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A Graphics Based Remote Handling Control System

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A GRAPHICS BASED REMOTE HANDLING CONTROL SYSTEM

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Abstract

A control and simulation system with an interactive graphic man-machine interface is proposed for the articulated boom in JET. The system shall support

- the study of boom movements in the planning phase,
- the training of operators by appropriate simulations,
- the programming of boom movements,
- the on-line control of the boom.

A combination of computer graphic display and TV-images is proposed for providing optimum recognition of the actual situation and for echoing to the operator actions.

Ein graphisch gestütztes Steuersystem für die Fernhandhabung

Zusammenfassung

Für den JET-Manipulatorarm wird ein Kontroll- und Simulationssystem mit einer interaktiven graphischen Mensch-Maschine-Schnittstelle vorgeschlagen. Dieses System soll folgende Arbeiten unterstützen:

- die Untersuchung der Armbewegungen in der Planungsphase,
- das Training der Operateure durch zweckmäßige Simulationen,
- die Programmierung der Armbewegungen,
- die direkte Steuerung des Arms.

Um die aktuelle Arbeitssituation optimal darzustellen und um die Aktionen des Operateurs wiederzugeben, wird eine Kombination von graphischen Darstellungen und Fernsehbildern vorgeschlagen.

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1. Introduction

For JET in-vessel manipulation, especially for limiter exchange, an articulated boom is used, which has 10 degrees of freedom, five of them are used for positioning the gripper, the other joints (gripper and "shoulder") are used for positioning corrections. Four of the positioning joints (A1-A4 in Figure 13 on page 25 are rotary joints, one is a translatory (trolley on rail, R)

The means for controlling these joints for positioning is the main issue of this paper. Especially the layout of the operator interface to the control system is discussed.

To outline the type of work to be supported by the control system, some typical subtasks should be listed.

- pick up a limiter from the transport cradle
- insert the boom into the torus
- insert a limiter into its working position
- withdraw a limiter
- grasp a limiter in its working position
- withdraw the boom out of the torus
- deposit a limiter on the transport cradle.

To study the problems related to the control of such a manipulator, an interactive simulator with graphic display was implemented in the Institute for Reactordevelopment (IRE), which is able to simulate the kinematic of the boom movement in real time. Figure 1 on page 2 is a hard copy of the simulator's display.

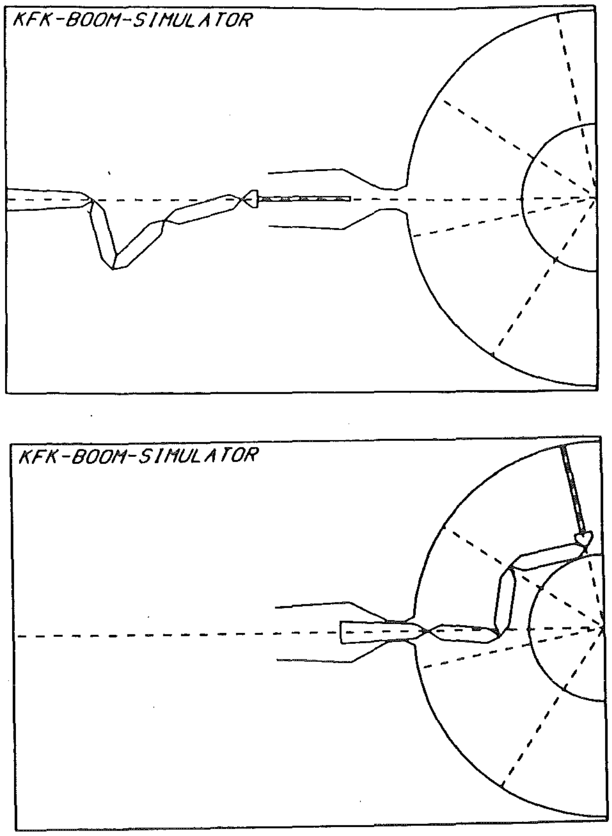

Figure 1. IRE-simulator's display

Working with the simulator shows that it is not a trivial task to control the boom movement only by presetting joint coordinates, that means by controlling the joint motors directly.

This is due to the environmental (space) restriction and to the complicated kinematic of the boom. Compared to a crane for example there are especially to main differences

- o the control coordinate system is not the same as the world coordinate system

- a response of the boom to an operator signal depends on the position of the boom.

Due to the kinematic restrictions of the boom joints and the tightness inside and outside the torus it is often a difficult problem to find a possible path between two positions.

To be able to predict the effect of a control signal, the operator is best supported by a graphic display, showing the whole boom and its environment.

As a result of these studies, we propose a control system, which integrates a simulator with graphic displays for visualization of the system states.

We are convinced that a simple display of joint coordinates is too abstract for an effective operator control of the boom and that the restricted view with a television camera is not an adequate tool, because it is not as abstract as desirable and not complete enough. The simulations have shown that a 2D-display of the boom and its environment is a useful base for operator decisions.

An important goal of a control system is to provide a suited man-machine interface using graphics and special control algorithms (e.g. coordinate transformations, move restrictions) to facilitate manual boom control. The basic idea of the proposal is to integrate a simulator and graphic displays to give the operator a planning aid and a complete view of the controlled system state together with and partially overlaid with TV-images. Using graphics, CAD-methods, and simulations in remote handling are discussed in [SILV83,TITU83,TRAC83]

RELATED PROBLEMS The control system as described in this paper presumes a closed loop feedback control system for the boom drives. The stability and accuracy of such a system and the avoidance of overshoots are studied with methods of modern modern control theory, especially using the "inverse model" method [BECK82]. These aspect are not covered here.

Also not discussed here, but of great importance is a good instrumentation of the boom. Because of the very restricted space between the boom and its environment in many situations, proximity sensors should be provided (e.g. to control the penetration of the boom into the vessel).

The problem of inserting the limiter into its working position using the special gripper drives (G, T, F, J) is not treated here. However, the system as proposed could be enhanced to serving as a man-machine interface during this task.

To support the work of the operator but also to be able to implement good algorithms, path optimization criteria should be studied, criteria like:

- o use only one joint drive at a time if possible
- o use joints close to gripper
- o start with positioning of arms (joints) far away from gripper
- o try to approach a position without changing drive direction (acceleration, backlash)

2. Systems Architecture

A control system for remote handling (Figure 2 on page 7) should support a close cooperation between man and machine, demanding for

1. a task oriented man-machine interface performed by

    - o graphical presentation of system states (control system and controlled system)
    - o a suited set of commands, accessible by usable input mechanisms.

2. flexible and powerful support in solving remote handling tasks, especially by

    - o simulation of tasks
    - o extented surveillance of operations (e.g. collision detection)
    - o automation of standard subtasks.

The state of the controlled system (boom and environment) are represented

- o by a 2D-model on a graphic screen, showing the desired geometry and the actual position of the boom (given by measurement or dynamic simulation), the environment, and completed by the field of vision of the TV cameras ("Boom/environment states and transitions" on page 13).
- o by one or more real images of TV-cameras, overlaid by a perspective view of the control system's 3D-model.

The system maintains several data bases, containing

- o environment and boom data,

- o states of the controlled system,
- o intrinsic transitions,
- o taught-in transitions.

Very important for the usability of the control system is proper choice of input device: keyboard with function keys, touch panel, mouse, joystick or a special hardware (control panel). In this paper, we do not yet fix the actual hardware to be used. However, the "Control commands" on page 21 define the functional capabilities of the various actions which the operator can request from the system. These commands can be implemented by different hardware.

This proposal at first shows the functionality of a control system, "Control system implementation" on page 43 explains how such a system may be modularized and implemented step by step.

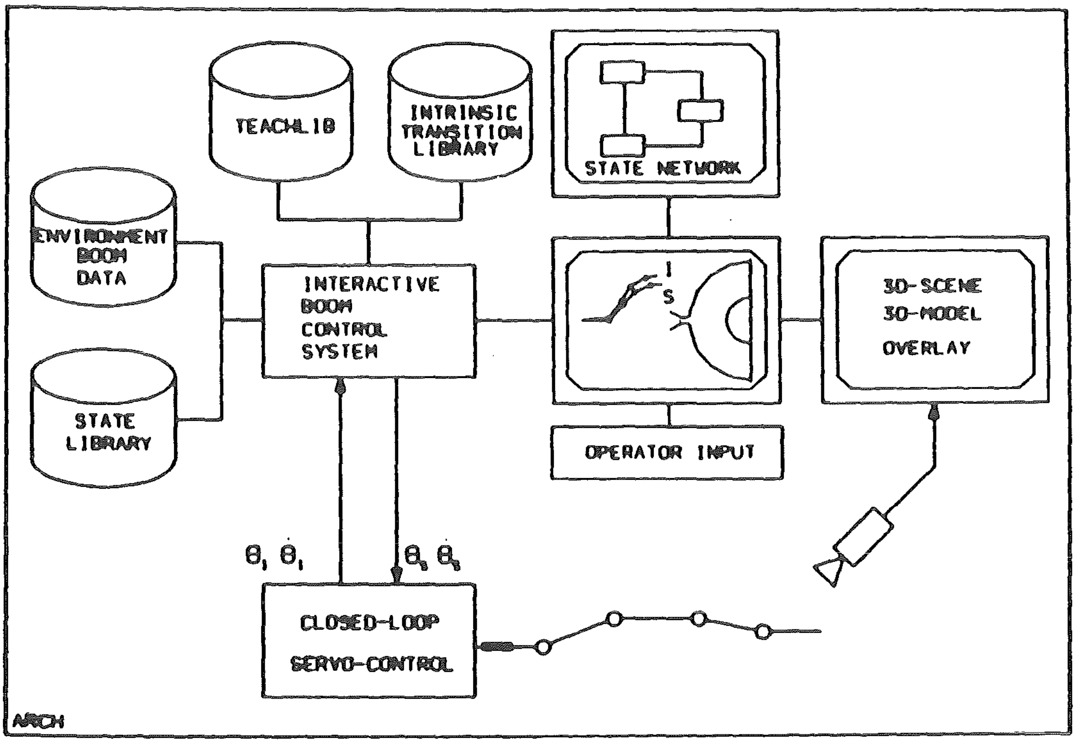

Figure 2. Systems architecture

3. Operating Modes of the Control System

A principal of the control system is to support the operator in planning and executing remote handling tasks. Therefore, the system should operate in the following modes (or control system states), also shown in Figure 5 on page 12.

DIRECT — The operator controls directly the actions of the boom via the control system. The screen shows the desired boom transition and the actual boom position, based on measurement. Using the TEACH-option all actions are stored to be repeated.

SIMULATION — The boom drives are not connected to the control system, the input of the operator takes an effect on the simulator. If the control system is able to simulate the dynamic behaviour of the boom, the control screen presents an "actual" position as in the DIRECT-mode. Basic simulation includes only kinematic simulation. Dynamic simulation (including inertia effects) may be added later. This mode too provides a TEACH-option, to be able to teach the system without the availability of the boom.

REPEAT — This mode of operation uses previously taught-in sequences of operator commands (stored in the DIRECT/SIMULATION mode with TEACH-option).

TUTORIAL — This mode serves for teaching operators to use the control system and the remote handling facilities effectively.

SERVICE In addition to these operating modes, installed for remote handling, there exists a further mode used for control system maintenance and enhancement: the SERVICE-mode. This mode is used by a system administrator to update system libraries or the system provided transition set.

The following table of commands is used as a basis for discussion of the command semantics.

The operator should not be burdened with a command language. He should use a "function key" language or some other means which are easily memorized. The detailed discussion of these commands follows in "Control commands" on page 21.

```
+-----------------------------------------------------------------+
| DIRECT [TEACH] [<cmd_d>]*                                        |
| SIMULATION [TEACH] [<cmd_s>]*                                    |
| REPEAT [DIRECT | SIMULATION] [<cmd_r>]*                          |
| TUTORIAL                                                         |
| SERVICE [<cmd_v>]*                                               |
|                                                                  |
| <cmd_d> ::= MOVE | HALT | RESUME | TRANS | RETURN | TROLLEY |    |
|             GRIPPER | SPEED | CAMERA | IF | TOLERANCES | END     |
|                                                                  |
| <cmd_s> ::= <cmd_d> | JUMP                                       |
|                                                                  |
| <cmd_r> ::= DIR | START | HALT | RETURN | CORRECT | END          |
| <cmd_v> ::= ESTABLISH | EDIT | END                               |
|                                                                  |
|                                                                  |
|                                                                  |
|                                                                  |
| Figure 3.  Operating commands                                    |
+-----------------------------------------------------------------+
```

command	comment
MOVE	move booms in chosen coordinate system
HALT	suspend boom movement
RESUME	resume movement from suspended state
TRANSITION	use predefined transition
RETURN	return to start state of transition
WAIT	wait for event or for some seconds
CORRECT	correction of boom movement using trolley and gripper
DIR	listing of taught transitions related to a state
SPEED	set speed of boom drives
ESTABLISH	establish new transition using TEACH-file
IF...	define conditional action
CAMERA	control of cameras, echoed on screen
GRIPPER	control of gripper
TROLLEY	control of trolley
TOLERANCE	present system tolerances
JUMP	jump from actual to specified state (position)

Figure 4. Command comments

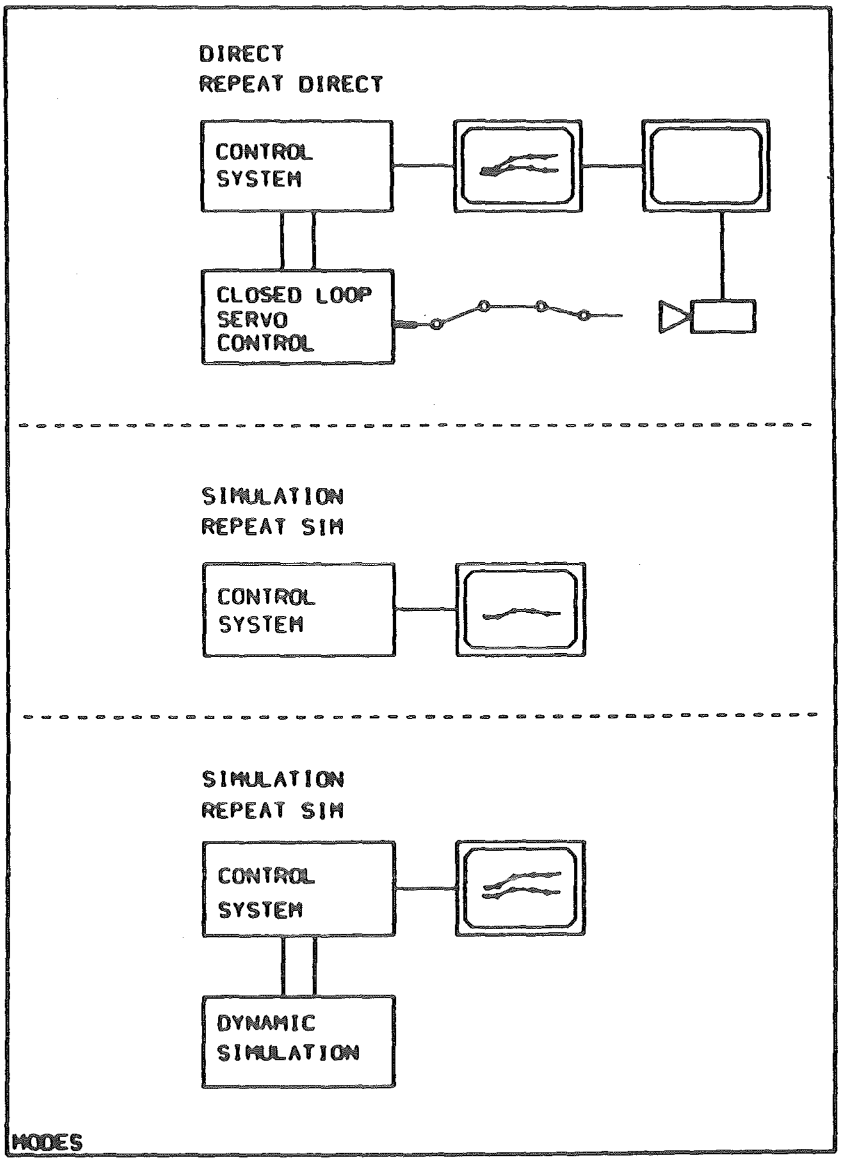

Figure 5. System modes

4. Boom/Environment States and Transitions

The overall control system behaviour is governed by a set of well-defined system states. In the DIRECT and REPEAT DIRECT operation modes, measured signals (such as joint angles) define in which state the system actually is. The allowed transitions between the states form a network. Such an organization enables the control system to supervise activities using specific constraints related to states or transitions between states. This controlling network should be relatively invariant. The operator should became rapidly familiar with this organization.

The system administrator will have special tools at hand to improve or change this state/transition network.

The definition of states is based on the geometry of the boom, because the main task of the control system is boom movement. Attributes of a state are related to the load of the boom and possibly other yet undefined signals.

The basic boom states and transitions are shown in Figure 6 on page 15 and Figure 7 on page 15

Such a diagram is not only useful for the system administrator, but also for the operator and the remote handling team. It introduces a clear naming for states and transitions which is essential for an effective discussion in problem solving. The whole system is functionally modularized allowing to discuss and to describe complex tasks in form of a set of appropriate building blocks.

Therefore this state diagram should be available on a screen, whereby the

- o actual state
- o preceding state
- o target state

should be specially marked with the possibility of visualization the related boom configurations on the displays.

Concerning the transitions, we distinguish between mandatory transitions, which have to be used, and recommended transitions, which may be used. Taught-in transitions may be added to recommended transitions simply by using the TEACH-option. The system maintains a catalogue of taught-in transitions and recognizes situations which coincide with start and end points of such transitions. They may be listed on request, accompanied by a comment, which has to be given, starting a teach-in. Intrinsic transitions are those, which are shown in the state diagram. Intrinsic transitions may be implemented as algorithms or as a taught-in command sequences, they are installed by the system administrator using the ESTABLISH-operation.

Figure 8 on page 16 and Figure 9 on page 17 show the special boom state and the intrinsic transitions. (These lists are to be considered as a first proposal, to be used for discussion: these lists are dependent on operating practice). The system manages three state vectors

- o the boom state, shown graphically from a functional point of view in Figure 8 on page 16, Figure 9 on page 17 and in a less abstract form as two 2D views (completed by the environment)

- o the environment state, including position of limiters and in vessel cameras (Figure 10 on page 18)

- o the camera state, showing the viewing angles of the used cameras (Figure 11 on page 19). The presentation of viewing angles intends to help the operator in orientation, to overcome the limited visual field, and to be able to assess distances, impossible using TV-cameras alone.

BTP	boom transport position
CAL	calibration position
OPP	outer park position
GRP	gripper removal position
LTP	limiter transfer position (cradle-gripper transfer)
BIP	boom insertion position
IPP	inner park position
LIP	limiter insertion position
LWP	limiter working position

Figure 6. Boom positions

CALB	calibrate the system
RMGR	remove gripper
MTGR	mount gripper
TRFL	transfer limiter
INSB	insert boom (into torus)
WTHB	withdraw boom (out of torus)
PARK	go to park position
INSL	insert limiter
WTHL	withdraw limiter
GETL	get limiter (grasp limiter)

Figure 7. Boom transitions

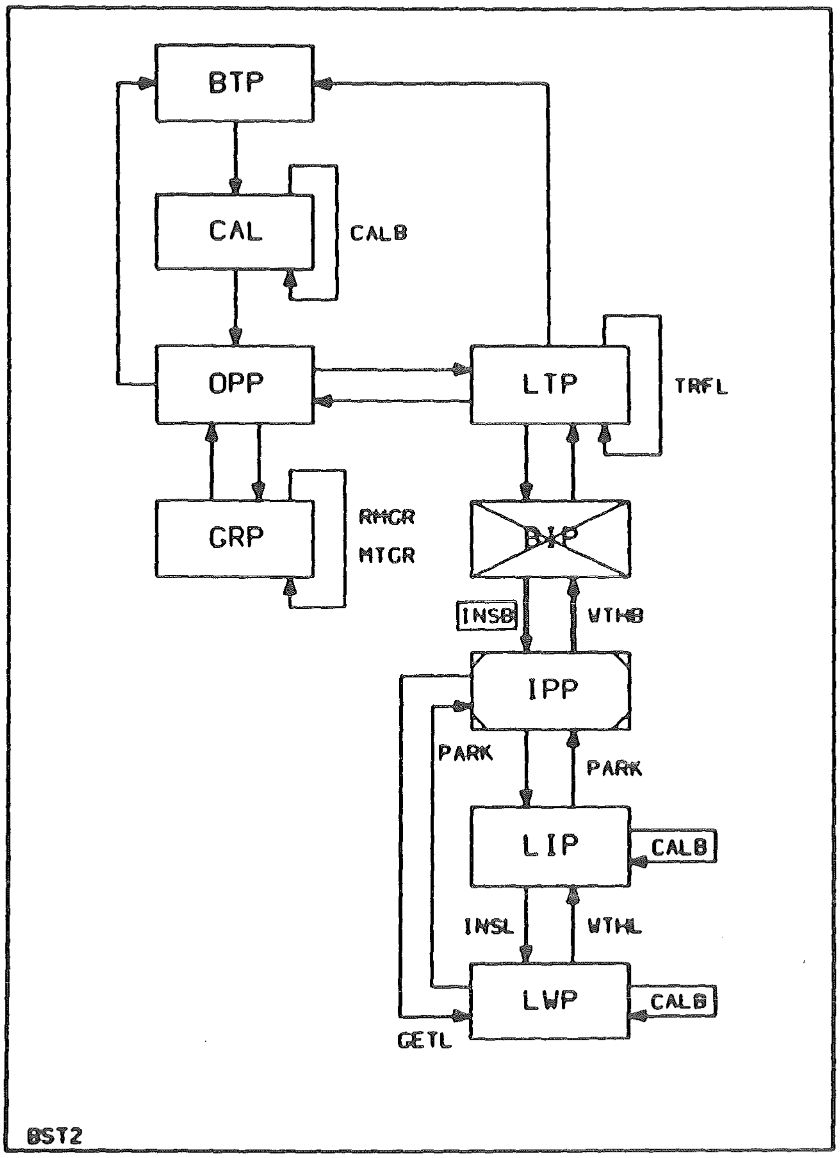

Figure 8. Boom state diagram 1

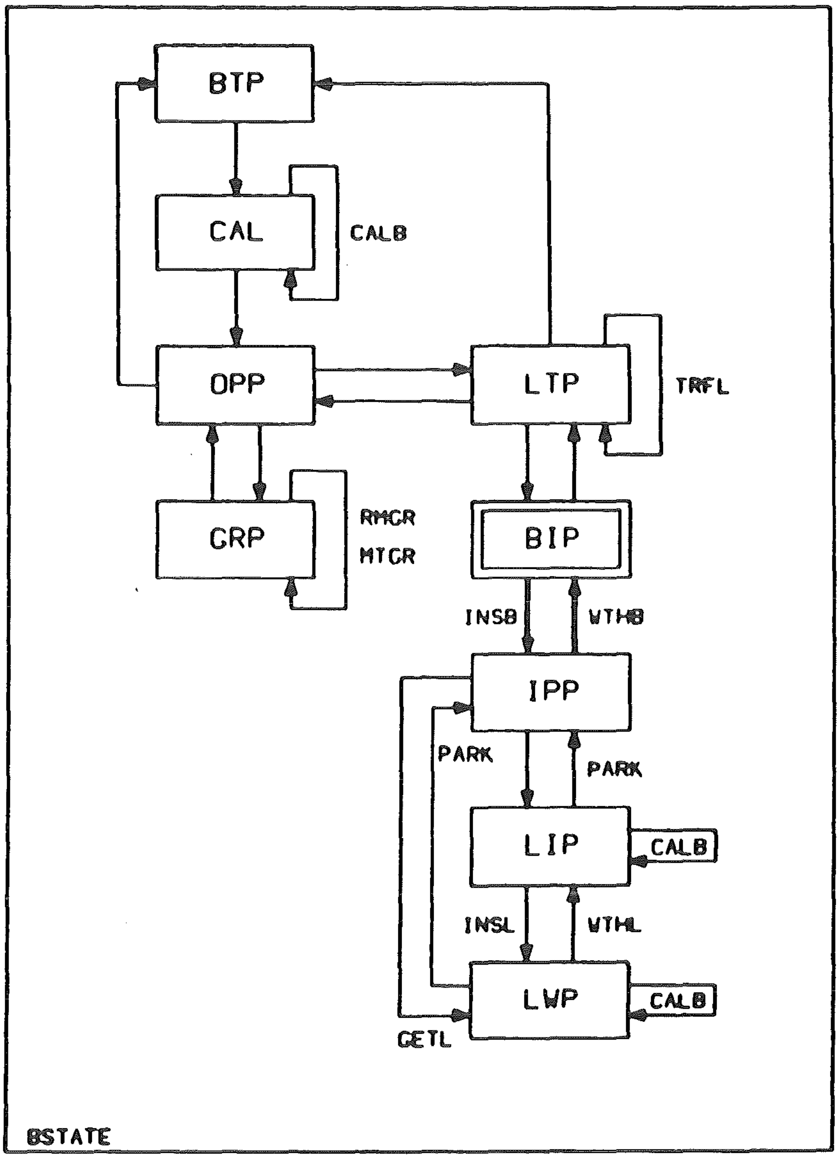

Figure 9. Boom state diagram 2

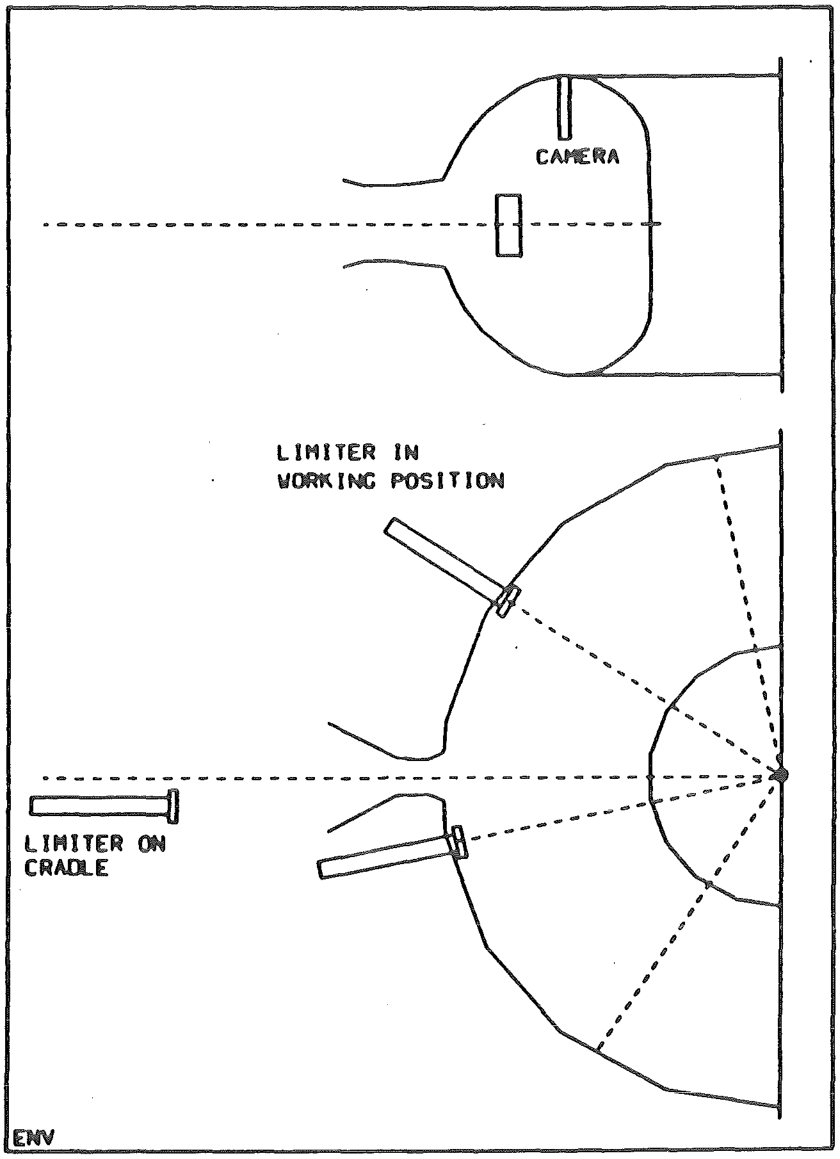

Figure 10. Environment state

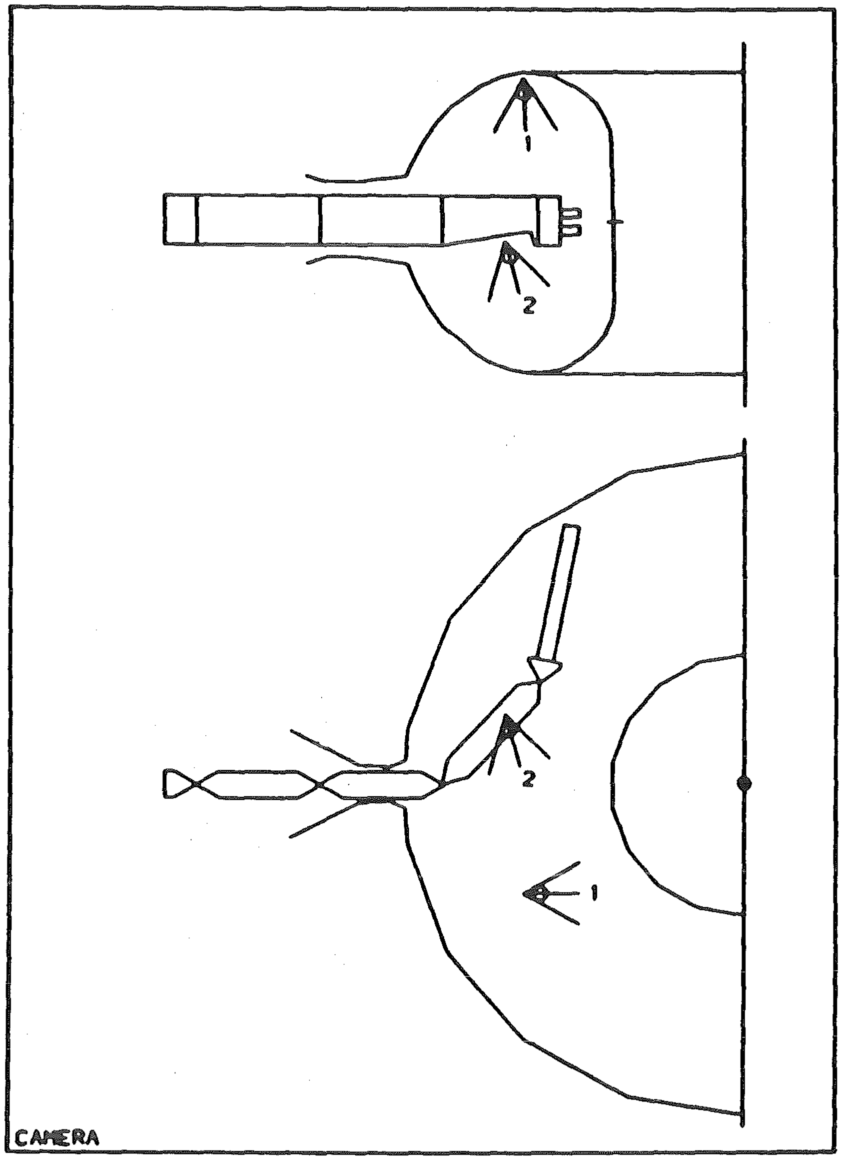

Figure 11. Camera viewing field

5. Control Commands

Having chosen one of the four operational modes introduced in "Operating modes of the control system" on page 9, the operator may use special commands (e.g. by pressing the corresponding buttons) to do the real work that means especially to move the boom.

The first part of this chapter discusses the central MOVE-command, followed by a shorter introduction of various other commands.

As previously mentioned, we do not discuss the real layout of the operating facilities, but the principles and semantics of the commands.

To demonstrate the principles, the layout shown in this chapter suppose a special hardware panel for the MOVE input.

An operator command and the presentation of its effects should be as task-oriented as possible, not just tool-oriented (e.g. motor on/off). A 2D computer generated graphic representation is used for communication the system state to the operator, bacause it conveys a more complete information in one glance than a number of TV-images, for instance. These TV-images are more valuable in controlling corrections of the position in detail (roll or yaw).

5.1 MOVE

As studies with a kinematic simulator have shown, one of the main problems in controlling the boom movement by an operator is the coordinate transformation, that is: the problem to imagine (predict) the boom movement, if only direct control of the joint drives is provided. The type of proper control commands largely depends on the state of the boom and the type of task to be solved.

In different situations the MOVE-command should be given in an appropriate coordinate system, to unburden the operator from complex coordinate transformations.

We therefore propose the use of the following coordinate systems:

1. Joint coordinates

2. Arm reconfiguration coordinates

3. Cartesian coordinates

Because the selection of a gripper position does not fully determine the configuration of the arm additional information is required, as will be shown.

The following sequence of figures shows a layout example of an input field based on a touch panel (lower part of picture) and an input-echo display. This display (boom state) will in reality be combined with the environment state display (Figure 10 on page 18) and, if available, completed by the system's response (or the system's response simulation).

The Figure 12 on page 26 and Figure 13 on page 25 serve to explain the meaning of the MOVE-figures serie. Figure 12 on page 26 shows the naming of the boom components, and Figure 13 on page 25 shows the symbols to present the actual boom kinematic.

The control of boom movement is monitored by 2D-graphic display showing the whole configuration. This is completed by the TV-images of several cameras. The relation of both pictures is given by a 2D picture continuing the viewing angle of the cameras and their direction of view. (Figure 11 on page 19), but the camera parameter may also be included in the standard 2D-image.

The following figures demonstrate examples of control interface layouts for control of the boom drives, supported by algorithms. The system knows three control groups.

1. Joint coordinates (Figure 14 on page 27)

   This is the most simple type of boom control, it enables the operator to turn on the movement of five motors individually by pressing the corresponding function key. The related speed may be changed too. The actual boom angle and velocities are digitally displayed on alphanumeric displays.

2. Arm reconfiguration (Figure 15 on page 28 to Figure 17)

   Simulations have shown that "arm reconfiguration" is useful for the operator in controlling boom movement. Since this operation requires running several motors at the same time in a coordinated manner, the operator needs special system support.

The kinematic boundary condition of this mode: trolley and gripper are fixed (are not moved) and the operator may change explicitly joint 1 or joint 4 as master joints, the other joints follow as slaves according to the proper algorithm. In the special case of a stretched arm, the operator has to decide, which configuration should be chosen. (see key "CHANGE CONFIG" and related arrow in the picture). There is a further reconfiguration problem given by a fixed gripper, braked A1,A2,A3, or A4 joint and moved trolley as shown in Figure 17 on page 29.

3. Cartesian coordinates

This mode distinguishes between several submodes

- Cartesian control of gripper (Figure 18 on page 30)

- Cartesian control of third arm (Figure 21 on page 32)

- Cartesian control of second arm (Figure 22 on page 33)

This type of motion calls for the control of at least two motors. For example, to insert the limiter into its fixture means to run the gripper on a straight line. The operator has to control one degree of freedom directly: the drive of the joint A1,A2, or A3. For the algorithm this angle is considered as constant. Figure 18 on page 30 shows the case of operator controlled A1-joint: The operator has to control, in addition, the direction of arm configuration when the A3-joint is stretched (CHANGE CONFIGURATION). Figure 21 on page 32 demonstrates the Cartesian control of the third arm: the joint A4 is braked, the control algorithm computes the angles for A1- and A2-joints. The operator may decide by CONFIG CHANGE, which configuration is to be used, starting from a stretched A2-joint.

Using A2 cartesian coordinates, the operator may only control a move in y-direction, (x-direction depends on the y-value), the A3- and A4-joints are braked.

A MOVE is interrupted by the operator (leaving the function key) as a sensor signal, named in a UNTIL-clause.

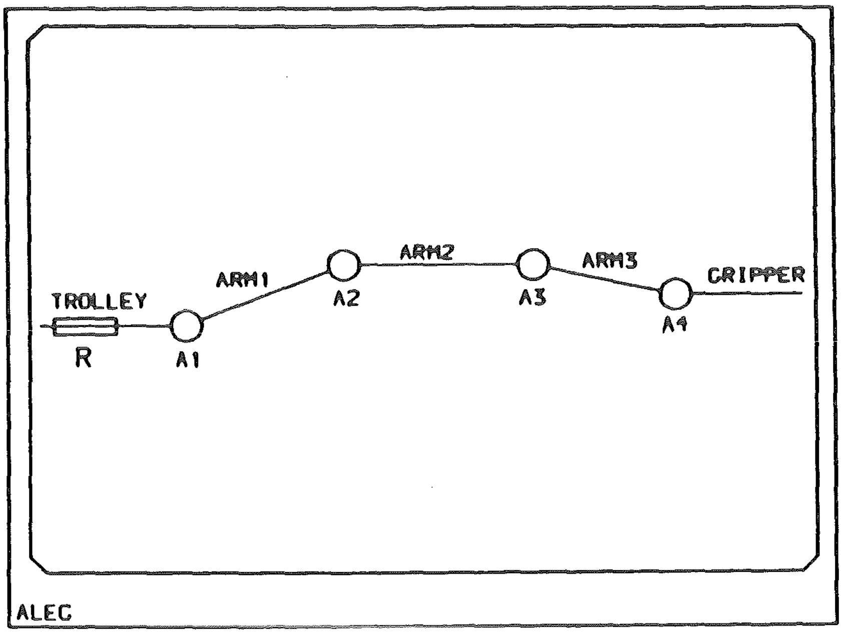

Figure 13. Boom element naming

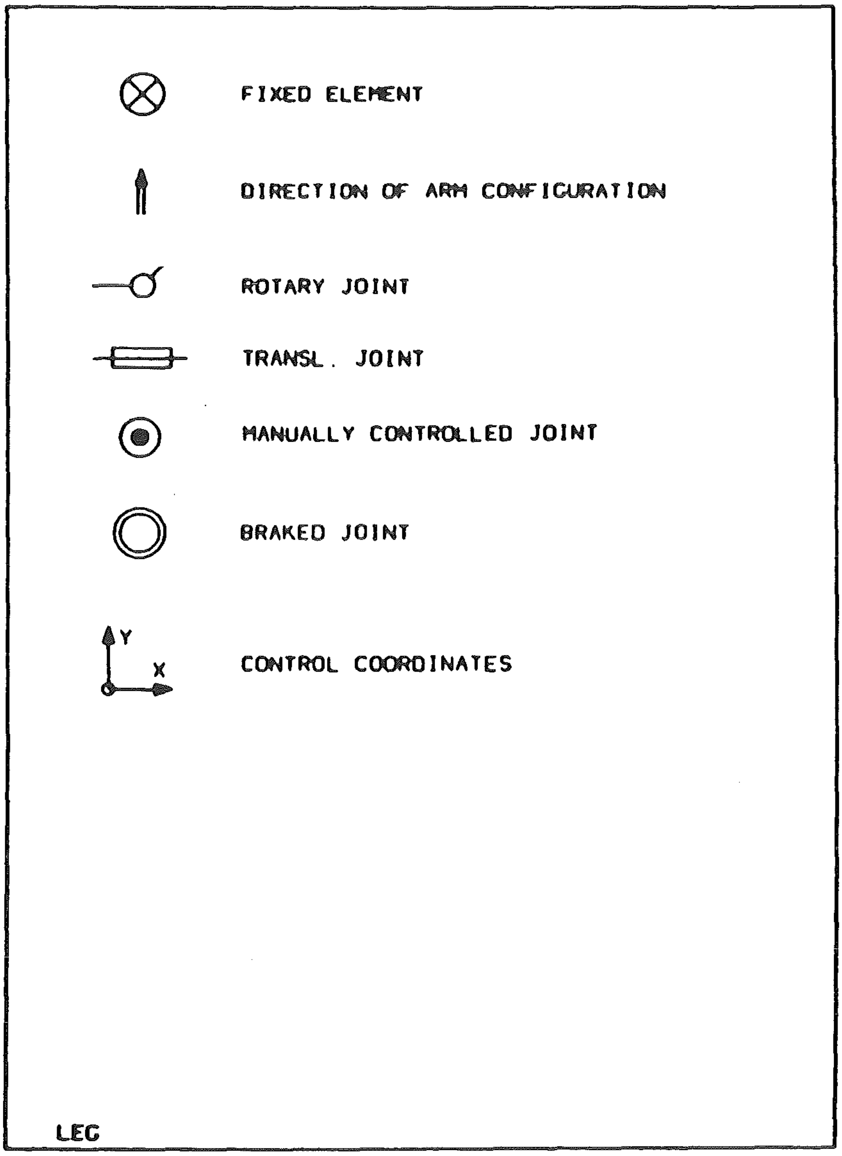

Figure 12. Boom kinematic symbols

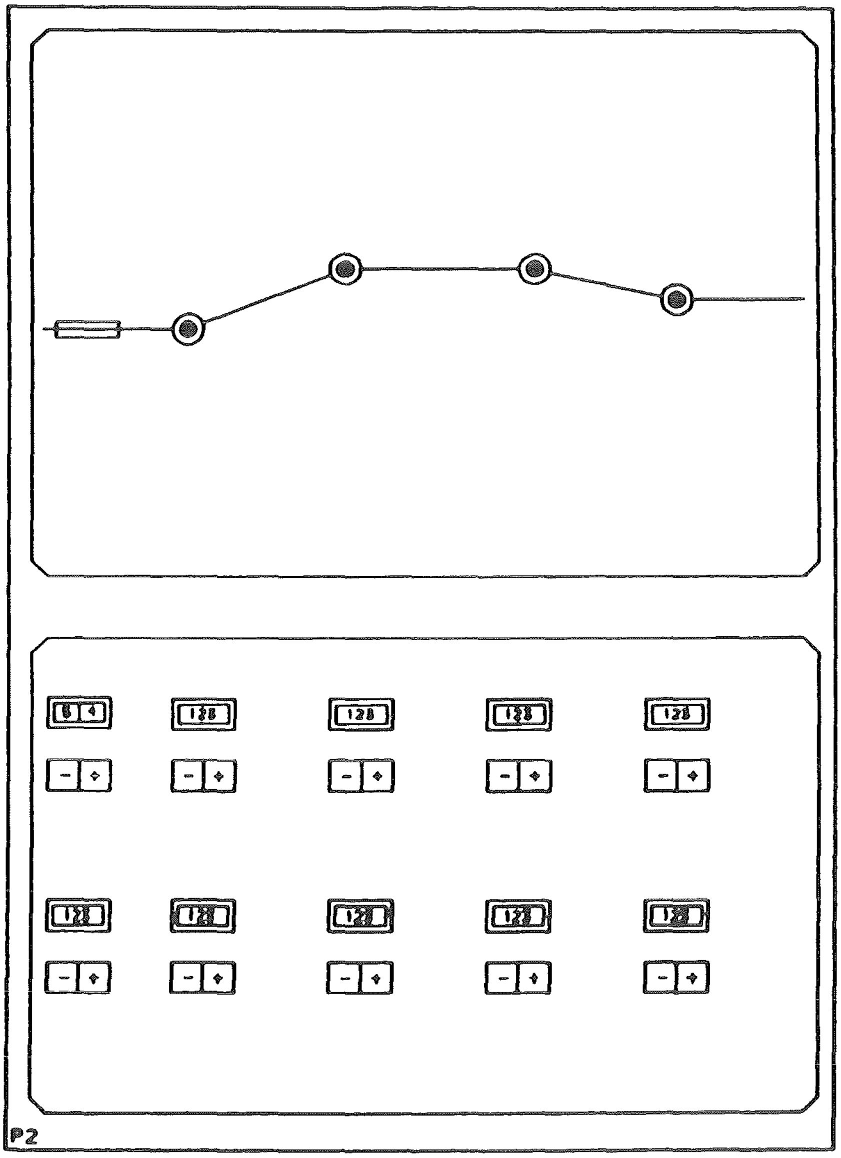

Figure 14. Joint coordinates control

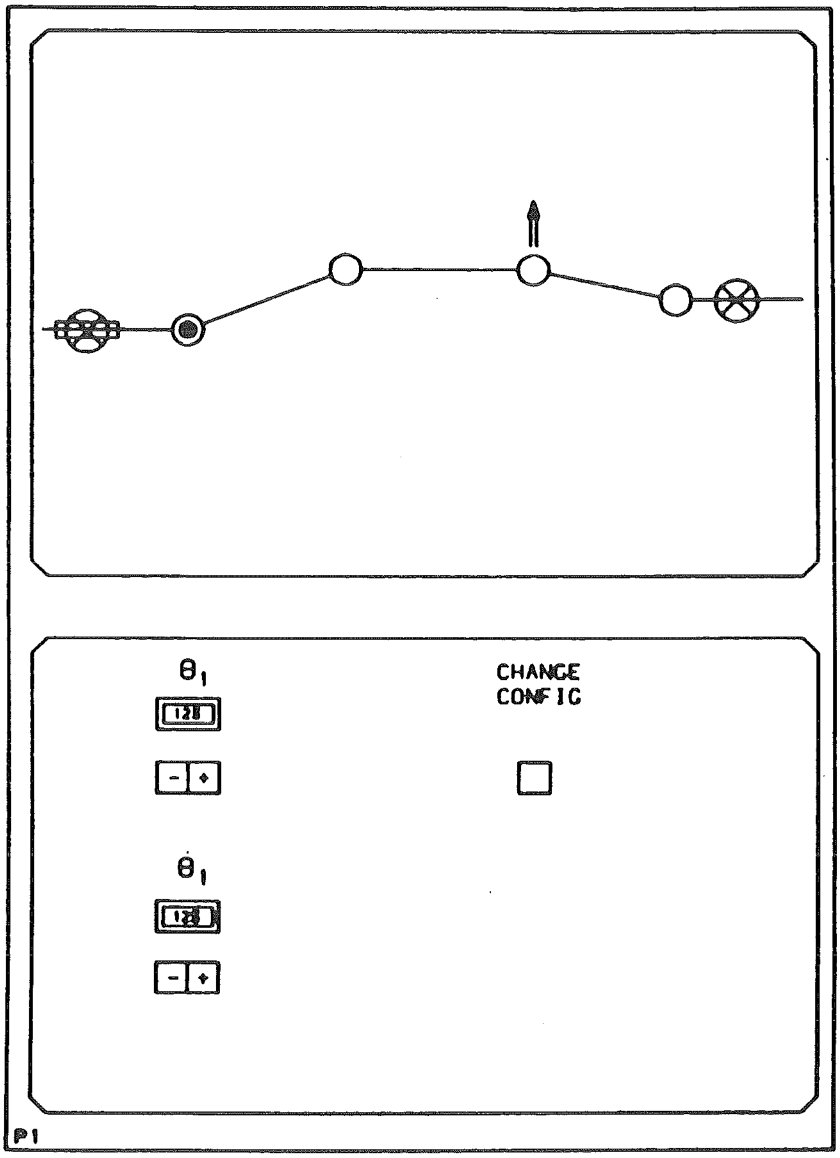

Figure 15. Arm reconfiguration control (mode 1)

p12

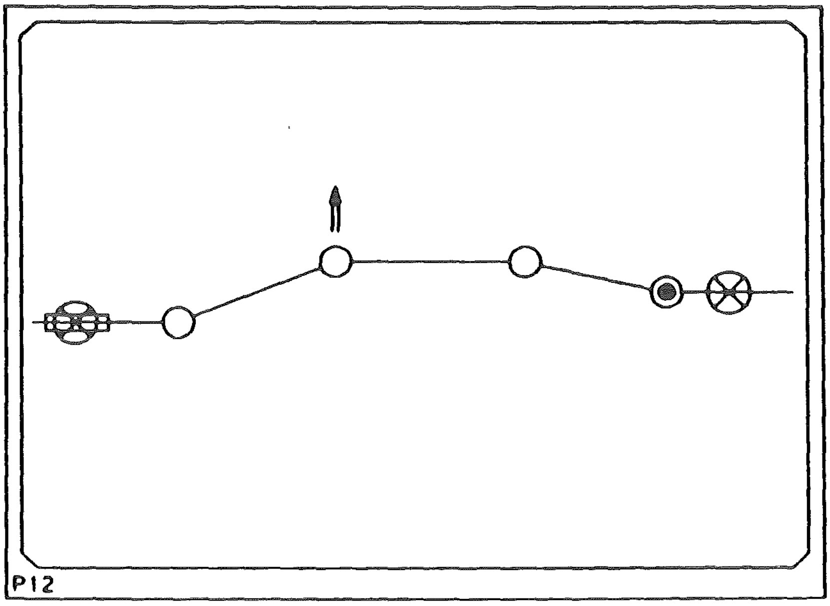

Figure 16. Arm reconfiguration control (mode 2)

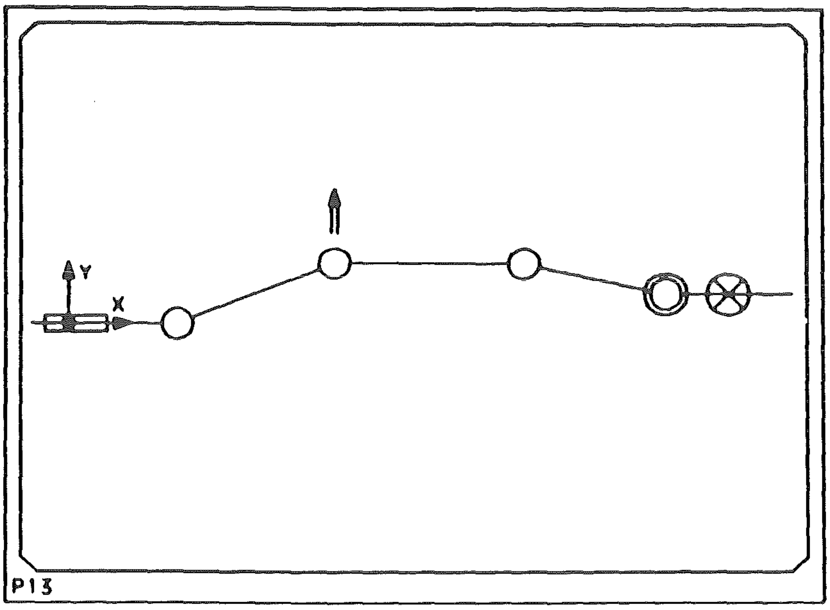

Figure 17. Trolley coordinates

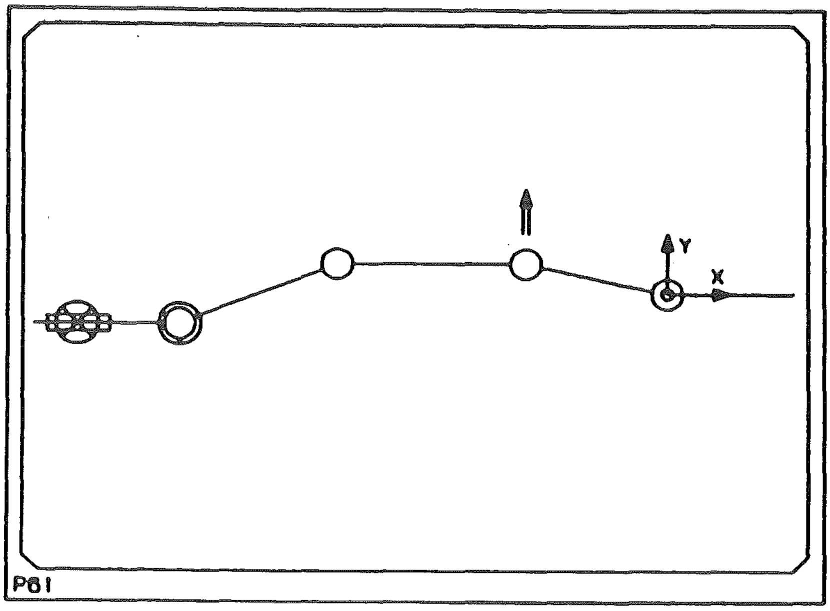

Figure 18. A4-coordinates control (mode 1)

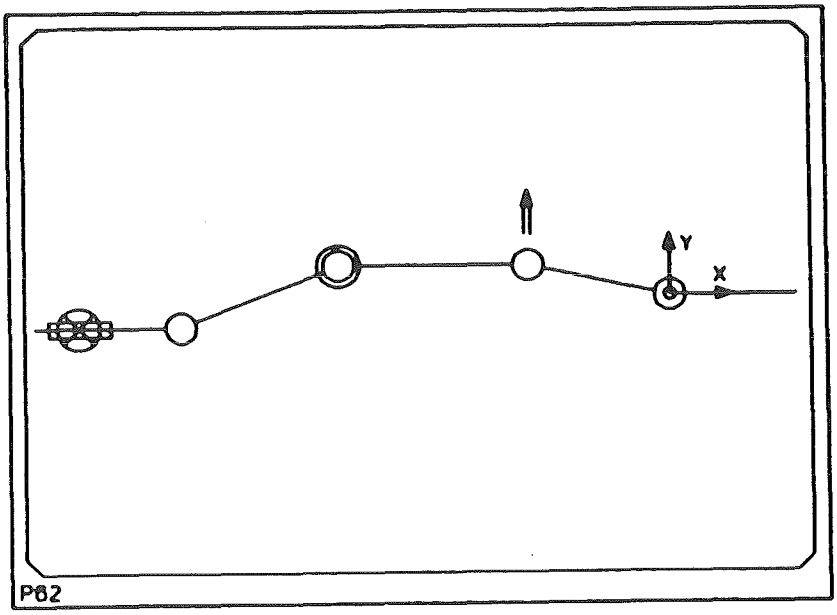

Figure 19. A4-coordinates control (mode 2)

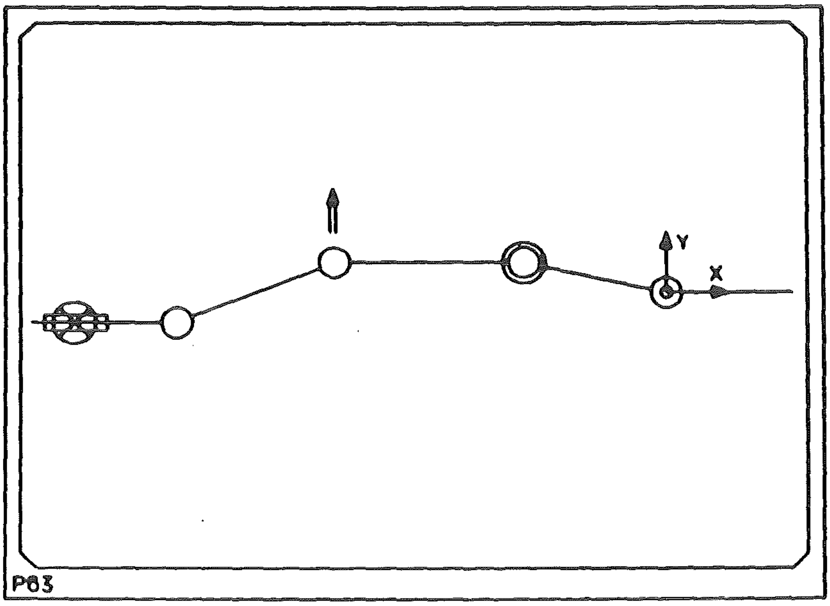

Figure 20. A4-coordinates control (mode 3)

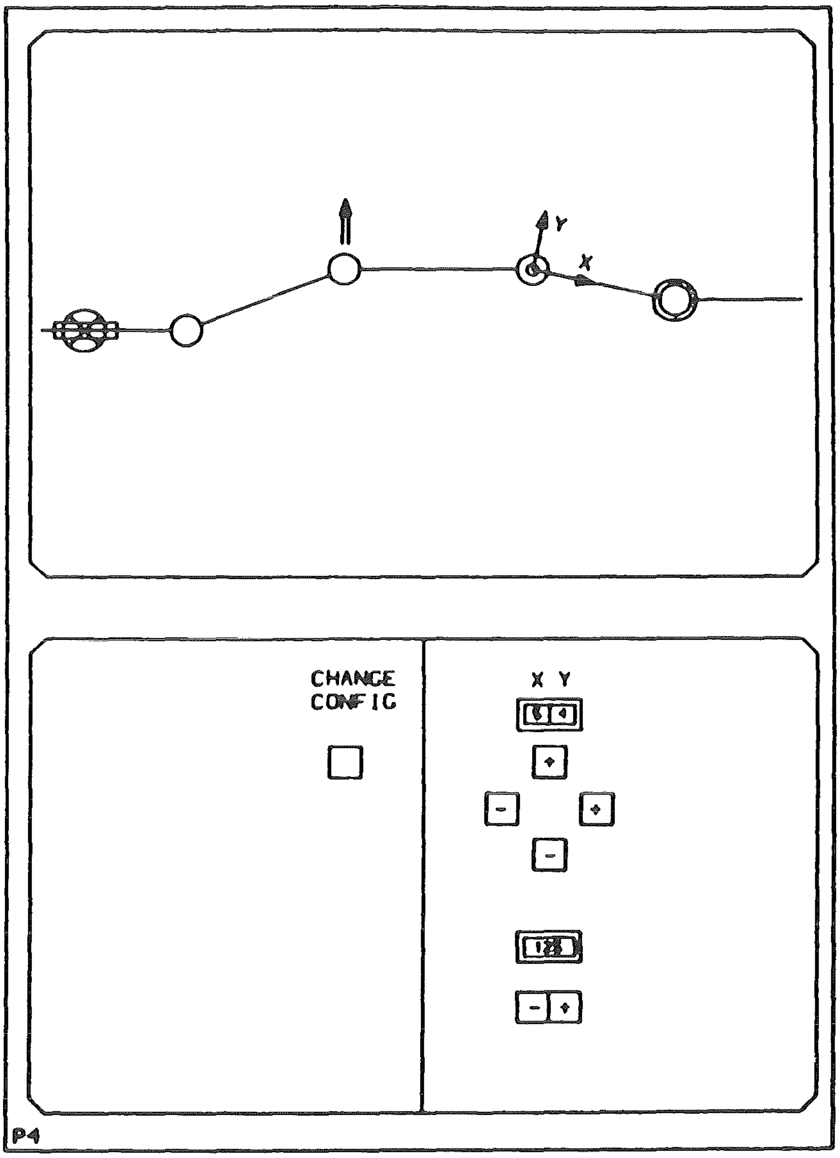

Figure 21. A3-coordinates control

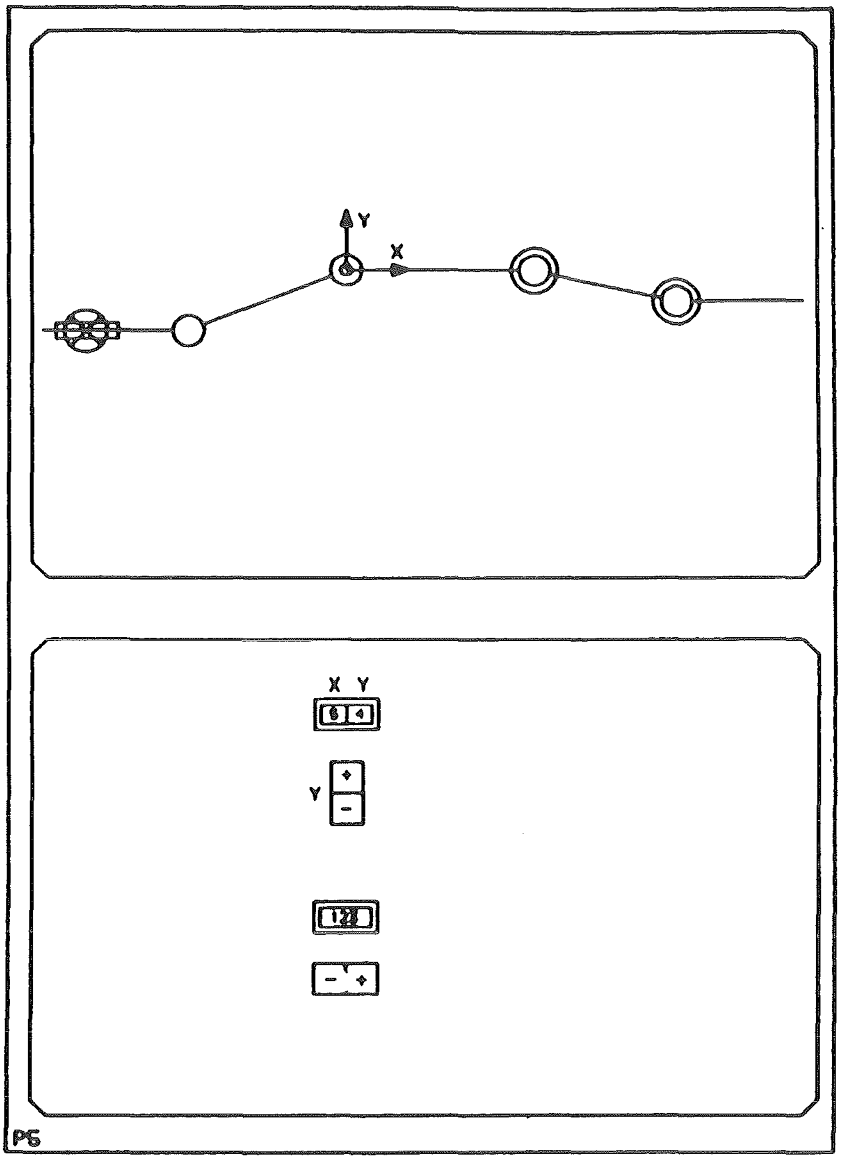

Figure 22. A2-coordinates control

5.2 HALT

Each transition (started by TRANS) may be interrupted (suspended) (for example, to correct the path based on off line proximity sensors or the picture of the TV-cameras).

5.3 RESUME

A suspended transition may be resumed from the point of interruption.

5.4 RETURN

An actual transition may be stopped, and the boom may be returned back to the start of the transition using the same path in reverse. To be able to return even not in TEACH- or REPEAT-mode, the system stores temporaryly each command sequence automatically. This feature supports obtaining a defined state from each situation.

5.5 DIRECTORY

This command lists all taught-in transitions available to leave the actual state. For each transition there is a short description available.

5.6 TRANSITION

Activates a named transition (intrinsic or taught-in), which may be interrupted by a named event.

5.7 SPEED

Changes the drive velocities.

5.8 WAIT

The system waits for a predefined event (e.g. from a sensor).

5.9 IF

Establishes a conditional execution of a command.

5.10 TROLLEY

Correction of an actual position may be done using the trolley pitch and roll (SX, SY) drives. Control panel and a related display are shown in (Figure 23 on page 38). Pitch control is mainly used to compensate bending of the boom by its load (using a simple model). The system computes this bending to be able to display it realistically.

5.11 GRIPPER

Contolling of gripper movement is supported by at least two views of the gripper as shown in Figure 24 on page 39.

5.12 CAMERA

Controlling of focus, zoom and aperture of the TV-cameras is symbolically echoed as shown in Figure 11 on page 19.

5.13 TOLERANCES

This command visualizes the possible state boundaries due to measuring tolerances.

5.14 WINDOW

To be able to control small corrections, the operator may set a display window for enlargement of the region of interest. The graphic display may be reset to its original scale using the RESET-option.

5.15 ESTABLISH

If the system is in SERVICE-mode, this command establishes a new intrinsic transition using a taught-in subtask or by providing a special algorithm.

5.16 EDIT

In the SERVICE-mode this operation serves to update the environment model. Measuring of the environment may be supported by the boom, equipped with appropriate sensors.

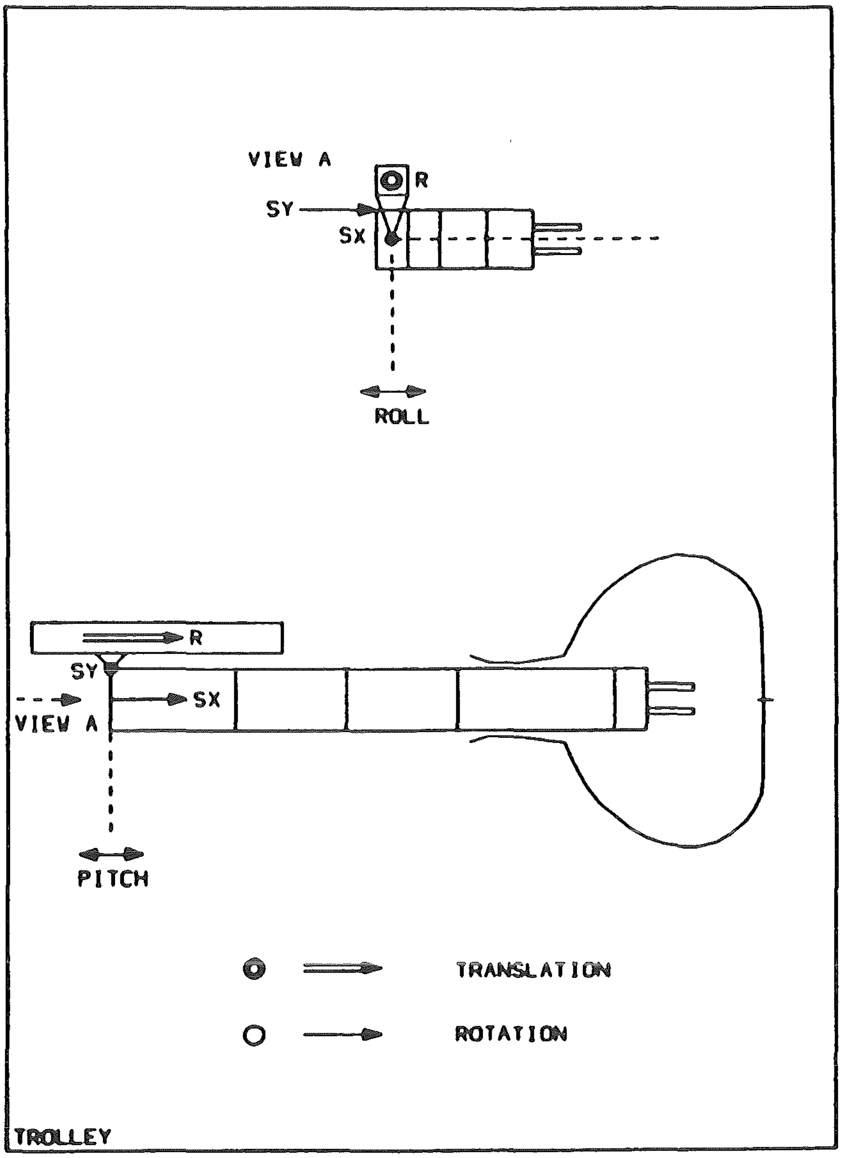

Figure 23. Trolley control

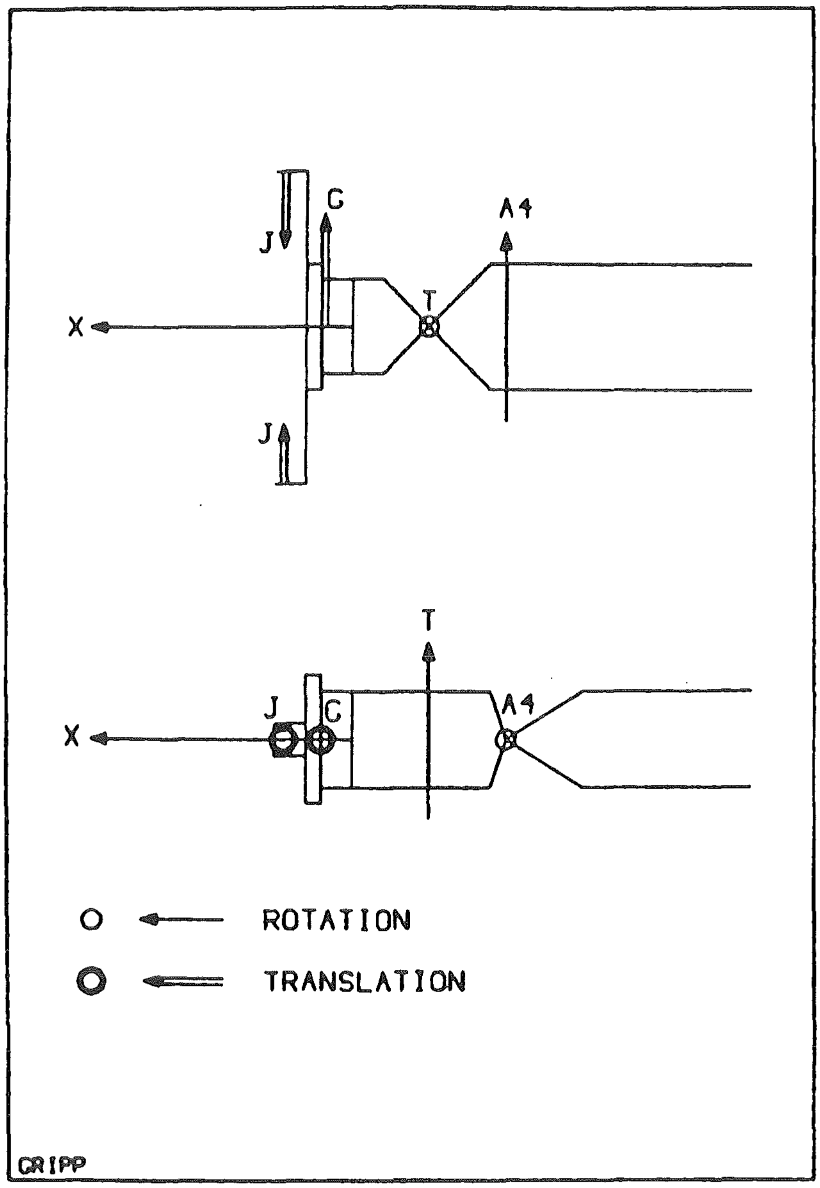

Figure 24. Gripper control

6. General Restrictions to Operating Control

Besides supporting the operator in path planning and path controlling, the system supervises all actions to avoid collisions.

Depending on the actual state or state transition, the control system pays attention to various restrictions or activates special input options to guide the operator. The system should be designed for flexible use of these abilities and for the probability of later additions. Some of these restrictions are listed below.

In some cases the passive surveillance may not suffice: then the control system has to be supported actively by sensors, especially by proximity sensors or end switches. Sometimes a recalibration of the boom system may be necessary.

Restrictions

1. Inside the vessel, moves are controlled by a collision detection algorithm, to avoid collisions with the wall, the inspection cameras, fixed limiters etc.. Collision detection outside the torus is concerned with the transport cradle, the neutral beam injector, and similar obstacles. This collision detection has to be supported by an appropriate set of proximity sensors for short distances, because the precision of the computed collision control is limited.

2. The movement of the boom is restricted by the boom design itself. Therefore, the control system has to notice the boundary values of the boom joints.

3. There are special transitions which should be restricted to an approved mode.

4. The operator actions in special situations (transitions) may be limited to an approved coordinate system for movement.

7. Control System Implementation

Starting from the functional description of the control system, we shall now propose a possible modularization of the concept related to the possibility of system implementation step by step. The whole system should be implemented in two steps, which could be roughly described by the following function.

1. Basic configuration (Figure 25 on page 45)

   This part is divided into two levels

   a. Closed loop servo control of the drives R,A1,A2,A3,A4 by joint coordinates and joint velocities. Boom positions are displayed alphanumerically.

   b. Path control

      - DIRECT-mode ("Operating modes of the control system" on page 9), that means manual control of boom movement in selected coordinate systems as discussed in "MOVE " on page 22 including the TEACH-option.

      - Optional a subset of the graphics based state presentation ("Boom/environment states and transitions" on page 13), to support manual control.

      - REPEAT-mode with the possibility of CORRECT, HALT, RESUME, RETURN ("Control commands" on page 21). A basic state control rejects REPEAT-transitions not starting at the actual boom position.

- o Collision detection based on a simple environment model, derived and recived from the "main control and simulation system" (step 2).

2. Progressive enhancement (Figure 26 on page 46)

   - o Simulation (starting with kinematic simulation) including the TEACH- and REPEAT-options to be able to plan and optimize tasks without the availability of the boom.

   - o Extended state and transition control to make operations more safe.

   - o Full graphic presentations as proposed in "Boom/environment states and transitions" on page 13.

   - o Implementation of the SERVICE-mode ("Operating modes of the control system" on page 9)

For this type of modularization we propose to implement the functions on three processors

1. a microcomputer or a network of microprocessors for the closed loop servo control of the boom drives (level 1 of step1)

2. a microcomputer with disk and graphic display for level-2-function implementation

3. a host computer (e.g. NORD 100) with appropriate graphic display to implement step-2-functions.

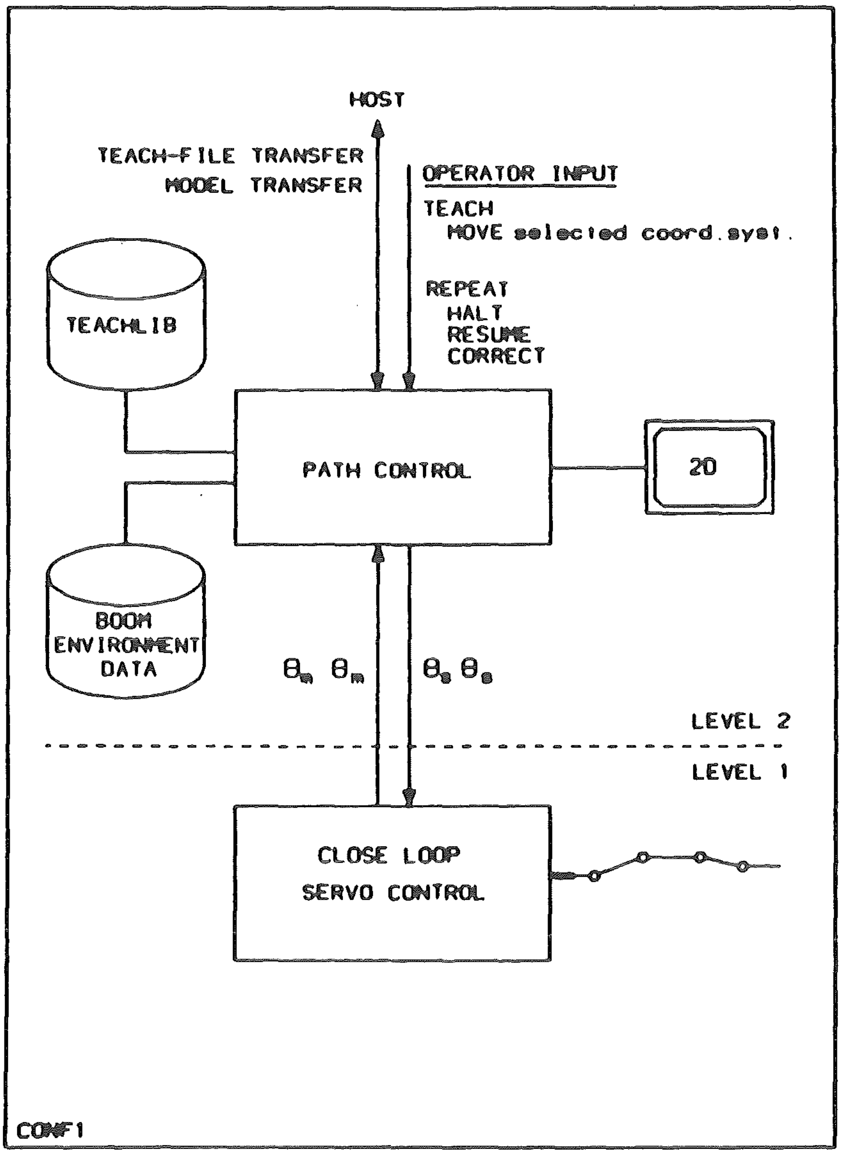

Figure 25. Basic configuration

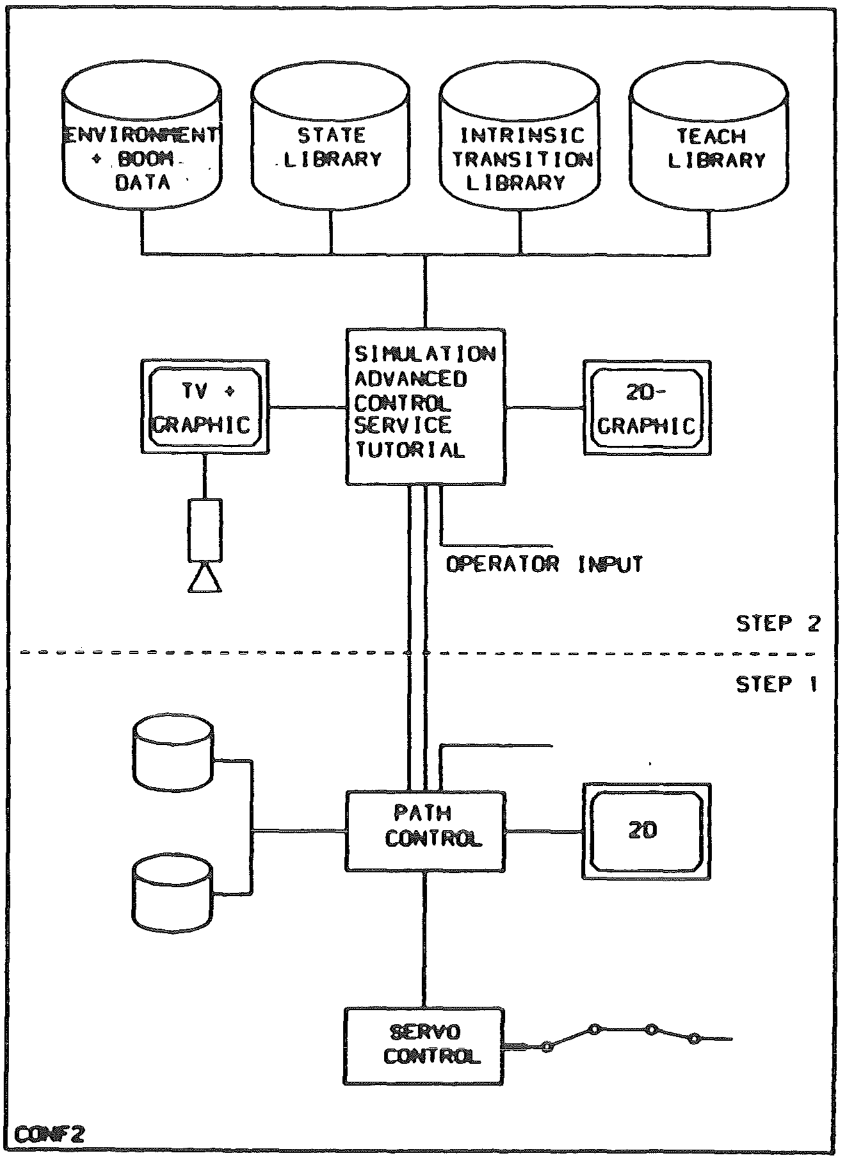

Figure 26. Enhanced configuration

8. References

BECK82 Becker,H. et al.: unveröffentlichter Bericht des KfK, 1982

SILV83 Silverman,E.B.: Robotic technology experiments for nuclear power plant inspection and maintenance. Proc. of the 30th conference on remote systems technology, Washington, November 1982, p.109-112.

TITU83 Titus,P.H.:Dynamic and geometric simulations of the TFTR in-vessel manipulator system. Proc. of the 30th conference on remote systems technology, Los Angeles, June 1982, p.81-88.

TRAC83 Trachsel,C.A. et al.:Fusion reactor remote maintenance and repair operations simulation using computer graphics. Proc. of the 30th conference on remote systems technology, Los Angeles, June 1982, p.103-106.

Appendix A. Teach-File Records

1. start state

2. goal state

3. boom load

4. environmental restrictions

    - state of limiter fixture
    - state of in-vessel camera position

5. SPEED

6. MOVE

7. RETURN

8. TRANSITION

9. IF <sensor> THEN ...

10. HALT

11. RESUME

12. WAIT <event>

13. TROLLEY

14. GRIPPER

15. CAMERA

Appendix B. Boom State Attributes

1. L-TETA1-TETA2-TETA3-TETA4 (principal joint coordinates)
2. trolley parameters
3. gripper parmameters
4. load (nothing/limiter x/manipulator)
5. camera parameters

Appendix C. Environment State Attributes

1. limiter positions (free/occupied)

2. cradle position

3. cradle load (free/occupied)

4. in-vessel camera position (working/withdrawn)