Controlling a Redundant Robot Arm by Means of a Haptic Sensor

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Abstract

This paper describes the hardware- and software-implementation of a touch-sensitive device on the manipulator arm of our anthropomorphic robot CORA. This so-called *artificial skin* is used to control the configuration of the manipulator while the robot is grasping for objects. By exploiting redundant degrees of freedom, this operator-induced movement constraint can be accounted for without changing the configuration of the end-effector.

Keywords

inverse kinematics, robot manipulator control, artificial skin, man-machine-interaction

1 Introduction

In robotics research the topic ”man machine interaction” (MMI) becomes more and more important. This development is driven by a number of factors: first, the research on sensor systems and signal processing has made great progress so that advanced and cheap man-machine-communication systems are available. With current vision processing systems it is possible, for instance, to track and recognize objects and even human faces. State of the art speech recognition systems can recognize (although not yet *understand*) fluent human speech. Furthermore, the entertainment- and toy-electronic market has discovered the appeal of puppets that can interact visually and acoustically with humans. However, even for industrial robotics the direct physical interaction between an operator and the robot provides new possibilities for efficient working processes. Commanding the robot by gestures, speech and touch is faster, more natural and easier than using a keyboard, a mouse and a monitor. The implementation of these natural communication channels on an anthropomorphic robot is the topic of our research. While our works on speech in- and output, visual object-, hand- and gaze-recognition are described in [Menzner et al., 2000], [C. Theis, 2001], [Hustadt, 2000], this paper gives a rough overview of our research on the integration of haptic input with manipulator control. Before we describe the haptic device that we call *artificial skin*, we present our anthropomorphic robot CORA in the next section.

2 The anthropomorphic robot Cora

The robot CORA(=**Co**operative **R**obot **A**ssistant, see Fig. 1) is the prototype of an assembly assistant fixed on a table and meant to physically interact with a human sitting across the table. It has a head with two degrees of freedom (DoF): pan and tilt. The head carries a stereo color camera system and microphones. The stereo vision system performs tasks such as object recognition, gesture recognition, the estimation of the human’s gaze direction and the estimation of the 3D position and orientation of objects.

CORA’s body consists of a redundant seven DoF manipulator connected to a one DoF trunk which is fixed on the edge of a table. For grasping rigid objects at any 3D-position in the working area, six DoF would be enough. However, the eight DoF of CORA’s arm trunk configuration guarantee a high degree of flexibility with respect to manipulation tasks under external constraints. Grasping, for instance, is possible in the whole workspace choosing different arm-postures without the necessity of changing the position or orientation of the end-effector. By turning the trunk joint, the robot can also change its configuration from left- to right-handed.

The sensor equipment and the configuration of the joints in CORA's body and manipulator arm are anthropomorphic, which means that they are structurally similar to the human body. Two of the manipulator arm's modules are covered with a touch-sensitive so-called *artificial skin* which will be explained in detail in the next section.

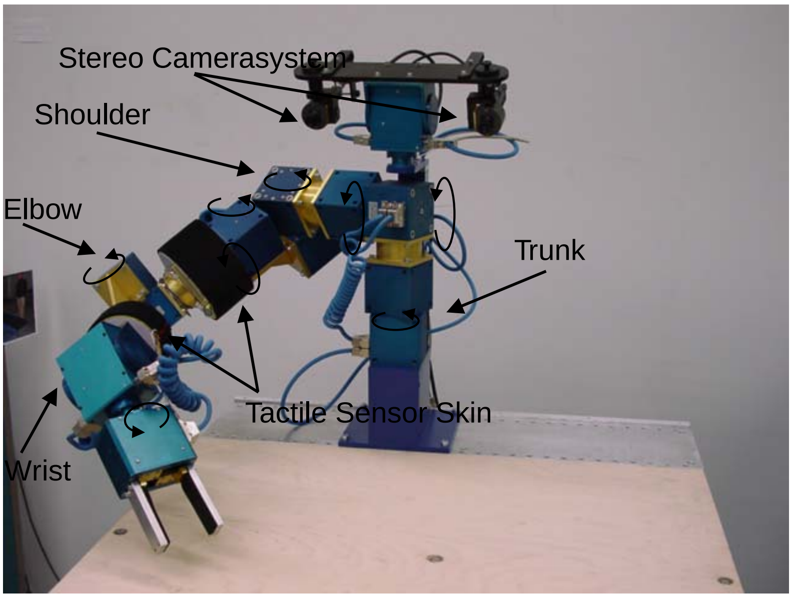

Fig. 1. The service- and assistance robot CORA. A seven DoF manipulator arm is mounted on a one DoF trunk which is fixed on a table. The robot possesses a two DoF stereo camera head with microphones.

When a human partner is sitting at the opposite side of the table, the robot and the human partner share the same eye-level. Relying on the stereo camera, the microphones and the artificial skin, CORA uses similar sensor channels as those available to the human partner. The restriction to audio, vision and touch and the redundant configuration of the arm put high demands on the control structure of the robot.

3 The artificial skin

The artificial skin, invented by the SIEMENS robotics group, is based on a conductive foam the conductivity of which varies with the pressure applied to it. This resistance or conductivity variation is used as the output of the sensor. The variation of resistance is measured by using the analog to digital converter of a PIC microcontroller. The sensing part of the skin is made of two layers of EVAZOTE-foam. Two electrodes are inserted in parallel on opposite sides of each layer. Those electrodes are connected to a so-called sensor board. On the upper layer one electrode is set to ground (0V) and the other to 5 volts so that the voltage varies continuously from 0 to 5 Volts within the material. The electrodes of the lower layer are both connected to the A/D converter of the microcontroller. The voltage of the lower layer is periodically varied between 0 and 5V. When force is applied to the upper layer, the voltage of the lower layer corresponds to the voltage of the upper layer depending on the position of the force so that the converter can read this position. Two analog switches are soldered on the board. They are used to set a defined calibrating voltage on the electrodes in order to measure the X and Y position. The same principle is used to measure the pressure.

We have covered two of CORA's arm-modules with the artificial skin mounted on a cylindric silicon cuff (see figure 1). The advantage of the cylindric cuff is that a scalar pressure value can be interpreted directly as a force vector perpendicular to the cylinder's surface defining the direction in which the limb should be moved.

4 Manipulator control with redundant degrees of freedom

The standard method for the control of robot arms is the so-called inverse kinematics, i.e the transformation of the six cartesian coordinates of the end-effector (3 position and 3 orientation) into the n-dimensional space of the robot's joint angles [Craig, 1989]. If the number of joints is less than or equal to six, like in the case of conventional industrial robot manipulators, the problem of inverse kinematics simplifies to the mathematical task of solving a well defined system of linear equations through a matrix inversion. However, if the number of degrees of freedom (DoF) of the manipulator exceeds the number of task coordinates, this problem becomes under determined and the inverse matrix becomes singular. This is the case for our anthropomorphic robot CORA (see Fig. 1): this robot has a seven DoF manipulator which corresponds to the joint configuration of the human arm (three DoF shoulder, one DoF elbow and three DoF wrist). In addition, CORA has an eighth degree of freedom in its trunk joint. This setup leaves us with the problem of calculating eight joint angles from only six task coordinates. Our solution to this problem is based on the closed form inverse kinematics for seven DoF-arms described in [Dahm and Joublin, 1997] which we extended by additional terms to deal with the eighth DoF as we will describe now.

4.1 Inverse Kinematics

With the forward kinematics, the position and orientation of the end-effector can be calculated directly from a set of known joint angles. For the grasping task however, we need to calculate a set of joint angles from a given position and orientation of the end-effector. Therefore, an approach for solving the inverse kinematics is required. To formulate the inverse kinematics for the eight DoF system, we have to solve the underdetermined problem we mentioned above. The position and orientation of an object to grasp determines the orientation and position of the end-effector. The end-effector's orientation determines the wrist-position $\vec{r}_{WST}$ in the basic coordinate system $({}^B\hat{x}, {}^B\hat{y}, {}^B\hat{z})$ through the limbvector $\vec{r}_h$:

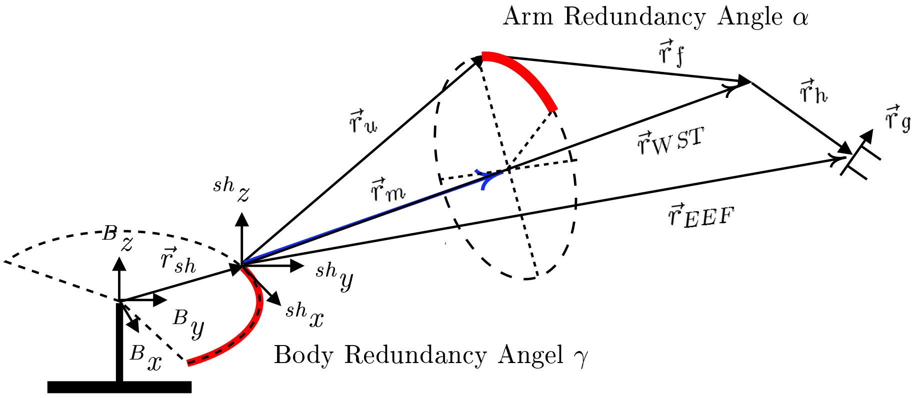

Fig. 2. The redundancy of the shoulder and the ellbow joints

$$\vec{r_h} = \mathcal{R}_z^{\phi_{EEF}} \cdot \mathcal{R}_y^{\theta_{EEF}} \cdot \hat{e}_x \cdot l_h \tag{1}$$

here, ϕ_{EEF} and θ_{EEF} determine the pan and tilt angle of the end-effector, $\mathcal{R}_x$, $\mathcal{R}_z$ are the rotation matrices around the z- and y-axes and l_h is the limb length.

The body orientation should be chosen with respect to the object and the human user. This means to bring the manipulator in an optimal grasping position while simultaneously using a right handed configuration when interacting with a right handed partner and a left handed configuration otherwise. This requirement fixes one redundancy through the determination of the trunk joint such that $\vec{r}_{eef}, \vec{r}_g, \vec{r}_{wrs}$ and $\vec{r}_{sh}$ are fixed. Now we make use of the formal representation of the spherical joints (shoulder,wrist): with the help of Fig. 2 it is easy to see that the only remaining degree of freedom of the arm is defined by a circle the center $\vec{r}_m$ of which lies on the connecting straight line between the shoulder and the hand. The radius R of this circle is defined by all possible positions of the elbow. We call this circle the *redundancy circle*. The values $\vec{r}_m$ and R can be easily calculated:

$$\vec{r}_m = \frac{|\vec{r}_u|^2 - |\vec{r}_f|^2 + |\vec{r}_{WST}|^2}{2 \cdot |\vec{r}_{WST}|^2} \vec{r}_{WST} \tag{2}$$

$$R = \sqrt{|\vec{r}_u|^2 - \left(\frac{|\vec{r}_u|^2 - |\vec{r}_f|^2 + |\vec{r}_{WST}|^2}{2 \cdot |\vec{r}_{WST}|} \right)^2} \tag{3}$$

Expressing the wrist position in spherical coordinates the position of the elbow can be written as

$$\vec{r}_u = \left(\mathcal{R}_x^{\phi_{WST}} \mathcal{R}_z^{\theta_{WST}} \mathcal{R}_x^{\alpha} \cdot \hat{e} \right) \cdot R + \vec{r}_m \tag{4}$$

with $\mathcal{R}_x$ and $\mathcal{R}_z$ being the rotation matrices around the x- and the z-axis and α being the so-called *redundancy angle*: the angle of the elbow on the redundancy circle. By specifying this angle α all limb vectors are known, the problem is no longer underdetermined and the usual inverse kinematics can be applied.

First we have to transform ${}^{B}r_{EEF}$ into the shoulder coordinate system, which is the arm reference coordinate system. This is done by

$${}^{sh}\vec{r}_{EEF} = \mathcal{R}_z^{-\theta_0} \cdot {}^{B}\vec{r}_{EEF}. \tag{5}$$

By calculating $\vec{r}_u$ as mentioned before, we obtain θ_1 and θ_2 based on the following relations:

$$\theta_1 = \operatorname{atan2}\left({}^{sh}r_u^z, {}^{sh}r_u^y \right) \tag{6}$$

$$\theta_2 = \operatorname{acos}\left(\frac{{}^{sh}r_u^x}{|{}^{sh}\vec{r}_u|} \right) \tag{7}$$

The next two angles belong to the elbow coordinate system. Hence, it is necessary to perform the corresponding transformation

$${}^{Elb}\vec{r}_f = \mathcal{R}_z^{-\theta_2} \mathcal{R}_x^{-\theta_1} \cdot {}^{B}\vec{r}_f \tag{8}$$

in order to calculate θ_3 and θ_4:

$$\theta_3 = \operatorname{atan2}\left({}^{Elb}r_f^z, {}^{Elb}r_f^y \right) \tag{9}$$

$$\theta_4 = \operatorname{acos}\left(\frac{{}^{Elb}r_f^x}{|{}^{Elb}\vec{r}_f|} \right) \tag{10}$$

In the same way we obtain θ_5 and θ_6:

$${}^{Wst}\vec{r}_h = \mathcal{R}_z^{-\theta_4} \mathcal{R}_x^{-\theta_3} \mathcal{R}_z^{-\theta_2} \mathcal{R}_x^{-\theta_1} \cdot {}^{B}\vec{r}_h \tag{11}$$

$$\theta_5 = \operatorname{atan2}\left({}^{Wst}r_f^z, {}^{Wst}r_f^y \right) \tag{12}$$

$$\theta_6 = \operatorname{acos}\left(\frac{{}^{Wst}r_f^x}{|{}^{Wst}\vec{r}_f|} \right) \tag{13}$$

The joint angle θ_7 describes the gripper orientation. We know that it is always perpendicular to $\vec{r}_h$. In addition to the transformation(11); we have to rotate $\vec{r}_g$ into the x,y-plane of the wrist coordinate system:

$${}^{Wst}\vec{r}_g = \mathcal{R}_z^{-\theta_6} \mathcal{R}_x^{-\theta_5} \mathcal{R}_z^{-\theta_4} \mathcal{R}_x^{-\theta_3} \mathcal{R}_z^{-\theta_2} \mathcal{R}_x^{-\theta_1} \cdot {}^{B}\vec{r}_g \tag{14}$$

$$\theta_7 = \operatorname{atan2}\left({}^{Wst}r_g^z, {}^{Wst}r_g^y\right) \tag{15}$$

The redundancy angle α can be used to meet additional requirements such as the task to avoid obstacles during grasping: the position of the elbow must be chosen such that it does not collide with any object in the way. An approach to this task will be described in the following section.

4.2 Linking the Haptic Interface

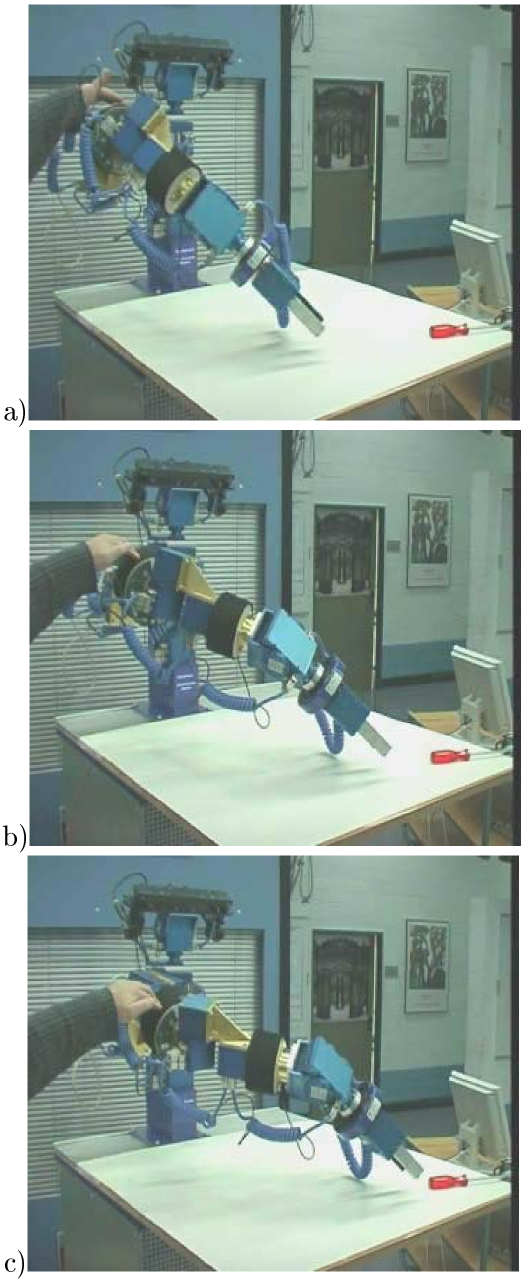

Fig. 3. A human user touches the skin and the system reacts by moving the elbow around the axis which connects shoulder and wrist without affecting the endeffector's position or orientation

In this section we describe how the information from the artificial skin is used to control the redundant degree of freedom of CORA's arm. To this end, forces which affect the upper cuff are interpreted as forces on the elbow. The force vectors determine the redundancy angle

α by means of a dynamical system: the force is directly proportional to the acceleration $\ddot{\alpha}$. By exploiting the redundancy of the seventh' degree of freedom, the position and orientation of the endeffector remains constant while forces applied to the artificial skin result in movements of the robot's elbow.

An application of this haptic control is the teach-in of specific grasping trajectories. The operator can correct an unnatural or not optimal movement trajectory by pushing the elbow in the desired configuration. Another application is obstacle avoidance: the operator can influence a grasping trajectory of the robot by driving the elbow away from objects by means of haptic input.

Some experimental results are shown in figure 3. In a) the robot arm start its trajectory and a human user touches the upper side of the cuff. The system detects a force, determines its value and calculates the force-direction with respect to the current arm posture. As result, the elbow starts to move in the direction of the detected force (see b)). In c), the endeffector completes its intended trajectory.

5 Conclusion and outlook

From our robotics research we draw the general conclusion that man-machine-interaction works best if the robot has an anthropomorphic shape and a human-like effector configuration. Given this anthropomorphy, the operator can influence the robot in a natural way. In this paper we showed how the interaction based on haptical input can be used to generate natural grasping trajectories. We have equipped only small parts of CORA's manipulator with artificial skin. However, by exploiting the redundant degrees of freedom, we can demonstrate smooth and stable grasping behavior under the influence of additional constraints imposed by the operator's touch input.

In addition to haptics, we have integrated more natural communication channels such as keyword speech, pointing gestures and gaze direction on our robot CORA. Based on the so-called *dynamic approach to robotics* [Schöner et al., 1995], we have implemented a number of behaviors which are acted out smoothly and naturally. The anthropomorphic communication channels provide a fast interface for the communication with the robot.

Further research in the domain of haptic input will focus on a force-torque sensor on CORA's wrist. By means of this very sensitive device, we will be able to literally take the robot by the hand and teach in grasping trajectories.

Acknowledgment

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REFERENCES

[C. Theis, 2001] A. S. C. Theis, I. Iossifidis (2001). Image processing methods for interactive robot control. In *10th IEEE International Workshop on Robot and Human Communication*, pages 424–429, Bordeaux and Paris, France. IEEE Roman 2001, IEEE. IEEE Catalog Number 01TH8591, ISBN 0-7803-7222-0, Library of Congress Number 2001094525.

[Craig, 1989] J. J. Craig (1989). *An Introduction to Robotics, Mechanism and Control.* Addison Wesley Longman Publishing Co;.

[Dahm and Joublin, 1997] P. Dahm and F. Joublin (1997). Closed form solution for the inverse kinematics of a redundant robot arm. Technical report, Institut für Neuroinformatik, Lehrstuhl für Theoretische Biologie, Ruhr-Universität Bochum.

[Hustadt, 2000] K. Hustadt (2000). Entwicklung eines verfahrens zur blickrichtungserkennung beim menschen. Master's thesis, Institut für Neuroinformatik, Lehrstuhl für Theoretische Biologie, Ruhr-Universität Bochum.

[Menzner et al., 2000] R. Menzner, A. Steinhage, and W. Erlhagen (2000). Generating interactive robot behavior: A mathematical approach. In J. Meyer, A. Berthoz, D. Floreano, H. Roitblat, and S. Wilson, editors, *From Animals to Animats 6: Proceedings of the Sixth International Conference on Simulation of Adaptive Behavior*, pages 135–144. The MIT Press/Bradford Books.

[Schöner et al., 1995] G. Schöner, M. Dose, and C. Engels (1995). Dynamics of behavior: Theory and applications for autonomous robot architectures. *Robotics and Autonomous Systems*, 16:213–245.