig's [4] hybird position/force controller. Although many of these approaches are not robust with respect to variations in algorithm parameters or to environmental disturbances, their efficacy has been demonstrated.

Research pertaining to tactile sensing, on the other hand, has largely consisted of the application of feature extractors to identify local object primitives [5], which when combined with each other or with other sensory modalities, can be used for object recognition. The feature extraction algorithms examined to date have largely been borrowed from the vision literature. There exists, however, very little work on how tactile data can be integrated with force/torque data in a real-time control loop to assist in parts-mating type operations.

It is the objective of the work reported here to develop a control, modelling, and planning system which can accomodate data from a variety of sensory modalities and develop an intelligent, real-time response for the manipulator. In addition a set of functional manipulation primitives should evolve which demonstrate the integrated, coordinated use of force, torque, and tactile array feedback for the performance of object manipulation and parts-mating tasks. A conceptual overview of the experimental system and its current implementation is described in Section II. In Section III the functional tactile/force primitives as they evolved with the context of edge tracking are described. Section IV presents the scenario for a demonstration illustrating the performance of the current system.

II. SYSTEM OVERVIEW

As shown in fig. 1, the system consists of two major levels. The upper level includes a modeler for the robot and its environment, a planning system, and a real-time process monitor. The lower level handles the coordinated control of a parallel jaw gripper with independently servoed fingers, the control of the robot itself, and the collection and analysis of sensory data. In the current implementation, only finger forces and torques and tactile data are used.

Real World Modelling and Planning

When planning for robotic manipulation tasks it is important to have an accurate representation of the world in which the robot resides. Our representation includes the robot and the known objects that make up its surroundings. The modelling system is designed to be capable of dynamically modelling the world in transition as the robot and the world states change. In addition, the modelling system can be used by a planning system to create a reliable trajectory plan for the manipulator. The planner modifies the state of the modelled world based upon the simulated actions of the robot predicting the consequences of these actions.

Object Modelling

Objects are currently modeled as convex polyhedrons combined into more complex shapes. This includes dynamic combinations such as the links that make up a robot arm. At the lowest level, an object is treated as a set of points that make up the vertices of the convex polyhedron. These points are used to make up the ordered sets that define the faces of the polyhedron. Since the polyhedron is treated as a rigid body, it is necessary to manipulate the points in space to have the polyhedron change state. The next higher level is the combination of these polyhedra into more complex objects. The spatial relations between polyhedra are specified through the rotation and translation transformations relating coordinate frames embedded in the objects. In addition it is sometimes necessary to merge objects into one system. For example, when the robot aquires a part, the part is considered as an extension of the end effector and is treated by the modelling system as part of the robot's frame.

Learning/Recognition

The learning system builds its representation of the real world based upon the sparse data obtained from the sensors [6]. The system has the capability of combining this sparse data and extracting an approximation of the actual object. As new data is added, the recognition system will plan a next move for further aquisition of data to identify an object. If a match with a known object cannot be made, the system either invokes the learning system or signals an error.

Display

It is important that the system operator be able to visualize the representations the modelling system creates. The operator needs to verify that the models created are correct, that the system generates viable plans for manipulation, that the system manipulates the models correctly, and that the modelled world continues to correspond closely to the real world as the task progresses. In addition, this system should operate with minimal time lag between changes in the real world and the displayed changes in the modelled world. Fast algorithms have been developed that allow manipulation of three dimensional representations of objects and that transfer these representations into a projective display. Hidden lines are removed to add further realism to the scene. This display system can be thought of as a high level debugger for the modelling system.

Manipulation Controllers

The lower level of the controller with its interface to the upper level (currently implemented on a Macintosh) is shown schematically in fig. 2. A Motorola 68010-based single board computer on a VME bus coordinates the control of the manipulator, the end efector, and the data collection from the sensors. The task plan, as formulated by the upper level, is decomposed into the required goal points for both the robot and the end effector. Either position/orientation (pose) or force/torque goal points for the robot can be specified. The desired Cartesian pose or force goal points for the robot are passed over a 16 bit bidirectional interface to the robot controller. The servos for the fingers are also implemented on the 68010 processor.

The manipulator controller itself consists of an LSI-11 residing on a Q-bus in which the trajectory and kinematic calculations are performed. If pose control is requested by the upper level, a simple trajectory plan is formulated to move the robot from its current position along a straight line to the goal pose, subject to velocity and acceleration constraints. If force/torque control is requested, small differential displacements and rotations are added to the current pose trajectory of the robot in the directions required to produce the required forces. The resultant inverse kinematic solutions are the joint set points which are in turn passed across a 40 bit parallel interface to a J-bus on which six 6502-type processors handle the servo calculations for the joints.

Sensors

Each finger of the end effector was instrumented with a Lord Corporation LTS-200 incorporating a six axis force/torque vector sensor and 10x16 tactile array sensor. The vector sensor has a force resolution of 0.01 lbs in force and 0.01 in-lbs in torque over a 0-20 lb range. The array sensor has a site-to-site spacing of 0.071 inches with a taxel deflection resolution of 0.002 inch over a 0.030 inch range. Both vector and array data are multiplexed, sampled, and scaled by a 6502-type processor and made available to the host system through an RS-232 serial interface.

As shown in fig. 3, in order to facilitate probing of objects which cannot fit within the fingers of the gripper, one LTS-200 was mounted on the outside of one finger and a second LTS-200 was mounted on the inside of the other finger.

III. MANIPULATION PRIMITIVES

As an initial test to demonstrate the capabilities of the system, it was decided to limit the object domain to prismatic objects which can be defined by straight edges. Primitive functions were then implemented to integrate tactile and force/torque data in control strategies appropriate for probing objects of this limited type. The manipulation primitives for the present object set are classified into three basic groups: object detection, edge detection and sensor reorientation, and corner detection.

Object Detection

An initial requirement for a force-based exploration system is to determine the presence or abscence of an object in a selected work region of the manipulator. A function was implemented which allows the operator to specify an approach path, an associated velocity along that path, and a force threshold which must be exceeded before the presence of the object is acknowledged.

Edge Detection

Following contact with the object, a strategy must be implemented to locate the features or landmarks critical to the identification of the object. For the current application, the top surface of the object was constrained to be parallel to the table top. As a result, after initial contact with the object, the sensor array was rotated such that the next approach path was at a 45 degree angle to the top surface. This angle of attack guarantees the optimal depth of impression in the array pad when the top edge of the object is probed.

At each probe contact point, feature extractors must be implemented to efficiently determine the presence or abscence of a straight edge on the array pad. The feature extraction process consisted of the following steps:

- threshold the raw array data
    - form a "scatter matrix" **M** [6] of order three from the thresholded data

$$\mathbf{M} = \sum_i w_i \, v^t_i \, v_i,$$

where $v_i = (x\ y\ z)_i$ with x,y representing the coordinates of the ith taxel in the plane of the sensor and z representing the displacement of the taxel normal to the plane of the sensor; w is a scalar weighting factor which can be adjusted based on *a priori* knowledge of the expected feature.

- perform an eigenanalysis of the scatter matrix **M**. Since the magnitude of the eigenvalues represent the relative dispersion of the feature patch along the eigenvectors, the eigenvalues provide a useful indicator for determining the presence of a straight edge. If the major eigenvalue is several orders of magnitude greater than the other two eigenvalues, than clearly the feature patch is spread predominately along one axis, and an object edge is present. If the two major eigenvalues are within an order of magnitude of each other, then a feature patch indicative of a surface has been encountered. Fig. 4 illustrates a typical feature patch resulting from contact with a straight edge with the eigenvectors **(x,y,z)** located at the centroid of the patch. Vector **y** points along a "best fit" line representative of the straight edge; vector **x**, a normal to **y** parallel to the plane of the array pad; and **z** is orthonormal to both. The coordinate frame **x',y',z'** is fixed in the array sensor.

Following detection of the edge, the sensor can be reoriented about vector **y** so that the edge of the object is brought into the plane of the sensor pad. This can be accomplished in several ways. The most reliable approach is to torque servo the robot until the measured torque about **y** is zero.

In order to maximize the displacement step size used to determine the next probe point, the long axis of the sensor can be aligned to the edge of the object by rotating the sensor about **z** until **y'** and **y** are parallel. This ensures use of the maximum amount of array surface area is available for edge detection. The desired angle of roll rotation ∂_z can be easily calculated from

$$\partial_z = \tan^{-1} (y_i, y_j) ,$$

where (y_i, y_j) are the x- and y-coordinates, respectively, of **y** written with respect to the { **x'**,**y'**,**z'**} frame.

Corner Detection

All of the functional primitives presented so far are directed towards detecting the object, locating an edge, and aligning the sensor pad with the object. It remains now to track along the edge until a corner is detected and then continue the process in a systematic manner until the object has been defined.

As in the case of edge alignment, there exist several possible strategies for corner detection. One possible strategy consists of withdrawing the sensor a small distance from the edge, and moving a distance less than or equal to length of the array pad in the direction along **y**, and then proceeding with the torque servo and roll realignment to reacquire the edge. When the edge does not extend across the entire length of the sensor pad, the object edge has been found. Disadvantages of such an approach include the length of time required to perform the torque servo and roll realignment at each probe point. In addition, when the corner is encountered and the edge trough on the array pad does not extend across the entire length of the pad, it can be difficult to specify the proper value for the desired torque about **y** to ensure that the edge lies on the plane of the sensor.

After some experimentation, a more robust detection method was developed. Following the torque and roll realignments, the sensor is withdrawn a short distance and rotated about **y** approximately 6 degrees. The robot is then force servoed in the **z'** direction until some desired contact force is achieved - typically 0.5 lbs. If a corner is contacting the pad, the feature patch will be bounded within the interior of the sensor pad and neither the top nor bottom rows of the array will be excited. If a corner is not present, i.e., the sensor is still on the straight edge, either the top or bottom row of the sensor must be excited, depending upon the direction in which the 6 degree rotation was performed. Provided the distance between probe points is less than the length of the array, probing in the direction along **y** will ultimately reveal the corner. In fact for objects less than 20 cm commonly used in our lab work, it is necessary to calculate the direction vector **y** only once rather than each time a probe is accomplished.

Object Identification

Following identification of edges and corners, it remains to develop a systematic prodedure to reveal enough key features to identify the object. After each probe, the coordinates of the centroid of the feature patch with respect to the { **x'**,**y'**,**z'**} frame are displayed by the real-time monitor along with the robot and its environment. After both corners corresponding to the end points of a given edge are recognized, the length of the edge is calculated. For the simple example demo described here, the length of one edge is sufficient to identify the object. Once the matching system has completed identification, it is modelled and displayed as any other poyhedral object. Fig. 5 shows a display from the modelling system illustrating the contact points from the probing operation of an unknown object along with the depiction of two objects whose identity has already been determined.

IV. DEMONSTRATION SCENARIO

In order to illustrate the functionality of the system as it is currently implemented, a demonstration was developed to identify, acquire, and palletize simple objects. The objects were designed to constrain the requirements on the system in several ways. First, as mentioned previously, the objects must consist of flat surfaces which intersect in straight edges. Secondly, in order to provide sufficient friction to prevent sliding or tipping as the object is probed, a large base was chosen. In addition, so that the object can be acquired by the gripper, the depth of the object was limited to less than 3 cm. The three objects chosen are illustrated in fig. 6. They are identical except in length: one object is 15 cm; a second is 10 cm; and the third is 5 cm.

Since a global sensing system such as vision has not yet been implemented, the placement of the objects was contrained to lie along a predetermined approach path. The object detection primitive described in Section III was used to move the robot on a path normal to the surface of the exterior array sensor until contact with the object was established. The top edge of the object was then located and the array sensor reoriented, also using the primitives described above.

Following the intial reorientation, the top edge was followed until a corner was detected, the sensor returned to the initial contact pose, and the top edge followed in the opposite direction until a second corner was detected. Since the objects differed only in the length of the top edge, identification could be made immediately following detection of the second corner. The object detection primitive along the approach path was then repeated until the next object was found. Detection and identification was continued in this manner until all three objects were identified and displayed.

The objects were then acquired using the gripper in order of size, from largest to smallest, and stacked in a corner between two perpendicular rails using the force servo to determine contact of the part with the rails. Fig. 7 shows the objects at the conclusion of the demonstration.

V. SUMMARY AND CONCLUSIONS

A system to model, plan, and control the real-time response of an industrial manipulator in a variety of sensory modalities has been presented. Manipulation functions were developed based on a pseudo-force control scheme which integrated both force/ torque and tactile array information into the control loop. A system employing selected manipulation primitives was used to develop an object recognition demonstration based on edge tracking. Despite the considerable number of constraints introduced to facilitate the demo, it is felt that the manipulation primitives provide a foundation for probing and manipulating objects of arbitray geometry not necessarily defined by straight edge-type features.

Work is continuing to enhance the capabilities of the system along several fronts:

- The interface to the robot controller is being improved to better facilitate force/torque control of the manipulator.
- Task, sensor processing, and gripper control, which currently reside on single computer board, will be distributed among several single board computers.

- The distribution of sensors will be improved by mounting two array sensors on either side of both fingers and moving the vector sensors to the base of the fingers.
- Novel finger designs will be examined increase the dexterity of the end effector.
- The upper levels of the system will be ported to a high speed graphics workstation to improve performance.

ACKNOWLEDGEMENTS

The authors wish to thank Paul Wolfe and Steve Buchner of the Advanced Technology Group within Lord Corporation for the development of the gripper system and the VME-based computer control system. This work was supported by the US Department of Defense Advanced Research Projects Agency under contract number N00014-84K-0098 and by Lord Corporation.

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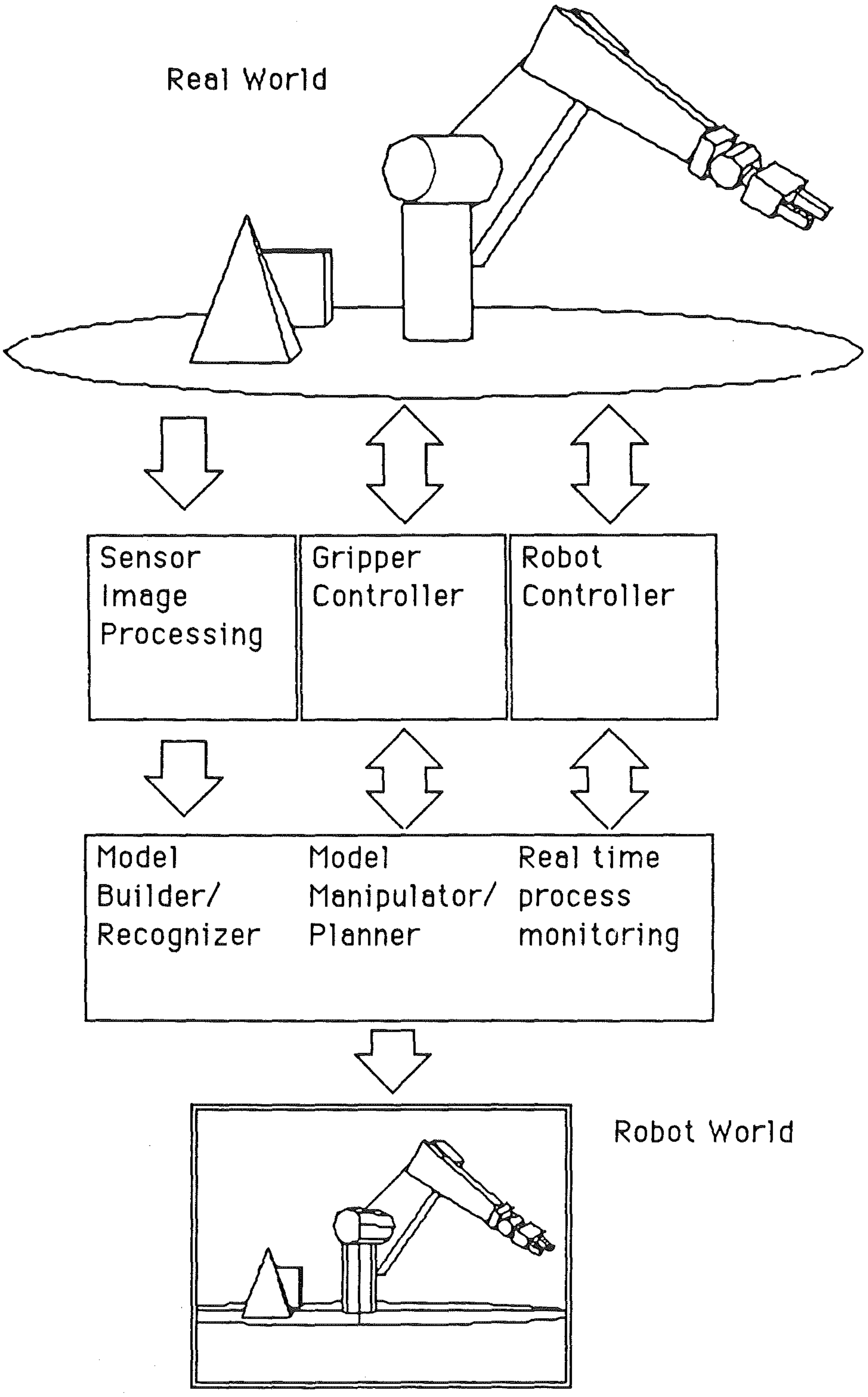

Fig. 1 Block Diagram of Control System Software

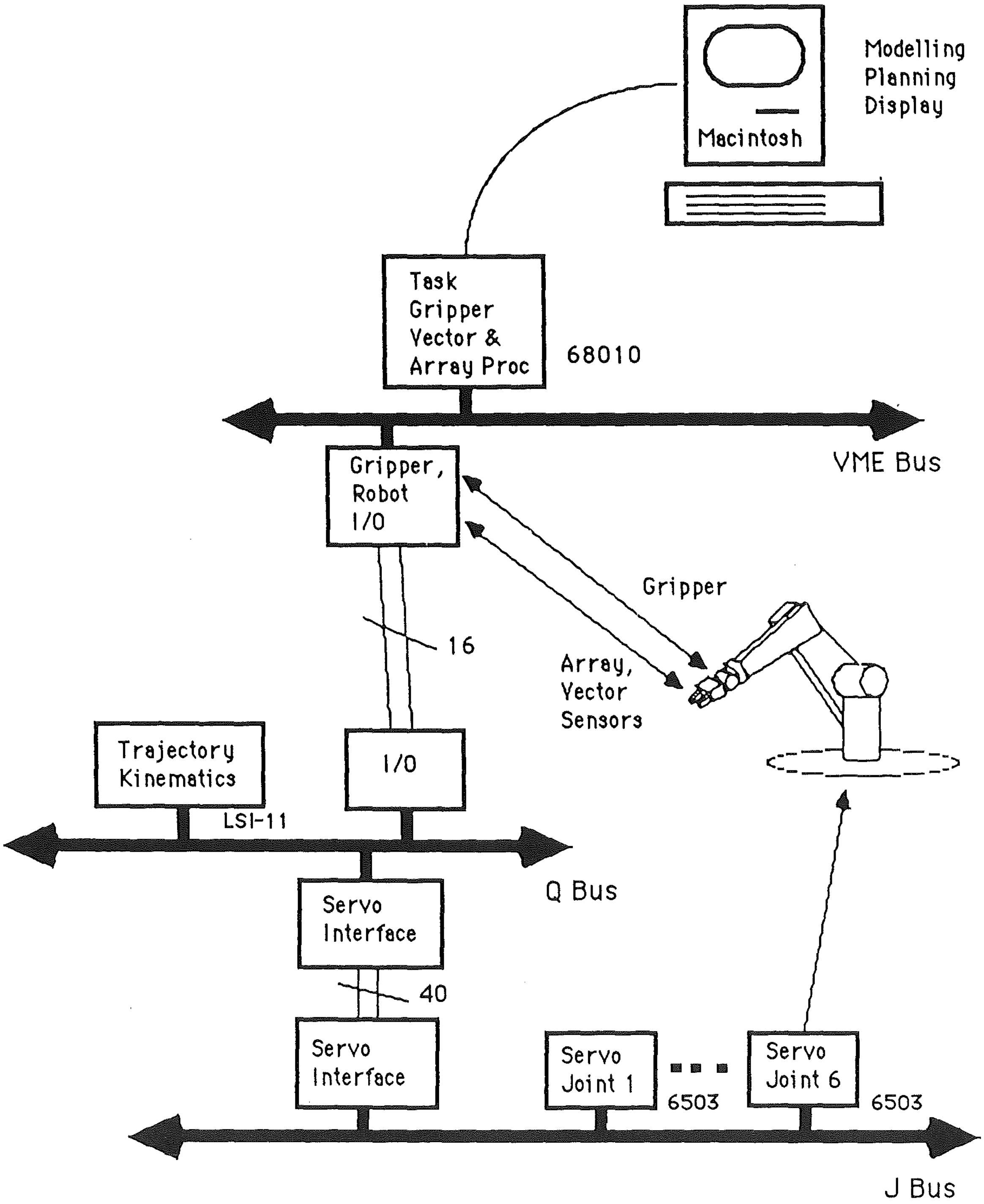

Fig. 2 Schematic of Manipulator Control System

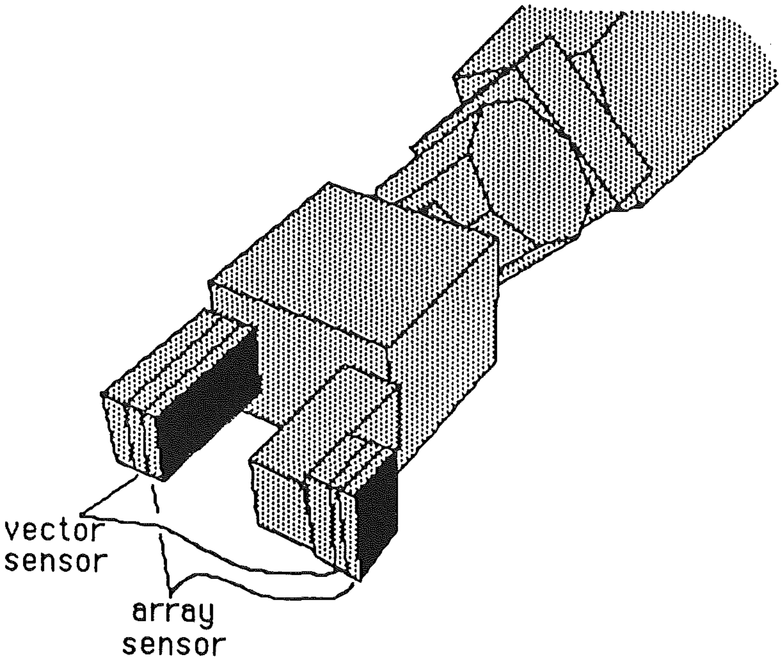

Fig. 3
End Effector Configuration

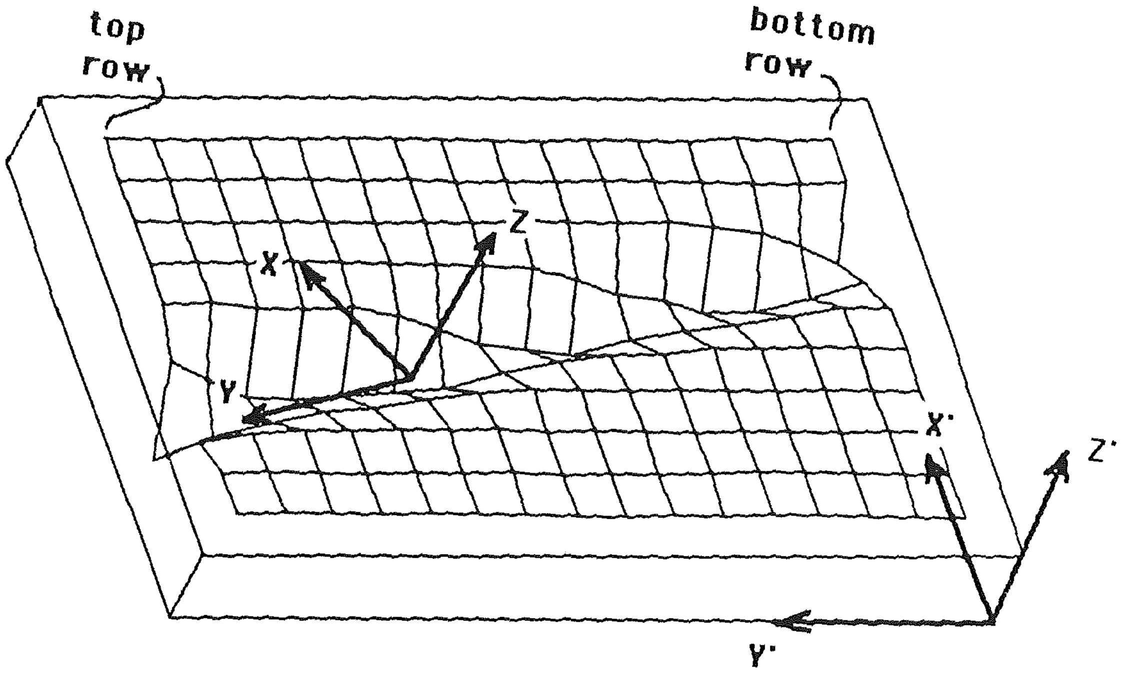

Fig. 4
Feature Patch From Straight Edge

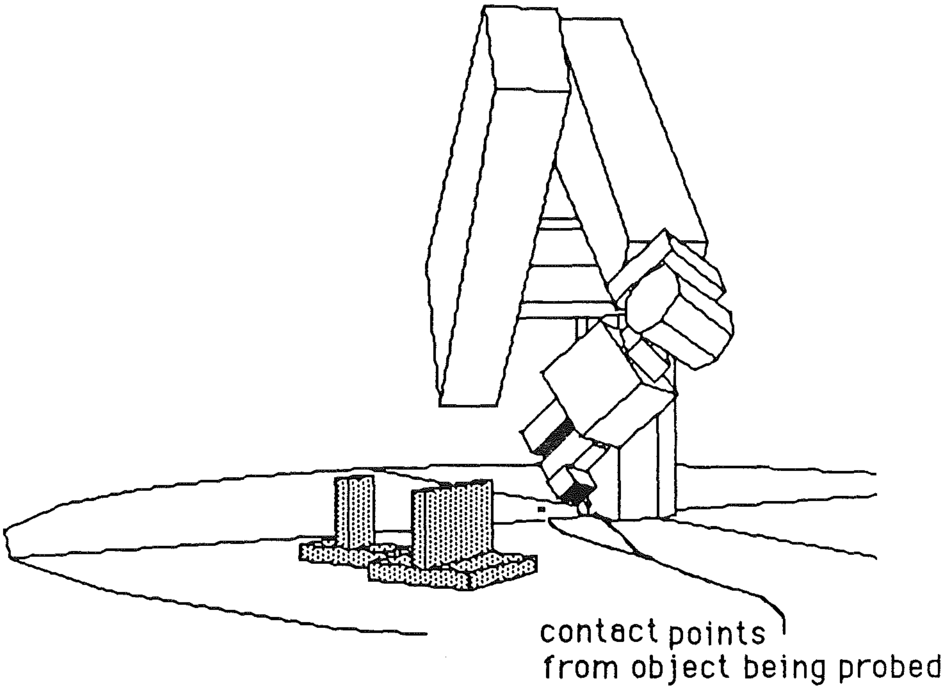

Fig. 5
Results of Modelling System
During Touch Probes of Unknown Object

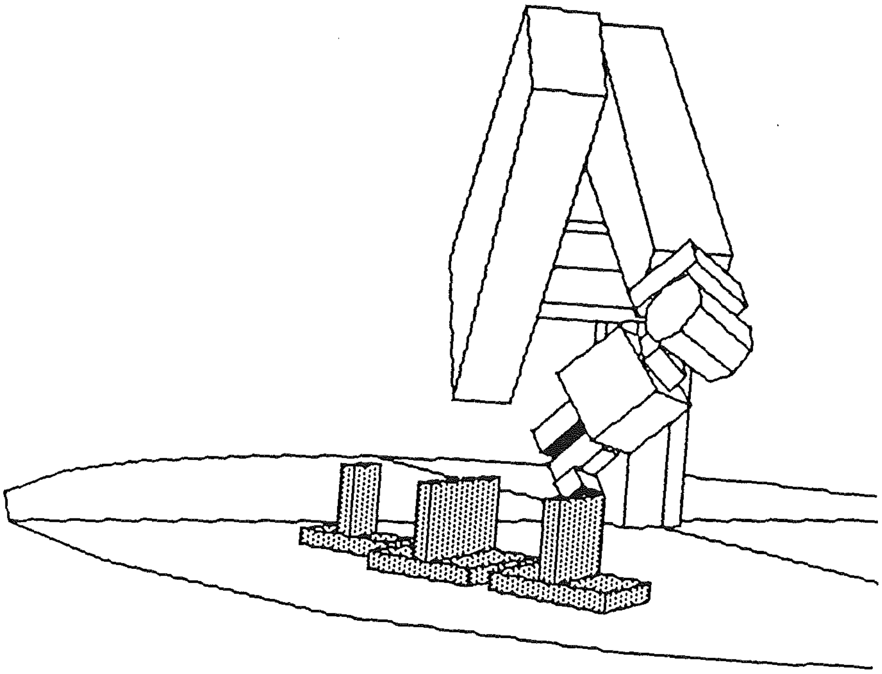

Fig. 6

Objects Used for System Demonstration

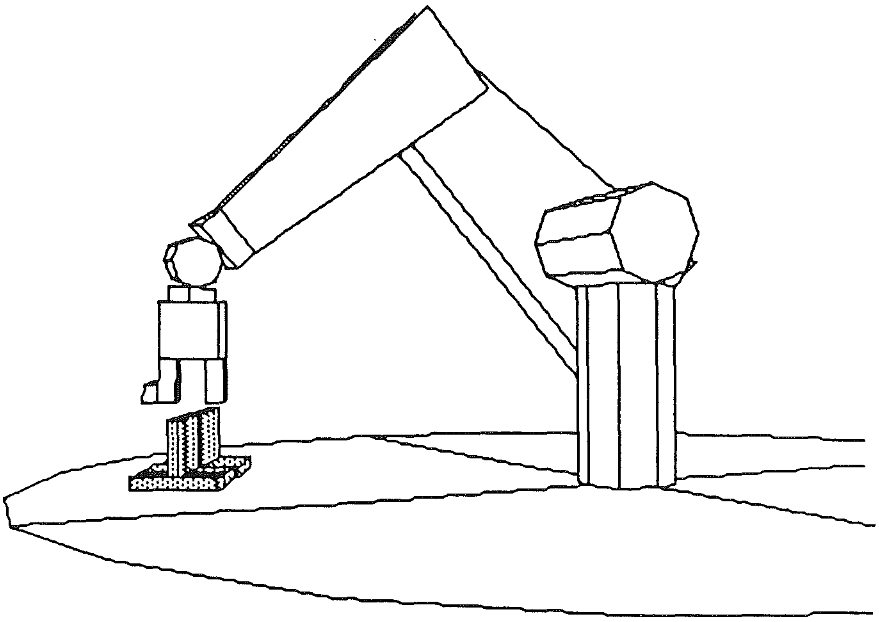

Fig. 7
Palletized Objects at Conclusion of Demonstration

Session

SENSORS (3)

Integrating Tactile and Visual Perception for Robotics

by

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1. Introduction

There has recently been a growing interest in developing methods for robotic tactile perception which can complement robotic vision. One reason for this interest is that contact sensing does not underconstrain scene interpretation (as does vision), and with proper proprioceptive feedback, touch can provide exactly the sort of absolute distance information that will complement vision best. Another reason for interest in tactile perception is that robots are usually engaged in contacting and manipulating objects in the course of task accomplishment, and so tactile sensing in the course of that contact utilizes the robots inherent capabilities. Finally, it is clear that tactile perception may provide scene information which is not available to visual sensors. Such information includes details of gripper placement, characteristics of visually occluded surfaces, compliance, roughness, and physical resistance.

Our research into robotic perception has proceeded in the following steps:

(1) Devise a set of appropriate tactile features, and develop methods for the extraction of these features from array force-sensed images.

(2) Develop (in simulation) methods by which sparse tactile data may be used to efficiently detect object identity and placement from a set of predetermined objects.

(3) Extend the object identification methods to permit the use of sensory information from arbitrary sources, and to test out the extension in the integration of simple visual data along with the tactile features.

2. Extracting Tactile Features

Tactile sensors exist which consist of a compliant surface capable of measuring force in an array of locations across the sensor. The sensor that we have been using provides a 16x16 array of 1 byte per location in an area of about 1 square inch†.

Early use of such sensors treated the input as a complete image of an object, and was therefore applicable only to the identification of small parts (eg. Hillis, 1981). Our approach has been to define a set of tactile features which may be extracted from the images, and to subsequently base interpretation on these features. This permits the use of tactile information in the recognition of arbitrarily large objects. We have chosen a set of features which maintains some compatibility with what is known about the operations of human touch (Lederman &

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†Barry Wright Corporation Sensoflex System.

Browse, 1987). This set includes 1. flush surface contacts, 2. edges, 3. corners, and 4. roughness. Each of the features is complemented with parameters such as curvature, orientation, etc. The featurs are detected and collected using a PDP-11/03, and processing takes place on a connected SUN-3 computer.

3. Tactile Object Recognition

We have simultaed a robotic environment in which a single object chosen from a set of nine objects is “placed” on a tabletop at random location and orientation. A small set of tactile features are made available to an interpretation process such as would be available if our tactile sensor were actually contacting the object.

An individual feature does not provide enough constraint to be able to identify and locate the object, yet for each of the feature types, there are strict limitations on the possible placement for each of the possible surfaces. We have formulated these constraints as templates which are instantiated with the sensor pad location at the time of contact. A complete description of these constraint templates is found in (Browse, 1987). The result of using the constraints is that for any individual feature, there are many possible surfaces that could have given rise to the feature due to sensor contact, but for each of the surfaces, there are tight positional constraints.

In the consideration of more than one feature, modified network consistency algorithms are used to compare the positional constraints and to prune all surface contact possibilities which are incompatible. The result is that a single unique interpretation usually remains after the consideration of only 2 or 3 tactile contacts.

We believe this technique offers considerable improvement over previous methods for the utilization of sparse perceptual data. One advantage of this method is that the system does not require explicit knowledge of the relative positions of the sensor contacts, and it works equally well if the contacts are obtained through sequential application of the same sensor or from the use of multiple sensors.

4. Extending to Intersensory Operation

The recognition system described above only requires that sensory data be mapped into positional and identity constraints in order for the consistency operation to apply. The recognition phase is not concerned with the source of such constraints, and so it is possible to develop these constraints in similar format on the basis of different perceptual sources.

To test out this idea, we have implemented (again in simulation) a system which presents constraints based on simple visual capabilities. These capabilities are the detection of line segments, their orientation and length. No effort is made to combine line segments into larger image structures, but rather the complete set of possible object placements that coincide with the detected line are entered into the interpretation system. This information is used along with the tactile constraints to yield interpretation even more efficiently (Rodger & Browse, 1986).

5. Future Work

We are continuing the same approach to intersensory integration for robotics, and our immediate plans are to implement the system for a PUMA-550 robot. We are devising more effiecient (and parallel) methods for tactile feature extraction, and we are extending the interpretation process to operate in multi-object environments, and with other forms of coarse level vision.

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Multi-Sensor Integration for a Mobile Robot Using Concurrent Computing[1]

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Abstract

This paper addresses methods for high and low level multi-sensor integration based on maintaining consistent labelings of features detected in different sensor domains. Implementation in a concurrent computing environment is discussed.
Keywords: Multi-Sensor Integration, Sensor Fusion, Consistent Labeling, Markov Random Field, Concurrent Computing, Hypercube, Simulated Annealing.

1. Introduction

One of the prerequisites for intelligent behavior in robotic systems is the ability to generate consistent, system-internal representations of the environment. In general, this is impossible on the basis of any single sensor domain. Hence, robotic systems are being equipped with an increasing number of different sensors that supply partly redundant information. Multi-sensor integration (MSI) designates the task of combining data and information from these various sensors such that a consistent world model, i.e. a model free of contradiction, can be generated, on the basis of which decisions concerning navigation, manipulation, etc. can be made. A panel of experts at a recent workshop on research needs for intelligent machines has identified MSI as an issue of highest priority[1].

The task is highly complex because of several circumstances related to the diversity of sensors. Depending on the physics underlying a particular sensor, the amount of time required to acquire data varies among different sensors, e.g. from on the order of seconds for sonar distance measurements to 1/30 second to digitize a TV image (with US TV frequency). The amount of time needed to perform quantitative analysis of sensor data and extract features also depends on the nature of the sensor. As an example, analysis of digital images is generally more time-consuming than the analysis of one-dimensional signals. This introduces

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scheduling and synchronization problems in a dynamic environment. The confidence associated with a sensor measurement depends on the situation in the environment, e.g. a sonar sensor tends to underestimate distances to room corners, and cannot detect open spaces between obstacles whose distance from each other is smaller than the width of the ultrasound beam. It follows that there should be a sensor hierarchy that depends on the environment as well as on the particular mission that the robotic system is performing. Thus, any mechanism for MSI must have access to the knowledge base describing the world model, and flow of information between different sensor domains must be possible at all stages in the data and information processing. Finally, it must be noted that the existence of a consistent representation of the environment on the basis of the available sensors is not guaranteed. A method for MSI must recognize such a situation and be able to deal with this uncertainty.

In advanced robotic systems with a high degree of autonomy for certain tasks MSI needs to be accomplished under real-time constraints. Real-time performance is dictated by the speed at which the robot must operate in order to accomplish a task and be economically viable. Thus, concurrent computing architectures should be considered for implementing methods of MSI. A distinction between distributed and parallel computing is appropriate. The former refers to the fact that part of the sensory data and information processing at a low level is performed at the location of the sensor, i.e. spatially distributed throughout the robotic system. The latter refers to parallel or concurrent architectures which are suited for integration algorithms, e.g. array processors, hypercubes, etc. Note that computing at the distributed sites can be parallel, e.g. intelligent vision or tactile sensors.

A system for MSI that incorporates all these features is not available to date. The objective of this paper is to describe an approach to MSI for a mobile robot that would be expandable by additional research to handle the complexity of the problem outlined in the previous paragraph. The methodology to be presented also lends itself to implementation on concurrent computers.

The paper is organized as follows: Section 2 gives a brief overview of relevant literature on MSI; a specific approach to low level and high level MSI in a concurrent computing environment is presented in section 3; section 4 presents some conclusions.

2. Review of literature on MSI

The scope of research and development falling under the heading MSI, also referred to as sensor fusion, is not well defined. Depending on the level of abstraction, i.e. mathematization, at which the problem is discussed, even results from the seemingly unrelated theory of finite groups (related to graph morphisms) can be of relevance to MSI. Obviously, an exhaustive treatment of all these aspects of MSI is beyond the scope of this article. In this section some of the MSI literature relevant to robotics is summarized briefly. In analogy to the characterization of methods for computer vision approaches to MSI can be categorized into low and high level methods. Low level MSI aims at combining the outputs from sensors at the level of the actual data supplied by the sensors, e.g. the merging of registered reflectance and range data from laser range finders. High level MSI deals with the integration of information extracted from the data collected by different sensors. The combination of object labels obtained from vision, heat, and acoustic sensors probing a scene may be viewed as an example for high level MSI. As in computer vision, there are methods that do not fit perfectly into either category, e.g. feature-based stereo vision algorithms.

Early work in MSI appears to have been driven by the necessity to support visual information processing aiming at image understanding by pieces of information from other sensor domains. In 1977 Nitzan et al.[2] described a laser-based system to acquire registered reflectance and range data for scene analysis. Although it took more than 2 hours to acquire a 128x128 pixel range image, the system was used to test methods for scene segmentation[3].

Military applications provided another incentive to pursue R&D in MSI. Bowman et al.[4] deal with high level integration of information supplied by 4 radar and infrared sensors on board fighter aircraft. These authors discuss the Bayesian approach for combining target labels in conjunction with Kalman filtering for target tracking. The severe time constraints associated with the application impose an a priori adoption of a sensor hierarchy. Rauch[5] discusses probability concepts for rule-based expert systems as decision aids for tactical data fusion. A more recent account of some work related to sensor fusion for military applications was presented by Waltz and Buede[6].

The number of publications on MSI-related work has been increasing since the early 1980s. Pau[7] presented some ideas on MSI from the point of view of Statistical Pattern Recognition, mostly referring to high level MSI independent of a particular application. Henderson et al.[8] introduced the concepts of logical sensors and multi-sensor kernel system as a uniform mechanism to deal with data from diverse sensors. No attempt was made to incorporate in the concepts the levels of confidence associated with pieces of information from different sensors. Flynn[9] reported on the combination of a sonar and an infrared proximity sensor in order to reduce errors inherent in both sensor domains. Allen and Bajcsy[10] combined stereo vision and active tactile sensing for recognition of objects. Ruokangas et al.[11] describe a system that integrates 2D vision and acoustic distance measurements for a stationary robot. Magee et al.[12] present results of experiments with intensity-guided range sensing as an approach to circumvent some problems associated with relatively long acquisition times for range data. The combination of static thermal and visual images obtained from outdoor scenes was reported recently by Nandhakumar and Aggarwal[13]. Durrant-White[14] discusses an approach to high-level MSI independent of the particular sensor domains involved. This approach combines uncertain observations into a minimum average risk best estimate of the robot's environment probed by several sensors. Preliminary results with vision and tactile sensing were reported. Tentative approaches to incorporating concurrent and parallel computing concepts into MSI methods have been described by Harmon et al.[15] and by Chiu et al.[16], who propose a programming environment involving data flow methods on a Butterfly parallel processor.

Although many interesting approaches have been described in the literature, some of them with encouraging results, there is a need for continued research at all levels of MSI[17] that will lead to efficient multi-sensor systems capable of operating under the time constraints dictated by mobile robots in operational environments.

3. MSI in a concurrent computing environment

The scope and contents of any discussion of MSI methods under the aspect of concurrent computing depends on the mathematical concepts into which MSI or MSI-related problems are being mapped. If, for example, the discussion is focused on the low-level integration of imaging sensors such as range and vision or different vision modules as in the case of depth from stereo, then the requirements concerning the concurrent computer architecture will be different than those for a method that performs high level integration of information from incommensurate sensor domains.

The concepts used here in order to formalize and solve problems in MSI are consistent labeling and the resolution of conflicts through selection of labels according to the maximum a posteriori probability criterion. This section will outline how these concepts can be employed for low and high level MSI, and how the methods involved can take advantage of concurrent computer architectures.

Given a set of objects, a set of labels, a neighbor relation among the objects, and a constraining relation among labels at pairs or n-tuples of objects, the labeling problem consists of assigning labels to all objects in a manner consistent with the constraint relation among the labels[18,19,20].

In the context of MSI a labeling problem occurs in every sensor domain. The objects correspond to features of objects measured by a sensor, the labels correspond to object descriptions, e.g. "chair", "automobile", etc. The label for each feature has associated with it a level of confidence which incorporates the degree of imprecision and uncertainty inherent in sensing and feature extraction. The a posteriori probability P(label|feature) expresses this level of confidence. It is calculated from the a priori probabilities by using Bayes' rule:

$$p(\text{label}|\text{feature}) = P(\text{label})P(\text{feature}|\text{label})/P(\text{feature})$$

Initial assignments of labels to features are made so as to maximize the a posteriori probabilities. Subsequently a parallel relaxation labeling algorithm[20] is executed in order to satisfy the constraints among the labels. As a result of this relaxation the assignments of labels do in general not satisfy the maximum a posteriori (MAP) criterion any more.

Integration of information from other sensors is accomplished through constraints that exist among labels in different sensor domains. In the case of binary constraints, i.e. integration of 2 sensors, a check is made whether 2 labels for a feature pair from the 2 sensor domains are in conflict. If this is the case then the label with the lower posterior probability is discarded, otherwise the 2 labels support each other.

It is assumed here that features from different sensors are in registration, i.e. the feature correspondence problem has been solved. This is a very important issue which is, however, beyond the scope of this paper. For an introduction to approaches for associating multiple measurements with multiple objects in a dynamic environment the reader is referred to a survey paper by Bar-Shalom[21].

The method for MSI outlined so far allows for several options: labelings can be computed concurrently and independently in each sensor domain. The subsequent integration can be performed in parallel over all sensor domains, resulting in a self-adjusting hierarchy of sensors that depends on the environment, or a sequence of sensors to be integrated can be followed, thereby incorporating a priori knowledge on an adequate sensor hierarchy for a paricular task. Moreover, it is possible to define a primary sensor, perform labeling in that domain, and to selectively request supporting evidence from other sensor domains, based on low posterior probabilities computed for the primary sensor. The approach also allows for modification of the prior probabilities in individual sensor domains based on the outcome of the integration process, thereby enabling learning.

In order to formalize somewhat the methodology outlined here, assume that there are 2 sensors S_1 and S_2. The formalism can easily be extended to K sensors. Each S_k supplies features $\{f_{ki},\ i=1,\dots,N_k\}$. For each sensor domain there exists a set of labels $L_k = \{l_{ki},\ i=1,\dots,M_k\}$. Let $L \subseteq L_1 \times L_2$ denote the constraints among labels in different sensor domains. Note that the label sets can be identical for all sensors. A labeling problem must be solved in at least one sensor domain. This can be accomplished as follows[20] (index k is dropped for simplicity): Let $p_i(l_n)$ be a measure of strength of association of label l_n with feature f_i. Initially $p_i(l_n)$ is selected to be the posterior probability of l_n given f_i. Let $R_{ij}(l_n,l_m)$ be equal to 1 if labels l_n and l_m are compatible for features f_i and f_j respectively, and equal to 0 for incompatible labels. An iterative, parallel procedure can now be formulated[22,20] that allows the computation of updated label assignments $p_i^{(s)}(l_n)$ starting from $p_i^{(0)}(l_n) = P(l_n|f_i)$:

$$p_i^{(s+1)}(l_n) = (p_i^{(s)}(l_n)(1 + q_i^{(s)}(l_n)))/ \sum_{m=1}^{M} p_i^{(s)}(l_m)(1 + q_i^{(s)}(l_m)),$$

where $q_i^{(s)}(l_n)$ is defined as

$$q_i^{(s)}(l_n) = \sum_{j=1}^{N} \sum_{m=1}^{M} R_{ij}(l_n,l_m)\ p_j^{(s)}(l_m)$$

The algorithm stops if successive iterates show no significant changes. For the resulting label assignments the posterior probabilities are computed. Subsequently the consistency of labelings across sensor domains is checked. If l_{1j} and l_{2j} are labels for an object measured by sensors S_1 and S_2 respectively then the label with the lower posterior probability is discarded if (l_{1j},l_{2j}) L. A schematic diagram showing the resulting MSI mechanism is depicted in Figure 1.

The implementation of this approach on distributed processors is straightforward. Parallel execution of the labeling algorithm has been described recently[23] for a semantic network array processor. The implementation of the methodology outlined here is currently underway at ORNL on an NCUBE hypercube concurrent processor (NCUBE Corp., Beaverton, Oregon). Experiments will be performed using the successor of a mobile robot described by Weisbin et al.[24] which is equipped with an on-board hypercube computer.

The remainder of this section deals with a different mathematical approach to the labeling problem that has recently been studied with great interest in image processing and pattern recognition: stochastic relaxation with simulated annealing[25,26,27]. In order to sketch the idea behind this approach it is necessary to introduce the concept of a Markov Random Field (MRF)[25]. Let S be a set of m sites, $N = \{ N_s \mid s \in S \}$ a neighborhood system of sites in S, i.e. a collection of subsets of S such that

$$\text{(i)}\quad s \notin N_s, \ \forall s \in S$$
$$\text{(ii)}\quad s \in N_r \Leftrightarrow r \in N_s, \quad \forall r,s \in S.$$

Let X be a set of random variables indexed by S, $X = \{X_s,\ s \in S\}$, and P a probability measure. X is called a MRF with respect to N if

$$\text{(i)}\quad P(X=x) > 0$$
$$\text{(ii)}\quad P(X_s=x_s \mid X_r=x_r,\ r \neq s) = P(X_s=x_s \mid X_r=x_r,\ r \in N_s) \quad \forall s \in S$$

i.e. the probability of a random variable at a site taking on a specific value depends only on the values of random variables at neighboring sites. Given a neighborhood system, a clique c is either a single site or a set of sites such that all sites that belong to c are neighbors of each other. Let C denote the set of all cliques. One of the crucial properties of MRFs for the application targeted here is the fact that X is a MRF with respect to N if and only if the probability distribution of X is a Gibbs distribution, i.e.

$$P(X=x) = \exp(-U(x)/T)/Z$$

where Z is a normalizing constant also called partition function, T is a parameter mostly referred too as temperature, and U(x) is a function also referred to as "energy", which can be written as

$$U(x) = \sum_{c\;\;C} V_c(x)$$

with "potential functions" V_c over cliques in N. For further details see for example Geman and Geman[25] or Wolberg and Pavlidis[26]. Assume that instead of X a distorted process Y=H(X) is observed. Under certain conditions on H[25,28] it can be shown that the posterior distribution

$$P(X|Y) = (P(Y|X)P(X))/P(Y)$$

is also a Gibbs distribution with energy

$$U_{X|Y}(x) = U(x) + K(x,y) \qquad (1)$$

where K is a non-negative function of the distortion H. Hence, maximizing the a posteriori probability of X given the data Y is equivalent to minimizing the energy $U_{X|Y}(x)$. Simulated annealing (SA), a technique developed recently[29,30] for the solution of combinatorial optimization problems can be used to find the global minimum of $U_{X|Y}(x)$. Briefly, SA is based on the idea of associating the values of variables in an objective function to be minimized with the states of a physical system. Therefore, bringing the physical system to a state of minimum energy by careful "cooling" is equivalent to minimizing the objective function. Convergence properties of SA have been addressed in the literature[25,31], and the inherent parallelism is being exploited in many applications[25,28,32]. In short, the Markov property of the process X|Y allows for parallel execution of the SA algorithm, and the Gibbs-MRF equivalence allows for convenient formulation of a model for the process.

In order to apply these concepts to the labeling problem in MSI let X=(F,L) where F is the set of features of objects in the environment measurable by the sensor, and L is the set of object labels. Let S be the set of nodes of a graph describing the relationship, i.e. constraints, among the features. Let Y denote the data, i.e. features corrupted by noise. Assuming a Gaussian $P(Y|X)$, for example, one can determine the term $K(x,y)$ in (1) explicitly[25]. After specifying the potentials in $U(x)$ to reflect the constraints among labels, i.e. ensuring that $U(x)$ is minimal if the constraints are satisfied, stochastic relaxation with SA can be used to solve this labeling problem. The terms in $U(x)$ could be specified as follows:

$$V_c(f_i,f_j,l_n,l_m) = \begin{cases} 1, & \text{if } R_{ij}(l_n,l_m)=0 \text{ and } i,j \in c \\ -1, & \text{if } R_{ij}(l_n,l_m)=1 \text{ and } i,j \in c \\ 0, & \text{otherwise} \end{cases}$$

Similarly, the integration of data from multiple sensors can in principle be achieved using this approach. Depending on the definition of the process X this methodology can be used for high and low level MSI.

4. Conclusions

MSI was defined as the integration of data and information from different sensors with the goal to produce a consistent description of the environment being sensed. The problem was formulated as a labeling problem which allowed to describe mechanisms for solution of both low and high level MSI, depending on the level of data reduction associated with feature extraction in the individual sensor domains. This approach provides for a flexible MSI strategy allowing for incorporation of prior knowledge concerning the sequence of sensors to be combined, or for a dynamically self-adjusting hierarchy of sensors. Posterior probabilities can be examined in order to decide whether a sensor-derived description of the environment is appropriate or inacceptable.

The methodologies can be implemented in a distributed parallel processing environment. The precise architecture for this environment remains to be determined. Testing of this approach on a mobile robot with multiple sensors including incommensurate sensor domains is necessary and will be performed in order to determine its applicability to an operational environment.

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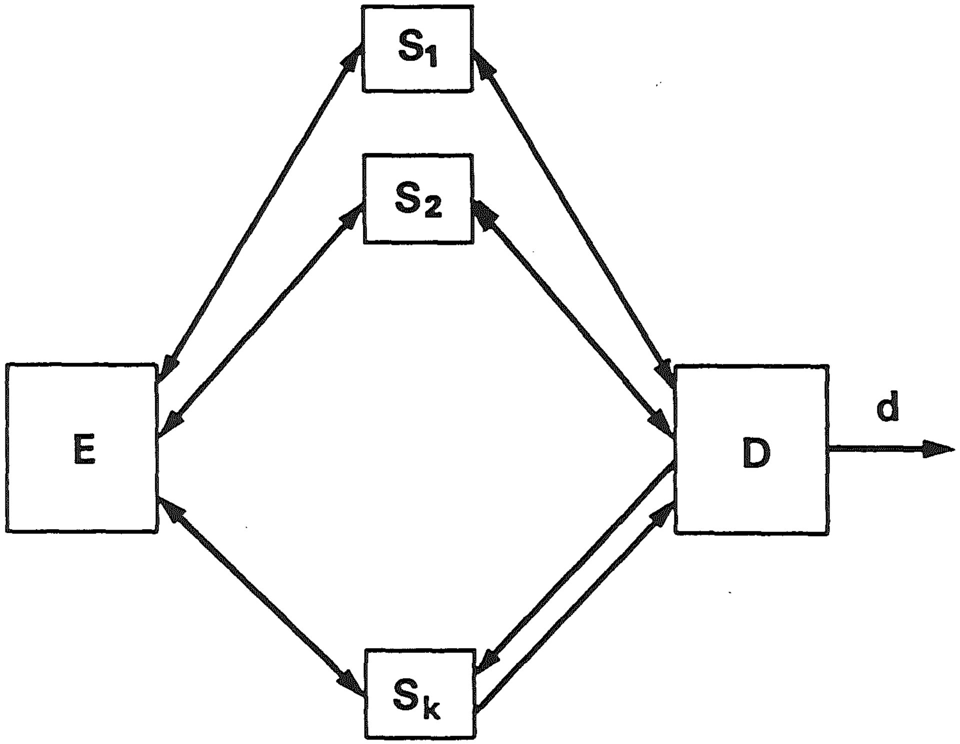

Figure 1: Sensors $S_1,\ldots,S_K$ actively or passively probe the environment E. The decision making system D integrates labelings supplied by the sensors and can adjust prior probabilities in the individual sensor domains. Ultimately the system arrives at a decision d concerning the contents of the sensed environment.

Session

STEPS TOWARDS MOBILITY

CHAIRMAN'S REPORT ON THE SESSION 'STEPS TOWARDS MOBILITY'

During the last few years, several types of autonomous mobile robots have been developed in Europe, Japan and the United States. Typical application areas are mining, inventory control, material disposition, work in atomic reactors, supervision of underwater oil-pipelines, application in space vehicles, leading of blind people and handling of bedridden patients. In principle, almost all vehicles consists of several autonomous subsystems. For example, one of them may be used for the navigation of vehicles, the other for planning and supervision of the work and a third one for sensor processing.

The autonomous intelligent vehicle will be able to plan, execute and supervise a mission along a route of a manufacturing floor. If a conflict occurs, it must recognize it and independently try to find a solution. The major components of the mobile platform are: the mechanics and drive system, sensor system, controller, computer architecture, planning and navigation system, world model, knowledge acquisition and world modelling modules.

The design of these components involves research knowledge from a variety of disciplines, e.g. physics, electrical engineering, computer science, and mechanical engineering. It is important to coordinate the cooperation of the different disciplines for the design, the construction and the interfaces of the overall concept of the autonomous system.

The papers of this session were primarily concernded with the description of robots for task-specific application, task planning and navigation techniques.

Prof. Hirose discussed a unique robotic device which can be used in a hostile environment to carry heavy loads. The basic building block of this robot is a bucket-like element provided with two wheels. Several of these segments are linked together to one transportation unit. Propulsion of this unit is obtained by a snake-like motion generated by actuators in the links of adjacent buckets. In this mode, the robot is capable of moving about a level floor. If obstacles or stairs are to be climbed, the individual bucket can be moved up and down relative to each other along sliding joints. The vehicle is controlled by a microcomputer.

Mr. Lutz addressed the use of autonomous vehicles for flexible manufacturing systems. This project is an interdisciplinary effort of several departments of the University of Munich to increase the flexibility of the material flow system in a factory. The objectives of the project are the integration of several autonomous mobile robots in a manufacturing environment, to provide autonomous locomotion and navigation of transport vehicles and to perform autonomous manipulation of parts and tools.

Dr. Hallam discribed a feature-based navigation system which is capable of directing an autonomous vehicle through a hostile environment using various sensors. In this effort, it is assumed that the perceived information stems from a noisy surrounding. A Kalman filtering technique is used to exploit sensor data from world-based or vehicle-based sensors. The succeeding analysis is focused on the noise propagation and convergence behavior of the control algorithms used. The system determines the motions of features relative to sensors, and it calculates which features have the desired motion information. A global stationary reference frame is generated to which all positions and velocities are recorded. Thereby it is possible to estimate the vehicles motion using the apparent motion of external objects.

Mr. Frommherz discussed the planner of the autonomous mobile assembly robot of the University of Karlsruhe. The input to this system is an assembly plan for a product. The first step to find a solution is the establishment of a precedence graph to determine the assembly sequences. Thereafter, the resources needed for assembly are selected and a collision investigation is made. Finally, the code is generated for the control of the assembly robot. During the planning phase, several expert systems are activated and a world model is consulted to render information about the workplace of the robot.

A similar approach to programming of assembly robots was discussed by Dr. Smithers. The aim of this research work is the design of an easy to use problem-oriented programming system for industrial applications. The work is based on experience gained from geometric reasoning techniques from the RAPT robot programming system, developed by the University of Edinburgh. Assembly planning will be done with the help of a hierarchical decomposition technique. The assembly plan is entered in an abstract way at the highest level and decomposed in several steps, and finally the control information for the robot controller is generated. The programming system will use sensor information from the robot and will be able to react to uncertainties of the robot world.

Dr. Sanderson gave an overview of the robot research at the Carnegie-Mellon University. There are several projects to develop autonomous mobile vehicles. The first vehicle is operated by a gasoline power plant and propelled by six wheels. An optical sensor system supervises th travel. The system can drive along sidewalks and employs its vision sensor to recognize the travel path and to watch for obstacles. In another experiment, a sonic navigation system is being investigated in conjunction with a three wheel robot. The robot has to find an unobstructed travel path to drive from a home base to a destination. A third system was built from a converted truck. It contains a sensor system and a navigator. The sensor data interpretation and the navigation is done with the help of a SUN-Workstation cluster contained in the truck. There were several projects discussed where the work of assembly robots was guided by tactile and vision sensors.

ULRICH REMBOLD

ARTICULATED BODY MOBILE ROBOT

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SUMMARY

To improve the function of industrial robots and enlarge its function into non-manufacturing tasks or critical works to substitute for human workers , highly advanced mobility have to be installed in the robot system. Several configurations were already proposed as the mobility mechanisms of the robot so far. Most of them were based on wheel or crawler. The wheel or crawler shows fairly good mobile function on a structured environment, but their mobility is quite restricted and not adaptive to the off-the-road terrain. To introduce the adaptability on the off-the-road terrain conditions, completely new mobility system should be introduced.

A legged vehicle is paid attention as one of the solution for this problem, and several studies are now under way. Especially in Japan quadruped walking vehicle with dynamic walking capability is seriously studied at present for the mobility system of the inservice inspection robot for the nuclear power plants as one of the main item of the Jananese goverment R&D project for robots for use in critical environment. The author have also been making succeesive studies on the quadruped walking vehicle, and until now demonstrated adaptive and dynamic walking by using the five mechanical models constructed. Through these experiments however the author came to believe that the legged robot systems have intrinsic demerit, i.e. the payload can not be so high compared with the wheel or crawler vehicle. In regard to this characteristics, legged vehicle is unfortunately not suitable for the nuclear power plant robot. Because it have to transport a great amount of loads such as the manipulators, sensors, computer, and power source to be an autonomous locomotor and at the same time it have to pass through narrow and curved pass designed for human workers.

To realize both the high adaptability to off-the-road terrain conditions and high payload function, the paper proposes a new mobile robot with articulated body. It is named KOURYU or KR. The articulated body of the KR consists of unit segments with cylindrical shape arrayed vertically. The unit segments are connected by two degrees of freedom actuators and makes active rotation around vertical axis of the unit and linear sliding motion along the vertical axis between the adjacent segments. The each segments also installed an active crawler at the bottom. By using the coordination control of these actuators, the proposed mobile robot KR has the function to exhibits snake like

locomotion just like a water flow. The functional advantages of the KR are;
1) It has a slender configuration and the active function to conform to the shape of the corridor. Therefore it can pass through narrow space.
2) Each units of the KR can be designed with simple mechanism. Therefore it posesses a high payload function. This characteristics can be stressed further more if it compared with other mobile system by the ratio of the payload and the space through which the vehicle can pass.
3) Weight of the payload can be distributed along the trunk and thus suitable to move on soft ground.
4) The KR can stride over obstacle or ditch by using the active slender body and its coordination control.
5) The KR can climb up and down the stairs only by using sliding motion of the units to vertical directions.
6) The KR can locomote with high velocity by using crawler motion while maintaining statical stability.

To verify the characteristics of the newly proposing mobile vehicle system KR, an experimental model vehicle of was constructed named KOURYU-1 or KR-1.

The KR-1 consists of 6 segments, 1.391mm in lenght, 393mm in height, 27.8kg in weight. Unit segment is made of cylindrical body with 206mm in diameter. It is mado of CFRP. The constructed model can be considered as one third model of the practical mobile robot. It is controlled by microcomputer with C language. Until now the KR-1 exhibited the locomotion over ditch and obstacle, high velocity (about 200mm/sec) turnig motion with right angle, climbing up and down motion on the model stairs.

To control the KR properly, many interesting controlling problem arises. The author is just now investigating these problems.

Feature-Based Navigation Techniques Contribution Proposal Summary

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1 Feature-Based Navigation.

The ability to navigate is an essential prerequisite for the construction of fully autonomous robotic vehicles. It is not merely required for the execution of planned activities, e.g. inspection or exploration, where the vehicle must move to a specified sequence of positions without supervision; it is also necessary for the registration and integration of sensory information obtained at different times during the vehicle's activities (e.g. for making maps), since the vehicle's position must be known in order to be able to make use of the sensory data.

Essentially, the navigation problem considered here reduces to the ability to estimate accurately the position and velocity of the vehicle at any time, using whatever information is available from sensors. The problem is complicated in practice by imperfect sensing systems and difficulties may be further compounded if substantial passive motion is present (as in marine vehicle navigation where the movement of the medium makes it impossible to remain stationary).

At Edinburgh we have been investigating a technique, "feature-based" navigation, which is able to exploit sensory information to assist navigation in the marine environment. The method is applicable to marine vehicles or other vehicles which are subjected to passive motions, but is equally applicable to the simpler navigation problem encountered with land-based vehicles. In this summary I shall outline the variety of problems addressed by the technique, the methods used, results and status of the work.

2 Problem Statement.

In order to make the feature-based navigation system as generally applicable as possible, the navigation problem has been cast in a very abstract form. The basic problem addressed by the system is this:

> Given a sequence of noisy estimates of the apparent motion of a number of features (reference points) in the environment, determine corresponding estimates of the motion of the vehicle and the features with respect to an arbitrary but fixed stationary frame of reference.

Effectively, the system is given motions of features relative to the sensor, and it determines which if any of the features have a proper motion, what their proper motion is, and what the motion of the sensor is. The global stationary reference frame is generated and maintained by the system as the 'frame of absolute rest' with respect to which all proper positions and velocities are recorded. It is arbitrary, but could be registered with an a priori world map if desired.

The features or reference points, for which sensor-relative motions are supplied to the navigation system, may be any entity in the external environment which is recognisable over time and is visible fairly frequently (though not necessarily continually). The type of sensing used may be anything appropriate to the class of features considered, provided it can provide the apparent motion estimates required by the navigation algorithm. Examples of features and corresponding sensors include bright easily identifiable patches on marine objects observed with a sonar ranger, optical marker tapes viewed using a rangefinder, or pieces of environmental objects observed using a multistatic television camera array.

The basic problem concerns the estimation of vehicle motion using only the apparent motion of external objects. This problem can be extended in two ways, both extensions being simpler than the basic problem:

☐ relative estimates of the vehicle motion may be directly available from incremental shaft encoders, rate gyroscopes or other sensors;

☐ absolute estimates of the vehicle motion may be directly available from compasses or world-based position sensors.

In each case the extra information available must be incorporated in a uniform manner into the estimation of vehicle and feature point motions.

Finally, the problem may also be extended to allow for the provision of partial information, for example from a Doppler sensor which can measure only the radial component of relative velocity. In this case, the input information is not only noisy but it comprises incomplete observations.

3 Applications Area.

The navigation techniques developed here are very widely applicable because of the generality of the problem formulation. However, we envisage applications principally in the marine submersible area and with land-based robot vehicles for which the problems are less severe and even better performance may be expected.

4 Research Course and Methods.

The navigation system has been designed using Kalman filtering techniques. The use of Kalman filters enables the system to exploit whatever data is available -- world-based or vehicle-based direct motion sensory information, incomplete observations, and the apparent feature motion inputs are all accommodated by the system in a uniform way. The system propagates estimates of the noise covariances of the various measurements and motion estimates and so is potentially able to utilise information provided as input in a near optimal way; the system can also function, with reduced performance, using a subset of the potentially available input data (this may arise, for example, if sensors fail, if features are obscured, or if computational resources are needed for more important tasks).

The principal research method employed in testing these ideas to date has been a controlled numerical simulation. A simulator generates apparent feature motions from a model which specifies the true feature and observer trajectories. Noise may be added to the observations or to the trajectories or both. These simulated data are passed to the navigation system which then estimates the observer and feature motions. The estimates are compared with the true, modelled, quantities and a variety of error and noise statistics can be computed; graphical and analytic displays of these statistics allows the researcher to assess the performance of the system.

5 Status and Results.

An implementation of the navigation system for full two-dimensional motion (translational and rotational) has been built and tested. The system worked satisfactorily, identifying moving feature points correctly provided the proportion of moving features was not too high (less than about 30%) and reducing the observation and observer motion noises by between five and twenty times (variance ratio between input noise and the output estimation error with respect to the model).

Extension of the algorithm to handle full three-dimensional motion is underway. The theoretical extensions are completed, and a trial implementation is being constructed.

The problem of determining which features are moving and which are stationary has been cast into a global cost minimisation problem; this provides a sound framework for taking the moving/stationary status decisions. In the two-dimensional system these decisions were made locally using a somewhat ad hoc statistical test.

6 Future Research.

It is intended over the next two years to analyse the three-dimensional algorithm both theoretically and practically. Theoretical analyses will focus on the noise propagation and convergence behaviour of the algorithm, while practical assessment will focus on the way the technique copes with realistic feature position and velocity errors of the type experienced using sonar sensors in deep water. The goal of this study is to interface the navigation system to a real sonar sensor.

In addition, we hope to attach the navigation system to sensors mounted on an autonomous vehicle and assess the performance of the system in the land-based vehicle context. This application will also allow us to experiment with incompletely observed feature motions.

7 Interest in Cooperation.

We are already engaged in a collaborative venture with British industry exploring the potential of this system for improving submersible navigation. Since we do not have an autonomous vehicle at present, we would consider collaborative work with partners possessing a vehicle that could host the navigation system.

8 Related Publications.

The following publications contain material relevant to the feature-based navigation technique. In each case I have indicated briefly what the document contains.

Hallam, 1987; "Computational Descriptions for Interdisciplinary Research in Vision", to be published in 'Real Brains, Artificial Minds' ed. J Casti & A Karlqvist, Spring 1987 (Proceedings of the 1986 Abisko Workshop)

A section of this paper formulates the moving/stationary feature discrimination task as a global cost minimisation problem.

Hallam, 1985; "Intelligent automatic interpretation of active marine sonar", Ph. D. Thesis, Edinburgh University.

A full description of the two-dimensional system is presented here, together with full results of the tests done on the implementation of that system. In addition, the basic ideas of the generalisation to three-dimensional motion are outlined.

Hallam, 1983; "Resolving observer motion by object tracking", Proc. IJCAI-8, Karlsruhe.

A brief account of a partially successful full two-dimensional motion version of the system. This paper is subsumed in the reference above.

Autonomous Mobile Robots in Production

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The increasing flexible automation demands the integration of flexible automated material flow systems. The handling, exchange and transport of workpieces, tools and chucks become an important step towards highly automated FMS. Furthermore, the increasing complexity of automated systems requires new solutions to reach a satisfying availability for a whole FMS and optimized control strategies to improve the return of investment.

The use of autonomous mobile robots in production systems can help to reduce complexity of system control by their ability of taking decisions and raise the flexibility in material flow and machine tool handling.

The presented research projects are part of the development of information processing technologies in automomous mobile robots for industrial production environment. The whole project is installed at the Technicel University of Munich. In the whole project several disciplines are involved as computer science, electronic engineering and industrial engineering.

During the first three years work is focused on three major aspects:

- integration of several autonomous mobile robots in an industrial manufacturing environment.
- autonomous navigation and locomotion of vehicles in the shopfloor
- autonomous material manipulation.

The presentation will give an overview of the general informationflow between the different units. The concept of integration of autonomous robots in shopfloor environment will be shown.

30

A Rulebased Planning System for Robots

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1. Introduction

The first step to automate robot systems was to make programming languages available to the user. With the help of CAD systems more sophisticated tools were developed for the modelling of robots and other cell components. These models can be used to plan interactively the selection of special components and the layout of an assembly cell. Instead of programming the physical robot the user is now able to develop robot software for the simulated robots. To achieve the final goal of a fully automatic system the functions of the human planner are to be replaced step-by-step by an automatic planning system, see fig. 1 .

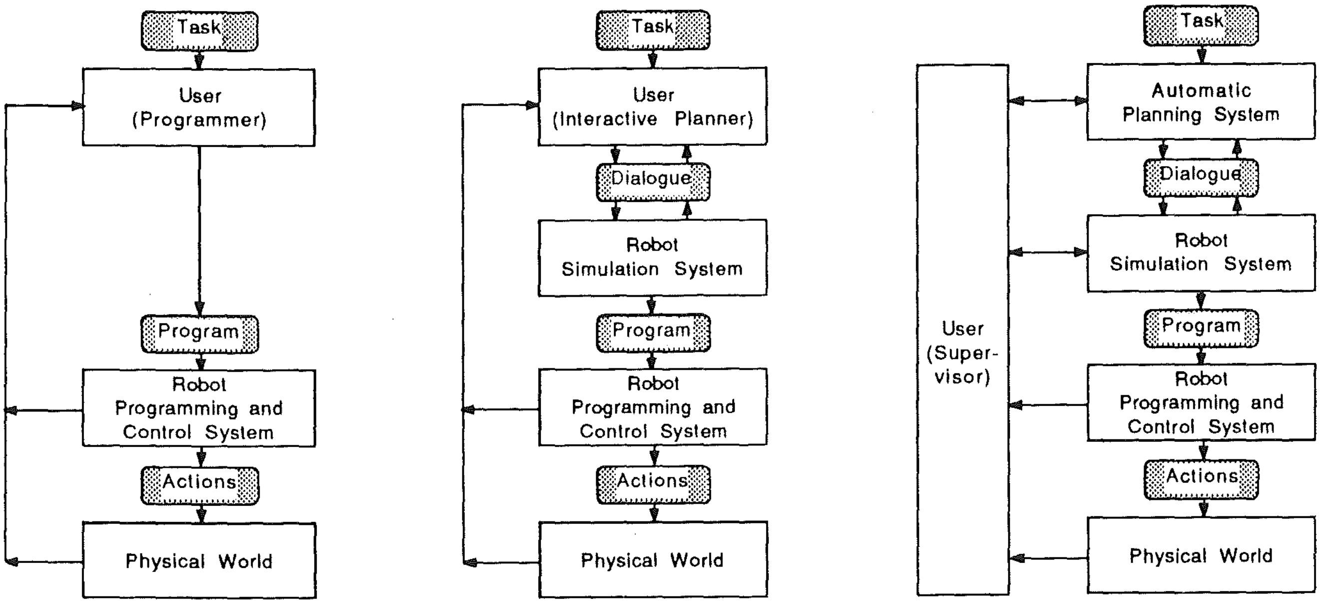

Fig. 1: Evolution of robot programming systems

The development and integration of interactive and automatic programming tools is part of the ESPRIT project 623 (Operational Control of Robot System Integration into CIM). This paper gives a short description of the system structure developed in the project and describes the knowledge based part of the planning system called Action Sequence Planner (ASP) in more detail.

2. The overall system structure

The system shown in figure 2 allows the user to specify a problem description (e.g. an assembly task) for the planning system with the help of graphical and/or textual tools. The specification of the goal configuration of the different workpieces can be done both on object level (by specifiing spatial relationships between objects) and on the explicit level (by specifiing the explicit position of a workpiece). The specified configuration is then analysed by a task analyser which determines the interdependencies between the different pick and place operations which are necessary to execute the specified task. After this step the problem description has the form of a graph which is the interface to the planning system. The so-called precedence graph will be explained later in more detail. The modules for the specification of the assembly task and for the task analysis are inside the user interface. This phase of programming is offline.

The planning system transforms the problem description into a sequence of commands for the assembly cell specified in the world model. The generated program is interpreted by the execution module which controls either the physical assembly cell or the model of the assembly cell in the simulation system.

The left-hand side of the diagram describes the way from the user to the (simulated) assembly cell, while the right-hand side describes the feedback from the process to the user. During the execution of robot motions a sensor system is activated to monitor the actions in order to detect possible errors. In case of an unexpected situation the error recovery module analyses the actual state. If a goal of the specified task cannot be achieved it specifies an intermediate task which has to be solved first in order to execute the original task.

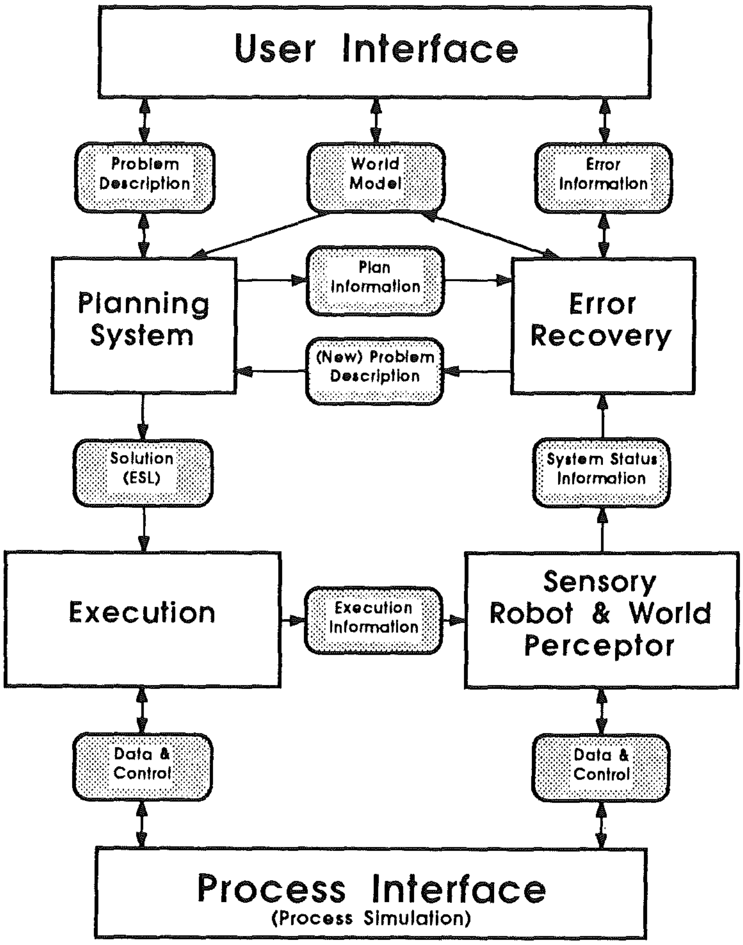

Fig. 2 The overall system structure

The presented structure does not change if the execution is connected to a physical or to a simulated assembly cell. In the first case the process feedback is provided by the sensor system, in the second case by an error simulation system or the user himself. The second approach is presented at the end of the paper where the integration of the ASP in the robot simulation system ROSI is shown.

3. The Planning System

The Planning System transforms a task oriented problem description (a precedence graph) into a plan which describes how the given problem can be solved by the assembly cell. For the transformation a detailed world model is needed containing a description of the cell components, the layout, the geometry of the different workpieces, etc..

The solution of the specified problem is represented in a robot level code, called Explicit Solution Language ESL. An ESL program can be translated into a program written in any other explicit programming language which can directly be executed by the physical or simulated robot system.

The plan contains a sequence of action elements like operations for pick and place, push, and turn with assigned resources (robot, gripper). To generate the plan it is necessary to select and order the plan elements. The next step is to detail these plan elements. Therefore, the Planning System consists of the submodules ASP (Action Sequence Planner) and AEP (Action Execution Planner), fig. 3 .

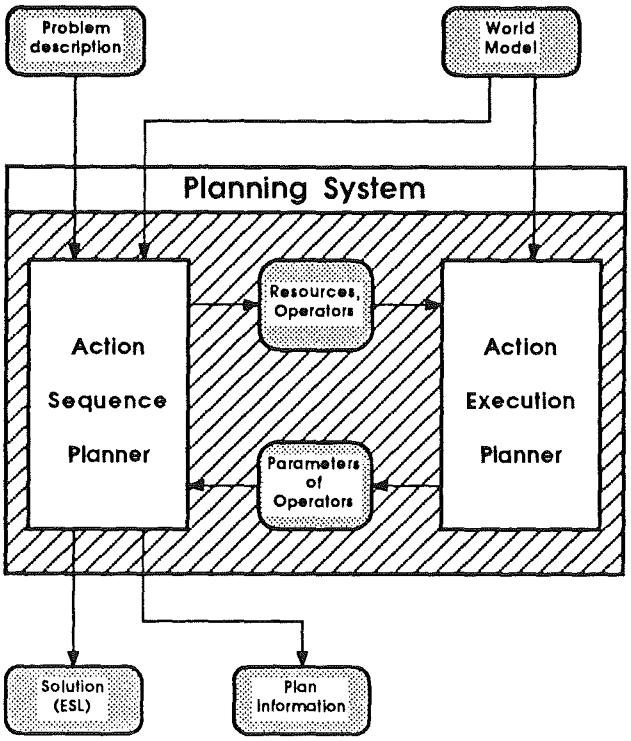

Fig. 3 : The components of the planning system

The ASP is responsible for the more global decisions of the planning process, like finding a feasable sequence of elementary actions for the specified task, assigning resources on the base of heuristics and specifiing the frame parameters for the selected move respectively grasp operations /Frommherz 86/.

The AEP is responsible for the detail planning of the selected actions. For the geometrical planning of the motions the AEP considers possible collisions of obstacles in the world with the robot, the gripper and the payload. The AEP is integrated into the planning process of the ASP. This means that a plan element proposed by the ASP is modified when it turns out that it cannot be executed due to geometrical constraints. E.g. if a pick and place operation cannot be executed due to the existence of obstacles either the proposed resources or the proposed operation have to be changed. In some situations there will be several different operations to realize a task. Then the ASP should propose to the AEP the operation which has the highest probability that it can be executed. This is done because the geometric planning is very time consuming.

A variation of this structure can be achieved by replacing the AEP by a simple motion planner which does not accomplish collision checks. This is justifiable since in a well designed assembly cell most pick and place operations can be done by the sequence

- transfer with empty gripper
- approach with empty gripper
- grasp workpiece
- depart with workpiece
- transfer with workpiece
- approach with workpiece
- ungrasp
- depart with empty gripper.

In this sequence the transfer motions usually are straight lines in the joint space and the approach/depart motions are straight lines in the cartesian space. Instead of using time consuming algorithms for collision checks the user has to inspect whether the generated operation is collision free or not. If he accepts the proposed operation the plan generation continues, otherwise a new operation is proposed. This system is a compromise between interactive and automatic programming, since the user has only to interact in extreme situations. However, this variation does not mean any difference in the functionality of the ASP.

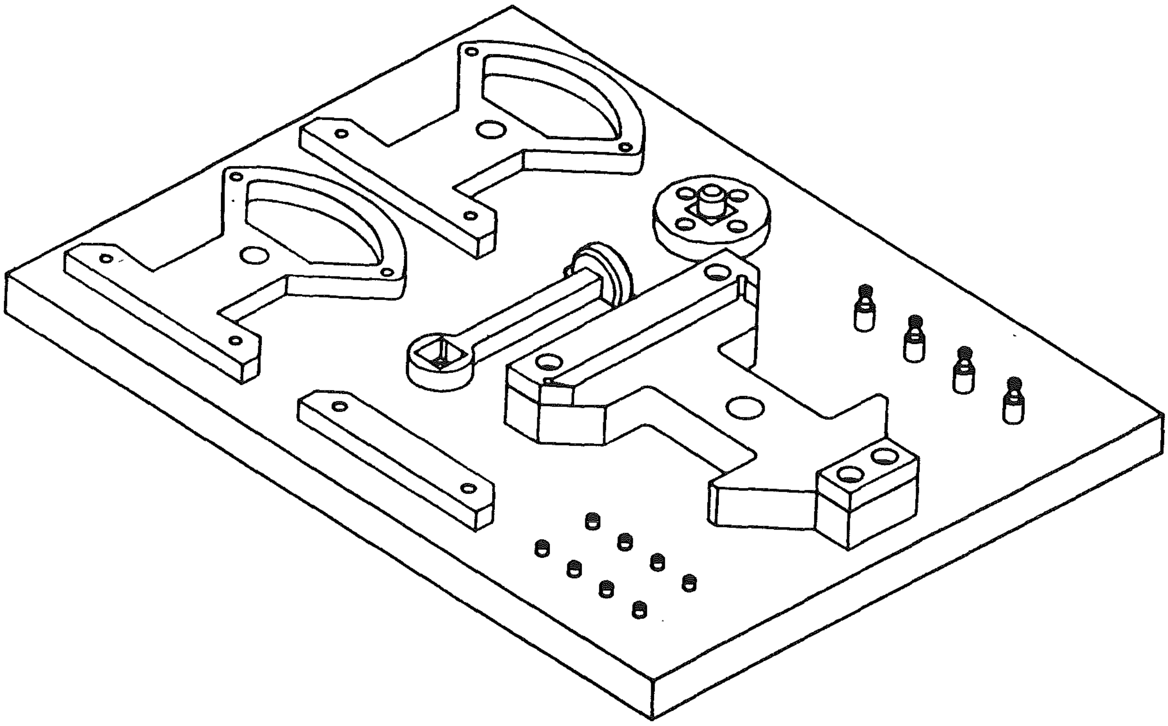

Fig. 4: The Cranfield assembly benchmark

4. The Action Sequence Planner (ASP)

The following sections describe the structure, the submodules and the interfaces of the ASP as it was designed at the University of Karlsruhe. To understand its functionality it is important to know how the problem is presented to the ASP. This is shown using the Cranfield Benchmark /Collins 84/ as an example.

4.1 The problem description

The problem description which is an input of the ASP is an elaborated form of task specification. In the case of an assembly task the specification contains a set of pick and place operations and a set of constraints related to their execution sequence. These constraints depend only on the task, not on the layout, components, etc. . This information may be represented by a precedence graph. The nodes represent the single pick and place operations and the edges the precedence relations. The precedence graph of the Cranfield Benchmark is shown in fig. 5. For example, it contains the information that a workpiece of type "shaft" has to be placed at position pos04 before a workpiece of type "lever" can be placed at pos07.

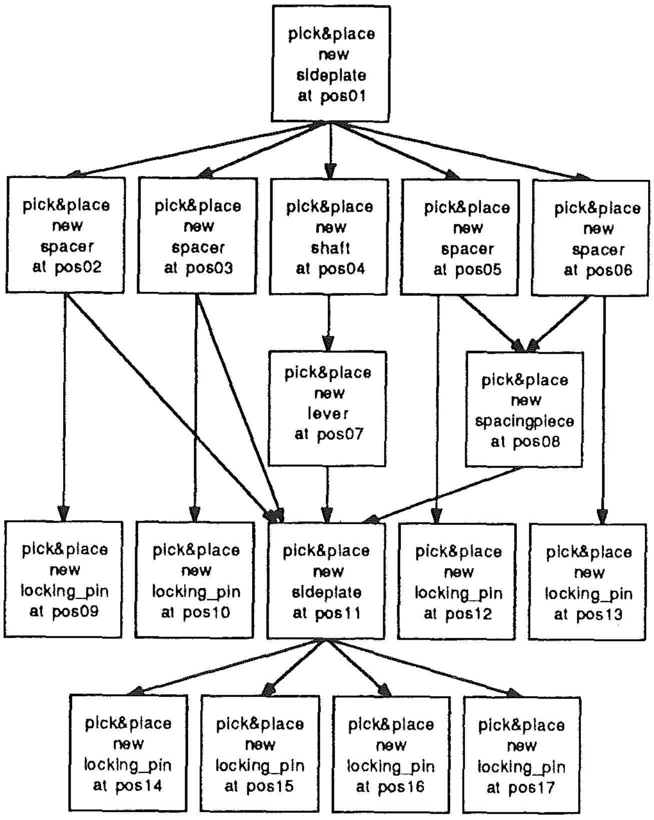

Fig. 5 : The Precedence Graph of the Cranfield Benchmark

In the task description only the type of the workpiece which has to be assembled is specified. E.g. "pick&place new spacer at pos02" means, that a new object of type spacer has to be picked and placed at the position pos02. The assignment to a special item of that type of workpiece is done by the ASP depending on the robot types, gripper types and the layout of the assembly cell. Fig. 4 shows the 17 parts of the Cranfield Benchmark in their initial positions.

4.2 The submodules of the ASP

The refinement of the ASP as it was designed at the University of Karlsruhe is shown in fig. 6. The ASP consists of a set of submodules which communicate via a common working memory. The ASP analyses the task specification and proposes a sequence of actions and resources which have to be refined by the subplanners. Since the planning of details like the geometrical planning of motions is very time consuming, the ASP utilizes heuristic knowledge to propose only promising plans to the subplanners. For different problem domains specific knowledge bases are provided for

- the evaluation of goals,
- the selection of the resources,
- the handling of obstacles and
- the planning of robot action details.

In the case of pick and place operations the subplanner for the refinement is called Motion Planner.

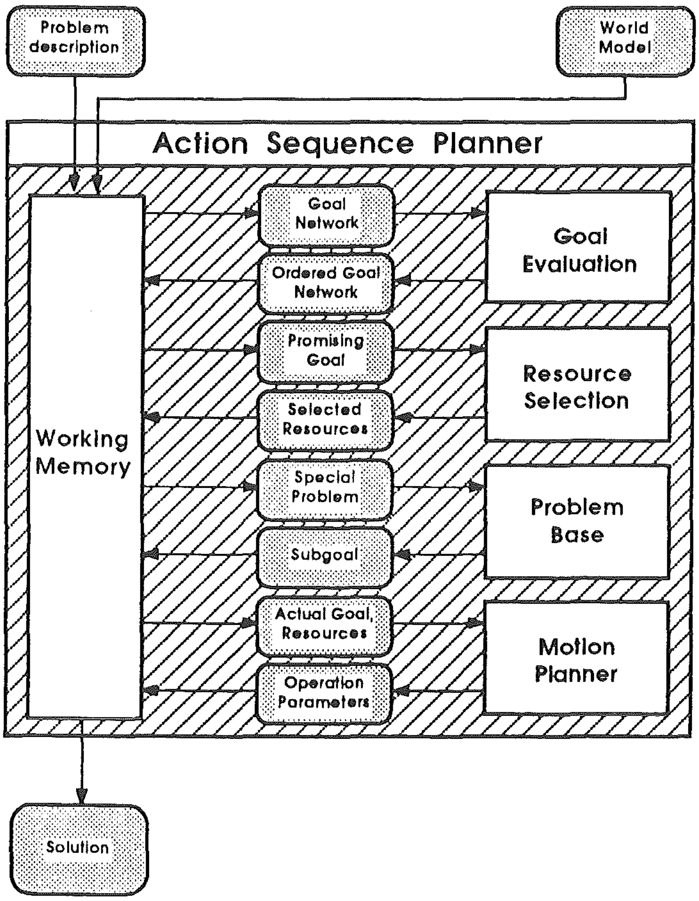

Fig. 6: The Structure of the ASP

The Goal Evaluation evaluates the possible sequences of the different subgoals which are given by the precedence graph. It contains rules which favour the promising goals. So the probability that problems will arise during the detail planning phase or during the execution is reduced.

The following rule gives an example for a heuristic :

> "If a workpiece of type x has to be assembled and there are different objects of type x available, use the nearest one first."

This strategy has the effect that workpieces which might be obstacles for later pick and place operations are used first. Moreover, the different paths should be without any intersections and the sum of their lenght should be a minimum. This example shows that the evaluation depends on the components and the layout of the robot cell.

In case there are several pick and place operations which can be executed, then the following heuristic chooses one to be executed first:

> "If there are several pick and place operations which can be executed, choose the one where the distance of the gripper and the center of the assembly task is minimal."

This heuristic reduces the danger of collision of the gripper with already assembled parts. Heuristics like these are simple and possibly may produce a wrong result in special cases. Therefore the system does not destroy possible solutions but orders them according to the heuristic rules.

The submodule for resource selection analyses which gripper type available in the robot cell may grip the workpiece in start and goal position of a pick and place operation. The special grip for the operation is selected such that the direction of the grip and the mating direction are equal, see fig. 7. This means that the gripper will not grip the workpiece on the side where it probably will contact to other objects.

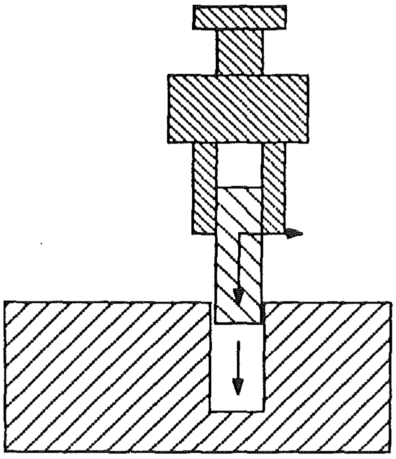

Fig. 7 : The grip direction should be the same as the mating direction.

After the selection of a type of gripper and the determination of the grip transformation the robot configuration for the start and the goal position is analysed. If there are several robots in the assembly cell which can execute the necessary motion, the robot which is able to do the job best will be selected to perform the pick and place operation. The arm selection uses the distance of start and goal position to the border of the joint space and to the cartesian working space of the robot as a criterion. This depends on the kinematics of the available robots.

To provide the information which is necessary for the resource selection different subroutines for geometrical calculations are needed. However, they do not take any possible collision among objects into consideration. This problem is treated in the submodule "motion planner" or alternatively by a user interaction.

To accomplish the resource selection a detailed description of the assembly cell and of the workpieces is needed. This includes

- models of the robots
- a geometric description of possible grip transformation between a type of gripper and a type of workpiece and
- a geometric description of the layout of the assembly cell.

The Problem Base contains rules for the special case that a goal of the task description can not be achieved directly, i.e. by executing one pick and place operation. E.g. the goal "pick&place new spacer to pos02" cannot be achieved directly, if a spacer at position pos02 would collide with another object X. A similar problem is given if all objects of type spacer are hidden by an object X. The solution of the problem is to find a location for the object X and resources which can pick and place the object X to that location. Then the subgoal to place X at that location is added to the task description. The "findspace" operation must take into account that X should not be an obstacle for later pick and place operations. Therefore, the entire task must be considered to find a suitable location for X. This problem is known as the interaction problem.

If the ASP succeeded in selecting a pick and place operation and a set of resources to perform it, the Action Execution Planner is invoked. As already mentioned in the introduction of the paper, this may be a sophisticated module which plans automatically a collision-free path for the selected robot using the submodules

- Grasp Planner
- Fine Motion Planner and
- Gross Motion Planner.

The AEP coordinates the results of the three subplanners. The second variation presented uses a simple motion planner which plans motions interactively. In both cases the results of this planning phase is the explicit solution of the given operation which is represented by the Explicit Solution Language.

5. The integration of the ASP in the robot simulation system ROSI

At the University of Karlsruhe the robot simulation tool ROSI is being developed. It is an interactive tool for the modelling and simulation of robots and the environment /Dillmann 86/. The subsystem for modelling allows to define physical objects like robots, carriers, conveyors, workpieces, etc. using the CAD package ROMULUS. With the help of a 3D-graphic editor the cell layout was designed. It consists of two robots of type puma 260 and the different parts of the Cranfield benchmark on the ground plate. Moreover, the editor was used to specify the assembly task by arranging the different workpieces on the screen. This data is used directly as an input for the ASP. The output of the ASP is a sequence of commands for the robots respectively the grippers. The resulting actions , e.g. motions of the arms with or without the grasped workpiece, moving of the gripper fingers are shown on the screen. The user who inspects the automatically planned operations can interact with the ASP to specify if he accepts the proposed operation or not.

The interfaces between the ASP and the modules for modelling and simulation is shown in fig. 8. The modelling modules as well as the simulator are submodules of the ROSI system.

For the implementation of a basic version of the ASP the representation language OPS5 was used. The first version was implemented on a VAX 750 (Unix) using a Franzlisp implementation of OPS5. A revised version of the ASP is implemented now on a µ-VAX II (VMS) using OPS5 version 2.1 (BLISS). The geometrical submodules which are mainly needed in the Goal Evaluation and Resource Selection were realized as external PASCAL subroutines. The ROSI system is also implemented in PASCAL on a μ-VAX II under VMS. For the Resource Selection the ASP uses the robot models of ROSI. So it is guaranteed that the planned robot motions are feasable.

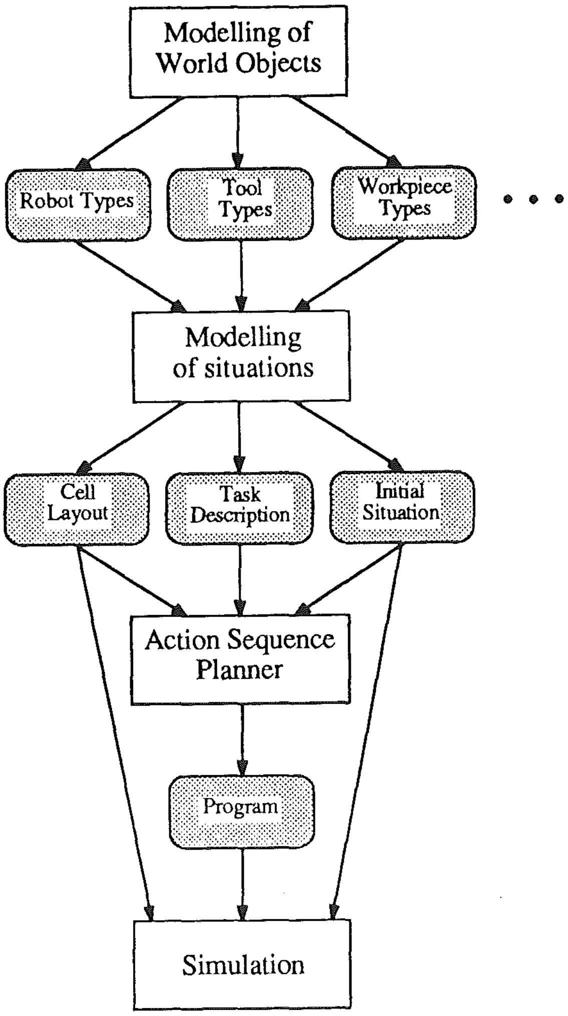

Fig.8 : Integration of the ASP into the robot simulation system ROSI

6. Acknowledgement

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A Behavioural Approach to Robot Task Planning and Off-line Programming

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1 Summary

There are two major limitations in today's robot assembly systems. Firstly, because they are not able to deal in a general way with the uncertainties encountered in typical real world environments they are limited to tasks which are subject only to simple uncertainties. Secondly, because they are not easily programmed they are limited to tasks which are to be repeated a large number of times before either being discontinued or modified. Within these limitations are such tasks as spray painting, spot welding, and simple parts assembly. To meet the demands of more complex assembly tasks, economic small batch manufacture, automated work in hazardous environments, or low-bandwidth tele-operation, we require robot systems which can be programmed at a higher and more problem-oriented level, and in such a way that robust programs can be economically produced without recourse to the robots themselves.

The two most serious practical problems contributing to these limitations are: firstly, that current methods of programming the use of sensors to handle uncertainties are ad hoc, ungeneralisable, difficult, and require highly skilled manpower; and secondly, that current methods of programming the motions of a robot to perform an assembly task are very tedious, especially if a high degree of reliability is required.

A great deal of research has been devoted to the problems of the automated generation of robot assembly programs from higher level specifications, such as the shape of the parts, and how they are to be fitted together. Unfortunately, practical realisation of this utopian ideal is at least decades away. It has not yet even been achieved for the simple case of a senseless robot, and the addition of sensors complicates the matter profoundly.

It is often supposed that these unpleasant difficulties are an inevitable consequence of the complexity of the real world, whereas we argue that they are a symptom of having chosen an unsuitable representation. We propose a new approach to programming sensor based assembly tasks, which we call programming in terms of "Behavioural Modules". We expect this:

- to simplify programming and validation of robot programs; - to simplify the off-line computational requirements; - to facilitate the construction of assembly planners; - to

provide a principled method of incorporating sensor use; - to simplify the uncertainty problem; - to provide early industrially useful spin-off.

2 Introduction and Background

In the 1970's the Edinburgh "Freddy" robot system [Ambler et al 1973] was the vehicle for much of our early AI work on the robotic assembly problem. Two major problems emerged. The first concerned the difficulty of programming a robot to do even a simple task. The basic reason for this difficulty was that when one wanted the robot to do something, such as fit a peg held in the gripper into a hole in the sub-assembly, one either had to specify the precise motions of the gripper in 6D configuration space, or else "teach" the required motions by controlling the movements of the robot in tele-operated mode. Both of these methods are difficult and tedious to get right. This raised the problem of how to simplify the programming of the motions of the robot. This problem has received a lot of research attention, with some success.

The second problem to emerge from the early Freddy work concerned the use of sensors in a robot program. This too proved to be difficult and error prone from the programmer's point of view. However, by using sensors an assembly could be performed successfully from a wider range of initial conditions, and in a world subject to more uncertainty, thus making the robot program more robust. It was clear that in general the use of sensing by a robot system would significantly improve its range of application and flexibility. This raised the problem of how to simplify the programming of the use of sensors. Until very recently this received little attention by assembly robotics researchers. It received more attention from those concerned with controlling sensor-rich devices, such as multi-joint multi-finger hands, and mobiles not requiring a specially constructed environment.

Today's commercially available robot systems still have to be programmed at the tedious and difficult level of gripper motions, and although some of the individual sensors have become a lot more sophisticated, e.g. vision, the use of these sensors by the robot is still rudimentary and awkward. This is due, at least in part, to the way they have been incorporated into robot programming languages.

The robot programming languages in industrial use today are based upon computer programming languages, with a number of useful robotic facilities added. The robot is treated like an output peripheral, and the sensors like an input peripheral. This is the obvious way to extend a computer programming language to handle a robot. One can in principle use such a computational model to make the robot do anything of which it is physically capable, just as one can in principle program any algorithm in any complete programming language; nevertheless, it is only one of many possible computational models of a robot, and just as a particular programming language is good for some tasks, and bad for others, so the question arises of the appropriateness of this model for programming robot assembly work. Because sensing and action interact via their connection in the real world, their separation into the input and output streams of a high level language, with sophisticated sensing and action "device drivers" behind the scenes, tends to lead the programmer, whether human or automated (an off-line planning system), to use high level detailed models of the world, in terms of which the sensing and action are co-ordinated.

We consider that the languages offered us by the robot manufacturers, such as VAL (Unimate, Adept) or AML (IBM), while they may be appropriate for systems integration programming of a robot work cell (such as adding new sensors), are unsuitably low in level for programming a robot assembly task, either for a human programmer, or as an output interface from an automated off-line programming system. For a human programmer they require an unnecessary degree of programming skill, and devotion to unnecessarily low level problems. In an automated planning system the detailed world and system knowledge and reasoning demanded in order to use such low level languages are theoretically difficult and likely to remain computationally intractable for the foreseeable future.

Because these current languages are unsuitably low in level for human programming, their industrial use for sensor based assembly has led to a serious skills bottleneck, and an economic disincentive to the industrial use of sensor based assembly robots. And because they are unsuitable as an output interface from an automated planning system, attempts to build such systems have found themselves beset by problems of computational intractability and theoretical complexity. This is one of the reasons why the automated solution to the robot programming problem is still so far away.

3 Raising the Level of Assembly Programming

Raising the level at which robot assemblies can be programmed has been attempted by a variety of approaches based on geometric reasoning [Taylor 1976] [Lozano-Perez 1980] [Latombe 1983] [Lozano-Perez et al 1984] [Mundy 1985]. At Edinburgh we developed a spatial constraint inference system incorporated into the RAPT robot programming system [Popplestone et al 1980]. This enabled the motions of the robot required to carry out a particular assembly task to be specified in terms of the spatial relationships between features of the parts, and thus in terms of how the parts were to be fitted together. For example, in order to put a peg into a hole the fact that the axis of the peg should be aligned with the axis of the hole is described to the RAPT system. From combinations of such spatial constraints, and knowing how the part is held in the gripper, RAPT is able to infer the location of the gripper which would satisfy the constraints. This is an important step in the transition between the description of an assembly in terms of how the parts fit together, and the robot motions to assemble the parts. RAPT is the most advanced implementation of its kind, as far as geometric reasoning goes, although, unlike some of the the other systems mentioned, it currently has no ability to reason about the use of sensors to reduce uncertainty. Fleming [Fleming 1985] proposes a way of introducing uncertainty reasoning into RAPT, and Yin [Yin et al 1984] proposes a method of introducing the use of vision to verify location.

4 Using Sensors to Handle Uncertainty - the Classic Approach

Consider first the case of a senseless robot. A senseless robot always performs the same sequence of motions, and the assembly happens as a side effect, given that all the parts are sufficiently well made and precisely located. The robot enacts the assembly motions in an ideal world. If this is not merely an exercise in simulation, but the robot program is meant to work successfully in the real world, then the real world must be contrived to be a good enough approximation to the ideal world of the robot, usually by ensuring that everything is sufficiently accurate. Much of the research on the automated planning and programming of assembly robots has begun with this paradigm of ideal assembly by a senseless robot. There has been a tacit assumption that once the problems had been solved in this simplified world, sensors could be added. The previously discussed nature of current robot programming languages, with sensing and action treated as the input and output streams of a high level language, supports this point of view. This in turn naturally leads to a design of planner where assembly operations are first designed in an ideal world, then subjected to uncertainty analysis, and the liabilities to failure due to uncertainty are fixed by introducing sensing (or other means of reducing uncertainty) at an appropriate point. We shall refer to this as the uncertainty fix-up paradigm.

This approach has served well as a research vehicle for investigating many of the important problems of the assembly planning task. Its deficiencies are becoming more prominent now that off-line planning and programming have reached the stage where research workers are moving away from their simulated worlds, and are beginning to consider the problems of systems integration and the practical execution of their robot programs in the real world. Investigation of the knowledge representation and reasoning requirements of the uncertainty fix-up paradigm, even to support the programming of the simplest assembly tasks, makes evident that what is required is well beyond today's techniques. The computational power required is also likely to be beyond that which today's computer systems can economically provide. We pursue these points in more detail below.

The explicit off-line programming of a robot's sensors requires the great variety of ways in which the robot motions and sensors can interact with the real world to be represented and reasoned about by the robot programming system. This requires sophisticated physical and mathematical knowledge about the way the robot and its sensors behave, and a good deal of common sense - the ability to reason qualitatively about causal partitioning in complex situations with many possible futures. For example, the system would have to be able to reason about friction, stiction, elastic collisions, elastic deformations, and vibration. It is known that automating common sense reasoning of this quality is at least decades away [Hayes 1978] [Bobrow 1984] [Hayes 1985], which rules out an early goal of complete automation of robot assembly task planning and programming involving reasoning about sensor use. This implies that in assembly planning systems (of this type) of the near future, humans must be actively involved, i.e., we should be considering systems which assist human planners rather than replace them.

Although current on-line systems have quite good programmability and computational resources, and are likely in future to improve in these respects, the uncertainty fix-up paradigm approach throws away a great deal of this power. The off-line system must therefore know a great deal about the on-line system, and the power of the on-line system can't be used to hide these complexities, all of which condemn this approach to computational inefficiency.

Such research work as has so far been done on uncertainty analysis does indeed suggest that it is likely to prove computationally intractable to implement an off-line first-principles approach [Brooks 1982] [Requicha and Tilove 1983] [Erdmann 1985] [Fleming 1985]. Further, the robot programmer may well spend time modifying a program to remove supposed liabilities to failure which are purely artifacts of this kind of analysis, and which have a vanishingly small probability of occurring in practice. This is because these uncertainty propagation techniques are based upon worst-case uncertainty bounds, which tend to generate unrealistic over-estimates in combination. This could be avoided by modelling the stochastic behaviour of the uncertainties, but the computational cost is then even greater [Durrant-Whyte 1987], as is the cost of acquiring this information in the first place.

A more general criticism is that the uncertainty propagation techniques developed so far are only applicable to linear programs. Their extension to iterative programs requires the solving as yet unsolved fix point computation problems [Latombe 1983]. Yet the familiar iterative programming constructs (do-while, repeat-until, etc.) are clearly required by the modular and repetitive construction of many industrial artifacts, such as the keyboard on which this is being typed.

Perhaps the most serious problem with the uncertainty fix-up approach, given that it will be costly in both development and execution time, is that it is in practice most unlikely to be adequate, i.e., an experienced human will be required in any case to fix those nasty little problems that will inevitably occur, but which the system did not predict. The most experienced human assembly planners fall victim to these nasty little problems, such as a sensor slipping out of calibration due to vibration, or the gripper fingers becoming polished or oily with use and beginning to slip. The knowledge and reasoning domain involved in predicting these nasty problems is that notorious AI problem area, common sense. It is therefore unlikely that we will in the foreseeable future be able to construct a significantly better system than an experienced human. And if we have to employ a human to catch what the system fails to handle, this raises the question of whether we could devise a support system - or indeed restructure the problem - so as to make it easier for the human to handle all of these problems, at a cheaper cost than trying hard (and failing) to automate them all. It is even suggested by some [Bobrow 1984] that there are some significant uncertainties of the real world which are inherently unpredictable. These are often due to the unmeasurably small quantities straddling a threshold of causal partitioning, and then being amplified by kinetic or potential energy. We make use of such cases to produce random factors in gaming, such as gaming dice or roulette wheels.

For these kinds of reasons, two of the major contributors to this classic approach, Brooks and Lozano-Perez of MIT [Lozano-Perez and Brooks 1984], have recently abandoned it, and adopted a behavioural kind of approach, Brooks in the case of mobiles [Brooks 1986], Lozano-Perez in the case of assembly robotics [Lozano-Perez et al 1987].

5 The Computational Metaphor Revisited

A useful analogy can be drawn between the on-line robot control system, which executes code generated by the off-line planning and programming system, and computer hardware, which executes code generated for it by high level language compilers and interpreters [Malcolm and Fothergill 1986]. Since computer hardware is a construction in the real world, and therefore subject to its various uncertainties, it is interesting to see how it has been contrived that this basically uncertain and noisy construction of transistors, the computer, can nevertheless perform its tasks with such flawless precision and repeatability. It is interesting because it suggests how to tackle the analogous problem in robotics, namely the reliable performance of a function in the face of the uncertainties of the real world, but in this case the dimensions of complexity are much less - voltage is much less complex than geometric shape.

For example, a bit held in a dynamic memory cell is a decaying voltage which only survives because it is repeatedly refreshed in time, and when this bit is read, what may start out as a fairly clean voltage level at the output pin of the memory chip, will both decay in level, and acquire a good deal of noise, as it travels towards the processor. Examination of the signal levels anywhere in a running computer will reveal the same story of noisy and decaying signals which, like a badly managed railway system, sometimes arrive early, sometimes late, and in some cases (of soft memory failures) may fail to arrive at all.

Early transistor-based computers were designed in terms of the ideal aspects of their components, e.g., a transistor regarded as a switch, and a track regarded as having no inductance or capacitance. Once this logical part of the design had been finished, uncertainty analysis was then performed to discover where unacceptable degradation of signal might have occurred, and components were added to clean it up. This was a difficult and tedious iterative process, which resisted all attempts to contain it within the design phase. The final and most expensive debugging phase of the design was always done by the engineers fault-finding on a constructed prototype.

Of course, experienced designers developed good design practices which obviated some of the simpler and more common problems, and it was from the generalisation and formalisation of these that the later highly successful VLSI design practices emerged.

The key to the success of modern VLSI design is the construction of modular units of behaviour which can easily be combined to produce higher level functions. The two key aspects of these modules are the information processing function of the unit (e.g., addition of two numbers), and the control of uncertainty. It is the control of the uncertainties of the real world which enables the clean expression of the information processing function. The processing function is expressed in terms of logical values, which are encoded by noisy and imprecise voltage levels, i.e., there is uncertainty. This uncertainty is controlled by standardising the interfaces between modular units so that the output uncertainties are significantly smaller than the input uncertainties; in other words, each modular unit will clean up the signals presented to it, within certain ranges. These ranges have been chosen so that they are wider than the worst inter-module degradation that the signals are liable to suffer under standard design rules. Designers can therefore freely combine these modules, being concerned only with the information processing aspects, confident that the uncertainties are well controlled from the outset. This modular control of uncertainty also permits the use of silicon compilers and automated function verification, since these automated tools need only consider the information processing aspects, which are inherently much simpler than the uncertainties.

This is a hierarchical system. There are similar input and output specification windows at work between the large components of the chip, and others between the smaller subcomponents out of which they are built, and so on. It is this modularity, guaranteed by the competence of the module inputs to handle degraded versions of the module outputs, which permits the use of so-called silicon compilers in VLSI chip design [Denyer and Renshaw 1985] [Davie and Milne 1986], and verification programs based upon models of VLSI component functionality [Barrow 1983]. At the level beyond the chip, the level of circuit boards, the same kind of process is at work in the specification of the backplane bus and its drivers and receivers.

The horrible problems of handling noise and uncertainty have been largely hidden within the lower levels of chip design. Thus these problems have not only been localised, they are also no longer dealt with by computer designers, but by the designers of the components that computer designers use, the chip designers. While some use is made of machine-specific chip designs (often to make reverse engineering by plagiarists difficult), the chip families are in general modular components applicable to large classes of digital circuit design. The considerable expense of designing a particular information processing function on a chip is offset by its use in large volumes in many different applications.

In the previously mentioned case of soft memory failures, where a signal may sometimes fail to arrive at all, special error-recovery systems are implemented which use Hamming codes to regenerate all failures of n or less bits, and warn of (virtually) all failures of more than n bits. To begin with these were specifically contrived from a number of chips, i.e., a macro level of functional modularity of behaviour, but they are now available in single chip form, i.e., they are now part of the atomic (chip level) behaviours available off the shelf to the digital circuit designer.

We suggest that there is a useful analogy between the electrical and temporal uncertainties which have been dealt with so successfully in this way in modern digital silicon technology, and the uncertainties of form and location which beset robotic assembly; and that the assembly problem can be simplified in a similar way, by the use of behavioural modules (in this case the behaviour of the robot and its sensors) which have definite competences in the sense of the range of tolerance of input error, within which they will produce outputs in the form of parts moved or fitted to within much finer tolerances. We expect that this will not only simplify and localise the problems of dealing with uncertainty, but that it will to a considerable extent remove the problem from the designer of the assembly program, giving it largely to the designer of the generic behavioural modules, common to many assemblies.

6 Programming In Terms of Behaviours

This means controlling uncertainty by constructing modular behavioural units which can be guaranteed to perform their intended actions (e.g. put peg in hole, acquire end of cable, or snap home fastener) within a certain range of uncertainty; and which leave the world in a more certain state than they found it. These behaviours are modular, so that they can be combined to form larger units. Planning and programming of the assembly process is thereby freed to concentrate on a simplified and ideal world. The real world is contrived to be a good enough approximation to this ideal world by the competence of the Behavioural Modules to manage uncertainty at a local level. Although the planning stage must be sure that the uncertainty presented to any Behavioural Module lies within its competence, much of this can be achieved by the use of assembly standards. The management of uncertainty thus largely becomes the province of the Behavioural Module design stage, rather than the planning stage. It is more easily handled here, because it is done with intimate on-line involvement. It is also more economical of time, because Behavioural Module design is done for an entire class of assembly problems.

For example, an assembly system might have a "peg in a hole" behaviour which is able to cope successfully with a range of different types and sizes of peg in the hole situations, including a degree of error in the alignment and location of peg and hole, thus removing the need for the programmer, or the off-line system, to worry about the details of whether a particular peg in a hole strategy will actually work for the particular type of peg and hole being considered. The problem is reduced to checking whether the particular instance lies within the competences of the general behaviours being used, e.g., "acquire peg", and "put peg in hole". In many cases the need for this kind of checking will be removed by means of standardised practice, such as a general rule that all methods of part supply will supply the part within certain bounds of variation about the nominal position; and that all acquisition behaviours can cope with that amount of uncertainty.

Note that these behaviours are modules which can be looked upon as operators which transform one world state into another. They have well defined preconditions and effects, and they can be combined to form larger behaviours. This brings the problem of planning the reliable execution of an assembly closer to the scope of existing AI resource based planners [Drummond et al 1987].

In summary then, assembly robot task planning should be done in terms of a hierarchical decomposition of the task into modules of behaviour, each module of which may contain its own level of sensing, along with other modules of behaviour, rather than in terms of fixing failed operations by the ad hoc addition of sensors. Thus, rather than dealing with uncertainty by elaborating its consequences through a sequence of actions down to a liability to failure of a particular action, and then repeating that elaborate reasoning for the various attempts to reduce the uncertainty; uncertainty is instead dealt with locally, in a simpler form, by containing it within the competence of a module of behaviour of appropriate level.

7 Differences in Problem Representation

In the uncertainty fix-up paradigm the issues of action and uncertainty management via sensing are dealt with sequentially in the off-line system, and sensing and action are combined at a high level in the on-line system. In the Behavioural Module paradigm the off-line design phase is freed from concern with the details of uncertainty; and action, uncertainty control, and sensing, are integrated from the lowest levels in the on-line system. To the two stage process of off-line planning and on-line execution in terms of the on-line programming language, the Behavioural Module approach adds a third stage of generic Behavioural Module design, applicable to a class of assemblies, in terms of which the assembly-specific off-line planning and on-line execution are performed.

These differences spring from the difference in the way sensing and action are handled. In the uncertainty fix-up paradigm sensing and action are considered to be primary divisions of the problem domain. In the behavioural paradigm the primary problem division is into behaviours. The whole task is one behaviour. Its subcomponents, such as acquiring a part and fitting it into the assembly, are behaviours. The wriggling of a peg to get it down into the hole is a behaviour. Sensing and action only appear as distinct entities when one splits the final atomic behaviour.

8 Caveats

This is a simplified story. While it is an important general characteristic of Behavioural Modules that sensing and action are entwined within them, it is by no means an essential characteristic, just as elephants may have less than four legs. There are also kinds of sensing it would be inappropriate to treat in this way. And the VLSI design analogy is misleading for the same reason that it is instructive: it is concerned with a much simpler kind of complexity than the geometrically dominated world of assembly robotics. These points are expanded below.

There can be behaviours which consist entirely of senseless invariant action; and there can be behaviours which consist entirely of perception. There are interesting classes of behaviour which consist almost entirely of action, but whose purpose is perceptual, and vice versa. One of the sources of confusion here is that our general concept of sensing is stubbornly vague and ambiguous, perhaps due to the efficiency and versatility of our own behavioural chunking of the world we live in as animals and conscious communicating agents.

We have been concerned in this paper with one particular kind of use of sensing: sensing which is used during an activity (a behaviour) to modify the actions in order to assure success of the goal of the activity. There are other kinds of sensing which it is not appropriate to elide within atomic behaviours in this way, such as sensing to decide what to do next (rather than how to do it), and which have their own important implications for the architecture of on-line robot control systems, and off-line planning and programming systems [Fox and Kempf 1985] [Fox and Kempf 1987] [Malcolm and Fothergill 1986].

It is tempting to see programming of assembly robots in terms of Behavioural Modules as "just" the importing of general principles of modularisation already successfully practised in the more mature design fields of VLSI and computer software design, and the idea of programming robots in terms of Behavioural Modules does owe its immediate appeal to intuitive recognition of these analogies; but just as these principles could not be applied in VLSI or software design before appropriate theoretical backing had been found, so theoretical backing must be discovered here too. In assembly robotics the problem is inherently more difficult. In the field of VLSI the dimensions of complexity (and of uncertainty) are few, and generally separable. The special difficulty of assembly robotics derives from the fact that the fitting together of shaped three dimensional parts is a problem in six dimensional configuration space. Not only are there more dimensions of complexity, but they are also interlocked.

9 Conclusions

After a lot of work on the various component sub-problems of the automation of assembly planning, the stage has been reached where it is possible to consider constructing experimental integrated systems, and to consider the issues of robust and reliable execution of plans in the real world. Investigation of these two issues of systems integration and real world execution is turning out to have important architectural and knowledge representation implications for both the on-line and the off-line components of assembly robot systems. The behavioural paradigm is a promising candidate for fruitful research in this area. It seems likely to produce early industrially useful spin-off in the form of improved programming techniques which can be used to advantage on current commercially available robot systems, and which will simplify the use of such off-line programming aids as are coming into use. By simplifying and generalising the incorporation of sensors, it will extend the industrial scope of assembly robots. It will facilitate the development of assembly planning systems, which are currently beset by problems of intractability. Note, however, that while this method can be used to advantage on many current robot controllers, the full benefits of the method demand a change of architecture.

It should be noted that similar behaviour-oriented ideas are already being pursued consciously in the area of mobile robots [Cudhea and Brooks 1987], VLSI design [Davie and Milne 1986]; and although not from explicit behavioural principles, nevertheless with promise, in the trajectory planning of jointed arms [Sun and Lumelsky 1987], road tracking [Kuhnert 1987], and attention-directed rapid vision [Johnston et al 1987]. This is not an exhaustive list, just the consultation of some recent proceedings for examples of this growing tendency.

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32

Workshop on
Manipulators, Sensors and Steps toward Mobility

May 11 - 13, 1987
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SUMMARY

PLANNING ROBOTIC MANIPULATION STRATEGIES IN UNSTRUCTURED ENVIRONMENTS

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In unstructured environments, robotic systems are required to perform tasks involving dexterity, perception, and planning. Task complexity is increased by the variety of manipulation operations required and the need to adapt these operations to particular circumstances based on sensory perception. Efficient task representation and decomposition is necessary for sensory integration, control synthesis, planning of resource utilization in autonomous systems. This paper reviews our recent work on task planning for manipulation and its implications for the design of systems to perform useful tasks in space, undersea, and other hazardous environments.

PROBLEM STATEMENT: Autonomous and telerobotic systems for unstructured environments must integrate many capabilities which are not present in current robotic systems.

- Real-time planning tools must exploit efficient representation of tasks and environments and facilitate both exploratory and goal-directed modes. Most current approaches to task planning have not been well-suited to real-time operation and new approaches to this problem which investigate the intersection of planning and control functions must be developed.

- Manipulation strategies must incorporate adaptive and learning capabilities in order to provide robust operation in uncertain environments. Current robot manipulation is programmable but not adaptive. Strategies, operations, and operation parameters are developed through human interaction.

APPLICATIONS AREAS: Many space-based robot applications such as materials handling, refueling, part replacement, system diagnosis and repair, are reasonably well-defined in the sense that objects, parts, and their relations are predesigned. Similarly in the maintenance and repair of nuclear plants, undersea structures, and other construction tasks, may be considered semi-structured tasks which utilize design models as a primary basis for representation and planning. In retrieval unknown objects in space or undersea, in repair of damaged equipment, or in exploration of poorly defined environments, manipulation tasks are less well defined and require increased role of hypothesized models and sensory exploration. Representational approaches are less dependent on pre-defined models, planning approaches are more integrated with control functions, and adaptive strategies are more important.

RESEARCH DIRECTIONS: Our current work on assembly and manipulation planning is based on several generations of flexible assembly workcells which we built and demonstrated for manufacturing applications [1]. These flexible workcells incorporated multiple robot arms, vision, tactile, and force sensing to accomplish tasks in electronics assembly, wire harness assembly, and assembly of instrument products such as printers and copiers.

Our current work on real-time planning decomposes control functions into Strategic, Tactical, Operational, and Device levels. In synthesis of the control structure for assembly, we view the planning of assembly as a path search in the state space of all possible configurations of the set of parts [2,3,4]. A syntax for the representation of assemblies has been developed based on contact and attachment relations. A decomposable production system implements the backward search for feasible assembly sequences based on a hierarchy of preconditions: release of attachments, stability of subassemblies, local separability of subassemblies, and global analysis of feasible trajectories. The resulting set of feasible assembly sequences is represented as an AND/OR graph and used as the basis for enumeration of solution trees satisfying system performance requirements. The AND/OR graph task representation has been shown to have desirable properties for real-time planning of tasks.

In order to plan operations we have developed a detailed analysis of sensorless [5,6,7,8] and sensor-based [9,10,11] approaches to manipulation. Description of the physics of pushed and sliding objects has been used to plan pushing and grasping operations including complex parts feeder designs. We have defined sensor-based control structures which use adaptive feedback control for visual servoing the position of a robot arm relative to an object. This work on sensor-based control is currently being extended to employ learning algorithms at the level of the motion primitive in order to improve performance by local adaptation in the face of uncertainty in the task environment.

PRESENTATION: The presentation for the workshop would overview our use of the 'configuration map' as a planning tool for sensorless manipulation, our experiments in learning algorithms for optimization of parameters in motion primitives, and illustrate the use of these approaches for robotic applications in space-based manipulation and repair.

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