ARMAR III – DESIGN OF THE UPPER BODY

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ABSTRACT

The goal of the collaborative research center 588 "learning and cooperating multimodal robots" in Karlsruhe is to create a humanoid robot that is able to support humans in a broad variety of different tasks alone or in cooperation with humans. The development of such a robot is a challenging task very different from the design of industrial robots due to a totally different target system of requirements. A learning Humanoid Robot must be able to solve momentarily unknown tasks under changing boundary conditions. The robot must be able to function in an environment originally designed for humans, not for machines. The following requirements for the design of a humanoid robot can be derived from these boundary conditions: A Humanoid Robot should have humanlike appearance, dexterity and manipulation. These requirements lead to a complex design process and a design which has to be highly spatially integrated as well as functionally integrated. This leads to complex interactions between system elements. The demand for mobility adds the requirement of a lightweight design. ARMAR III is the current Humanoid Robot of the collaborative research center 588 which has a modular structure. The modules for neck, torso and arms were designed and built at the Institute of Product Development (IPEK) at the University of Karlsruhe (TH). The design of these modules of the upper body is presented in this article.

1. INTRODUCTION

The collaborative research centre 588 "Humanoid Robots – learning and cooperating multi-modal robots" was established by the "Deutsche Forschungsgemeinschaft" (DFG) in Karlsruhe in May 2001. In this project, scientists from different academic fields develop concepts, methods and concrete mechatronic components for a humanoid robot that can share its working space with humans. The long-term target is the interactive work of robots and humans for example in the kitchen. For instance a simple task like putting dishes into a dishwasher requires sophisticated skills in cognition and the manipulation of objects. Communication between robots and humans should be possible in different ways, like speech, touch or gestures, making an intuitive handling easier for the human. As this is the main focus of the collaborative research centre a humanoid upper body on a holonomic platform for locomotion has been developed. It is planned to increase the mobility of ARMAR by replacing the platform by legs in a future product generation.

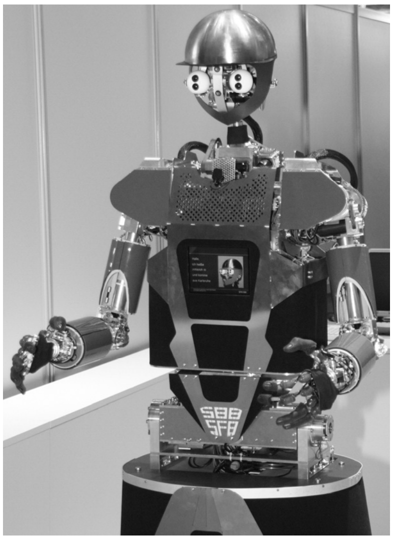

Fig. 1 ARMAR III

The robot ARMAR III was presented to the public at the computer fair CEBIT in spring 2006 in Hannover, Germany. Highly integrated mechatronic systems, like Humanoid Robots, pose great demands on a systematic proceeding in development. Mechanic, electronic, software and control subsystems are combined in a very small installation space. Because of the spatial requirements and because of the functions which can only be realized in collaboration of all domains the system cannot be divided into subsystems that are allocated to the domains. This leads to strong functional and spatial dependencies. At the start of the development in a preliminary work the general demands on the total system of the robot have to be transferred into requirements on subsystems to ensure the functionality of the robot. Before this the total system has to be divided into parts that show attributes of a unit. These units are corresponding to modules. In a Humanoid Robot these modules are the joint complexes, like the wrist and the elbow in the arm. The range of functions of these modules is provided by several functional units. These functional units are considered an entity but they can not be designed without consideration of other functional units because of the strong interactions between them. An example for this is the drive of a joint that can not be designed without paying attention to the joint kinematics, the requirements of the control system, the force and position sensors in the drive and the joints, the design space and many more. This is why the function units cannot be designed separately and added in the end. These units have to be developed in a special order that adapts to the interdependencies. This leads to a minimum number of iterations in the development process.

In this paper the general requirements on the Humanoid Robot of the SFB588 are shown. Than the different modules which were designed according to the proceeding described above, are visualised

Most mechatronical modules have been designed and built at the Institute of Product Development (IPEK) at the University of Karlsruhe (TH). The results of this works are presented in this article.

2. TARGET SYSTEMS AND REQUIREMENTS

Since the robot is to get into contact with humans in order to fulfill various functions, it is important that the robot is accepted by the human. A human-like appearance is as important as the ability to move like the human. Specific demands [2] on kinematics, dynamics and the design space have to be considered. An example for one of these requirements is that all rotational axes of one joint intersect in one common point. At the same time a good control is wanted in order to run all degrees of freedom as individually as possible. As actuators only electric motors should be used. In order to realize the abilities mentioned above, different types of sensors are necessary in every degree of freedom. The goal was the integration of an angular position measurement with an encoder on the motor, an absolute angular position measurement close to the joint and a measuring of the forces.

For energy efficient operation of an autonomous system, it is necessary to achieve a lightweight design. It is especially important to design these components as light as possible which are moved in highly dynamic motions and which contribute mainly to the relevant inertia of a module.

Some of these requirements, like accuracy for the positioning of an end-effecter and a structure that is as light as possible, are contrary design goals. This is only one of the problems in the design of a humanoid robot structure that demonstrates the difficulty of such a design task.

3. DESIGN OF UPPER BODY

The robot ARMAR III has a total of 49 degrees of freedom and can be divided into a humanoid upper body and a holonomic platform for locomotion. The upper body consists of the following modules: two arms with shoulder, elbow, wrist and hands, head, neck joint, thorax and torso joint. The head and the holonomic platform were developed at the “Forschungszentrum Informatik” (FZI) and the hands by the “Institut für Angewandte Informatik” in Karlsruhe [3]. The remaining modules, which are presented in this article, were created at the “Institute of Product Development”.

The kinematics of these modules and a CAD model are shown in fig. 2.

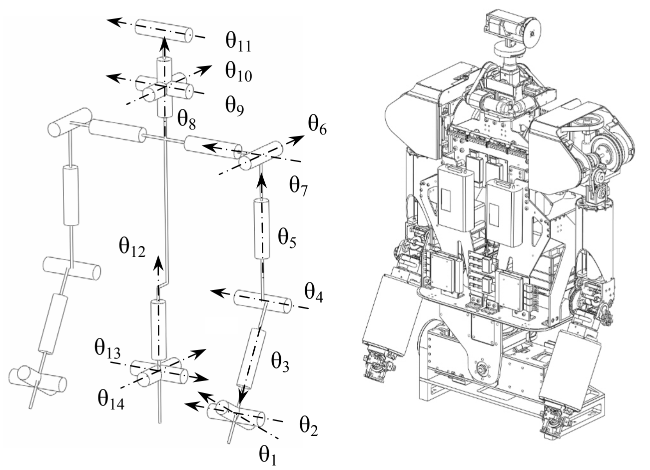

Fig. 2 Kinematics and CAD model of upper body

The size of the design space and the motion space of ARMAR III are similar to that of a human person with a height of approximately 175 cm. The most important dimensions of the upper body can be seen in fig. 3.

Table 1 gives an overview of all modules with the corresponding degrees of freedom and the motion range. Both arms have seven degrees of freedom. The three degrees of freedom in the shoulder provide a relatively wide range of motion. Together with two degrees of freedom in the elbow as well as in the wrist, the arm can be used for complex manipulation tasks that may occur in the primary working environment of ARMAR III, the kitchen.

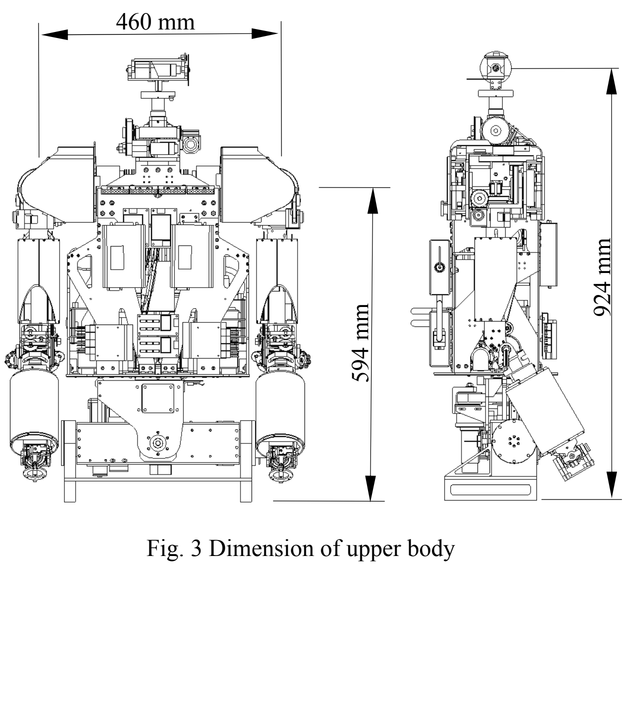

Fig. 3 Dimension of upper body

	Part		D.O.F	amount	total
Degree of freedom	Wrist		2	2	4
	Elbow		2	2	4
	Shoulder		3	2	6
	Neck		4	1	4
	Torso		3	1	3
	Upper body				21
Movable range	Wrist	θ_1	-30° to 30°		
		θ_2	-60° to 60°		
	Elbow	θ_3	-90° to 90°		
		θ_4	-10° to 150°		
	Shoulder	θ_5	-180° to 180°		
		θ_6	-10° to 180°		
		θ_7	-45° to 180°		
	Neck	θ_8	-180° to 180°		
		θ_9	-45° to 45°		
		θ_{10}	-45° to 45°		
		θ_{11}	-60° to 60°		
	Torso	θ_{12}	-180° to 180°		
		θ_{13}	-10° to 60°		
		θ_{14}	-20° to 20°		

Table 1. Specifications of parts of upper body without hands and head

3.1. Shoulder joint

The shoulder joint is a series of three joints. The first, a roll joint, actuates the raising of the arm in front of the body. The second, a pitch joint, allows the lifting of the arm at the side of the body and the third one enables the rotation of the upper arm. The drives for all three joints are located in the body segment next to the joint. This configuration of the drive train allows independently driven motion of the three axes. The drive of the first joint is mounted parallel to the driven joint. The drive torque is transmitted via a toothed belt to the driven axis and transfused by a harmonic drive gearing to the shoulder. The drive torques are measured with strain gages that are attached to a torsion shaft that is integrated between the gearing and the joint. The drives of the pitch movement of the shoulder and for the rotation of the upper arm are arranged very similarly. Both motors are located with an offset and orthogonal to the driven axis. For this reason the shoulder could be downsized. A worm gear transmission is fixed to both joints. Between the worm gear and the motor a tooth belt is tightened. The drive torques of these two movements are determined by force sensors that measure the axial forces in the worm gear shafts.

An optical position sensor is attached to each of the three joints of the shoulder. The sensors allow quasi-absolute angular position measurement based on incremental optical sensors [4].

The electric cables for the arm and the bowden cables for the drive of the elbow are guided through the shoulder. Therefore the transmission and the torsion shaft of the drive of the first joint are hollow inside and the upper arm consists of a hollow shaft.

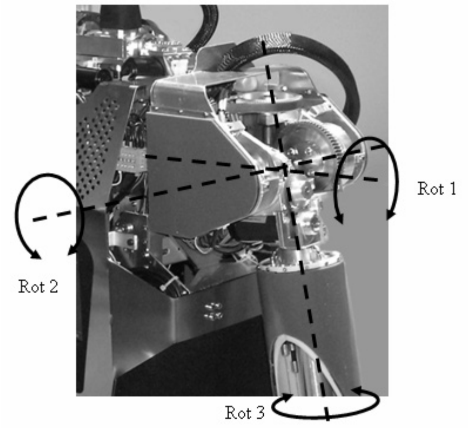

Fig. 4 View of the shoulder joint from the side

A touch-sensitive artificial skin sensor is attached to the front and rear part of the shoulder casing [5]. This gives the user the possibility to communicate with the robot by touch, for instance the robot can be directed by pushing or pulling the shoulders or the user can get the robots attention by tapping its shoulder.

3.2. Elbow joint and upper arm

The elbow joint of ARMAR III has two degrees of freedom. Thus bending as well as a rotation of the forearm is possible. The drive units, consisting of motor and Harmonic Drive transmissions, are not in the arm, but are located in the thorax of the robot. Thus the mass as well as the necessary

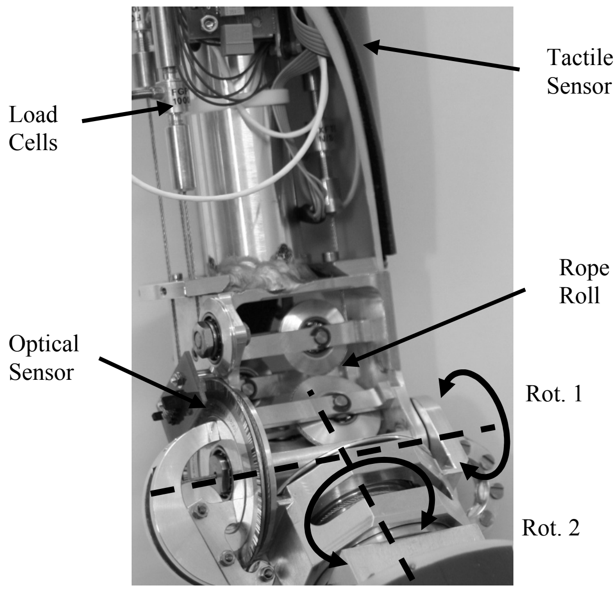

Fig. 5 Elbow joint

design space of the arm are strongly reduced, which leads to better dynamic characteristics and a slim form of the arm. The additional mass in the thorax contributes substantially less to the mass inertia than when the drive units are placed in the arm. Due to this concept load transmission is

implemented with the use of wire ropes, which are led from the torso through the shoulder to the elbow by rolls and Bowden cables. In order to make an independent control possible of the two degrees of freedom, the wire ropes for the turn of the forearm are led through the axis of rotation for bending of elbow. With altogether twelve rolls this rope guide realizes the uncoupling of the motion of bending the elbow from rotating the forearm. This solution leads to small friction losses and a compact design.
Like in the shoulder the angular measurement is accomplished by encoders attached directly to the motors as well as optical position sensors that are located directly at the joint for both degrees of freedom. In order to measure the drive torque, load cells are integrated in the wire ropes in the upper arm. As each degree of freedom in the elbow is driven by two wire ropes, the measuring of force in the wire ropes can be done by difference measurements, whereby influences on the measurement results, such as drifts in temperature, are not taken into account. A further possibility for the measurement of forces offers the tactile sensor skin, which is integrated in the casing of the upper arm.
By placing the drive units in the thorax, there is enough free space left in the arm. Therefore the electronic components for processing the sensor signals can be installed in direct proximity to the sensors in the upper arm.

3.3. Wrist joint and forearm

The wrist has two degrees of freedom. Its rotational axes intersect in one point. ARMAR III has the ability to move the wrist up and down and as well to the side. This was realized by

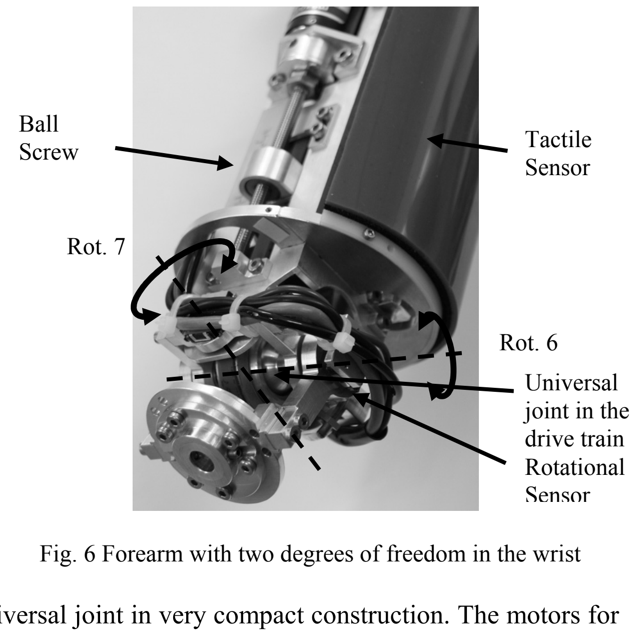

Fig. 6 Forearm with two degrees of freedom in the wrist

universal joint in very compact construction. The motors for both degrees of freedom are fixed at the support structure of the forearm. The drive train of the joint Nr..6 consists of a ball screw and a wire rope, that is driven linear by the screw nut and supports the joint via a pulley. The drive train of the joint Nr.7 hast to lead the drive power cross the rotational axis Nr.6. This is done by a universal joint inside of the wrist. This lead to a dependency of this movement to the one crossed because auf the cardan joint.
The gear ratio is obtained by a ball screw and a toothed belt or a wire rope. The load transmission is almost free from backlash. By arranging the motors close to the elbow joint, the centre of mass of the forearm is shifted towards the body, which is an advantage for typical movements of the robot.
The angular measurement in the wrist is realized by encoders at the motors and with quasi-absolute angular sensors directly at the joint. To measure the load on the hand, a 6-axis force and torque sensor is fitted between the wrist and the hand [3] (not shown in fig.6). The casing of the forearm is also equipped with a tactile sensor skin.
The support structure of the forearm consists of a square pipe. This rigid lightweight structure offers the possibility of cable routing on the inside and enough space for electronic components on the exterior at the same time.

3.4. Neck joint

The complex kinematics of the human neck is defined by seven cervical vertebrae. Each connection between two vertebrae can be seen as a joint with three degrees of freedom. For ARMAR III the kinematics of the neck has been reduced to a serial kinematics with four rotational degrees of freedom. Three degrees of freedom were realized in the basis at the lower end of the neck. Two degrees of freedom allow the neck to lean forwards and backwards (1) and to the side (2), another degree of freedom allows rotation around the longitudinal axis of the neck. At the upper end of the neck a fourth degree of freedom allows nodding of the head. This degree of freedom allows more human-like movements of the head and improves the robots ability to look up and down and to detect objects on the ground directly in front of it.

For the conversion of torque and rotational speed, the drive train of each degree of freedom consists of Harmonic Drive transmissions either as only transmission element or, depending on the needed overall gear ratio, in combination

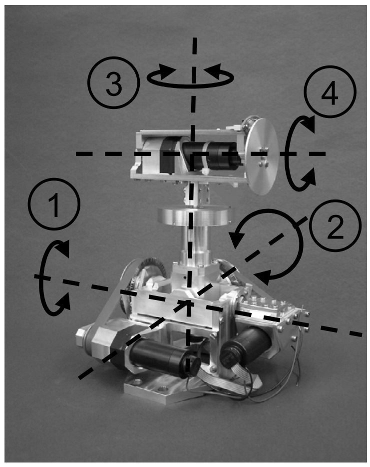

Fig. 7 Neck joint with four degrees of freedom

with a toothed gear belt. The drives are mounted to the body segment next to the joint. For this reason the joints are independent to each other. With these concepts, the drives for all degrees of freedom in the neck are practically free from backlash. The motors of all degrees of freedoms are placed as close as possible to the rotational axis in order to keep the moment of inertia small. The sensors for the angular position measurement in the neck consist of a combination of incremental encoders, which are attached directly to the motors, and quasi-absolute optical sensors, which are placed directly at the rotational axis.

3.5. Thorax

The thorax of ARMAR III is different from the other parts of the upper body. The thorax has no degree of freedom. For this reason, its design will be focused on the topology optimization and the arrangement of mechanical and electrical components, which must be assembled in the thorax. For instance the four drive units for the elbows have to be integrated in the thorax to decrease the weight of the arms. The electrical components for the upper body, such as two PC-104s, four Universal Controller Modules (UCoM), A/D converter, DC/DC converters and force-moment controllers, are also considered for the spatial arrangement.

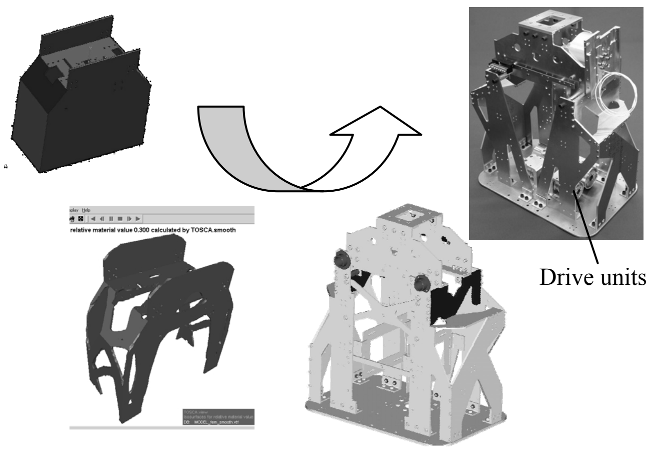

Fig. 8 Topology optimization of the thorax

The design of the thorax was determined by computer aided topology optimization and consists of high-strength aluminum plates. Not only topology optimization, but also the arrangement of components is important for the thorax design. All components were modeled and iteratively positioned in CAD model to obtain an optimized location for each component. The result of the optimizations is shown in fig.8. In the figure it can be seen that all four drive units, that are relatively heavy, are located at the bottom of the thorax to minimize the necessary torque in torso joint. All components are arranged symmetrically to balance the weight between the left and the right side of the upper body.

3.6. Torso joint

The torso of the upper body of ARMAR III is divided in two parts, the thorax and the torso joint below it. The torso joint allows motion between the remaining upper body relatively and the holonomic platform, similar to the functionality given by the lower back and hip joints in the human body. The kinematics of this torso joint does not exactly replicate the complex human kinematics of the hip joints and the lower back. The complexity was reduced in consideration of the functional requirements which result from the main application scenario of this robot in the kitchen. The torso joint has three rotational degrees of freedom with the axes intersecting in one point. The kinematics of this joint, as it is described in table 1 and fig.9 is sufficient to allow the robot to easily reach important places in the kitchen. For example in a narrow kitchen, the whole upper body can turn sideways or fully around without having to turn the platform.

One special requirement for the torso joint is, that all cables for the electrical energy flow and information flow between the platform and the upper body need to go through the torso joint. All cables are to be led from the upper body to the torso joint in a hollow shaft with an inner bore diameter of 40mm through the point of intersection of the three rotational axes. This significantly complicates the design, but the cable connections can be shorter and stresses on the cables due to compensational motions, that would be necessary if the cable routing was different, can be avoided. This simplifies the design of the interface between upper and lower body. For transportation of the robot these two parts can be separated by loosening one bolted connection and unplugging a few central cables.

In the torso joint also electronic motors are used as actuators for a homogenous drive and control concept. Due to the special boundary conditions from the cable routing, all motors had to be placed away from the crossing point of the three axes and the motor for the vertical degree of freedom (Rot.3) could not be positioned coaxially to the axis of rotation. The drive train for the degrees of freedom Rot.1 and Rot.3 consists of Harmonic Drive transmissions and toothed belt transmissions. The drive train for the degree of freedom Rot.2 is different from most of the other drive trains in ARMAR III as it consists

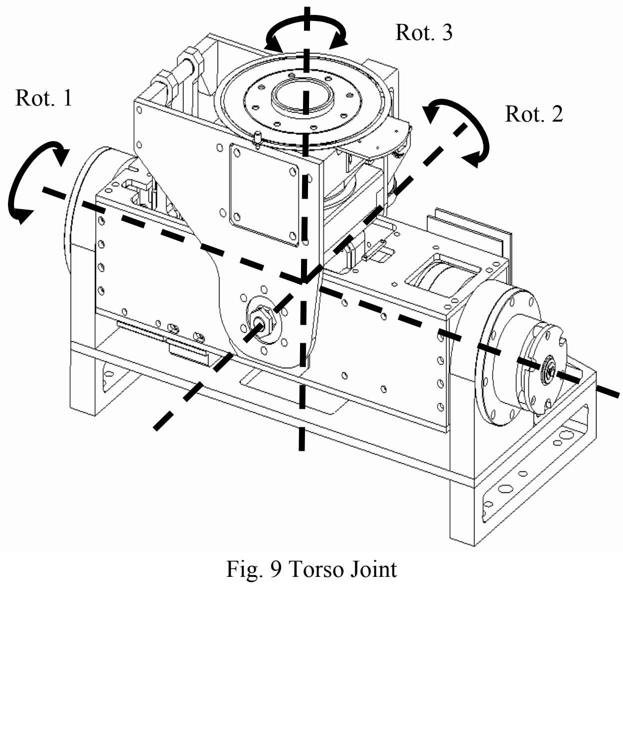

Fig. 9 Torso Joint

of a toothed belt transmission, a ball screw and a piston rod which transforms the translational motion of the ball screw into the rotational motion for moving the upper body sideways. This solution is suitable for the relatively small range of motion of 40° for this degree of freedom and was chosen because a high gear ratio can be achieved and the motor can be placed away from the driven axis and away from the point of intersection of the rotational axes.
In addition to the encoders, which are directly attached to the motors, 2 precision potentiometers and one quasi-absolute optical sensor are used for the angular position measurement.

4. CONCLUSIONS AND FUTURE WORK

The description of the individual modules of the upper body of ARMAR III showed the large complexity of this system. How described initially, this results from various boundary conditions and high requirements, which are made against a humanoid robot. A great number of these problems were solved within the development of the mechanical design. Thus for example the two arms possess seven DOFs each and show at the same time humanlike proportions and dimensions respectively. In this context also the sensor concept, providing the measurement of position, velocity and forces, can be mentioned, which represents the basis for high-quality control systems.

On basis of these results at the Institute of Product Development researches on the field of methods are undertaken which support the development process of such complex systems. The management and cooperation in multidiscipline teams or computer-aided optimization methods, capturing wide parts of the system behavior, is in the focus of these researches. By the help of these methods the next generation of the Humanoid robot is to be improved, for example regarding a further reduction of the weight.

5. ACKNOWLEDGMENT

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