Building Bodies for Brains: The Mechatronics of Anthropomorphic Robot Arms

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Abstract. The paper reviews various projects on humanoid robots with a focus on the design of anthropomorphic robot arms. Common approaches are identified and future design requirement are outlined. The second part of the paper presents a novel model for the design of an anthropomorphic robot arm with 10 degrees of freedom. The design is directly derived from the biomechanics of the human arm. The characteristics of the robot arm are analyzed with respect to workspace volume and inner singularities. Finally future challenges in the design of humanoid robots are outlined.

1 Introduction

Traditionally, robots are used in tasks that are highly repetitive or that are dangerous for humans. For this purpose robots are integrated into production lines as stationary machines. Cooperation of various robots in the same task is scarce and each robot acts as stand-alone devices in its own separated, well-known workspace. The main applications of these robots are welding, painting or assembly tasks in the automotive industry.

A second step in the development of robots are mobile and telecontrolled robots. In contrast to the traditional robots, these robots are built in small numbers for special-purpose applications e.g. environment exploration, toxic waste handling or tasks in outer space. To cope with the unstructured and previously unknown environment in which these robots work, new planning and control concepts (e.g. reactive control or human-supervisory control) are developed. Complementary to the control concepts, the environment perception and its modeling are under investigation.

A third step in the evolution of robotic systems is the development of animal-like robots. They introduce the "nature-is-best-approach" into robotics. Starting with insect- and serpentine-like robots, the focus has moved towards mammals and finally towards humanoid robots. The main scientific challenges are the imitation of the animals' biomechanics as well as their behaviors. The next section gives a closer look on various humanoid robot projects and their paricularities.

2 Humanoid Robots

The probably best known projects on humanoid robots are:

- *P3 of Honda* [11]: The robot is a full body humanoid including arms, legs and a head. Special attention is paid on the mechatronics and the control of bipedal walking.
- *Waseda Humanoids* [6]: Various full body humanoids and many components have been developed. The main investigation interests are mechatronics and vision as well as the integration of components into a complete humanoid system.
- *Cog* [3]: The robot is stationary. It is composed of a torso, arms and a head. It serves as a research vehicle to investigate machine-learning and human-machine interaction.

The projects show the strong interdisciplinary aspect of humanoid robots and the wide range of research interests. Nevertheless all disciplines share a common development approach that aims at:

- *Similarity in appearance*: Humanoid robots should look as much as possible like humans. The familiar appearance attracts humans and is fundamental for a natural human-machine interaction.
- *Similarity in behavior*: Motion and behavior of the robot should be similar to a human. This makes the robots predictable for humans. Cooperation and machine-learning is eased.
- *No similarity in technology*: Humanoid robots are machines and make use of engineering technology. Humanoid robots do not pretend to be "living systems" in a biological sense.

Summarizing the above aspects, the aim is *similarity not identity* to humans. The following sections are concerned with anthropomorphic robot arms as essential part of humanoid robots. It is investigated to what extend the existing anthropomorphic robot arms are similar to the human arm. Finally a novel design for a robot arm is proposed.

3 Mechatronics of Anthropomorphic Robot Arms

One of the main differences between the human arm and the existing robot arms is, that robot arms are composed of joints with only one degree of freedom (dof) each. Joints with more than one dof like e.g. the ball-socket-joint of the human shoulder are technically not feasible and therefore not applied in todays' humanoid robots (see the aims outlined in the previous section). Instead simple, one-dof-joints are grouped into kinematic chains, that provide for a functionality similar to the human arm.

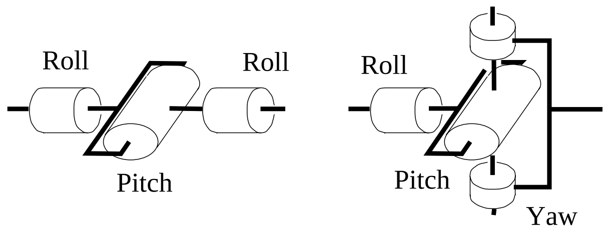

Fig. 1. Two joint complexes: roll-pitch-roll and roll-pitch-yaw.

In the following the design of robot arms is described using the concept of *roll–*, *pitch*- and *yaw*-joints. Figure 1 shows some typical examples. The aggregation of various joints replacing a functional unit of the human arm is in the following referred to as a *joint complex*. The human arm consists of four joint complexes: The shoulder girdle, the shoulder, the elbow and the wrist.

Author	Robot	Type of Joint			
		Shoulder Girdle	Shoulder	Elbow	Wrist
Inoue [11]	P3	-	P-P-R-	-P-R-	-P-R
Takanishi [6, 21, 18]	WABIAN	-	R-P-R-	-P-	-R-P-R
Brooks [3]	Cog	-	R-P-R-	-P-	-R-P
Wada [23]	TTAR	-	R-P-R	-P-R-	-P-R
Dillmann [4, 2]	ARMAR	-	R-Y-R-	-P-R-	-P-Y
Inaba [9, 10]	-	Y-	-P-	-R-P-	-R-P
Konno [14]	Saika	-	R-P-R-	-P-R	-
Kuniyoshi [15]	ETL-humanoid	-	R-P-R-	-P-R-	-P-R
Hwang [8]	Centaur	-	R-P-R-	-P-	-R-P
amtec [1]	-	-	P-R-	-P-R-	-P-R
GMD [12]	JANUS	-	R-P-R-	-P-R-	-Y

Table 1. Arms of humanoid robots

In table 1 an overview of the existing anthropomorphic robot arms and their kinematic characteristics is presented. It is apparent, that all the existing robot arms are based on roll-pitch-roll or roll-yaw-roll sequences. These kinematic patterns favor a modular and space-saving design. Moreover the range of motion of each of the joints is large. However, the main disadvantage of this design is the singularity, that occurs if both roll axes become parallel. High joint velocities in configurations of the robot arm, that are close to the singularity are the result (so called joint flipping). This can cause damage to the robot's hardware, difficulties in robot programming and presents high risks to work safety [19]. Thus the use of roll-pitch-roll kinematics contradicts to some extend the aspired application of humanoid robots in man-machine cooperation. Consequently the development of singularity-free kinematics is a future research goal for humanoid robots.

A second problem of roll-pitch-roll and roll-yaw-roll kinematics presents the use of novel actuator concepts like e.g. artificial muscles [22, 5]. In contrast to the traditional concepts these actuators do not act directly on the joint axis but interconnect two links at points distant to the joint axis. This way a leverage is achieved (compare e.g. the elbow joint). Yet it restricts the range of motion of each joint to a maximum of 180^{o}. One of the strong advantages of roll-pitch-roll and roll-yaw-roll kinematics, namely the large range of motion in each of the joints, is negated. The future development of robot arms should therefore take into account, that on one side the joint limits of each of the joints do not exceed 180^o and that on the other side the overall workspace of the human arm is fully covered.

Another characteristic of the existing anthropomorphic robot arms is that the joint axes are oriented along with the main geometric axes of the human body. For the robot arm in zero position (the arm hanging downwards) the joint axes are generally oriented from caudal to cranial, from dorsal to ventral or from medial to lateral. Although this simplifies the design and control of the robot arm, the geometric axes of the human arm are not identical with its functional axes [13]. Hence, to improve the functional agreement between the human arm and future anthropomorphic robot arms, it is necessary to adapt the design more closely on the human biomechanics. Only this way a behavior of the robot arm can be achieved that matches well with its natural counterpart.

Finally, almost all of today's anthropomorphic robot arms have 7 dof. They are composed of a shoulder complex, an elbow complex and a wrist complex. By contrast the shoulder girdle of the human arm is neglected. Yet the shoulder girdle has a large influence on the manipulation capacity of the human arm [16, 17]. It enlarges the workspace, enables two-arm manipulation and it is fundamental to absorb shocks. The shoulder girdle has therefore to be taken into account in the design of future humanoid robots.

4 A Novel Anthropomorphic Robot Arm

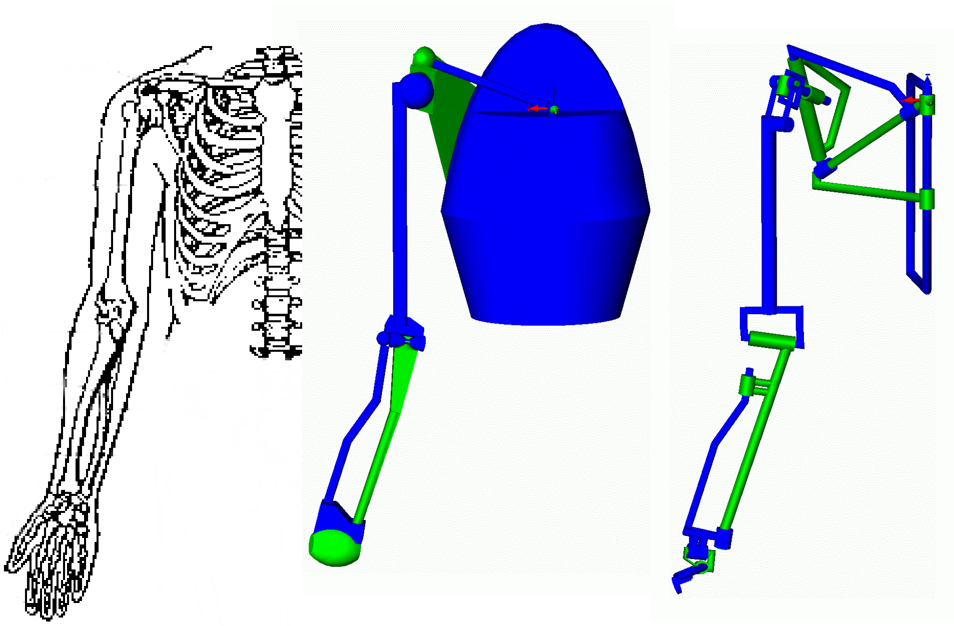

Fig. 2. The robot model and its natural counterparts

In this section a model of a novel robot arm is presented, that takes into account the design requirements outlined in the preceding section. Figure 2 illustrates the anatomy of the human arm, the derived close-to-nature model and the final model of the anthropomorphic robot arm. The robot arm has 10 dof and includes the joint complex of the shoulder girdle, the shoulder, the elbow and the wrist. Table 2 shows the Denavit-Hartenberg parameters of the arm. The angles Θ_i determine the configuration of the robot arm in zero position. In the following the details of the joint complexes are discussed one by one.

The shoulder girdle (articulatio sternoclavicularis, art. acromioclavicularis, art. thoracoscapularis), that consists of the clavicle, the shoulder blade and the thorax is replaced by a mechanism with 3 dof. In the human arm the clavicle and the shoulder blade form together with the thorax a closed kinematic chain. In the presented robot model this closed kinematic chain has been approximated by an open kinematic chain. Triangular bar structures are used for each link to make the shoulder girdle more rigid and to relief the joints of torque.

The human shoulder joint (articulatio humeri) is a ball-socket joint with 3 dof. The same movableness is achieved in the robot arm by grouping three hinge joints with one dof each in a roll-yaw-pitch sequence. The axes of the three joints intersect in a single point, that corresponds to the center of rotation in the articulatio humeri.

Joint complex	Joint	coordinate system	Θ (in ^{o})	d (mm)	α (in ^{o})	a (mm)
Shoulder girdle	Art. thoraco-scapularis	$(xyz)_{ts1}$	36.6	0	118.7	0
		$(xyz)_{ts2}$	-29	227	-123	0
		$(xyz)_{ts3}$	-107	122	135	-20
Shoulder	Art. humeri	$(xyz)_{sh1}$	-9	-55	-90	0
		$(xyz)_{sh2}$	90	0	-90	0
		$(xyz)_{sh3}$	-81	-40	-128	-339.5
Elbow	Art. humeroulnaris	$(xyz)_{hu}$	-7	-35	90	0
	Art. radioulnaris	$(xyz)_{ru}$	-6	296	-90	-12
Wrist	Art. radiocarpea	$(xyz)_{rc1}$	103	23	90	-20
		$(xyz)_{rc2}$	28	10	-110	-10

Table 2. Denavit-Hartenberg parameters and zero position of the robot arm

The whole joint complex is positioned with respect to the shoulder blade to reproduce the functional aspects of the human shoulder.

The elbow consists of two joints. The first joint (articulatio humeroulnaris) links the upper arm to the main bone (ulna) of the forearm and enables forearm flexion and forearm extension. The second joint (articulatio radiounaris) links the ulna to the radius; it is responsible for forearm rotation. In the robot arm the kinematic structure is matched with two hinge joints. As in the human forearm, the robot forearm is split into two links. This improves stability.

Finally an equivalent to the human wrist has been developed. The human wrist consists of eight carpus bones, that behave like a bag filled with gavel. In a prior study [20] the main functional motion axes of the wrist have been identified. In correspondance with these functional axes the two hinge joints are placed in the robot model.

Considering the developped model of the robot arm as a whole, the similarity between the human arm and the robot arm is obvious. In addition to the similar appearance, the position and the orientation of the joint axes match the functional characteristics of the human arm. Thus a similar behaviour to the human arm is expected by the robot arm. The next section will evaluate the behaviour characteristics of the proposed robot arm in detail.

5 Workspace and Singularities of the Robot Arm

To describe the behaviour characteristics of the proposed robot model two definitions are introduced:

- *Configuration-space of a robot arm:* n-dimensional space of the independent joint variables (also referred to as Lagrangian coordinates), where n is the degree of freedom of the robot arm.
- *Workspace of a robot arm:* Multitude of points in the space of position coordinates, that are reachable with the robot's endeffector.

One should note, that the definition of the workspace for a robot arm referres only to the position of the endeffector and not to its orientation.

To determine the workspace of the proposed robot model, the configuration space of the robot is specified at first. Table 3 shows for the independent joint variables θ_i of the robot arm the lower limits θ_{min} as well as the upper limits θ_{max}. The joint limits have been choosen to match the movableness of their natural counterparts as much as possible. Moreover the condition, that none of the joint ranges exeeds 180^o (see section 3), is satisfied. The ranges of the joints of the shoulder girdle and of the shoulder are even below 120^o. This simplifies the actuation of the robot model with artifical muscles.

The workspace of the robot model is computed by mapping the configuration space into the three dimensional space of position coordinates. Figure 3 shows the results. The x-axis runs from medial to lateral, the y-axis runs from dorsal to ventral and the z-axis from caudal to cranial. The origin of the coordinate system corresponds to the incisura jugularis of the human body. The workspace of the robot arm forms approximately a sphere. Inside the workspace, there are no workspace holes. A closer look reveals, that the workspace is restricted towards medial-dorsal-caudal. This area corresponds to the zone behind the back of a human, where the movableness of the human arm is limited too. Thus the workspace restrictions of the robot model agree well with the workspace of the natural counterpart.

Besides the workspace analysis, singularities are another important issue in the evaluation of the behaviour characteristics of robot arms. Generally, a configuration of a robot arm is called singular if the rank of the robot's

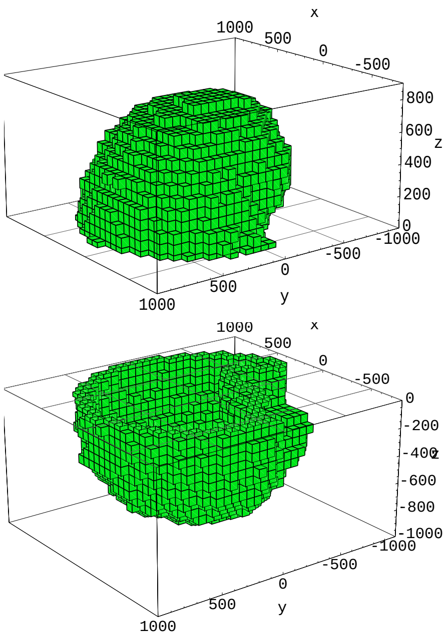

Fig. 3. Workspace boundaries of the robot arm (in mm).

Joint complex	Joint	Joint variable	θ_{min} (in ^{o})	θ_{max} (in ^{o})	$\theta_{sing,1}$ (in ^{o})	$\theta_{sing,2}$ (in ^{o})
Shoulder girdle	Art. thoraco-scapularis	θ_{ts1}	-28	25	-36.6	143.4
		θ_{ts2}	-24	17	-151	29
		θ_{ts3}	-28	0	-73	107
Shoulder	Art. humeri	θ_{sh1}	-80	30	-171	$\mathbf{9}$
		θ_{sh2}	-30	60	-90	90
		θ_{sh3}	-110	10	$\mathbf{-99}$	81
Elbow	Art. humeroulnaris	θ_{hu}	-90	65	-173	$\mathbf{7}$
	Art. radioulnaris	θ_{ru}	-170	0	-174	6
Wrist	Art. radiocarpea	θ_{rc1}	-85	85	-103	$\mathbf{77}$
		θ_{rc2}	-55	15	$\mathbf{-28}$	152

Table 3. Joint limits and joint angles with potential singularities

Jacobian J is reduced. In these configurations the Jacobian J can not be inverted. At the same time the motion of the robot's endeffector is loosing a degree of freedom. For robot arms two types of singularities exist:

– *Singularities at workspace boundaries*.
– *Inner singularities* (singularities inside the workspace).

The control and the behaviour characteristics of robot arms are particularly worsening by the occurence of inner singularities. Inner singularities do not only occure for the robot arm as a whole, but also for each of the joint complexes (compare the roll-pitch-roll complex of section 3). The condition for the occurence of an inner singularity of a joint complex is, that all of its joint axes are alligned parallel to a common plane [7]. These configurations have been computed for the robot model. For each joint the values $\theta_{sing,i}$, in which the joint axis and the two preceeding joint axes run parallel to a common plane, are summarized in table 3. It can be seen, that most of the singular values $\theta_{sing,i}$ are outside of the joint range and therefore they do not have to be considered. The robot model as a whole and each of its joint complexes are free from inner singularities. Thus the behaviour characteristics of the robot model are suitable to build an antropomotphic robot arm.

6 Conclusions

In a review of the existing projects on humanoid robots a common approach is identified. The aim is to achieve similarty with humans in appearance, in behaviour but not in technology.

A closer look on the mechatronics of anthropomorphic robot arms shows, that the dominating design concept is to use roll-pitch-roll kinematics. The disadvantages of this concept are discussed and the design requirements for future antropomorphic robot arms are outlined:

– Design of robot kinematics, that are free of inner singularities, to improve the behaviour characteristics and to easen control.
– Adaption of the design on the biomechanics of the human arm (in particular functional aspects) to improve similarity in behaviour.
– Restriction of the range of motion in each joint to a maximum of 180^o to enable actuation with artifical muscles.
– Incooperation of the shoulder girdle to enlage the robots workspace and to improve the robots dexterity.

A model of an anthropomorphic robot arm is presented, that complies with the above requirements. The model is directly derived from the biomechanics of the human arm and can be used to build an antrhopomorphic robot arm. The model has 10 degree of freedom and includes the shoulder girdle, the shoulder, the forearm and the wrist. The analysis of its workspace and the investigation of inner singularities show good agreement between the robot arm and the human arm.

However many questions in the design of mechatronics for anthropomorphic robot arms remain unsolved. The mass distribution of the robot arm has to be similar to the human arm to improve the similarity in bahaviour. A skin with taktile sensors is needed. The control of artifical muscles has to be improved. And –one of the most important issues – a light weight energy supply has to be developped.

All these issues will need both, fundamental research and interdisciplinary cooperation. Taking into account the immensly growing computationl power and the rapidly growing state-of-the-art in informatics, it is probable that the more modest advances in mechatronics can not catch up. The performance of humanoid robots with therefore be limited by the slow advances in mechatronics. Thus one of the important challenges for the future of humanoid robots is to build "bodies for brains".

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References

1. amtec GmbH. Produktbeschreibung morse, 1998.
2. K. Berns, T. Asfour, and R. Dillmann. Armar - an anthropomorphic arm for humanoid service robot. In *Int. Conference on Robotics and Automation*, 1999.

3. R. Brooks, C. Breazeal, M. Marjanovic, B. Scassellati, and M. Williamson. The cog project: Building a humanoid robot. In *Int. Workshop on Humanoid and Human Friendly Robots*, Tsukuba, Japan, 1998.
4. R. Dillmann, K. Berns, and T. Asfour. Concept and prototype implementation of a humanoid robot. In *IARP First International Workshop on Humanoid and Human Fiendly Robotics*, 1998.
5. B. Hannaford, J. Winters, C. Chou, and P. Marbot. The anthroform biorobotic arm: A system for the study of spinal circuits. *Annals of Biomedical Engineering*, 23:399–408, 1995.
6. S. Hashimoto and et al. Humanoid robots in waseda university – hadaly-2 and wabian. In *Int. Workshop on Humanoid and Human Friendly Robots*, Tsukuba, Japan, 1998.
7. J. Hollerbach. Optimum design for a seven degree of freedom manipulator. In *2nd Int. Symp. of Robotics Research*, pages 215–222, 1985.
8. Y. Hwang, S. Knag, S. Lee, M. Park, K. Cho, H. Kim, and C. Lee. Human inerface, automatic planning and control of a humanoid robot. *International Journal of Robotics Research*, 17(11), 1998.
9. M. Inaba. Robot-brained humanoid project. *Journal of Advanced Robotics*, 11(6), 1997.
10. M. Inaba, F. Kanehiro, and S. Kagami. Remote-brained ape-like robot to study full-body mobile behaviours based on simulated models and real-time vision. *Journal of Advanced Robotics*, 11(6), 1997.
11. H. Inoue. A platform-based humanoid robotics project. In *Int. Workshop on Humanoid and Human Friendly Robots*, Tsukuba, Japan, 1998.
12. Janus. http://borneo.gmd.de/as/janus/new/janus/publi.html, 1999.
13. I.A. Kapandji and J. Koebke. *Funktionelle Anatomie der Gelenke*. Ferdinand Eneke Verlag, Stuttgart, 1984.
14. A. Konno, K. Nagashima, R. Furukawa, K. Nishiwaki, M. Inaba, and H. Inoue. Development of a humanoid robot saika. In *IEEE Int. Conf. on Intelligent Robots and Systems*, pages 805–810, 1997.
15. Y. Kuniyoshi and A. Nagakubo. Humanoid as a research vehicle into flexible complex interaction. In *IEEE Int. Conf. on Intelligent Robots and Systems*, 1997.
16. J. Lenarcic and A. Umek. Simple model of human arm reachable workspace. *IEEE Transactions on Systems, Man and Cybernetics*, 24(8), 1994.
17. J. Lenarcic, A. Umek, and S. Savic. Considerations on human arm workspace and manipulability. In S. Stifter and J. Lenarcic, editors, *Advances in Robot Kinematics*. Springer Verlag, 1991.
18. T. Morita and S. Sugano. Developement of an anthropomorphic force-controlled manipulator wam-10. In *8th International Conference on Advanced Robotics, ICAR*, Monterey, USA, July 1997.
19. M.E. Rosenheim. *Robot Evolution*. John Wiley, New York, 1994.
20. Ch. Schäfer and R. Dillmann. Kinematic design of a humanoid robot wrist. In *International Symposium on Robotics and Automation*, 1998.
21. A. Takanishi, T. Matsuno, and I. Kato. Developement of an anthropomorphic head-eye robot with two eyes. In *IEEE Int. Conf. on Intelligent Robots and Systems*, 1997.
22. B. Tondu, A. Daidie, M. Conscience, and S. Ippolito. Design and simulation of a 7-dof anthropomorphic arm actuated by mckibben artifical muscles. In *International Workshop on Robot and Human Communication, RO-MAN*, Takamatsu, Japan, 1998. IEEE.
23. M. Wada and S. Mikami. Towards third-arm robots: Humanoid robotic arm for cooperation between human and robots. *Journal of Advanced Robotics*, 11(6), 1997.