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Programming of Manipulation Tasks of the Humanoid Robot ARMAR

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Abstract

An autonomous mobile humanoid robot able to assist in a workshop environment and interact with human beings, must have the basic capability of learning manipulation tasks by demonstration. In this paper two aspects to reach this goal are considered. First we describe how the mechanics must be constructed to manipulate objects like humans do. Then we propose an approach to transfer human arm movements of typical manipulation tasks to the humanoid robot ARMAR. In order to support our concept the anthropomorphic humanoid robot ARMAR is developed.

1 Introduction

Our research in the field of humanoid robots is based on the recognition that a complex, intelligent behaviour of a robot with human-like skills can only be carried out through the permanent interaction between cognition components, the robot system itself and a human operator who demonstrates typical actions. In cooperation with human beings humanoid robots should share the same working space and should react human friendly. This requires them to be highly flexible, autonomous and adaptive to new situations. The design of such humanoid robots requires a high extent of integration of mechanical, electronical and computational technologies.

Although being a very complex task, the application, the locomotion and the intelligence of humanoid robots capable of human-like manipulation seem to arise in the near future. Recent examples of humanoid robots are the Honda robot [13], the WABIAN robots of the Waseda University [9] and the Saika robot [10] in Japan, the Cog robot in USA [4], and the Arnold robot of the Ruhr University Bochum, Germany [1]. The manipulation capabilities and intelligence of these robots are still far away from the human ability in solving complex manipulation tasks.

We develop the autonomous mobile humanoid robot ARMAR with a torso, two anthropomorphic arms and a simple gripper. For the detection of the environment a head equipped with a stereo camera system will be used. The aim of our research is to implement manipulation tasks on ARMAR. The manipulation ability of ARMAR has to be comparable to that of a human. Through direct interaction between a human operator and the robot typical movements of the arms and of the torso are generated. Based on this, skills should be derivated as parts of different manipulation tasks. In the following the first steps to reach this goal are described. Starting from the mechatronics concept of our humanoid robot ARMAR, we show the way typical movements of a human arm can be transfered to ARMAR. At the end of this paper early experimental results are reported.

Figure 1: The humanoid robot ARMAR.

2 The mechatronics concept of ARMAR

In order to achieve a high degree of mobility and to allow the simple and direct cooperation with humans, the structure (size, shape and kinematics) of the arm and of the torso should be similar to that of a human. Up to now it is not planned to use legs for the locomotion of the machine, since in a workshop environment it is not necessary to have such a flexible locomotion system. In fact one function normally supported by legs is the change of the total height. This influences the workspace of the two arm system. However we installed a telescopic joint in the torso of ARMAR to have also this degree of freedom. In the following we report a detailed description of the mechatronics concept.

2.1 Mechanical construction

Mechanically, the humanoid robot ARMAR consists of an autonomous mobile wheel-driven platform, a body with 4 DOF, a two arm system with a simple gripper and a stereo camera head. The total weight of ARMAR is about 45kg. The mobile platform consists of two active driven wheels fixed in the middle of an octagonal board and another two wheels as passive stabilisers. The maximum velocity of the platform is about 1m/s.

The anthropomorphic body of the robot is placed on the mobile platform and support a rotation of about 330°. It also can be bended forward, backward and sideward. To adapt the height of the robot, a telescopic joint is included in the body. With this joint the total height of the machine can be increased by 40cm. Currently it is not planned to use legs for the locomotion of the machine.

For the dual arm system of ARMAR, we designed two anthropomorphic arms, each having 7 DOF and a length of 65 cm (including the gripper). Since the robot should support a simple and direct cooperation with the human, the physical structure (size, shape and kinematics) of the anthropomorphic arm is developed as close as possible to the human arm in terms of segment lengths, axis of rotation and workspace. The anthropomorphic arm design is based on a simplified kinematics model, which approximates the kinematic, kinetic and anthropomorphic characteristics of the human arm. At present a simple parallel jaw gripper is implemented.

Table 1 reports the mechanical parameters of different joints of ARMAR. Further details about the mechanics of ARMAR can be found in [3].

	joint	Range of motion	angular velocity	torque
Body	ϕ_1	330°	$200°/s$	5Nm
	ϕ_2	120°	$30°/s$	60Nm
	ϕ_3	120°	$30°/s$	60Nm
Arm	θ_1	170°	$60°/s$	15Nm
	θ_2	170°	$40°/s$	40Nm
	θ_3	320°	$140°/s$	15Nm
	θ_4	140°	$60°/s$	15Nm
	θ_5	330°	$80°/s$	2.5Nm
	θ_6	90°	$75°/s$	4.7Nm
	θ_7	90°	$75°/s$	3.6Nm

Table 1: Mechanics parameter of ARMAR's arm and body. The joint variables $\theta_1 - \theta_7$ are shown in Figure 2. $\phi_1 - \phi_3$ correspond to the different joints of the body: ϕ_1 describes the rotation of the two arm system, while ϕ_2 and ϕ_3 specify the forward, backward and sideward bending of the torso.

2.2 Control architecture

The control architecture of ARMAR is hierarchically organised. It is divided into computer architecture and software architecture. The computer architecture consists of three levels: the micro-controller level, the PC level and the PC-network level. The micro-controllers are directly coupled with special power electronic cards, which control 4 motors. The micro-controllers are connected via Can-bus with an internal industrial PC.

The tasks of the micro-controllers are divided into two main areas. The first is the information processing and the control of each joint which includes the evaluation of the sensor signals and the generation of control parameters for the drives. All sensors are directly coupled with the micro-controller and they deliver both digital signals and analogue signals. The latter are converted by the internal AD-converter of the C-167, while digital signals are generated by joint encoders and counted by the micro-controller. The second area is devoted to serve the PC level, including the management of the communication link to the PC. The currently used PC is equipped with a Pentium-processor (400MHz) and a special CAN-card.

Modules like collision avoidance, trajectory planning, sensor data interpretation (e.g. forces when gripping an object) and the task planning are running on the PC. The PC is connected via wireless Ethernet to a PC-network. Programs for simulation and special GUIs for the monitoring and the control of ARMAR are running on these external PCs.

To handle the real-time requirements of the control, a modular control architecture is developed. As operating system Linux as well as Real Time Linux are used. The choice was motivated by the availability of a high number of devices and of source codes. The standard Linux kernel runs with a lower priority as a task of the RT-Linux kernel. For the efficient implementation of the different control levels, the object oriented module MCA [12] is implemented, since it enables rapid development and the exchange of control algorithms at different control levels.

2.3 Sensor system

Each joint angle as well as the rotation of the forearm, upper arm, shoulder and body can be measured with a resolution of less than 0.1^o. Also current and the voltage of each motor is determined by the power electronic card. For gripping various kinds of objects an artificial skin is placed on the inner side of the four fingers. It is realized by measuring the electrical resistance of the conducting rubber that is divided in several fields of an array. By analysing the generated sensor signal it is possible to determine the position of the contact force.

Additionally, it is planned to include stain gauges on different parts of ARMAR, gyroscopes and acceleration sensors for collision measurements, and for the determination of the position and orientation of the body of ARMAR. To detect the environment a stereo camera system will be fixed on ARMAR. This work is still under development. The concept of the stereo camera system is derivated from the environment detection concept implemented for our six-legged machine LAURON II [2]. The sensor system of the mobile platform is similar to those of our wheel-driven autonomous platforms. For more details see [5], [6], [7], [8].

3 Programming of manipulation tasks by demonstration

For the programming of manipulation tasks based on the demonstration of a human operator it is essential that the movements of the arms can be recorded in an easy way. The arm movements have to be natural, which means that the movements should not be restricted to part of the whole workspace. We use two commercially available position sensors called FasTraks (see http://www.fasttracker.com) are used to measure the positions and orientations of the elbow and the wrist. The main problem of this tracking system is that the measurements of the positions is performed with a low accuracy. From the overall concept this is not relevant because only the characteristic of the arm trajectories are used. This means that not the exact position of each measurement point is transfered to the two arm system of ARMAR.

Our approach in programming of manipulation tasks can be divided into three main parts:

- Capturing and analysing of human arm movements demonstrated by a human operator. We assume that the arm movement is kinematically represented, and that the dynamics for human manipulation tasks can then taken into account as a postproccesing step. We do not need to consider the dynamics unless we need realistic velocity distribution for manipulation motions.
- Transfer of the demonstrated movements to ARMAR using an inverse kinematics algorithm because most manipulation tasks are specified in terms of the object trajectories.
- Adaption of body/arm movements of ARMAR according to the description of the object to be manipulated and to the information about the robot environment.

Up to now the first two steps of the programming approach are implemented. Starting from the human arm movement detected by the above mentioned tracking system an adequate model of the human arm is selected. The two sensors are attached to the elbow and wrist of the human arm. The arm configuration can then computed from the sensor data using a specialised inverse kinematics algorithm. In order to compute the joint angles of the robot arm corresponding to the operator's current arm configuration, we assume that the shoulder positions are fixed. In the following the used human arm model is introduced and the calculation of the joint angles of the arms of ARMAR is presented in detail.

3.1 The human arm model

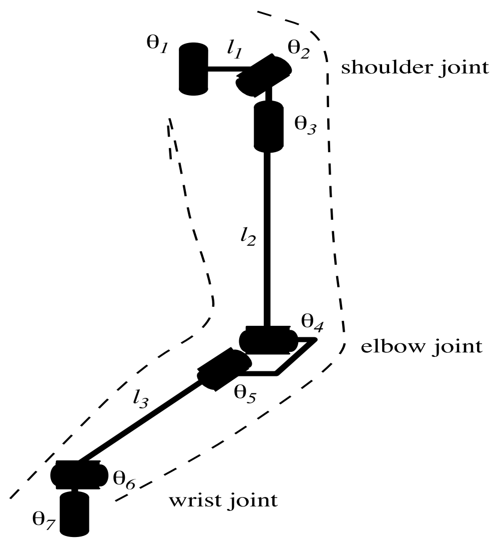

Figure 2: Kinematics model of the human arm

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The implementation of the human arm model is used to examine its kinematic behaviour when moving. We use a biomechanical model of the human arm consisting of 10 DOF. This model should not be seen as a biomechanical model of a human arm which has to consider the bones, muscles or tendons. The model reproduce the kinematic, kinetic and the anthropomorphic characteristics [11]. Since our simulation system allows to fix different DOFs as well as changing the different link lengths, we can decide which DOFs are necessary for performing the demonstrated manipulation task. The resulting kinematics model of the human arm is then used to transfer the manipulation task to ARMAR. In figure 2 a simplified kinematic model of the human arm consisting of 7 DOFs is presented.

3.2 Transfer of movements to ARMAR

Based on the elbow and wrist trajectories of the human arm model, the joint angles of the arms of ARMAR are calculated via inverse kinematics. The problem when solving the inverse kinematics of the 7-DOF robot arm (i.e. when computing the seven joint angles θ_1, θ_2, θ_3, θ_4, θ_5, θ_6 θ_7) arises from the underdetermination of the inverse kinematics. In the following, we present an analytical-geometrical method for a closed form solution of this inverse kinematics problem.

3.2.1 The kinematic model

Figure 3 shows the reference and link coordinate systems of ARMAR's arm using the DH-representation. The values of the kinematic parameters are listed in table 2. They correspond to the home position pictured in the link coordinate diagram of figure 3.

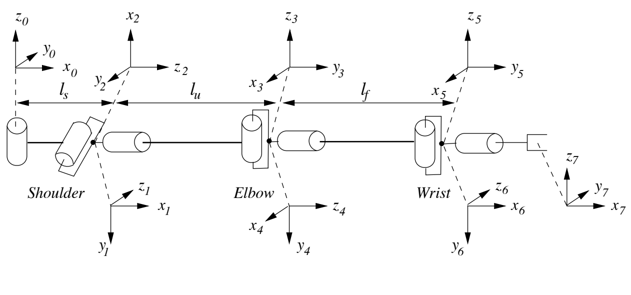

Figure 3: The kinematics model of ARMAR's arm and the link coordinate systems

3.2.2 The redundancy of the arm

The robot arm redundancy can be described by the rotation of the centre of the elbow joint about the axis, that passes through the wrist and the shoulder joint. The feasible positions of the elbow around this axis are defined by a curve. This curve can be derived from the fact that the ending point of the upper arm describes an ellipsoid centred on the shoulder joint $(0, 0, 0)$ and that the starting point of the forearm describes a sphere centred on the wrist (x_w, y_w, z_w). Since both of these points have to be the same, the redundancy curve results from the intersection of the ellipsoid and the sphere. For a given position and orientation of the end effector we calculate a possible position of the elbow (x_e, y_e, z_e), based on the arm geometry and the mechanical joint constraints. Once having the elbow position, the remaining joint angles are then easy to determine.

i	θ_i	α_i	a_i	d_i	Rang
1	0	$-90°$	30	0	$-85° \cdots 85°$
2	$-90°$	$-90°$	0	0	$-85° \cdots 85°$
3	$90°$	$90°$	0	223.5	$0 \cdots 320°$
4	0	$-90°$	0	0	$0 \cdots 140°$
5	0	$90°$	0	270	$0 \cdots 330°$
6	$90°$	$-90°$	0	0	$-45° \cdots 45°$
7	0	$90°$	140	0	$45° \cdots 45°$

Table 2: DH-Notation

We now outline the method by which we determine the joint angles of the seven DOF robot arm. First we calculate the minimal and maximal values z_e^{min} and z_e^{max} of the elbow and we chose an arbitrary value $z \in [z_e^{min}, z_e^{max}]$. We consider the intersection of the ellipsoid and the sphere mentioned above and the plane $z = z_e$. The result is two circles with radius r_2 and r_1, respectively (see figure 4).

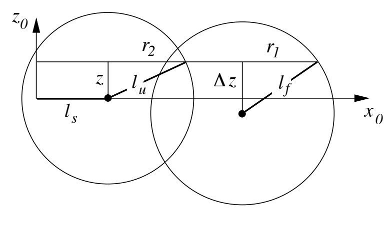

Figure 4: Geometrical construction

The radius r_2 and r_1 are easy to calculate from the geometrical construction in figure 4:

$$r_2 = l_s + \sqrt{l_u^2 - z^2}$$
$$r_1 = \sqrt{l_f^2 - (\Delta z)^2} \qquad \Delta z = \| z_w - z \|$$

where l_s, l_u and l_f are the link lengths of shoulder, upper arm and forearm, respectively. The two points provided by the intersection of the circles represent two possible positions of the elbow. A point of intersection must satisfy the necessary but not sufficient condition:

$$\sqrt{x_w^2 + y_w^2} \leq r_1 + r_2 \qquad (1)$$

In order to get z_e^{min} and z_e^{max}, substitute r_2 and r_1 in equation (1) and solve for z.

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We investigate the inverse kinematics problem for an arbitrary value of $z \in [z_e^{min}, z_e^{max}]$, which at first we found in the allowable interval and then we compare the results with those obtained for the "best" value of z. With the latter we indicate the value that minimises the joint angle changes, i.e. the objective function:

$$E(\theta) = \sum_{i=1}^{7} (\theta_{i,cur} - \theta_{i,cal})^2, \qquad (2)$$

where $\theta_{i,cur}$ and $\theta_{i,cal}$ represent the current and the calculated value of the joint angles, respectively. Note that in order to apply the evaluated joint angles to the control of the robot arm it is necessary to take into account the mechanical joint limits. We investigate also how to avoid switches between two angle domains if a joint limit is reached.

3.2.3 Determination of the joint angles

The position of the elbow (x_e, y_e, z_e) can be chosen within the interval $[z_e^{min}, z_e^{max}]$. Once the elbow position is known, the joint angles θ_1 and θ_2 can be directly calculated:

$$\begin{aligned} \theta_1 &= atan2(\frac{p_y}{p_x}) \text{ or } atan2(\frac{-p_y}{p_x}) \\ \theta_2 &= atan2(\frac{-p_z}{c_1 p_x + s_1 p_y - l_s}), \end{aligned}$$

where s_i and c_i are $sin(\theta_i)$ and $cos(\theta_i)$, respectively. Now it is possible to determine the orientation of the upper arm $\vec{r}_u$ and of the forearm $\vec{r}_f$. Then we can evaluate θ_3 and θ_4:

$$\begin{aligned} \theta_3 &= atan2(\frac{-s_1 o_x + c_1 p_x}{-s_2 c_1 o_x - s_2 s_1 o_y - c_2 o_z}) \\ \theta_4 &= atan2(\frac{c_2 c_1 n_x + c_2 s_1 n_y - s_2 n_z}{c_2 c_1 a_x + c_2 s_1 a_y - s_2 a_z}) \end{aligned}$$

Since we have the elbow position and orientation θ_5, θ_6 and θ_7 can be solved with the following formulation:

$$A_5 \cdot A_6 \cdot A_7 = A_4^{-1} \cdot A_3^{-1} \cdot A_2^{-1} \cdot A_1^{-1} \cdot T_n = T_{elbow}$$

Therefore θ_5, θ_6 and θ_7 can be evaluated as:

$$\begin{aligned} \theta_5 &= atan2(\frac{o_y}{o_x}) \text{ or } atan2(\frac{-o_y}{-o_x}) \\ \theta_6 &= atan2(\frac{o_z}{-c_5 o_x - s_5 o_y}) \\ \theta_7 &= atan2(\frac{-s_5 n_x + c_5 n_y}{s_5 a_x - c_5 a_y}) \end{aligned}$$

Once a closed form equation for each θ_1 to θ_7 is derived, it can be implemented directly.

4 Experimental Result

The inverse kinematic algorithm has been implemented within a simulation tool and then tested on the 7-DOF arm. We perform an experiment in which the arm is forced to follow a "critical" trajectory from the joint angle change point of view. Figure 5 shows the changes in the joint angles generated by the trajectory for the arbitrary value of z_e we found at first (solid) and for the "best" value of z_e, which minimises the objective function $E(\theta)$ in equation 2 (dashed). The angle of the elbow joint is the same in both cases.

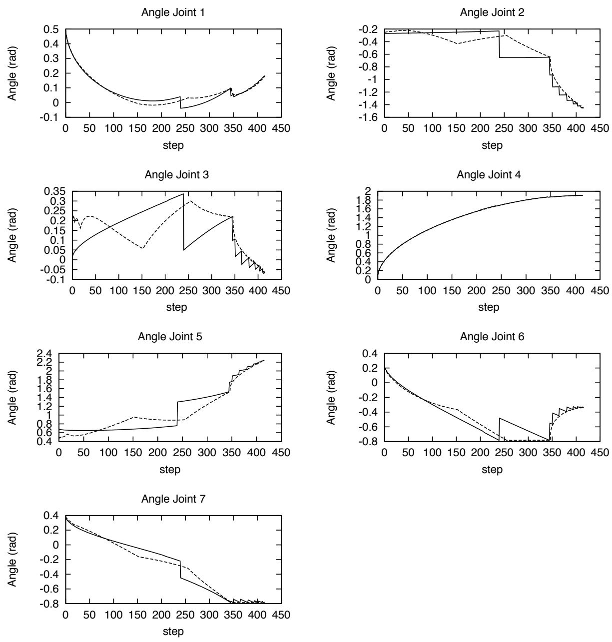

Figure 5: Trajectories of the joint variables θ_1 to θ_7

Single-Arm Motion planners are developed for two types of motion: point-to-point (PTP) motion and curve-tracking (CT) motion. The Inputs of motion planners are specified by a human operator. The Outputs of the motion planners are sequences of joint angles, and are executed in the simulation and then with the real robot via the controller we used.

5 Conclusion

In this paper we present an approach to transfer the human arm movements of typical manipulation tasks to the humanoid robot ARMAR. The mechatronics concept of our humanoid robot ARMAR is also introduced. Starting from a human arm model the transfer of movements during a manipulation task is shown. The inverse kinematics problem of obtaining joint variables of a 7-DOF redundant manipulator is investigated. A closed form solution to determine the elbow position is presented. Experimental tests are carried out on the robot ARMAR. Early manipulation tasks are also performed to demonstrate the capabilities of the humanoid robot. Figure 6 shows a typical manipulation task which should be performed by ARMAR.

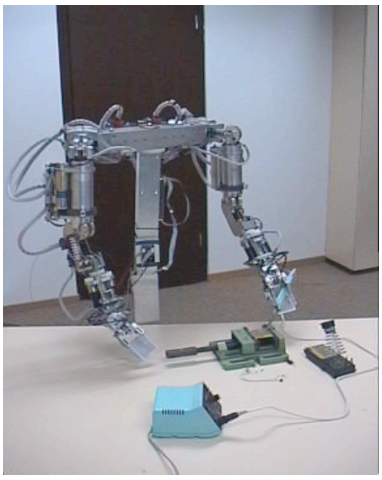

Figure 6: The aim of our research. ARMAR is performing a manipulation task, which was demonstrated by a human supervisor.

In the future we intend to install a stereo camera system for the detection of objects and the description of the environment. With the help of this information the last step of our approach – the adaptation of the ARMAR's movements – will be implemented.

Dual-arm motion planner for coordinated motion and body-motion planner as well as an intelligent control systems that use joint-torque sensors to perform tasks involving contacts and forces are to develop.

References

[1] Th. Bergener, C. Bruckhoff, P. Dahm, H. Janen, F. Joublin, and F. Menzner. Arnold: An anthropomorphic autonomous robot for human environments. In *In SOAVE'97, Selbstorganisation von adaptivem Verhalten*, 1997.

[2] K. Berns, V. Kepplin, and R. Dillmann. Terrain and obstacle detection for walking machines using a stereo-camera-head. In *IECON 98*, volume 11, Aachen, Germany, August 1998.

[3] K. Berns, H. Vogt, T. Asfour, and R. Dillmann. Design and control architecture of an anthropomorthic robot arm. In *ICAM 98*, Okayama, Japan, August 1998. Addison-Wesley Publishing Company Inc.

[4] R.A. Brooks, C. Breazeal, M. Marjanovic, B. Scassellatti, and M.M. Williamson. The cog project: Building a humanoid robot. In Japan Tsukuba Center for Institute, Tsukuba, editor, *IARP, First International Workshop on Humanoid and Human Friendly Robotics*, pages I–3, October, 26-27 1998.

[5] B. Giesler, R. Graf, and R. Dillmann. Fast mapping using the log-hough transformation. In *IROS 98*, Victoria, Canada, 1998.

[6] R. Graf, M. Rieder, and R. Dillmann. A nearly holonomous driving concept for a mobile robot. In *5th international coinference on Intellegent Autonomous Systems - IAS 98*. Sapporo, J, June 1998.

[7] R. Graf, M. Rieder, and R. Dillmann. A new driving concept for a mobile robot. In A. Ollero, editor, *IFAC Workshop on Intellegnt Components for Vehicles - ICV 98*, pages 115–120. Sevilla, ES, March 1998.

[8] R. Graf and P. Weckesser. Roomservice in a hotel. In M.A. Salichs and A. Halme, editors, *3rd IFAC Symposium on Intellegnt Autonomous Vehicles - IAV 98*, volume 2, pages 641–647. Madrid, ES, March 1998.

[9] S. Hashimoto. Humanoid robots in waseda univeristy -hadaly-2 and wabian-. In *IARP First International Workshop on Humanoid and Human Friendly Robotics*, pages pp. I–2, 1998.

[10] H. Inoue. A platform-based humanoid robotics project. In Japan Tsukuba Center for Institute, Tsukuba, editor, *IARP, First International Workshop on Humanoid and Human Friendly Robotics*, pages I–1, October, 26-27 1998.

[11] J. Lenar̃cič and A. Umek. Simple model of human arm reachable workspace. *IEEE Transactions on System, Man, and Cybernetics*, 24(8):1239–1246, August 1994.

[12] K.-U. Scholl. Mca - eine modulare steuerungsarchitektur fr autonome roboter. Technical report, Forschungszentrum Informatik an der Universitt Karlsruhe, 1998.

[13] URL: www.honda.co.jp/home/hpr/e_news/robot/.