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DESIGN AND DEVELOPMENT PROCESS OF A HUMANOID ROBOT UPPER BODY THROUGH EXPERIMENTATION

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The development of a humanoid robot within the scope of the collaborative research centre 588 has the objective of creating a machine that closely cooperates with humans. This development area presents a new challenge to designers. In contrast to industrial robots - for which mechanical rigidity, precision and high velocities are primary requirements - the key aspects here are a lightweight construction, prevention of hazards to users, and a motion space that corresponds to that of human beings. In order to meet these requirements, the robot must have manlike appearance, motion spaces and dexterity. Additionally, its kinematics should be familiar to the user, its motions predictable, so as to encourage inexperienced persons to interact with the machine. The design of the body of a mechatronical robot, which is intended to imitate the mechanical and sensory properties of humans, can only be realized in an intense iterative process. This article is to give insight into the development processes of exemplary mechanical constructions, presently worked on at the University of Karlsruhe (TH). The design of single body parts and their improvement will be presented. Details - why these improvements lead to a higher performance of the complete system - are discussed. This is a status report on current development in this area.

Keywords: Humanoid Robot; design; modular; lightweight.

1. Introduction

The aim of the developments discussed in this article is the design of a Humanoid Robot that is able to cooperate with humans.[1] The robot follows instructions independently - e.g. in a kitchen with tasks such as unloading a dishwasher.

The mechanical design of a humanoid robot is fundamentally different from that of industrial robots. Industrial robots generally meet the following requirements: mechanical stiffness, accuracy and high velocities. The key aspect of the movements of a humanoid robot, however, is not its accuracy, but the ability to cooperate with humans. In order to enable a robot to interact with humans, high standards are set for sensory senses for controlling these movements. Its kinematic properties and its range of movements has to be adjusted to humans and their environment.[2] In order to prevent humans from instinctively refusing to cooperate with the robot, it should resemble humans in its outer appearance and should not be able to move in a way that exceeds the possibilities of human motion. As the robot will be working in close contact with humans, it is important that it poses no threat to them. This can be attained by an elastic light-weight design and by limiting the speed of its movements. The reduction of the moving mass also leads to a reduction of the driving power. Resulting from this, smaller and lighter motors and gears can be used, thus reducing further the kinetic energy stored in the system. As a consequence, the storage of energy is facilitated.

The basic designs have been obtained mainly by using two different methods, namely: DIC (Development by Internal Competition) and Concurrent Engineering.[3] Several independent development teams competed with each other while working on the same task. These competing groups obtained the same requirements regarding the efficiency of the robot parts. This methodical procedure resulted in various, partly exotic approaches to the design of the different components (neck, arm, pan-tilt unit, hip). Advanced developments contained various, very promising concepts for the humanoid robot's individual degrees of freedom. After optimizing, the concepts that best fit together were combined and realized as a prototype. In the meantime, the second version of the components resulting from an iterative process out of the first version, is assembled. These components will be presented in this article.

2. Mechatronical body segments of the Humanoid Robot

2.1. *Concepts*

By means of the aforementioned development methods, several design concepts for the mechanism of the upper part of the Humanoid Robot's body, including sensors and actuators, could be created.

These differ in drive type and construction of the joints. However, the number and position of the degrees of freedom and the dynamics requirements of all designs are identical. The concepts (fig. 1) which will not be elaborated on in this article, resulted from a large number of previously developed drafts of the respective joints. For each complete design, the best combination of individual solutions was chosen and subsequently further developed.[4] The selection was done for each application by means of virtual experiments on movements.

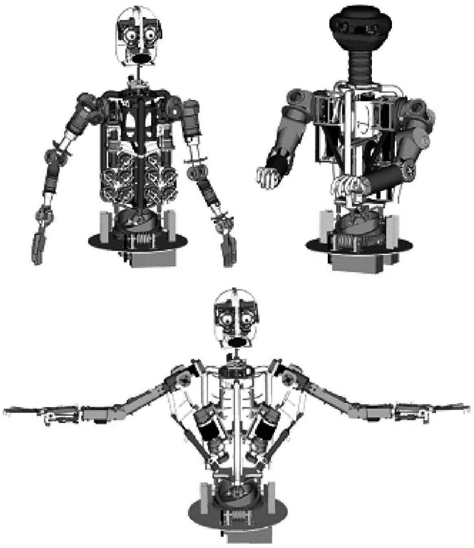

Fig. 1. Humanoid upper body concepts.

2.2. *Upper part of the body*

Fig. 2. Upper body of a Humanoid Robot.

The concepts shown above served as a starting point. The most promising parts of several upper bodies were put together, further developed and built up as prototypes. Besides the necessity to meet the requirements of each joint if the upper body is put together, the selection also considered the need for an unproblematic combination. At the present, the parts are assembled in a stiff torso (fig. 2). In the future, a joint with three further degrees of freedom will be included into the hip area of the upper body.

An elastic upper body is fixed around the main frame of the torso and is covered by a big so-called ”pullover”. This soft covering is advantageous for it can adapt to various situations. The torso is fixed on a platform that is movable in every direction. At a later stage, the robot will be built on two legs, for which the presented upper body will be used. This is why great emphasis is put, on the one hand, on a low total weight[5] and on the other hand, on placing the center of gravity as low as possible inside the upper body.

2.3. *Arm*

2.3.1. *Requirements*

The arm has 7 degrees of freedom and is able to slowly move a weight of 3 kg when extended. At full dynamics (90°/s), a mass of 1 kg can be manoeuvred safely in its hand. To attain these high dynamics at moderate driving torques, the arm and especially its moving segments are designed as light-weight structures.

The absolute position of the gripper has to be measured by angle sensors in the arm joints with a tolerance of ±5 mm. In comparison to industrial robots, these are inexact movements, but they are sufficient for the activities of the Humanoid Robot. In the future the position of the gripper is to be adjusted optically by means of cameras mounted on the robot’s head as eyes. This corresponds to the exact movements of vertebrates, adjusted with the help of their eyes. In each joint, the forces of the respective torques are measured in order to enable a load-dependent regulation. A rotational speed measurement is carried out in each degree of freedom via encoders, which are connected to the motors. The sensory parts have to meet the following requirements: low weight and minimal required construction space. This is why it is necessary to include new sensory systems[6], which, despite these restrictions make it possible to record information with a high resolution and have a good repeatability.

In order to connect the joints to the power and signal supply, the entire arm is designed as a hollow structure. The drives should be connected to the joints via oscillation-free and backlash-free drivelines. All joints are driven by servo motors because these can easily be regulated.

2.3.2. *Arm version one*

The first version of the arm (fig. 3, left arm of the upper body) achieves a light-weight design by consequently removing the driving motors from the moving parts of the arm thus contributing to aforementioned safety aspects.[7]

Three different power transmissions are used to transmit the driving torque from the motors in the torso to the joints in the arm. Different drive lines were chosen in order to gain experience in operation.

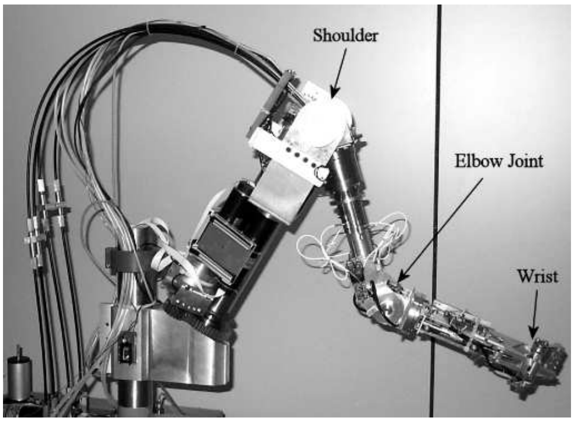

Fig. 3. General view of arm version one (seven degrees of freedom).

2.3.3. *Arm version two*

The second version of the arm was further developed from the first version and fitted in the torso as a right arm (fig. 4).

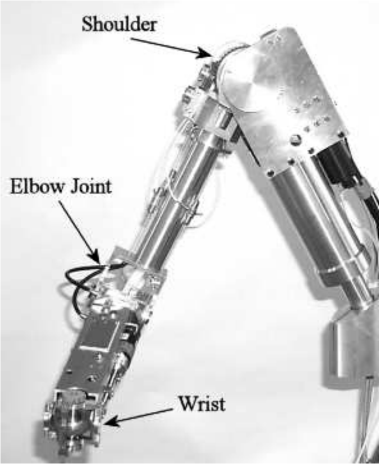

Fig. 4. General view of arm version two (seven degrees of freedom).

It has the same kinematics as the first version. Primary changes were made in the drive lines of all degrees of freedom. These further developments were necessary, because the arm showed oscillation phenomena in experiments. Due to this reason all drive lines were reduced in length and the use of spur gears or bevel gearing was avoided in the complete arm. Additionally, in order to solve the drive problems, the changes result in further substantial weight reduction. The total weight of the arm could be reduced by 49 %, and the weight of the moving parts of the arm by 34%. These changes resulted in a clear improvement of the oscillation problems, especially since the drives are connected almost without clearance. Each of these changes is presented below by comparing the joints of the two arms.

2.4. *Shoulder joint*

2.4.1. *Shoulder joint version one*

The shoulder joint has 3 degrees of freedom. These are driven by special space-efficient gear transmissions (fig. 5a) that enable to remove the three drive entities from the arm. The three compact motor-, gear-, and torque sensory units are fixed to each other. Only when the arm is moving forwards and backwards (rot. 1) do these units turn around the shaft that supports the entire arm. By reducing the moving mass, this design of the drive units reduces the moment of inertia of the entire shoulder joint for all possible movements. Precise, absolute measuring optical sensors are built in as angular sensors for all degrees of freedom. For rotation 1 and 2, these sensors could be mounted directly onto the joint. For reasons of space, rotation 3 can only be detected after a translation from the joint.

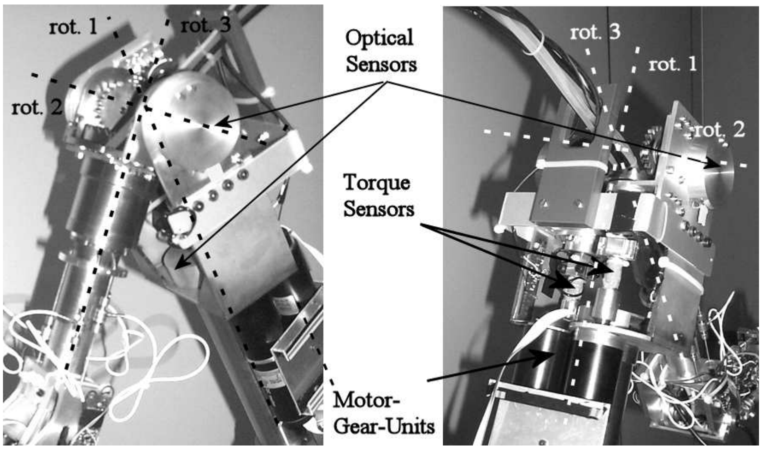

Fig. 5. Shoulder joint version one (three degrees of freedom): a) front side b) backside.

To enable a regulation of the force, the torque that is created by the drives in the drive lines is measured. Therefore a torsional wave with several DMS is mounted between the driven joints and the gear unit (fig. 5b).

During high dynamic shoulder movements, sometimes the drive train has oscillation problems. The length of the drive train is obviously responsible for this phenomenon. This is especially problematic for the adjustment of rotation 2, which is coupled with rotation 3. The other two movements of the shoulder are carried out independently.

2.4.2. *Shoulder joint version two*

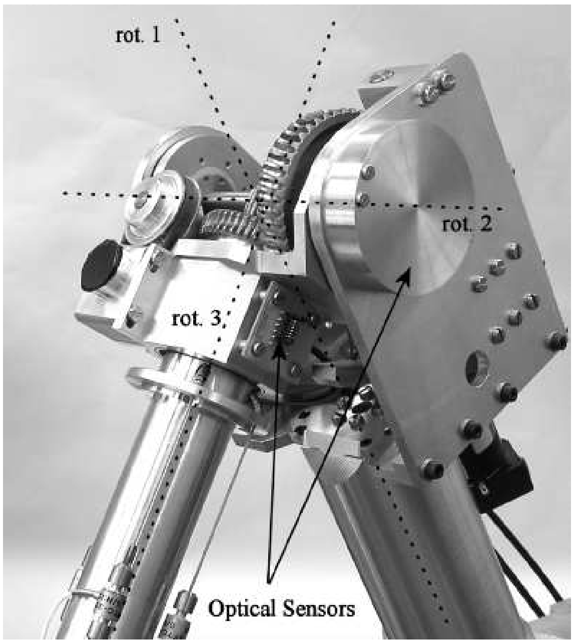

Fig. 6. Shoulder joint version two (three degrees of freedom).

Due to the oscillation problems in dynamic movements the three degrees of freedom were decoupled in the second version (fig. 6). Therefore, the drive of the upper arm rotation (rot. 3) is mounted in the arm. Instead of a planet wheel, a worm gear and a toothed belt transmission is used for translation, because these are significantly smaller and lighter components. The lifting of the arm is also driven by a worm gear and a toothed belt transmission (rot. 2). The drive for the arm's rotation around the axis (cocked 30° in the body) is integrated in the load-bearing axis. For the transmission a Harmonic Drive gear is used. All together the three drivelines of these three degrees of freedom are considerably more compact, shorter, and are built with less clearance than in the first version. This leads to a reduction of weight, better dynamics, and at the same time a smother run.

The measurement of the torque for the two degrees of freedom that are driven by worm gears is carried out via measurement of the linear forces in the worm gears. To do so, sensors equipped with DMS, decoupled from the torque via a bearing, are used. The measurement of the torque for the first degree of freedom is achieved with the use of a hollow shaft that is equipped with DMS. The shaft is located between the Harmonic Drive gear and the shoulder.

The position measurement of the three degrees of freedom is carried out by small, special manufactured absolute optical sensors that have a resolution of at least 0,1°. Due to the changes in the drive lines, the shoulder could be designed in a noticeably more compact way, stiffer, and about 50% lighter than version one.

2.5. ***Elbow joint***

2.5.1. *Elbow joint version one*

The elbow joint (fig. 7) enables the bowing (rot. 1) and rotating movement (rot. 2) of the forearm.[8] The driving motors and the transmission are relocated in the torso. Force transmission is implemented with the use of wire ropes. The motors drive a disc, around which a wire rope is wound. An external location of all drive components has the advantage of substantial weight reduction of the moving parts of the arm. This leads to a positive effect on the arm's dynamics.

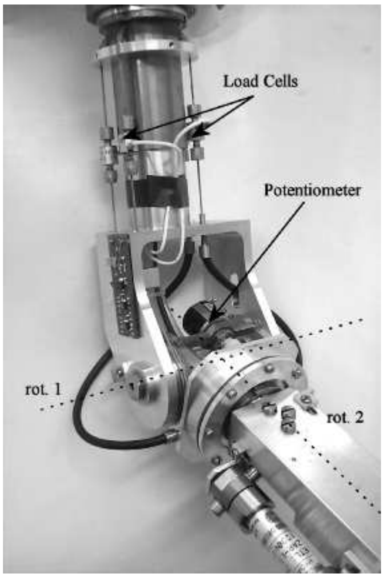

Fig. 7. Elbow joint version one (two degrees of freedom).

The angular measurement is realized by rotary potentiometers located in the joints. In order to measure the drive torque, load cells are built in the wire ropes directly in front of the joints. Yet, friction losses in the bowden cables do not influence the measurement results. Each degree of freedom in the elbow is driven by two wire ropes. Therefore measuring the 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.

During operation, in some arm positions high friction forces resulted in the bowden cables. These have to be summed up additionally for the drive motors. This happens especially when the bowden cables are guided around bends to the drive motors due to a twisted position of the shoulder.

2.5.2. *Elbow joint version two*

The basic design of the elbow (fig. 8a) joint and the sensory parts is left unchanged. Nevertheless the joint is designed in a more compact way, and by using cable sheaves (fig. 8b) the wire ropes are placed with fewer bends in the shoulder. This cable guidance reduces the bending of the Bowden cables when the shoulder is in a twisted position, whereby friction forces can be reduced considerably. It allows higher preloading of the wire ropes, which leads to a more direct drive of the axis of rotation. Due to a change of the bearing used for the rotation of the forearm, it was possible to design a smaller joint, so that the manoeuvrability to bend the elbow could be improved. By reducing the size and a better use of material, the elbow joint two could be build up 30% lighter than version one.

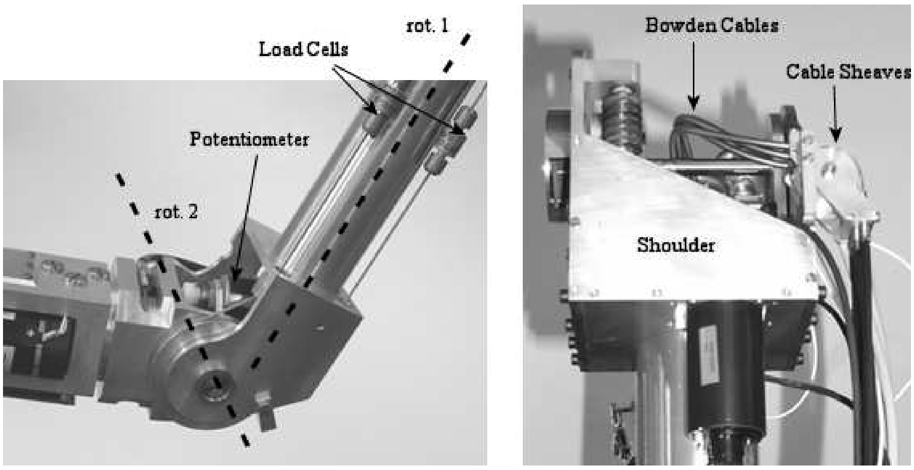

Fig. 8. a) Elbow joint version two (two degrees of freedom), b) cable selves in the shoulder.

2.6. ***Wrist***

2.6.1. *Wrist version one*

The wrist (fig. 9) has two degrees of freedom and is moved by two hydraulic slave cylinders. These are connected to the master cylinders via hydraulic pipes. These master cylinders are placed in the torso and are driven by servo motors.

The carpus is attached to frame a), which is tilted by a hydraulic cylinder in order to perform the up and down movement (rot. 1). The second cylinder is directly connected to the cardan joint and enables the alternating motion of the hand (rot. 2). The Kinematic of this type facilitates the mounting of both cylinders rigidly into the forearm, hence maintaining the forearm's slim shape in each position.

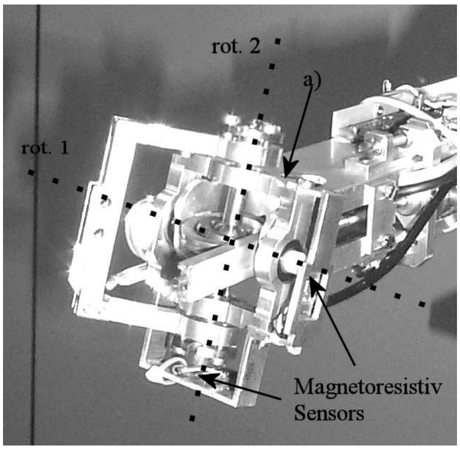

Fig. 9. Wrist version two (two degrees of freedom).

The angular measurement in the wrist, which requires comparatively the least accuracy among all joints in the entire arm, is implemented by means of magnetoresistive sensors.[9] These sensors have the advantage that they need little space only. To measure the load on the hand, a 6-axis force and torque sensor is fitted between the wrist and the hand[10] (not shown in the picture).

During operation, the hydraulic drive systems displayed problems regarding the regulation of exact repeated moves. The reason for this is the elasticity of the long hydraulic lines. Another negative aspect are leakage losses that occur in hydraulic systems that are in use. This has proved to be problematic, especially in close vicinity of electronic parts.

2.7. ***Wrist version two***

Wrist version two (fig. 10) is also designed as a universal joint: This joint-mechanism has proved to be very useful. The hydraulic drive cylinders are replaced by servo motors which are positioned directly in the wrist. Transmission is achieved by a toothed belt and a spindle. This further development contradicts previous guidelines that were to relocate the drive motors for the moved parts of the arm in the torso. However, it is justified by the lower weight of the drive motors compared to hydraulic cylinders.

In addition, by using the kinematics described above no other heavy gear has to be used. These changes result in a direct drive which displays essentially less disturbing elasticity und a reduction of weight of the forearm of 40%. Furthermore, a drive unit in the torso is not needed.

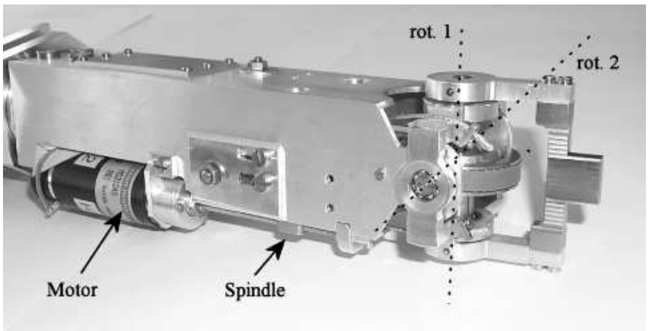

Fig. 10. Wrist version two (two degrees of freedom).

2.8. *Neck joint version one*

The neck joint (fig. 11) has 4 degrees of freedom. In the lower neck segment, the nodding (rot. 1) and tilting (rot. 2) movement is enabled by two linear guided carriages. The neck shaft is inclined by a universal joint. Turning of the head (rot. 3) is made possible by turning the neck shaft. This movement is driven by a motor below the neck. In this design, a big part of the mass is stiffly stored in the torso, having a positive effect on the system's dynamics.

An additional joint in the upper neck enables a human-like range of view. It is used for the nodding motion of the head (rot. 4), which allows the robot to e.g. look at the tip of his toes.

The angular measurement in the neck joint is implemented by resistance sensors. The neck mechanism, which effects bending motion by performing linear motion, has proved useful in several movement tests. However, it was not possible to permanently suppress the clearance in the gear connections. Nevertheless, this only leads to problems when the movements are very dynamic, because the angle is measured - independently of the drive - directly at the moving parts.

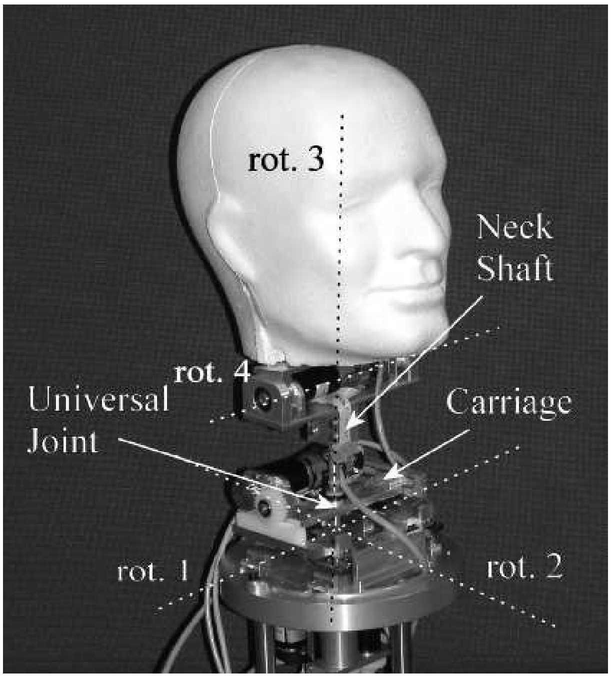

Fig. 11. Neck joint version one (four degrees of freedom).

2.9. *Neck joint version two*

Even though the kinematics in the first neck joint, which initiates the nodding and the sideways bending of the neck in linear movements, has proved very useful, the kinematics of the second neck version have been changed. These changes became necessary in order to avoid the clearance that appeared in the drives of the first version. The basic joint of the lower neck region is a cardan joint that is directly driven by two electric motors with an Harmonic Drive transmission. Based on the kinematics the angular movement for nodding and bending the neck was increased to ±45°. Turning of the head is enabled by a drive unit in the spine. The kinematics and the sensory movement for the fourth degree of freedom remain unchanged (fig. 12).

Changing the joints also had positive effects on the angular sensory movement, since the neck angles now can be directly measured by high-resolution, optical sensors that can be adjusted at the cardan joint. This basic change in the concept of joints in the lower neck segment allows the determination of the position of the head with a resolution of 0,1° and motion without clearance. This accuracy is needed for image recognition with a stereo camera system that is implemented in the head.

The neck of the second version is produced at the moment, therefore no pictures

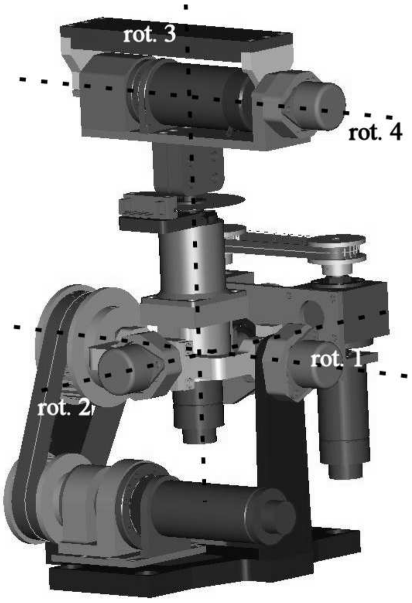

Fig. 12. Neck joint version two (four degrees of freedom).

but only CAD illustrations of the entire construction are available.

2.10. *Pan-Tilt Unit*

For image recognition, mounting a high resolution digital stereo camera system in the robot's head is planned. The two cameras can be moved independently of each other by two camera movement units (Pan-Tilt Units) for two degrees of freedom (fig. 13). In order to be able to conduct distance measurements with the help of the cameras by triangulation, a positional accuracy of less than 0.1° is necessary. The orientation of the cameras toward different objects is possible in less than 0.1 s, which represents an angular velocity of more than 1200°/s and consequently requires high angular acceleration. These high dynamics are made possible by separating the motors from the movements. The required measuring accuracy is obtained by means of highly resolvent optical incremental encoders. In this case, the necessity for a reference run after each start-up (i.e. a short "rolling of the eye" when "waking up") is considered acceptable.

The separation of the driving motor from the camera's movement is enabled by a gear, which effects a horizontal movement of the camera via a hollow shaft. A second shaft is guided by this hollow shaft and effects vertical movement.

In order to be able to integrate the Pan-Tilt Unit without problems into the head of the robot in the future, the angular measurement device will be redesigned as an open system without a casing. By doing so, it will be possible to use smaller

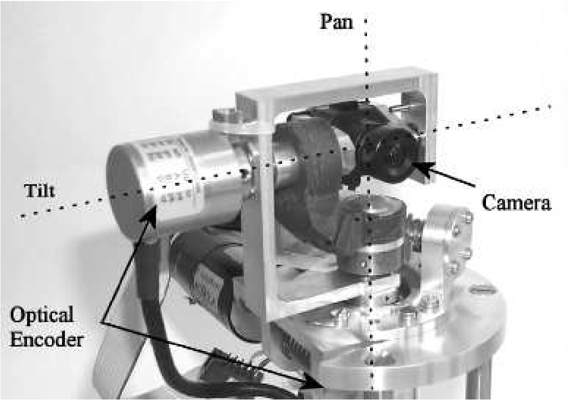

Fig. 13. Pan-Tilt Unit (two degrees of freedom).

drive motors due to reduced moments of inertia.

3. Summary

This article presents the iterative developing process of humanoid robot parts. These body segments were designed and built at the Institute of Product Development at the University of Karlsruhe (TH).

The first concepts of the upper body of a humanoid are shown. From these concepts the first segments were built as prototypes in an evolutionary process. The design concept of these parts, especially the arm and the neck, is introduced. The problems which occurred during high dynamic operation of these body segments are explained, and details responsible for these effects are discussed. These experimental results led to the design concept of the next version. The joints of the second version of the arm are compared with the former versions.

Furthermore the build up of the Pan-Tilt Unit is represented.

Acknowledgments

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