

The Humanoid Robot ARMAR: Design and Control

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Abstract. This paper addresses the mechanism design methodologies, specification, and control strategies of a mobile manipulation system for the humanoid robot ARMAR, that has to work autonomously or interactively in cooperation with humans in dynamic unstructured environments such as workshops or homes.

1 Introduction

Robots of the current generation have been used in fields isolated from the human society. They suffer major shortcomings because of their limited abilities for manipulation and interaction with humans. Humanoid robots are expected to exist and work together with human beings in the everyday world such as hospitals, offices and homes and to serve the needs of elderly and disabled people [1]. These robots must be able to cope with the wide variety of tasks and objects encountered in dynamic unstructured environments. In cooperation with human beings humanoid robots should share the same working space and should react human friendly. Therefore, they need a light-weight body, high flexibility, many kinds of sensors and high intelligence. They have to be adaptive to new situations and capable of performing tasks in dynamic environments. Their design requires also a high extent of integration of mechanical, electrical and computational technologies.

Since very ancient time, humans have been trying to replicate humans. Between 1495 and 1497 Leonardo da Vinci designed and possibly built the first articulated anthropomorphic robot [2]. Recently, humanoid robotics has received much interest in the robotic research community, and many significant results have been achieved worldwide [3–11]. The manipulation capabilities and intelligence of these robots are still far away from the human capability in solving complex service tasks. At the Forschungszentrum Informatik Karlsruhe (FZI) the humanoid robot ARMAR is developed for applications like assistance in workshops or home environment [12] (see figure 1). Main focus of our research is the programming and execution of manipulation tasks of ARMAR by a direct and real-time mapping between the robot and the person, which demonstrates the task.

2 The Mechatronics of ARMAR

The humanoid robot has twenty-five mechanical degrees-of-freedom (DOF). It consists of an autonomous mobile wheel-driven platform, a body with 4 DOF, two anthropomorphic redundant arms each having 7 DOFs, two simple gripper and a head with 3 DOF. The total weight of the upper-body of ARMAR is about 45kg. This section describes the mechanics, sensor system and computer architecture of the robot.

2.1 Arms and Hand

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. We designed two anthropomorphic arms, each having 7 DOF and a length of 65 cm (including the gripper). Details about the mechanics of the arm of ARMAR are reported in [13]. Currently, a simple parallel jaw gripper is implemented, however a new humanoid five-fingered lightweight hand with only one actuator and 21 DOF is under construction [14]. The new hand is designed for anatomical consistency with the human hand. This includes the number of fingers, the placement and motion of the thumb, the proportions of the link lengths and the shape of the palm. The new hand accommodate automatically to the shape of grasped objects. It has also the ability of performing most of human hand grasping types.

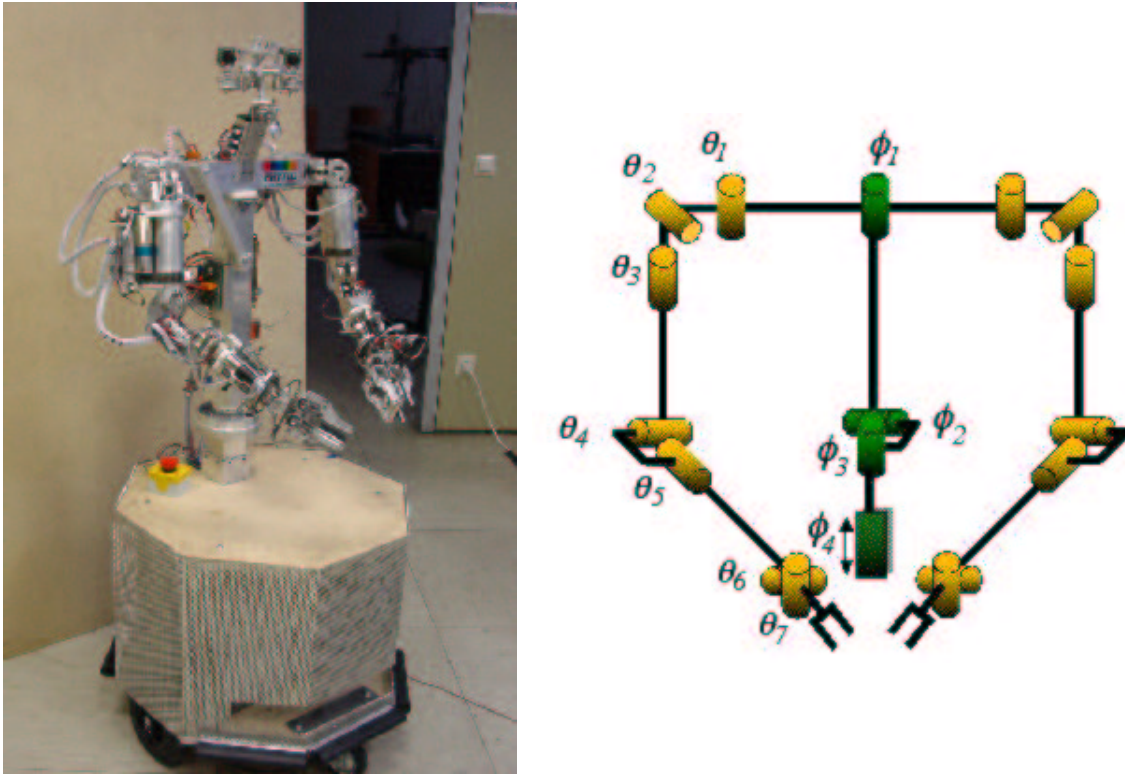


Fig. 1. The humanoid robot ARMAR and its kinematics model. The joint variables $\theta_1 - \theta_7$ are the arm DOFs. $\phi_1 - \phi_4$ correspond to the different joints of the torso: ϕ_1 describes the rotation, while ϕ_2 and ϕ_3 specify the forward, backward and sideward bending of of the upper body. ϕ_4 represents the telescopic joint of the body.

2.2 Mobil Platform

There are several requirements for the locomotion system of a humanoid robot to deal with a dynamic unstructured environment. Mobility is necessary to extend working space and to perform cooperative tasks with humans. Stability of the mobile system is the most essential to insure human's safety. From this remarks, we use an autonomous mobile wheel-driven platform. It has an octagonal ground-plan with a diameter of 70 cm and a differential drive concept with two active driven wheels on the sides. Two passive, free rotating wheels are also used. The maximum velocity of the platform is about $1 \frac{m}{s}$. The platform is equipped with ultrasonic sensors, a planar laser-scanner (see section 2.4), and sufficient battery power to allow for autonomous operation. Up to now it is not planned to use legs for the locomotion of the robot, 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 robot. However, we installed a telescopic joint (ϕ_4) in the torso of ARMAR to have this degree of freedom too.

2.3 Torso and Neck

The upper body of ARMAR has 4 DOF (figure 1). It is placed on the mobile platform and supports a rotation of about 330° . It also can be bent forward, backward and sideward (circa 110°). To adapt the height of the robot (180 cm), a telescopic joint is included in the body. With this joint the total height of the robot can be increased by 40cm. The Neck of ARMAR has 3 DOF.

2.4 Sensors

The sensor system consists of angle encoders for each joint with a resolution of 0.1° . The current as well as the voltage of each motor are measured and determined by special power electronic card. For gripping various kinds of objects an artificial skin is placed on the inner side of the gripper. It is realized by measuring the electrical resistance of the conducting rubber that is divided into several fields of an array. To detect the environment, a stereo camera system is fixed on the head of ARMAR. 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. The sensor system of the mobile platform includes eight ultrasonic sensors and a planar laser-scanner. Both types of sensors are used for a collision free navigation of the robot.

2.5 Computer Architecture

The computer architecture of the robot has been designed to be modular. It is hierarchically organized and 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. Currently, the robot is controlled by a cluster of C-167 micro-controllers and a standard PC. The micro-controllers are coupled with special power cards, which control four motors. The micro-controller boards are connected via CAN-Bus with a maximum transfer rate of 1 Mbit/s to the PC. For real-time requirements 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 is implemented, since it enables rapid development and the exchange of control algorithms at different control levels [16]. Figure 2 shows the hardware and software architectures applied to the humanoid robot.

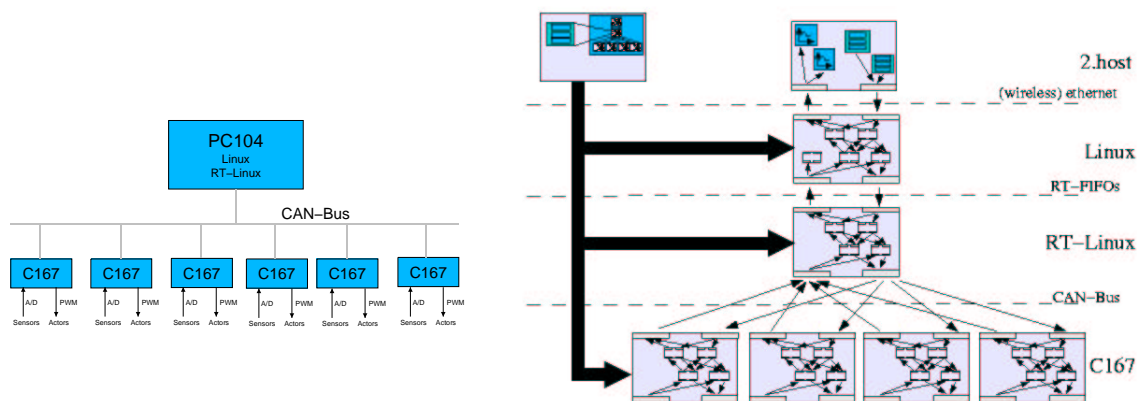


Fig. 2. The hardware (left) and software (right) architectures.

3 Control

Manipulators are one of the most important hardware components of humanoid robots. So, safety and robust control is essential requirement for successful execution of cooperative manipulation tasks with humans. Robustness, stability and safety are of greatest degree of importance in the case of humanoid robots. The implementation of full dynamic control on a robot still remains a challenge to robot scientists and researchers today. It is known that the performance of a robot can be improved with the including of the robot dynamics into its controller. However, the complexity and, more important, the lack of knowledge about the dynamic parameters of the robot, lead robots to be controlled mostly by PID control, where the control is done independently for each joint.

Since ARMAR's tasks are currently limited to those requiring low speed, the dynamics effects from high-speed motions can be neglected. Therefore, position joint controllers are used, because they can better deal with nonlinear friction. The purpose of a position controller is to drive the motor so that the actual angular displacement of the joint will track the desired angular displacement specified by a preplanned trajectory. The joint-angle measurements of the arms and body of ARMAR are obtained by accurate encoders. A robust robot control requiring only position measurements is easy to implement and increases the dynamic performance of the robot manipulator. Nevertheless, when velocity and force sensors are available, feedback of the velocity and forces can be added to improve the performance of the system. Figure 3 shows the structure of the controller we use. The fuzzy-like module chooses a set of parameter of a classical position joint controller depending on the configuration of the arm. The sets of parameter are established through experiments.

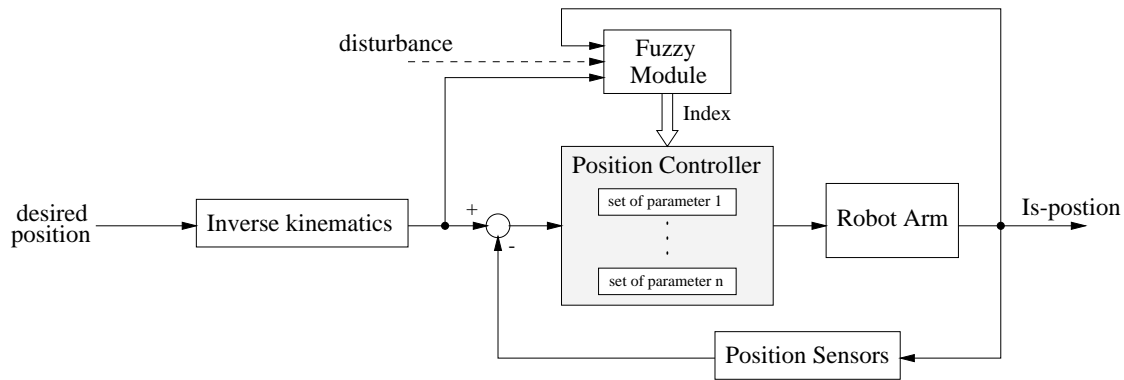


Fig. 3. The structure of the controller

For the control problem of the dual arm system of ARMAR only the kinematic control is considered. The control problem is solved in two stages: first, an inverse kinematic problem is solved to transform task variables into the corresponding joint variables for the arms and body of the robot. The obtained joint variables are input of a suitable joint control scheme. The coordination is then solved at the inverse kinematics level while the arm interaction can be considered at joint control level.

4 Programming of manipulation tasks

The programming of manipulation tasks is done by a direct mapping of the human arm movements to the robot. Firstly, tasks are demonstrated by a human operator and the manipulation trajectories are recorded. In the following, the programming approach of the manipulation tasks is described.

4.1 Motion Capturing

Many motion capturing devices are commercially available these days and different techniques are used in order to track the body motion of a person. Most of them suffer drawbacks such as: low update rate due to the sensor characteristics and pretty low communication bandwidth. We use two commercially available position sensors called FasTraks. The positions and orientations of the elbow and the wrist are directly provided. The human arm movements are only kinematically represented, and the dynamics for human manipulation tasks can be taken into account as a post-processing step. It is not necessary to consider the dynamics unless realistic velocity distribution for manipulation motions is required.

4.2 Determination of the Arm Configuration

The transfer of demonstrated movements to ARMAR is provided by an inverse kinematics algorithm. This is necessary because most manipulation tasks are specified in terms of the object trajectories. The presence of a redundant joint in the arm of ARMAR results in infinite distinct arm configurations with the same hand position and orientation. The redundancy of the arm can be described by the rotation of the center of the elbow joint about the axis, that passes through the wrist and the shoulder joint (see figure 4). 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 centered on the shoulder joint and that the starting point of the forearm describes a sphere centered on the wrist. Since both of these points have to be the same, the redundancy curve results from the intersection of the ellipsoid and the sphere. The elbow position, together with the hand position, forms a complete representation of the posture of the arm.

For a given position and orientation of the end effector and based on the arm geometry, we calculate a possible position of the elbow, which is optimal with respect to some criteria (joint movement time, mechanical joint constraints, singularity avoidance, redundancy resolution resulting in human-like motions of the robot and "comfortable" joint movements). Once having the elbow position, the remaining joint angles are then easy to determine. For a complete description of the algorithm refer to [15]. So, instead of using time consuming iterative solution of inverse kinematics, an analytical, geometrical, closed form solution is provided.

Starting from the human arm movement detected by the above mentioned tracking system, the arm configuration can then be computed from the sensor data using the 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.

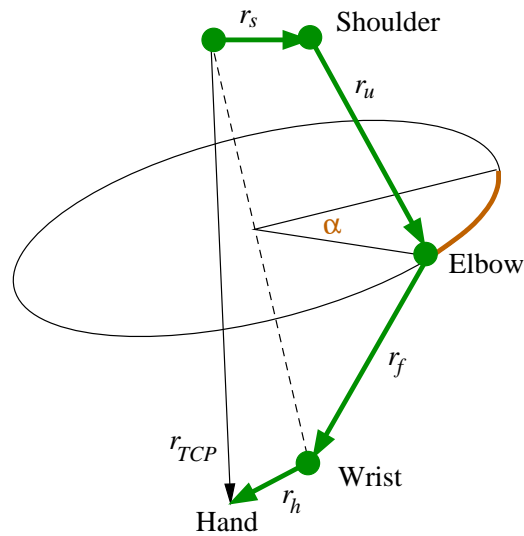


Fig. 4. Determination of the arm configuration: The elbow position, together with the hand position, forms a complete representation of the posture of the arm. The redundancy of the arm is described by a curve in the cartesian space.

4.3 Motion Mapping to ARMAR

Based on the elbow and wrist trajectories of the human arm, each joint angle of the arm of ARMAR is calculated via inverse kinematics. The arm motion is mapped directly to the corresponding humanoid arm motion: vertical motion of the human arm are mapped to the elbow joint and vertical shoulder joint of the robot arm, whereas horizontal motions are mapped to the horizontal shoulder joint¹. This mapping strategy can easily be extended to realize also neck and torso motions. The final step of the programming approach will be to adjust all joint angles according to the description of the object to be manipulated and the robot environment.

5 Conclusion and Further Work

In this paper, the mechanisms and control scheme of the mobile manipulation system for the humanoid robot ARMAR are described. A closed form solution of the inverse kinematics of the redundant arm of the robot is provided and an approach to transfer the human arm movements of typical manipulation tasks to the humanoid robot ARMAR is also proposed. Single arm motion planners are developed for point-to-point motion and curve-tracking motion. The Inputs of the motion planner 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 controllers we used. A simple dual-arm motion planner for coordinated motion is developed. This motion planner considers the closed kinematic chain of both arms and the object. We also implemented an object-oriented software system that allows a fast debugging of behavior-based control in a graphical simulation environment. It can be used simultaneously to the control of the real robot. Early manipulation tasks are also performed to demonstrate the capabilities of the manipulation system of the humanoid robot. Figure 5 shows a typical manipulation task performed by the robot.

Further work will concentrate on the extension of the sensor system, the integration of a human operator, the recognition of the environment, the integration of knowledge bases and human-friendly interfaces, and the

¹ The vertical shoulder joint allows the shoulder to move in the sagittal plane (forward/backward direction). The horizontal shoulder joint allows the shoulder to move in the transverse plane(outward/inward direction).

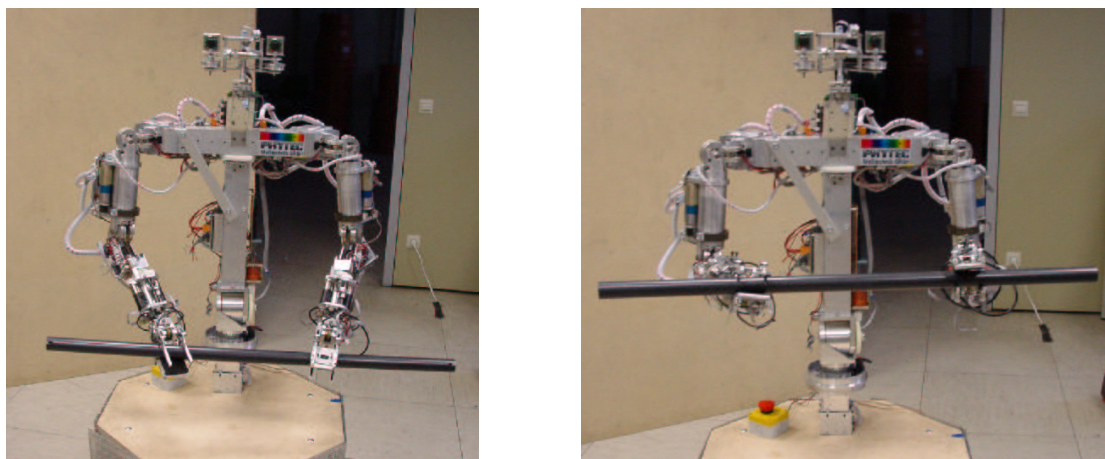


Fig. 5. ARMAR is performing a manipulation task, which was demonstrated by a human supervisor.

implementation of service tasks. For the control system, intelligent controllers able to perform tasks involving multiple sensor information are to develop. Control strategies for the coordinated motion of the whole humanoid robot (platform, torso, arms and head) are also required for the successful execution of complex manipulation tasks. In addition, the control system for the navigation of the mobile platform will be implemented in order to provide a collision free navigation and to integrate mobility in manipulation tasks.

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