Control of ARMAR for the Realization of Anthropomorphic Motion Patterns

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Abstract

In this paper we present the current state of our humanoid robot ARMAR. We introduce different subsystems that were developed based on the intended application, i. e. service in a household environment. The paper primarily addresses the control strategies, computer architecture and the generation of humanlike motions. We present experimental results showing the generation of ARMAR's motion trajectories based on the observation of human motion and the control techniques that were applied to follow the generated motion trajectories.

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. They perform various tasks improving the quality and efficiency of manufacturing. Humanoid robotics is a new, challenging field of robotics. 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. Within this class, maybe the most promising are home robots or personal robots [4]. In cooperation with human beings humanoid robots should share the same working space and should react human friendly. Therefore, they have to feature human-like characteristics in behavior regarding motion, communication, intelligence and structure. Their design require an intensive integration of computer hardware, sensor technique and advanced control strategies.

There is a long history of people attempting to replicate human beings with machines that appear humanoid. Between 1495 and 1497 Leonardo da Vinci designed and possibly built the first articulated anthropomorphic robot [5]. Recently, humanoid robotics has received much interest in the robotic research community and has taken many shapes and forms. Many significant results have been achieved world-wide [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20]. 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 has been developed for applications like assistance in workshops or home environment [16]. Our primarily research objectives are the development of anthropomorphic sensor- and actuator-components replicating human features, their integration to build a humanoid robot and the investigation of control methods and motion coordination schemes to achieve human-like responses.

The paper is organized as follows. Section 2 gives an overview of the mechanics of ARMAR and section 3 describes its control architecture. In section 4 the control scheme of the dual arm system and an appropriate closed-form solution of the inverse kinematics problem, which computes the arm con-

figuration to execute manipulation tasks, are presented. Section 5 describes the generation of humanoid robot motions based on the observed human motion. The method is applied to ARMAR by performing a "knocking" task and the results are presented.

2 System overview

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 arms are designed to be light in weight and to achieve a high degree of mobility and simple and direct cooperation with humans. Therefore, their structure (size, shape and kinematics) are similar to that of a human. Each arm has 7 DOF and a length of 65 cm and a total weight of 6 kg (including the gripper). Details about the mechanics of the arm of ARMAR are reported in [17]. Currently, simple parallel jaw grippers are mounted on the end of each robot arm, but a new humanoid five-fingered lightweight hand with only one actuator and 21 DOF is designed for anatomical consistency with the human hand [18]. 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 accommodates automatically to the shape of grasped objects. It has also the ability of performing most of human hand grasping types.

The upper-body of ARMAR has 4 DOF. It is placed on the mobile platform and can bend forward, backward and sideward. 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. A stereo camera system serves as ARMAR's eyes.

The locomotion system of the robot is designed 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 essential to insure human's safety. Therefore, we use an autonomous mobile wheel-driven platform. It has an octagonal
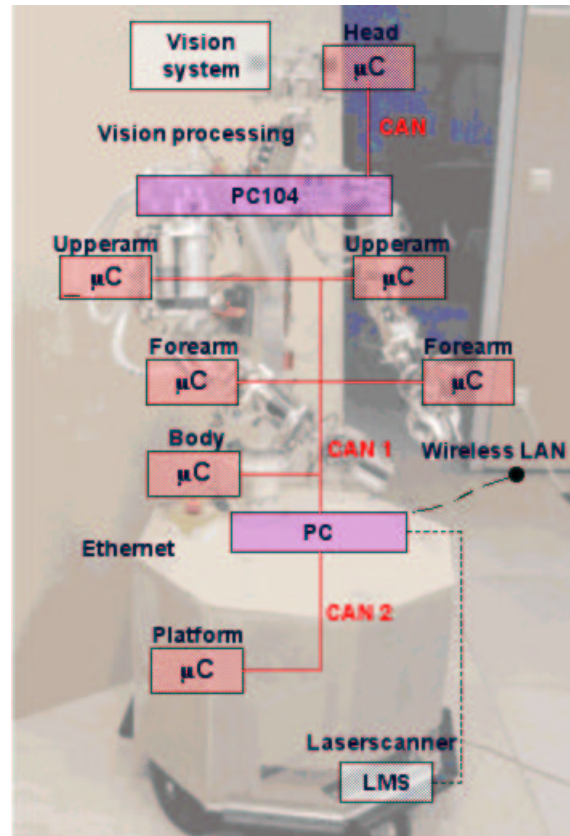

Figure 2: The computer architecture of ARMAR.

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 a planar laser-scanner, that is used to ensure a collision free motion of the robot and to enable the integration of mobility into manipulation tasks. The battery power is sufficient to allow for autonomous operation for ca. 6 hours.

3 Concept for the control architecture

Because there are normally several development cycles to develop and optimize a humanoid robot and because of rapidly change of the available electronic components and sensors (mainly concerning the performance) the design concept for the control architecture of ARMAR was realized in the following way:
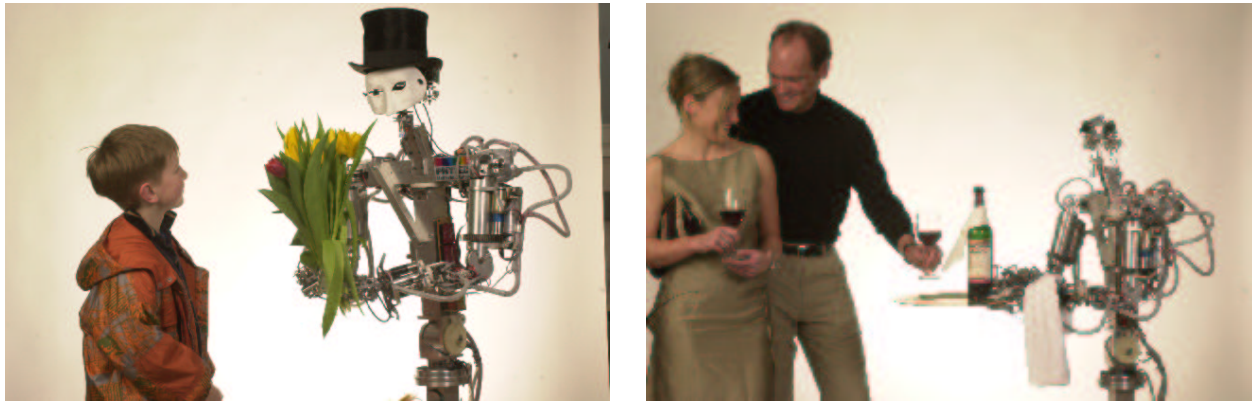
Figure 1: The humanoid robot ARMAR: buddy and servant in the everyday world.

Modular structure The development and improvement of single dedicated modules is less difficult than designing a complex system board and seems to be more efficient concerning time and expense. The Expansion of the functionality was possible as well as the replacement of modules which have become obsolete and insufficient in performance.

Scalability A flexible system development strategy was performed. The rapid realization of subsystems as well as a whole prototype robot was possible in short time without being restricted in the implementation of functionality at any time. E.g. at the beginning of the ARMAR project we developed the 7 DOF robot arm with complete computing components. Without any changes this arm was installed in the body of ARMAR.

Small Dimensions The mounting and positioning of several small sized modules guaranteed an efficient use of the existing space and geometry of the machine. The mechanical integration of the electronic components led to a compact mechatronic system.

Effort and Costs Whenever possible the use of standard components was given preference to the development of new components on our own. Because of the increasing spreading of embedded portable systems one can profit from products designed for low power applications and big number of pieces in mass production and therefore low cost as long as these components meet the specific constraints of the humanoid robot system.

In the following a short introduction to the control architecture is given. More information concerning the modular control architecture can be found in [21].

An internal industrial PC performs the main control tasks e.g. behavioral planning, calculation of trajectories and communication with the environment (Man Machine Interface). At the second level 80C167 micro-controllers are connected with the PC system via CAN-Bus. They are installed in industrial controller boards (Phytec, miniMODUL-167) and execute the basic functions like close-loop joint control (actuator control, recording the signals of joint encoders), sensor data acquisition and precomputation. At the base level each sensor and actuator is connected directly to the microcontroller boards. The modules of the different levels all have been developed observing the constraints which are important for mobile robots. The circuitry has been optimized for power consumption, less weight and small dimensions. The power consumption of all electronic components sensors and actuators is about 150 Watts. This allows the use of the whole system for more than 6 hours (with two internal lead accumulators). Furthermore the components are adapted for an easy integration in the entire system.

The use of different hardware and operating system units results in a three level system: C167, RT-Linux and Linux. In order to achieve a clear arrangement of those levels modular controller software architecture is used. This software architecture allows the programming of all levels in the same way. The C++-class library hides the communication between the levels. Hence, the system develop-

ers can focus on the development of methods while the communication is done automatically. Every method of the controller architecture is realized in a C++-class module. The modular architecture allows the manipulation of each parameter of every module via LAN while the system is running. This possibility results in small and fast development cycles. The manipulation tools run on the Linux part of the system so that critical parts that are assigned to the real-time part are not directly influenced by the manipulation itself. The detachment of the user interface from the controlling PC disburdens the internal PC. For example, the user interface can include high-end graphic animations without straining the controlling mechanism too much. Linux is also used as development platform. All parts of the software architecture are compiled with GNU-C++-(cross-) compilers. The C167-programs are downloaded via CAN-bus during the initialization of the system.

4   Control

4.1   Motor control

The arms are one of the most important hardware components of humanoid robots. So, safety and robust control are essential requirement for successful execution of cooperative manipulation tasks with humans. Robustness, stability and safety are of extremely important for 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 inclusion 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 controllers, 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 pre-planed 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 arm. The control system consists of angular position, velocity and force (current) control. The controller run with a conventional linear controller. The angular velocity is estimated from encoder position measurements. Nevertheless, when velocity and force sensors are available, force and velocity feedback can be added to improve the performance of the system.

4.2   Kinematics control

The execution of manipulation tasks 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 an infinite number of distinct arm configurations with the same hand position and orientation. A given motion task, defined in terms of operational coordinates $x(t)$ can be accomplished with infinite robot arm configurations $\theta(t)$.

The elbow position, together with the hand position, forms a complete representation of the posture of the arm. The redundancy of the arm can be described by a curve in the Cartesian space. 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 local criteria (joint movement time, mechanical joint constraints, singularity avoidance, redundancy resolution resulting in human-like motions of the robot, "comfortable" joint movements and joint motions that would be executed by the human arm in the same motion task). Once we have the elbow position, the remaining joint angles are then easy to determine. For a complete description of the algorithm refer to [19]. So, instead of using time consuming iterative solution of inverse kinematics, an analytical, geometrical, closed form solution is provided.

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 of the robot. The obtained joint variables are used as an input of a suitable joint control coordination scheme.

5 Trajectory generation

Motion capture is the process of generating motion trajectories from the marker data captured by an optical tracking device. The motion capture approach exploits the similarity between the humanoid robot motion and human motion to generate humanlike trajectories. It is commonly used in the entertainment industry and computer graphics for the generation of believable animations and is closely related to the idea of imitation learning which has been seen as a means to speed up learning in complex high dimensional motor systems such as humanoid robots [1].

The basis of our approach is the establishment of the relationship between the human body kinematics and the humanoid robot's kinematics. This is achieved by modeling the human performers kinematics by a model standard for humanoid robots, only scaled to the physical size of the human performer. This is done by a calibration procedure described below. Since the humanoid robot's kinematics is similar to the human body kinematics (that's why it is called humanoid), a large range of human motions can be accounted for in this way.

The placement of a body in Cartesian space is determined by the position and orientation of a coordinate system rigidly attached to one of the body parts and by the values of joint angles about body axes. Regardless of the kinematic parameter system in use, the actual values of the parameters (joint angles) depend on the choice of local coordinate systems attached to the body parts because they specify transformations between them. It is essential that local coordinate systems are chosen in such a way that the parameter values at every body posture can be mapped on the robot's joint angles at the equivalent robot posture. Therefore we orient the local body part coordinate systems on a human performer in such a way that they are all aligned when the performer stands in an upright position with extended arms and legs and that their axes are parallel to the main body axes in this configuration.

If the local coordinate systems are selected like described above, the joint axis locations are the only kinematic parameters that still need to be estimated. To estimate these parameters, the subject is asked to perform a set of movements, which are measured by a motion capture system. He or she should exercise motions around all relevant degrees of freedom if the method is to return an unambigu-

ous answer. Instead of trying to estimate all joint locations in one big optimization process, we decided to split the estimation in ten separate smaller optimization problems: neck, waist, left and right shoulder + elbow, left and right wrist, left and right hip + knee, and left and right ankle.

We parameterized the joint axes by twists. Using this parameterization, two independent parameters were derived for each joint axis location. Apart from joint axis locations, we also need to estimate the position and orientation of the body in space as well as the joint angles to match the model markers with the measured marker positions. To make the optimization process smaller, we estimate all the degrees of freedoms prior to the joints under consideration in a separate optimization process. The optimization procedure then involves only the joint angle locations that need to be estimated and the corresponding joint angles. Still, the resulting optimization problems are very large. The number of parameters increases with the number of measurement times. In our experiments, we typically used 300 measurements in each of the ten optimization problems and therefore needed to estimate 906 or 1208 variables per optimization problem. To solve such big optimization problems we utilized a subspace trust region approach and sparse matrix algebra.

The model of a human performer does not need to be estimated from scratch at the beginning of every motion capture session. In the next motion capture session, we only need to measure the position of markers at zero configuration. ¿From this data we can estimate the new local marker positions and the positions and orientations of local coordinate frames. The joint axis positions remain the same as in the old kinematic model and can be used again without performing a repertoire of motions in order to estimate them anew.

Using the scaled kinematic mapping generated by the above calibration process, we can generate humanoid robot motions that are perceptually similar to the motion of the human performer. To attain this, we minimize the differences between the measured marker positions and the marker positions generated by the recovered joint angles for each frame of motion over the set of body configurations. However, the straightforward approach of sequentially estimating body configurations at each measurement time has several deficiencies because of occlusion problems, kinematic singularities and

local minima in the optimization criterion. The motion generation process can be made more reliable by recovering complete trajectories instead of separate configurations and by exploiting our knowledge of how people move to generate the motions. Such information can be incorporated into the movement recovery in the form of regularization terms. Thus, perception becomes an optimization process trying to find a trajectory that predicts the measured data well and deviates the least from what we know about human movement. We utilized B-spline wavelets to efficiently represent the joint trajectories and to automatically select the density of the basis functions on the time axis.

The presented approach has been originally developed and tested on another robot [2, 3]. Although ARMAR has a different kinematic structure, we could apply this technique to the generation of anthropomorphic patterns for ARMAR without any modifications.

6   Results

The method of the generation of anthropomorphic motion patterns is tested according to the knocking task. Figure 3 show the joint trajectories of the generated motion and of the real robot motion. The diagram's for motions in the shoulder joint θ_1, the elbow joint θ_4 and the hand joints (θ_6 and θ_7) deserve special attention, because of their participation in generating the required motions of the task "knocking". The diagrams in figure 3 show that the characteristics of the real motion of the robot arm are similar to the generated motions from human motion capture data.

Additionly to the mapping of the generated motions from human motion capture data, we pursue the idea of the realization of basic behaviors. These are the motion patterns, required for the execution of typical manipulation tasks in a household environment. Examples of such kind of behaviors are: watering plants, carrying big objects together with a human, reach actions and coordinated two arm tasks.

7   Further work

The further work concentrate on the improvement of 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. Also the vision system for the recognition of the environment and human-friendly interfaces will be implemented.

Beside the implementation of basic behaviors based on anthropomorphic motions several other tasks will be performed in the near future. The AR-MAR project will be sponsored in the range of the SFB program "Humanoide Roboter", which includes 11 research groups located in Karlsruhe, Germany. The whole program is sponsored by the Deutsche Forschungsgemeinschaft (DFG). Concerning the ARMAR project several mechanical components will be improved and the sensor system will be increased mainly for measuring forces on different parts of ARMAR. Also the components of the control architecture will be renewed; new powerful electronic boards will be included. Both will be finished in the next year. In parallel a totally new upper body system will be developed (ARMAR II). One of the aims is the design of a light-weight system with special emphasis on a new 7 DOF arm and a body with at least 4 DOF. Also we have started to build a new sophisticated robot head which allows the integration of several cameras and microphone arrays. For this head a new neck will be constructed.

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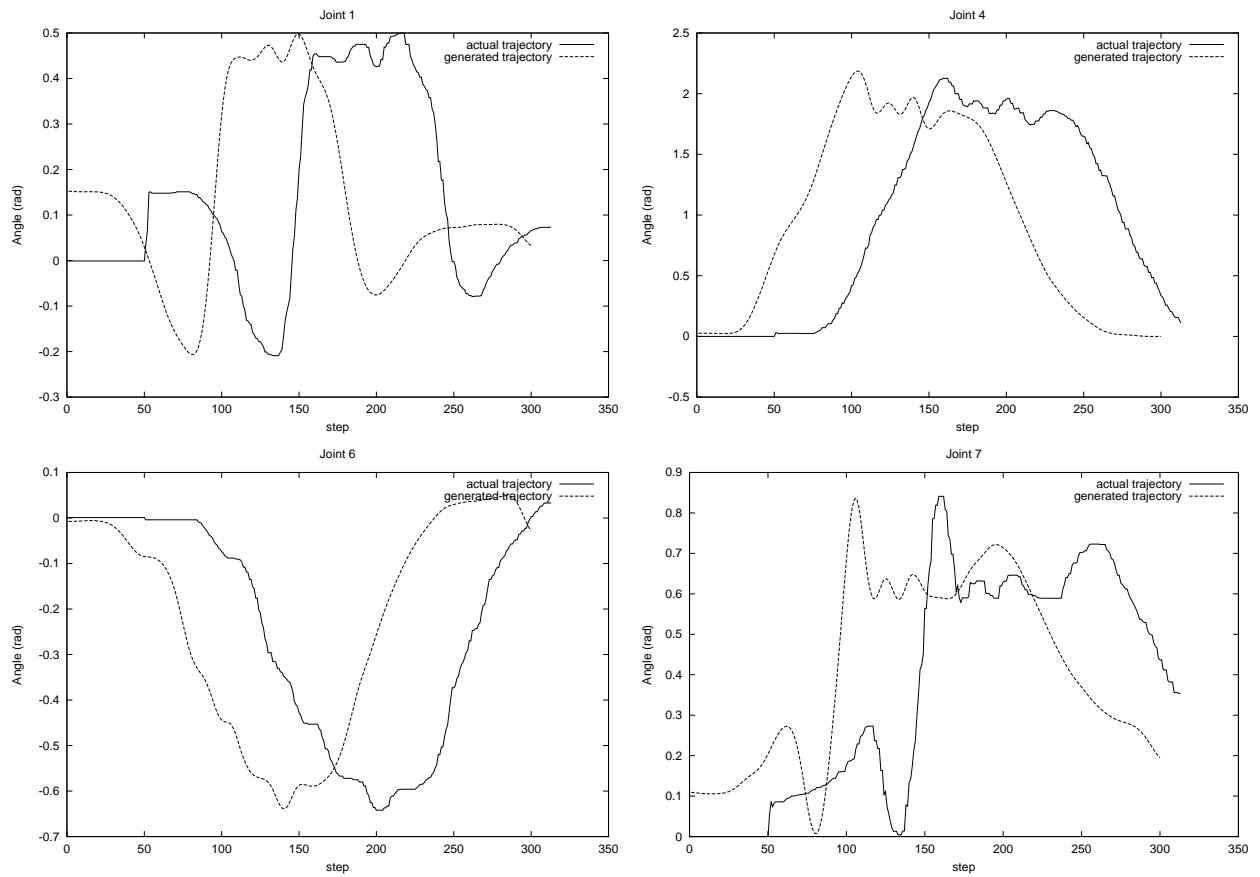
Figure 3: Trajectories of the joint variables θ_1 (shoulder), θ_4 (elbow) and the hand joints (θ_6 and θ_7)

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