Advanced Re-Engineering Approach in Humanoid Robot Development

[Sebastian Feldmann]

Abstract—**Based on new findings from human communications research, which show that in a social environment robots are accepted only if they are able to perform natural human movement, this contribution presents a new approach to improve the development process of humanoid robot prototypes under the term of social acceptance. Using the examples of the human shoulder- and the human hip-movement, there will be examined how the concept of re-engineering can be introduced at humanoid robot development in early stage. It is demonstrated how the inclusion of knowledge about the anatomic basis of human movement can help to overcome major problems of acceptance currently discussed by the literature under the term Uncanny Valley.**

Keywords—**Re-Engineering, Humanoid Robot, Uncanny Valley, Skeleton, Development**

I. Introduction

Humanoid robots are going to become more and more part of today's social live. Current prototypes are able to perform autonomously a series of complex decisions; therefore they can operate independently in various difficult situations. However, a humanoid robot that is to be used in a private environment or e.g. in hospitals can do its job only if it is also accepted by the human partner.

Today's robots got various disadvantages at their motion capabilities. As research has shown, even smallest nuances in dynamic motion and posture can make a big difference as to whether a humanoid robot is conceived as sympathetic and interesting or whether it will elicit a negative emotional response from the perceiver. Clearly, the best technological properties are of little help if no one is willing to spend money on them because of the negative attitudes they provoke. Until now, the question whether a dynamic motion elicits positive or negative approval ratings from the perceiver, was hardly considered at the early stage development. Deficiencies in appearance resulting from the dynamic motion were tried to overcome by an improved appearance. This works well at the static case, but during dynamic motion, the human eye subconsciously recognizes the smallest deviation from what it feels the proper human way to act. The problem is compounded by the fact that the aversion induced by the way a robot moves increases the more its appearance gets human-like.

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This seemingly paradoxical phenomenon, known today under the term Uncanny Valley, was first noted by the Japanese roboticist Masahiro Mori in 1970 [1] Surprisingly up to the present day, humanoid robots causes major problems of acceptance with the broad public. The biggest challenge in future development process is the problem that the Uncanny Valley only becomes visible at the moment the finished system starts dynamic action. At this point, subtle discrepancies with typical human movement will become visible. It is argued, that exactly these differences have to be remedied at the beginning of each robotic development process. The objective here is to introduce an innovative and consistent concept that provides the possibility to overcome fundamental problems at humanoid robot prototype development in order increase the acceptance by the human counterpart. These issues can be justified in anatomical, technological or controlling characteristics.

II. Realistic Human Skeleton Motion vs. Robot Prototypes

A. Fundamentals

At a first point the question should be examined to what extent and in what detail genuine human motions can be reproduced in order to keep a human-like appearance of a humanoid robot prototype.

Figure 1. Influence of lateral head-flexion at estimation of another person, "The Madonna del Magnifican" painted by Sandro Botticelli (left), changes in front of our eyes from a humble and modest woman to a confidently mistress - Just by moving the sloping head into an upright position (right) [3]

In the year 1999, S. Frey already demonstrated at his findings that an observer strongly responses at one specific aspect of human communication theory: When an actor moves his head in a particular manner. A head tilt at just a few degrees causes in totally different reactions by the human observer. A person that was attributed with words like gentle and empathic will now be described with abhorrence and arrogance, as shown in Fig.1. This subconsciously statement was met spontaneously

and independent from any culture all over the world [3]. This short example clearly demonstrates in which way the human eye influences how we asses other persons by visual perception. The risk exists, that if a humanoid robot is not able to perform this lateral head flexion, it might cause in serious adverse reactions by the human observer. This small effect then makes the difference to fall into Mori's Valley or not. Equal effects can be observed at other important joints like shoulder, hip or body posture. The human knee rather performs an active rolling at transversal axis around the Condyles/Condyles lateralis, $\theta_{TA}[0° \ to \ 150°]$. This generates a rolling-offset that is small enough, to not being recognized by the human eye. Examined more closely, there can be seen, that there is not only a point rotation at one fixed axis at all. Thus it is totally sufficient to ignore this motion difference and keep the point rotation for implementation into a robotic knee joint at this case. Contrary the head-, shoulder- and hip-joint, is certainly an important area to support human appearance at the dynamic motion.

B. Typical Problems at current humanoid robot Prototypes

Fig. 1 implies that slightest nuances of the human body's posture decide about the first impression at any human observer. If and what kind of human motion can be reproduced by the humanoid robot strongly depends on certain conditions at the robots structure. The following *eight fundamental factors* for deviation from the human motion have been identified:

- Available degrees of freedom *(DoF)*
- Arrangement of each joint
- Dimensions and weight of the effectors
- Drive performance
- Backlash at gearbox and joints
- Trajectory planning and controller
- Elasticity of the basic structures
- Sensors accuracy

There are several good examples for missing DoF's and insufficient arrangement of the robots joints. At the humanoid robot platform KHR-2 [2] or MAHRU [4] the difference between functional structure and missing human movement capabilities can be displayed in a very good way, e.g. Fig.2. The problem of the dynamic motion control has been solved outstandingly. The robot is able to walk autonomously and perform several tasks with his arms. However, looking at the human likeness during complex dynamic motion reveals a serious difference to natural motions. Certainly the purpose of constructing this kind of robot was to create a autonomous two legged robot. But this example descriptively illustrates the deficits at a number of several common robotic prototypes. The shoulder-joint, Fig. 2.A, constitutes a typical robotic shoulder joint with *2 DoF* (rotation, pivoting). Furthermore the joint is attached exterior to the robots torso. Thus it does not obtain the necessary degrees of freedom, angle of movement and the para mounted movement of the human clavicle, e.g.

Fig. 3. The neck area doesn't provide the possibility to manipulate the head in a human way. Further examples of parts with insufficient movement capabilities can be seen at Fig. 2 D/C. MAHRU is controlled by a human operator and a motion capturing system in real-time. As easily can be seen, the movement capabilities of the arm are limited to less dimensions and different arrangement of joints, than the human ones [4]. This leads to a high invariance between the captured data-set and the final robot motion. Nonetheless it's appearance was celebrated euphorically.
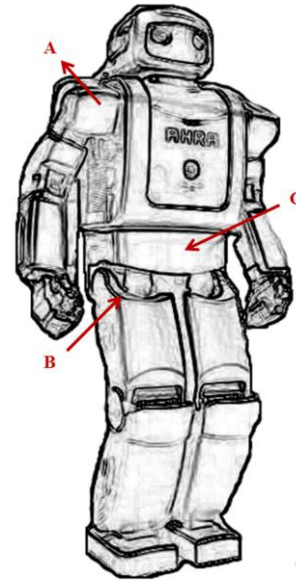

Figure 2. Current problems in the execution of humanoid motions shown at the example of humanoid Robot developed by KIST, A: Insufficient DOF at the shoulder joint B: Insufficient movement possibilities at Hip-Joint C: Missing Pelvic Joint D: Missing Neck Joint, in accordance to [2]

The relevant question therefore is: What exactly is the reason that the robot generates such a high acceptance at the human observer? And why doesn't the robot fall into the Mori's Valley? The reason is that this robot doesn't even look very human-like. And that's exactly the reason why people excuses mistakes and tolerate insufficient motion behavior. They don't even expect the same motions that a real human being would perform.

Of course this is an example of a very functional robot-prototype layout. Several studies exists that are dealing with anthropomimetic robots tin order to imitate the whole human musculoskeletal system and its motion capabilities, e.g. ECCEROBOT [5] or the human-like robotic arm invented at the University of Osaka [6].These prototypes recreates the human skeleton structure closely. But most of the published articles refer neither detailed information about sizes nor information about motion angles or even degrees of freedom. It remains to be seen if these robot prototypes meet the necessary requirements of human motion. Especially the dynamic behavior might be a problem.

The concept of HUMECH (Chair of Mechatronics, University Duisburg-Essen) especially was designed to investigate theories of human communication in order to give realistic

approach in reproducing human motions. At a first step the human skeleton structure has been investigated. In particular the human shoulder is a structure of joints with the largest range of motion at the human body [7]. It consists of overall 3 individual joints. Important to mention are [8]:

- Sternoclavicular-joint: Joint between clavicle (collarbone) and sternum (breast-bone) (Fig. 3.b);
- Acromioclavicular-joint: Joint between clavicle (collarbone) and scapula (shoulder-blade), (Fig. 3.c);
- Glenohumeral-joint: The actual shoulder-joint placed between humeral head (upper arm) and the articularsurface of the scapula (shoulder-blade), the glenoid, (Fig3.a);
- Scapulothoracal lubricating layer: Sliding of the scapula (shoulder-blade) at the back of the thorax (chest). Attached to the shoulder flows the humerus (upper arm).
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Through the inclusion of the clavicle-movement possibilities, a significantly larger movement range is provided to the human upper arm. As a disadvantage this goes to the detriment of the stability. Are these significantly relevant joints of the robot not arranged exactly at the original position of the human body, humanlike movement-trajectory cannot be reproduced. Similar to this, the dimensions, the *DoF*'s and the possible movement angles at the shoulder joint influences the workspace of each robot kinematics. As shown at Fig. 3 the human shoulder provides *3DoF* at each clavicle joint. In addition to this, there exists a kind of actuation offset that widely expands the possible workspace of the endeffector (human hand). This extended actuation offset causes in many well-known problems at implementation into a robot. Furthermore these actuators need equal mechanical characteristics to provide the same acceleration and transmitted forces like the human being. This causes in one of the key problems due physical restrictions.

Nowadays, there are a number of possible propulsion concepts like solenoids, DC-, Servo-motors, Hydraulic and Pneumatic Cylinders. However compromises have to be made on propulsion power, moving angle and possible dimensions. Fig. 2.B displays further typical differences from human (Fig. 4) to robotic movement capabilities. Due increasing costs, simplified calculation at kinematics and limited space a functional setup is the most common solution at today's human robotic hip-joints. Particular attention to the natural movement of the human hip was not necessary during construction.

The negative effect will be visible at the finished robot prototype, e.g. leg crossing or performing different kind of leg-rotations during dynamic motion. The kinematic and bio-mechanical layout of the human hip-joint has been woefully neglected during conception development. The human hip-joint consists of the hip-socket (acetabulum) and the femoral head (caput ossisfemoris). The hip socked is composed by parts of the osilion, the os pubis and the osischii, which are connected by a Y-shaped fugue that yet again is connected at the area of the acetabulum.

The upper edge of the pan is stabilized by a cartilaginous rim, the acetabular. The femoral head is approximately a spherical extremity of the femur, which fits into the hip-socked. It enables a connection between the leg and the torso. The hip joint lies within the connective tissue socket, like a nut lying in its shell, which is a subtype of a ball-joint (articulatiospheroidea). A ball and socket joint has the ability to rotate about the three orthogonal *X,Y,Z*-axes. With respect to the hip, the Femur can rotate back and forward (flexion/extension), medial and lateral (adduction/abduction), and can rotate "toe in toe out"(internal/external rotation). Palpation of the hip also demonstrates that the femoral head can be translated (displaced) laterally.That is, when it moves out or away from the acetabula cup. This lateral displacement, although an important property of the hip joint, had not been adequately studied prior 1983 [10]. The amount of displacement is simply the laxity of the joint. The maximum amount of displacement of the femoral head in neutral position is not limited by the length of the round ligament as once thought. Instead, "it is dependent on the relative volume of the synovial fluid in the joint, acting in combination with the joint capsule" [11].

Thus the human hip joint is moved in a spherical rotation around the hip bone, caused through the actuation offset from Femur to the hip-bone. This motion is totally different from the rotation at rigid rotation-axis transposed at KIST and many other conventional robotic-systems. Additional expenditures during development and layout pay off as soon as the humanoid interacts and imitates human tasks and motions. Additionally the transversal motion makes the hip-joint much more flexible than expected. It's a significant challenge to gain this function through common technologies.

C. *Further problems occurring due insufficient movement capabilities*

Fig. 2.B and Fig. 2.D demonstrates the occurring problems due missing movement capabilities. Fundamental *DoF*ʻs like neck and pelvic rotation have been ignored. Movements like lateral head flexion are not possible. This causes in a missing acting and communication possibility, e.g. to support human machine interaction. Analyzing the human locomotors system, results automatically in new conventions for movement possibilities and speed and acceleration at each robotic joint, as well as the maximum backslash in each particular joint of the human body. Based on this features an initial approach on the identified critical parameters must be generated, before the construction of the robotic skeleton should start. Rigorous compliance of this conditions helps to overcome existing fundamental problems at the Uncanny Valley.
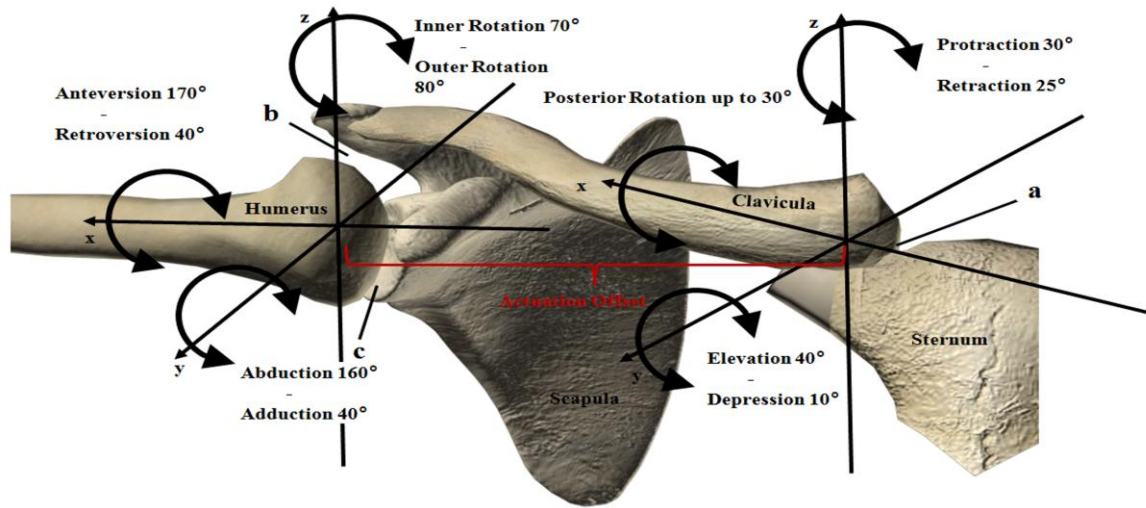
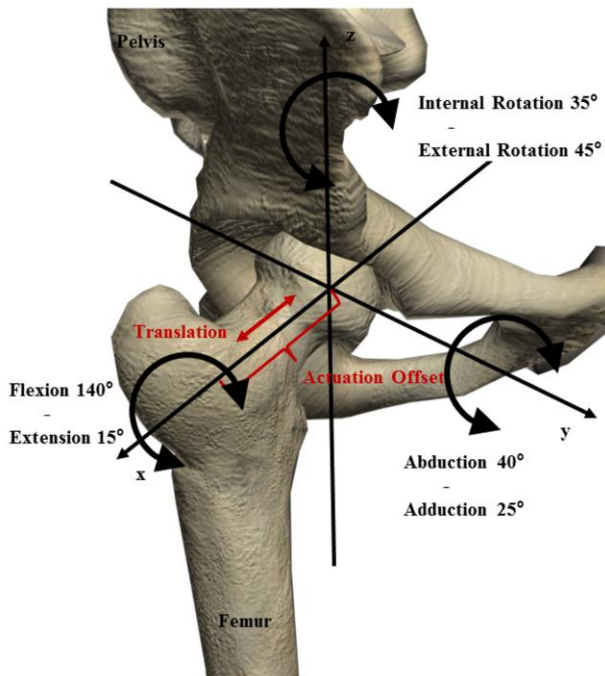Figure 3. Extended human shoulder kinematics in conformity to [9]

Figure 4. Extended human hip kinematics in conformity to [9]

I.   Human Skeleton Re-Engineering Approach

The first goal of this concept is to archive a consistent basic skeleton setup that is taking account to the fundamental requirements of dynamic human motion and simultaneously implements sensors and actuators with the dimensions of an average sized human being. To ensure this during a dynamic sequence of motion, therefore a fundamentally new and systematic approach is required to consistently follow these anatomical reference conditions. At a prior research project the most appropriate actuators had been chosen in order to reproduce human motion trajectories with minimum deviation [13]. A comprehensive approach could be found at the Hardware-Reverse Engineering. A pioneering elaboration at this topic by M.G. Rekoff, defines the Reverse-Engineering as „The process of analyzing a subject system to identify the systems components and their interrelationships and create representations of the system in another form or at a higher level of abstraction"[12]. The process of reverse engineering will be extended through the enhanced re-engineering approach by Chikofsky and Cross, in order to obtain the determined parameters. Re-engineering is the examination and modification of a specific system. „The re-engineering already contains a certain proportion of the process of reverse engineering (to achieve a more abstract description of a system), followed by properties of forward engineering or restructuring. This may include modifications in terms of new requirements that are not met by the original system"[12]. With the aim to reconstruct it into a different way, and transferring this new modified approach of the robot skeleton, compare Fig. 5.

Especially the early inclusion of modifications to the robot model makes this an interesting approach to gain fundamental redesign of the robot skeleton. Comparing the "actuators" of the human body and mechanical ones, fundamentally different material properties of human body-tissue and muscle fibers in comparison to technical drive components are present. A couple of anatomy studies are sufficiently known e.g. [19], that deals with the properties of the human musculoskeletal system. At a first step this results will be transferred to a standardized human skeleton model, Fig. 5.C.1. The Dimensions will be scaled to an average male human being [14] and in a further step transferred to an abstracted bone skeleton-model, which keeps the necessary connection nodes. This virtual bone model was developed and optimized for the use with the script animation tool SCANIMFBX [15], Fig 5.B. This tool was developed to overcome disadvantages of conventional motion capturing methods, in order to reproduce realistic human motions. It based on findings of the "Berner System", which was developed to code human motion through a common script-language [16]. The parameters of this bone model were archived to the fundamental requirements of human motion. These requirements were re-implemented to the bone Skeleton to identify features that were necessary to keep, Fig. 5.C.2.
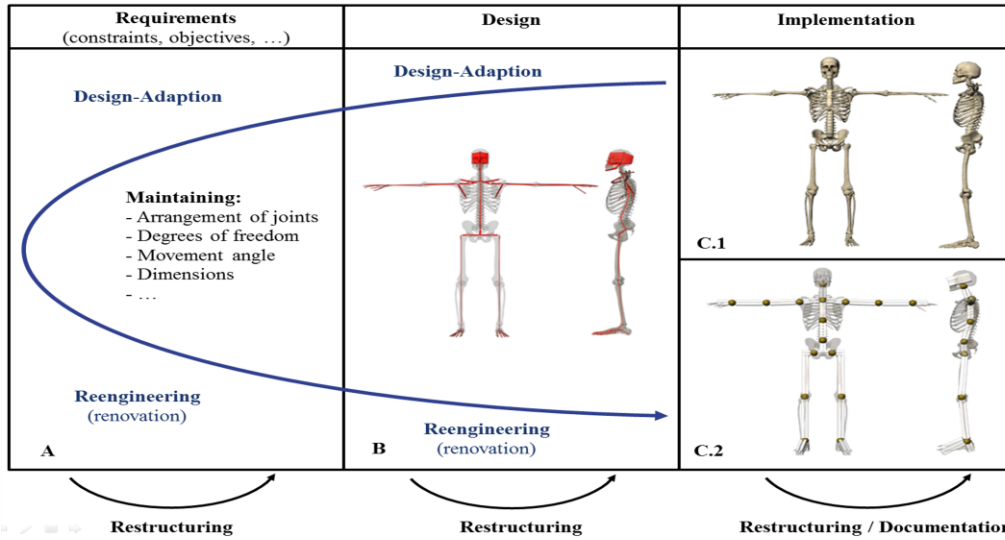
Figure 5. Re-engineering approach in humanoid robotics based on Chikofsky and Cross [12]

In order to keep the equilibrium between mobility and flexibility of the human shoulder, a modification was made respecting the predetermined motion parapets of the human body.

II. Transferring Results to the Development Process

Finally the identified parameters lead to the rope-actuated humanoid robot model shown at Fig. 6. The actuators are tensioned over a pair of ropes to each *DoF*. The big advantage is that the weight of the actuators was outsourced. Thus an overall weight reduction of 80 percent compared to conventional actuators could be archived at the skeleton structure [13]. The most important step during the re-engineering process was to keep dimensions and *DoF* of the skeleton structure. Several simulations showed rope-driven actuators have the possibility to perform rather equal accelerations with minimum backlash compared to conventional electrical cylinders and DC motors [13].Fig. 6 shows a schematic view at the current important solutions of the humanoid robot model. The tensioned ropes were led through Bowden-cables, which provides free movement at the stomach area, Fig. 6.1. The Bowden-cables strongly increase the friction of the synthetic rope so the distance has to be minimized at all.

Table 1 displays the current success at human shoulder re-engineering process. The rope driven actuators need similar space as the human body joints. They provide same acceleration and movement speed, as shown at a prior study [13]. The pre-load of the ropes is about *12 N*. The used synthetic rope (Dyneema®, 2 mm diameter) provides the following Parameters: weight: *180 g / 100 m*, linear tensile

strength *350 daN*. The operating elongation function can be approximated with:

$$f(x) = -0.0061x^3 + 0.0605\,x^2 + 0.078\,x + 0.0006 \quad (1)$$

At a coefficient of determination $R^2 = 0.9995$. The overall angles of the human body can be maintained with two restrictions. Compared to the human body, the inner-rotation of the shoulder part is currently not available. The posterior rotation of joint b has to compensate this disadvantage. The abduction possibility in negative direction of the shoulder joint is *30* degrees less than the human one.

TABLE I. HUMECH SKELETON SHOULDER STRUCTURE CHARACTERISTICS COMPARED TO HUMAN SHOULDER (DoF), FIG. 6

Joint (Fig. 6)	Weight	Humanoid Robot Motion Angle	Human Motion (Fig.4)
a:	245g	+/-170° rotating	+30° protraction -25° retraction
b.1:	345g	+/-170° rotating	+/-30° posterior - rotation
b.2:		+/-90° pivoting	+40° elevation -10° depression
c.1:	345g	+/-170° rotating	+170° anteversion -40° retroversion
c.2:		+130 / -50° pivoting	+160° abduction -40°adduction
d:	235g	+130 / -50° pivoting	+150° flexion -15° extension

The *50th* percentile of the anthropometric dimensional data, corresponding to an American male provides the foundation to the skeleton data [14]. As can be seen, the robot's dimensions are still bigger than the ones from the human skeleton but at the robot's construction site there is still space for further improvement. The future goal is to reach the human skeleton dimensions, what has to be done in future projects. The motors themselves will be controlled by DSpace® real time environment at a sample time of *1 ms*. At the next step human motions, scripted by SCANIMFBX has to be transferred to the actuators of the humanoid robot. With the advantage of low-weight construction combined with realistic

coded human motions, there are currently good conditions to find a way over the valley.
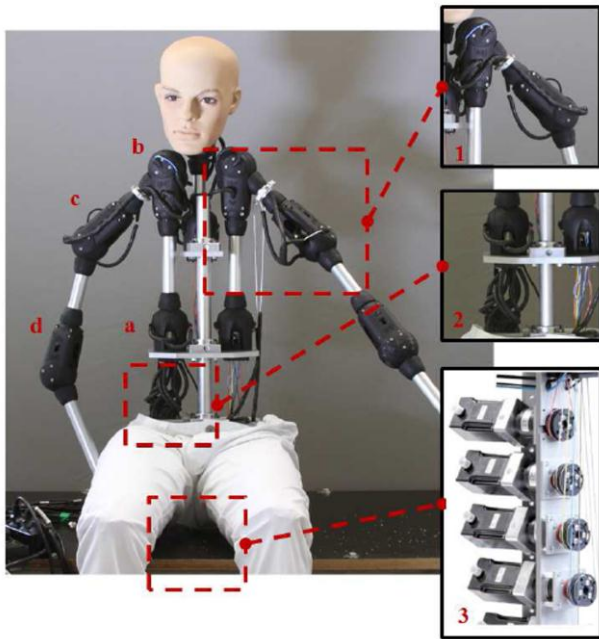

Figure 6. Features of the humanoid Robot HUMECH; 16 DoF(Upper Body) + 3 DoF(Torso); Right upper arm structure: a: rotational shoulder joint (1DoF), b: rotation, pivoting shoulder joint (2 DoF), c: Rotating, pivoting upper arm joint (2 DoF), d: pivoting elbow joint (1 DoF)

III. Conclusion and Discussion

This contribution to human robotic development showed a concept of the rope driven lightweight humanoid robot prototype HUMECH developed at the Chair of Mechatronics at University Duisburg-Essen. At the initial step there was demonstrated how a novel skeleton setup can be generated under influence of the re-engineering approach by Chikofsky and Cross. The generated structure with its DoF´s was implemented at the example of the human shoulder parts. The expected goal for this setup is to demonstrate realistic dynamic behavior and finally combine the robot motion-model with the motion-database of the Virtual Human project to defeat the disadvantages in motion at humanoid robotics. One of the important steps in future is to compare the possible acceleration behavior and workspace with the human being. Furthermore the motion-capabilities have to be extended at the shoulder, torso-, wrist- and stomach-area. The motor control requires particular attention, because the elastic backlash due lightweight construction increases significantly. Nevertheless this approach has enormous potential to find a way over the valley due early stage re-engineering.

Acknowledgment

Sebastian Feldmann received his M.S. degree in Mechanical Engineering and Management at the University Duisburg-Essen in 2010. He works as scientific employee at the department of mechatronics. The research topics are humanoid robotics, medical assistance robots, sensing and image processing as well as product development involved distributed locations.

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