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MECHATRONICAL DESIGN OF A HUMANOID ROBOT IN AN EDUCATIONAL PROJECT

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1 Introduction

The development of a Humanoid Robot within the scope of the collaborative research centre 588 has the objective to create a machine that closely cooperates with humans. This leads to requirements such as low weight, small moving parts (no potential danger for persons in case of collision) as well as appearance, motion space and work movements following the human example. One reason for the last point is the requirement for the robot to operate in surroundings designed for humans. Another aspect is the acceptance by technologically unskilled users, which is likely to be higher if the robot has a humanoid shape and calculable movements.

A Humanoid Robot is a highly complex mechatronical system, as the functional requirement can be achieved only by the interaction of mechanical components with extensive sensor technology, state-of-the-art actuators and highly developed software. The development of mechatronical products is a major field of research in our institute.

2 Product design methodology for mechatronic systems

Successful development of complex mechatronic systems is only possible in a close cooperation of specialists of the involved fields of mechanics, electronics, and information technology (fig. 1). Discipline-based partial solutions cannot provide - or only with significant delay - the desired result.

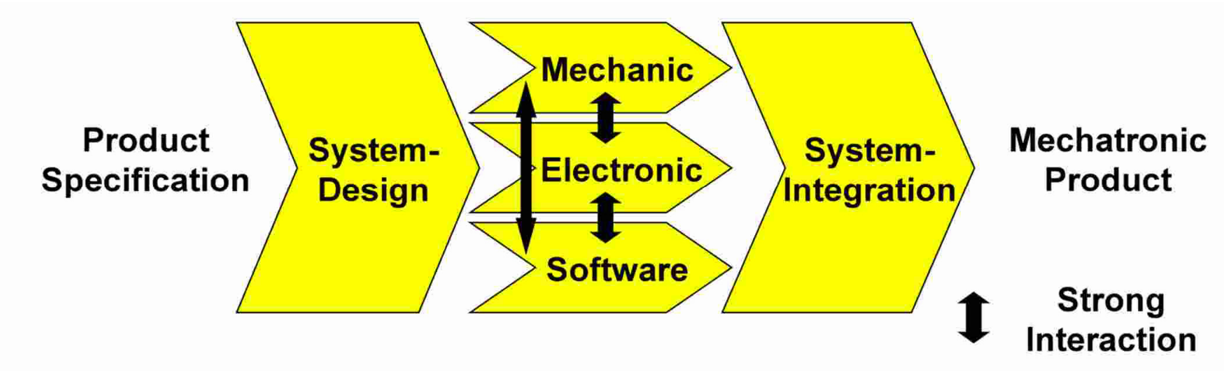

Figure 1. Product design methodology for mechatronic systems

The development process of technological systems can be carried out according to the V-model (fig. 2) [2]. After analyzing all demands on the total system it is divided into subfunctions and subsystems that are developed simultaneously (left branch of the V-model). After verifying the subfunctions and testing the subsystems (e. g. the robot wrist including all actuators and sensors), these subsystems are gradually integrated and the initial operation phase can begin (right branch of the V-model). The working structures with the necessary working surface pairs and connecting channel and support structures are defined according to the element model “working surface pairs & channel and support structures” developed at the Institute of Product Development [3].

The development of technological systems is originally an iterative process involving the development of physical and mathematical models. These models help to verify hypotheses, to simulate and therefore to predict properties of the future system. Additionally the model helps to gather information – which in this state is not available – about the real system, e.g. the tensile stress of certain design components. Due to the complex hybrid structure, model development and simulation are of even greater significance with regard to the mechatronic product development process. As tools and software are much discipline-oriented and often cannot communicate with another, the process is even more difficult. This is an important research task in the field of mechatronics. The over-all solution, which is still in the conceptual and design phase of the developing process, can contribute to the build-up of the prototype. This is the current state of the Humanoid Robot at the University of Karlsruhe. The design is also an iterative process, into which experiences from preceding development stages are to be included.

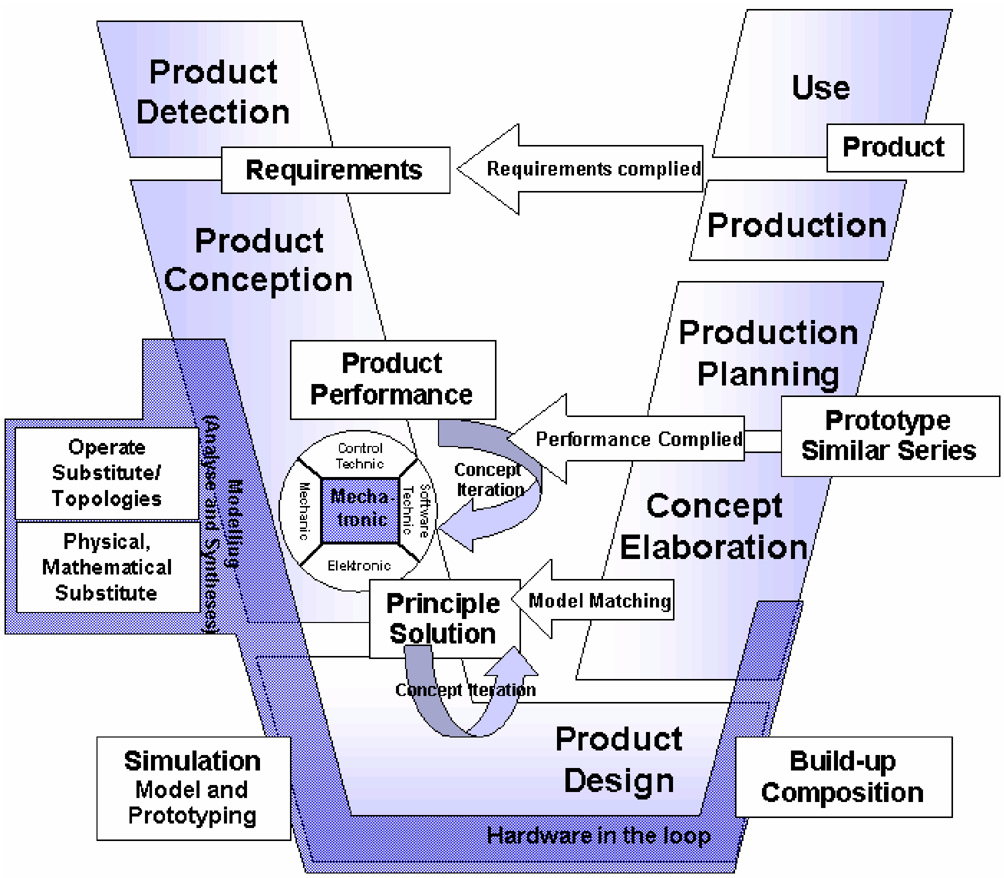

Figure 2. V-model. Reference for developing mechatronic products

2.2 DIC-method, team-oriented development with internal competition – development of designs

The DIC-method (Development by Internal Competition) is a way to increase the efficiency of team-oriented development processes. The incentive of internal competition between development teams of the same task is used for finding the optimal solution.

Several development teams consisting of specialists in all involved subjects worked in competition in order to develop concepts for several subsystems of a Humanoid Robot during a period of approximately six months. By using the approaches of concurrent engineering and the DIC-method, a large number of different solutions were developed. Each of these concepts consists of a multitude of component solutions for the mechanical structure of individual joints, sensors and actuators. This large number of conceptual suggestions is the basis for the currently continuing development.

By means of the aforementioned development methods, several designs for the mechanism of the upper part of the Humanoid Robot's body including sensors and actuators could be created (figure 3). These designs have different types of actuators and different designs of the joints. The number and position of the degrees of freedom also the dynamical requirements of all designs are identical. The designs, which will not be elaborated on in this article, resulted from a large number of previously developed drafts for the respective joints. For each entire design, the best combination of the single solutions was chosen and further developed. The selection was made by the means of virtual experiments on the movement for each kind of application.

The major development subject of the Humanoid Robot's upper body is the arm [4]. The arm in this project has 7 degrees of freedom. Maximum speed of the rotary motions of the arm was set to 90°/sec. It is able to hold a mass of 3 kg in hand and to move 1 kg with full velocity. However, the demanded positioning accuracy of the gripper is not as high as it usually is with industrial robots. For positioning the hand, an accuracy of +/- 5mm is sufficient. The drive torque in every joint is measured to enable force control [5].

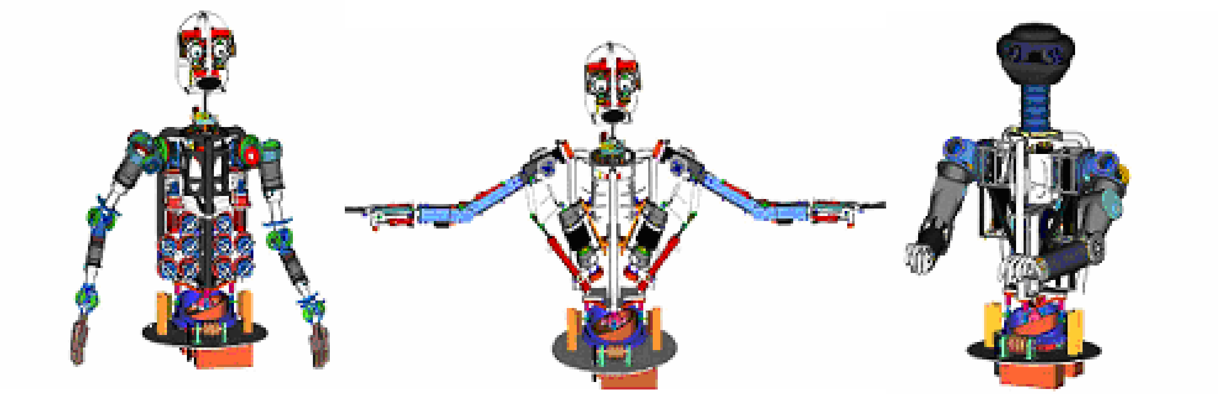

Figure 3. Designs of the Humanoid Robot's upper body part

3 Design of the prototypes of the first version

3.1 Arm

Three different designs of the arm were created by students in the aforementioned educational process. These designs were combined with the help of the students as part of their graduated studies of mechanical design [6]; the result was the construction of the arm. This arm could be further developed using the knowledge that was documented in the development process. This procedure strongly enhanced the performance of the arm. The progress of arm design is shown in figure 4.

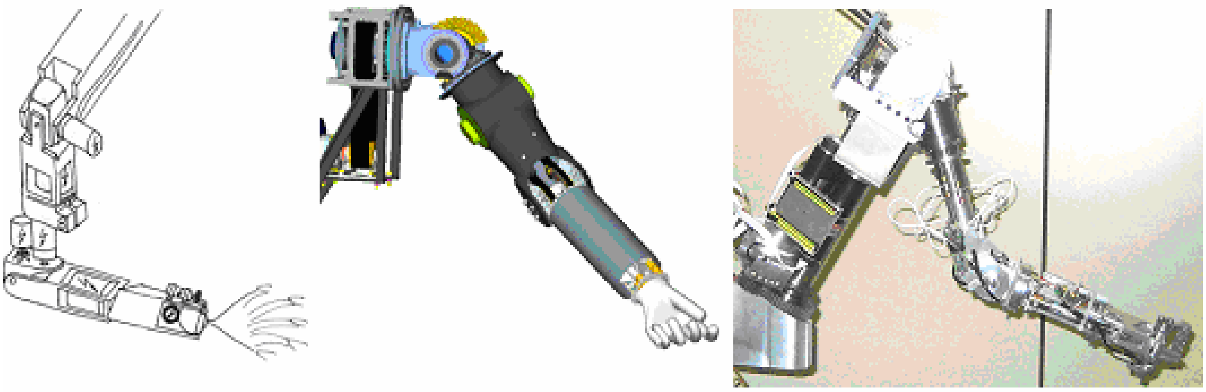

Figure 4. Arm with 7 degrees of freedom

3.2 Neck

The neck has four degrees of freedom. Three of them are located in the lower neck part and enable the head to bend forward, backward, sideward and to rotate. The upper neck part is to enable the nodding movement. Each neck joint is provided with precise absolute angular sensors.

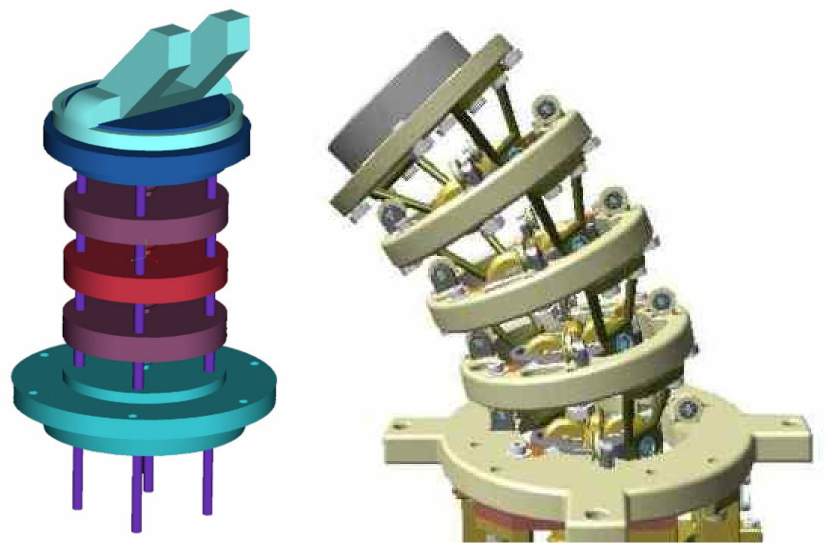

Figure 5. Vertebra robot neck, design, draft

For the design of the neck, similar to the procedure of designing the arm, several teams of students competed according to the DIC-method in solving the same development task. The working atmoshere was very productive and led to obtain several interesting solutions. One type of neck has to be mentioned here in particular: it was designed similar to the neck of a vertebrate. The single vertebra disks can twist relative to each other in a small angular range (fig. 5). However, this design was not further developed because it is not likely to deliver the necessary angular accuracy. A different neck design was further developed instead and assembled as a prototype (fig. 6). This mechanism drives the nodding movements of the neck by two linear guided carriages.

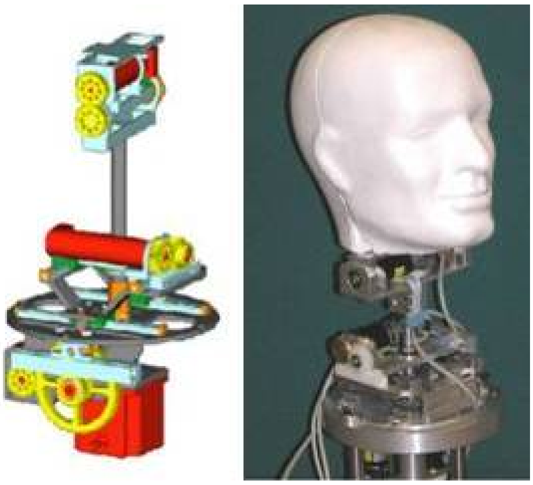

Figure 6. Neck; design, prototype

3.3 Pan-tilt unit

Another focus was set on developing a new pan-tilt unit that equips the eye or the camera with large dynamics for two degrees of freedom. According to the instructions, the camera can be set from one direction to the opposite in 0,1 seconds, a fact that leads to a very large angular acceleration.

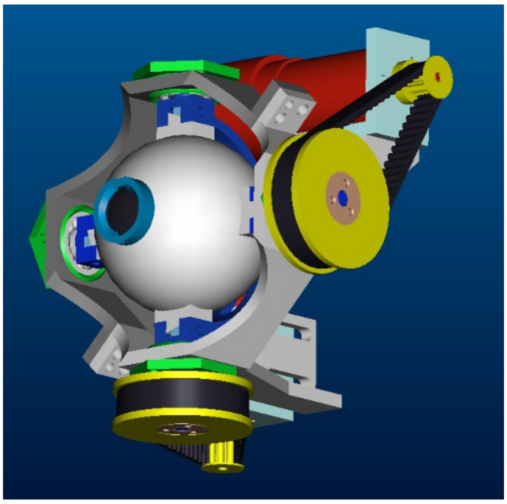

Figure 7. Design of the pan-tilt unit copying the human eye

The competing students developed several interesting designs. One of these designs tries to copy the human eye (fig. 7). A camera, representing the pupil, is fixed in a sphere similar to the human eyeball. The eyeball can be moved with the required dynamics with two degrees of freedom.

This design has not yet been assembled as a prototype because in the first place a solution was sought that guarantees a secure function. In the case of this design, the problem of the sliding bearing of the sphere was not completely resolved for the necessary angular acceleration. Instead, a pan-tilt unit that is based on conventional mechanics was developed up to a prototype stage. An important step in this design was the relocation of the drive units away from the movements.

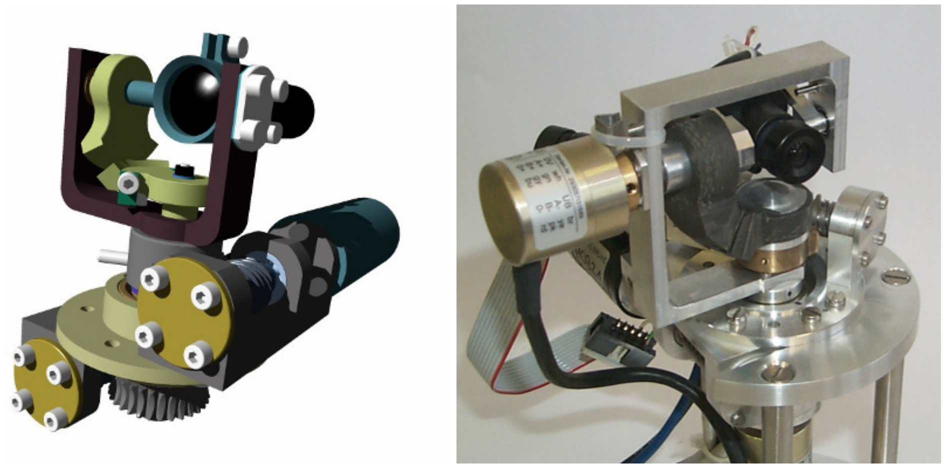

Figure 8. Pan-tilt Unit; design, prototype

4 Improvement of the prototypes by means of a new development methodology for Humanoid Robots

4.1 Development methodology for Humanoid Robots

4.1.1 Specification of the target system

This method [7] is based on the conventional V-model for mechatronic products, but was refined for the specific use to develop the body parts of Humanoid Robots [fig. 9].

The target system of Humanoid Robots depends on the tasks that the robot has to carry out and the additional properties it should possess. The kinematics of the total system are based on the kinematics of humans, but concerning the number of degrees of freedom, which is reduced to a minimum in order to limit the effort for the design and regulation of the robot. With the help of the basic regulation concept, with which the Humanoid Robot has to operate, the necessary lines of dynamics and sensors are determined.

The specification of the target system of Humanoid Robots is achieved by splitting the solution-neutral requirements among the subsystems joints, actuators and sensors. Additional requirements, such as providing construction space inside the body or applying a tactile skin, are considered in every development step.

4.1.2 Specification of the object system

This stage of the development process concerns about the design of subsystems – joints, actuators and sensors. So far, the construction requirements have been already collected and defined. In order to carry out the whole development process, optimal time and result, the subsystems must not be independently developed and finally combined to other subsystems, because many troubles become visible only after their combination. Instead, to avoid that problem, it must be carefully considered with other important systems during the development. From this method, a functioning total system is guaranteed and a pre-selection of the components is running effectively. To obtain the conceptual pre-selection, preceding knowledge of specifications of components is now considered, not only to classify but also to select the varieties that can be integrated in the related system. For example, during the selection of the actuator, the type and specification of the force sensor must be examined to perform force measurement in the drive unit and then, in the next step of development, a specific force sensor will be finalized. This procedure ensures that the desired data can be correctly measured from the drive line.

The joint selection, which can be constructed with the MKS-System, is the first subsystem being specified in this development. This is due to the fact that it has the largest influence on the total system. In order to complete the joint selection, at first, drive principle, angular sensors and bearing structure are designed abstractly. And then the driving units and their torque and velocity transmission will be determined. The force and velocity sensors are conceptually determined for this step as well. The real existing sensors can be now integrated into the system, which depend on a multi-body system of real joints and drive units.

After this step, all design of components of mechanics, actuators and sensors are determined, also the bearing structure, which previously was only vaguely determined, can be finalized.

4.2 Application in the education

For further development of the components, the students used the method described in chapter 4.1. This development method, which is presently being improved at the Institute of Product Development, is very suitable for the application in educational projects where the basics of intense teamwork are taught. This procedure led to very interesting results that are presented in the following. The students applied the method remarkably, evaluate objectively the advantages and disadvantages of the different partial solutions and also examining the solutions of the previous version.

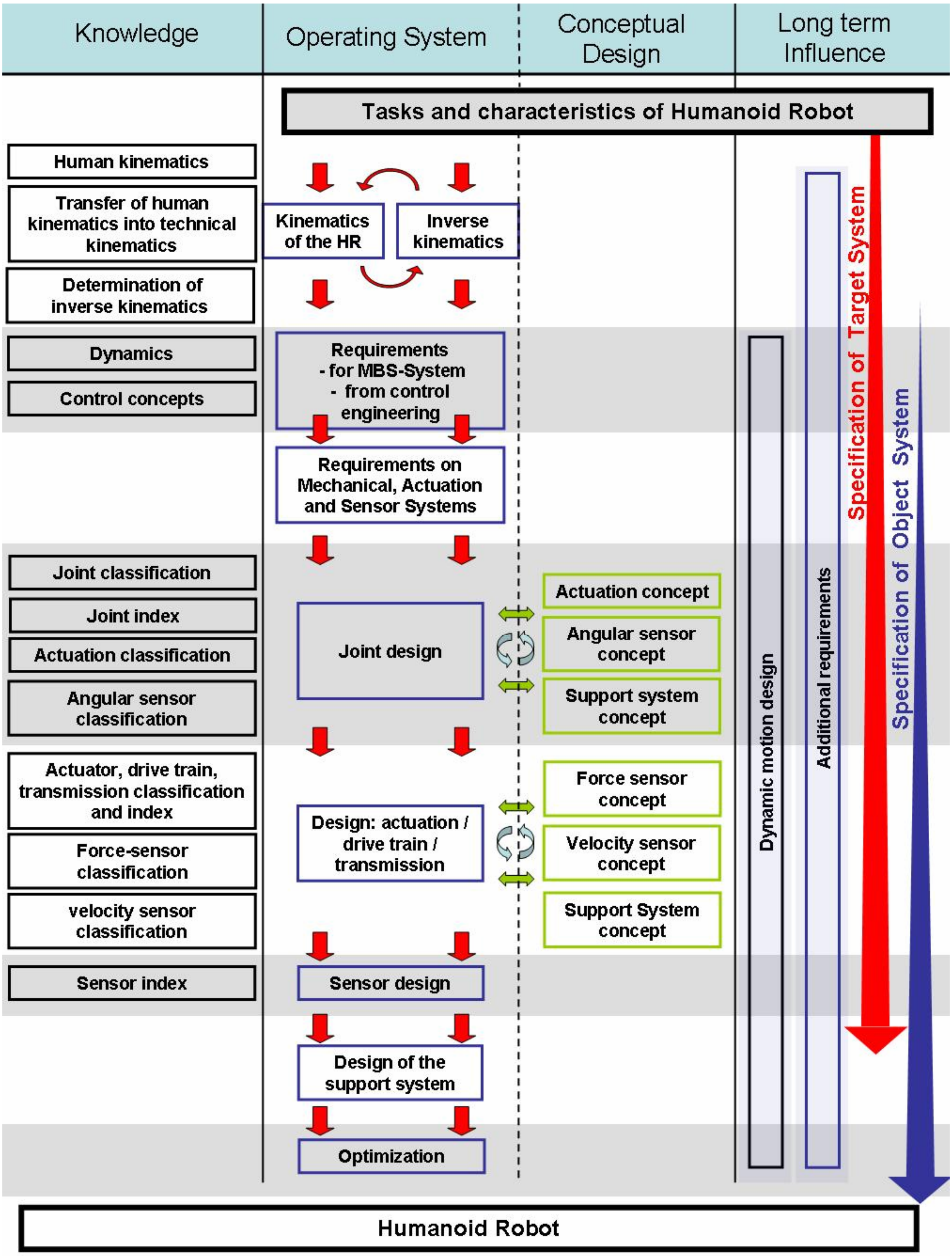

Figure 9. Development process for the body of Humanoid Robots

5 Further development of the body parts of the Humanoid Robot

5.1 Arm

With the help of the aforementioned development method, an improved stage of the arm was designed [7]. It has the same number and orientation of degrees of freedom as the previous model, but its total weight is reduced by half. The dynamic behaviour was improved and the joints can be controlled more accurately

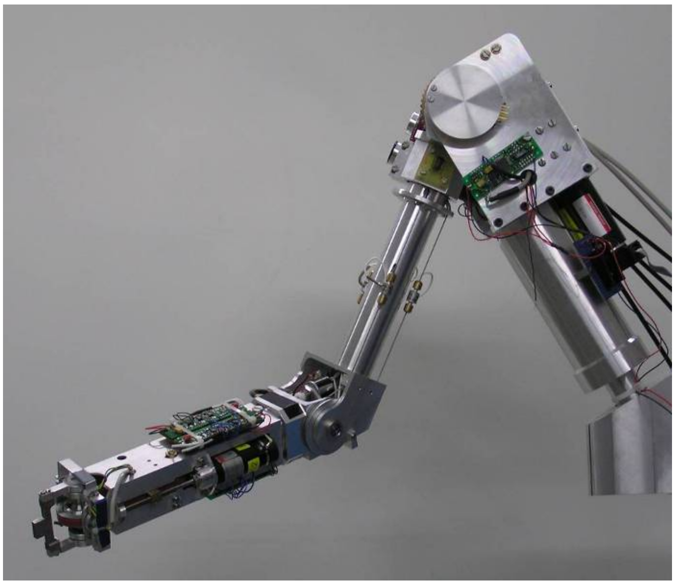

Figure 10. Robot arm of the second generation

The remarkable reduction of the total weight of the arm was made possible by evaluating all of the subsystems while considering their interaction.

For example the wrist: the arm of the first version was designed actuator-free, i.e. all drives were removed from the arm and placed in the torso, so that the moving parts of the arm were made lighter without the weight of the drives and the gears. The wrist is a cardan joint with two degrees of freedom that was driven by two hydraulic cylinders in the first arm version. The pressure was generated in the torso with electro motors. In the second arm version [8], the improvement was not achieved by changing the joint, but by differing from the precondition to remove the drives. As opposed to this until then basic principle, two drive motors were reintegrated into the lower arm. The additional heavy gears could be replaced by a refined combination of spindle- and cable pull transmission (or serrated belt transmission) fig. 11). Altogether, the stiffness of the drive unit was hereby significantly increased and the total weight was also reduced because the electro motors weigh less than the hydraulic cylinder.

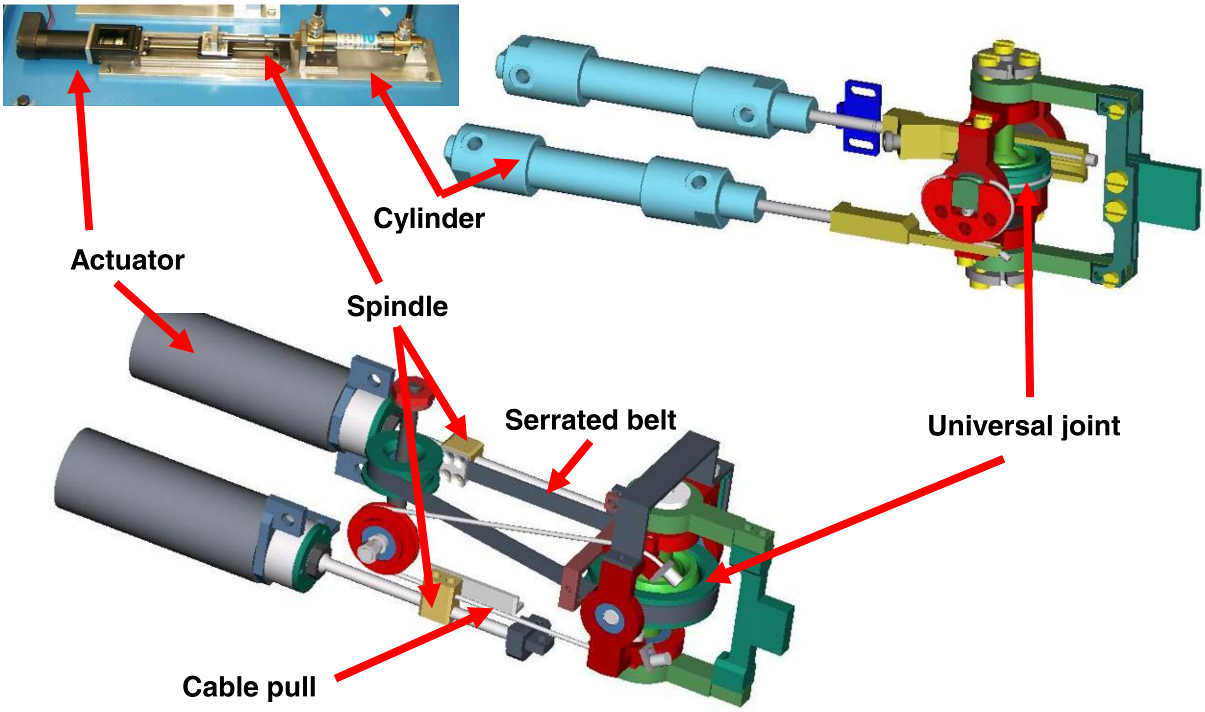

Figure 11. Top: wrist and drive unit of the first generation removed to the torso; Below: wrist and drive unit of the second version

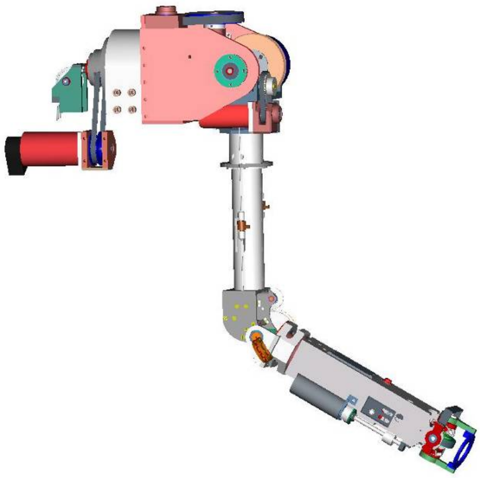

Figure 12. Virtual arm of the third generation

In the meantime, a further development of this arm was able to be designed virtually within the scope of another student project (fig. 12). The most important change here was a scaling down of the shoulder drive mechanics. This reduction was achieved by a horizontal alignment of the shoulder's axis of rotation that had led diagonally into the body in the previous version. The changes resulted from another orientation of the principally similar kinematics in the shoulder. The gear unit, including the force measuring, was shorter for the reduced available space and the drive motors for this degree of freedom were stored in another level by means of a serrated belt.

5.2 Neck

The methodical development process also supported the further development of the neck. Clearance problems which occurred in the drive lines during operation of the older version, had to be eliminated. The joint kinematics functioned according to an innovative principle (see fig. 6), in which linear movements induced the rotary movements of the neck. In spite of this, the next generation has totally different joint mechanisms (fig. 13), because the previous generation cannot be driven with newly designed, clearance-free drive systems. Altogether the new neck unit is a clear improvement in comparison to the previous model.

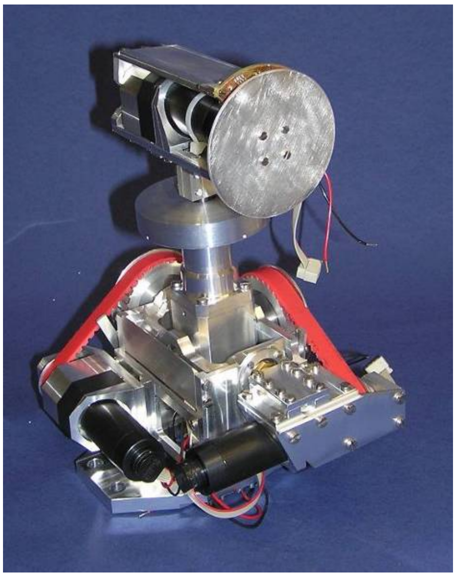

Figure 13. Neck unit of the second generation

5.3 Pan-tilt unit

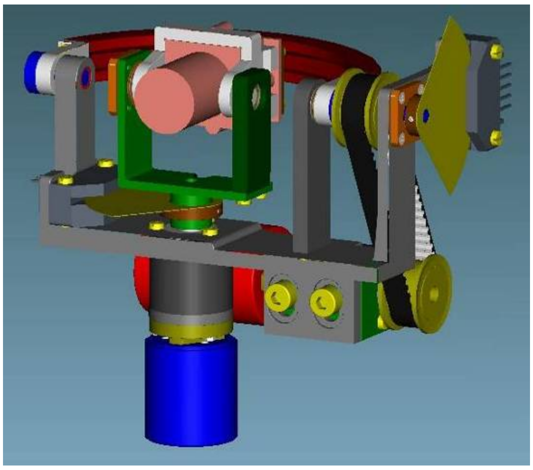

Figure 14. Pan-tilt unit of the second generation

In the first version of the pan-tilt unit (fig. 8), a clearance in the drives occurred during operation that complicated the exact orientation of the camera. In the second version, this clearance had to be prevented and the moving mass had to be reduced.

The systematic application of the developed method presented above resulted in a completely new design for the pan-tilt unit [9]. The kinematics and the connection of the joints with the drive were changed (fig. 14). The significantly smaller, exactly optical angular sensory parts were decoupled from the motions, a fact that led to a substantially smaller rotation mass.

6 Conclusion

This article presents how the mechatronic parts of the upper body of a Humanoid Robot were developed within the scope of several student projects. The applied development methodologies are described and the achieved results are presented. At the Institute of Product Development, a specific development method for the mechatronic components of Humanoid Robots is being improved on. By means of this method, a basic further development of the robot components was carried out within the scope of a student project. The changes achieved by the method are demonstrated by means of examples.

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