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Possibilities of force based interaction with robot manipulators

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1. Introduction

One way of interaction between a human and a robot manipulator is the interaction via forces and torques. We will call it also force guidance. For this purpose the human acts on the robot arm or on the robot end-effector. From the interaction forces and torques than a suitable motion of the robot is generated.

This kind of human robot interaction may be useful e.g. for the comfortable teach-in process. Commonly, positions and orientations of the robot tool are taught by the operator using the manual control pendant. With the keys on this device he or she moves the robot in joint or in task space. To improve the usability of the robot, some manual control pendants are additionally equipped with a more intuitive teach in device. It is called 6D mouse or space mouse (Hirzinger & Heindl, 1986). For further optimization of the teach-in process another way to move the robot would be force guidance. It will be shown that it is possible, with some differences, both in joint or in task space.

Force based human robot interaction can be seen as a special kind of active robot force control (Zeng & Hemami, 1997). To perform this, the robot has to be equipped with a force/torque sensor (Gorinevsky et al., 1997). Usually this sensor is mounted in the robot wrist and it measures forces and torques in all Cartesian directions. The cost of such a 6D F/T sensor can exceed 10% of the price of a low payload six axes articulated robot. For that reason it should be searched for an alternative possibility of force/torque measurement. One idea is to estimate the interaction forces and torques from the joint motor currents. For this purpose an algorithm is presented and verified with experiments.

Besides the kinematics of the robot motion during human robot interaction also its dynamics is important. For its representation the so called target or desired impedance behaviour will be defined as the relationship between interaction forces/torques and the velocity components of the robot motion. The simplest desired impedance behaviour is the behaviour of the mass damper system. Moreover, there are some more variants and additional features, e.g. the intuitive collision avoidance which will be described in this article.

Apart from the desired impedance behaviour selected and parameterized by the operator the dynamics of the robot system has been respected. It depends on the access level of motion generation. Commonly, the robot motion is controlled by the trajectory generator. However, some robot systems permit the direct access to the position or velocity control loops which is favourable in all kinds of robot force control.

Source: Human-Robot Interaction, Book edited by Nilanjan Sarkar,
ISBN 978-3-902613-13-4, pp.522, September 2007, Itech Education and Publishing, Vienna, Austria

One special application of force based human robot interaction is robot teleoperation. Sometimes it is necessary to perform it with force feedback. A very simple structure of such a teleoperation system will be proposed. It consists of a slave robot controlled by a force guided master robot.

2. Kinematics in force based human robot interaction

The basic structure of a robot system controlled by an operator via forces and torques is shown in Fig. 1.

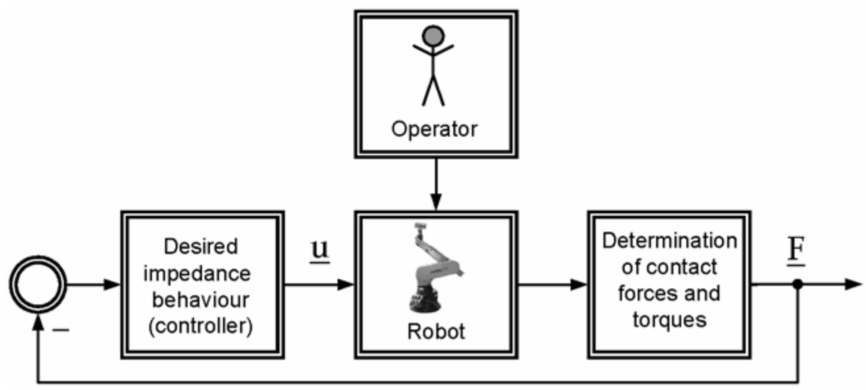


Figure 1. Basic structure of force based human robot interaction

The contact forces and torques $\underline{F}$ caused by the operator are determined e.g. by F/T sensor. From the measured values the desired impedance behaviour computes a suitable motion of the robot represented by the vector of the actuating variables $\underline{u}$. This structure may be also understood as zero force/torque control. Apart from the desired impedance behaviour which determines decisively the dynamics of the robot motion, the kind of space where the motion is performed specifies the robot behaviour during force guidance. Generally, it can be distinguished between robot guidance in task space or in joint space.

2.1 Force guidance in task space

First, it will be assumed that the forces and torques act only on the end-effector of the manipulator and the values are measured by a 6D F/T sensor mounted in the robot wrist. The measured values already free of gravitational forces/torques and transformed into tool coordinate frame are represented by vector $\underline{F}_T$:

$$\underline{F}_T = \begin{bmatrix} F_{T_x} & F_{T_y} & F_{T_z} & M_{T_x} & M_{T_y} & M_{T_z} \end{bmatrix}^T \tag{1}$$

Using the current rotational matrix $\underline{R}$ of the robot

$$\underline{R} = \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix} \tag{2}$$

which describes the orientation of the tool coordinate frame with respect to the base coordinate frame (McKerrow, 1995), the force and torque values from (1) can be transformed into the orientation of the base coordinate frame:

$$\underline{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} n_x & s_x & a_x & 0 & 0 & 0 \\ n_y & s_y & a_y & 0 & 0 & 0 \\ n_z & s_z & a_z & 0 & 0 & 0 \\ 0 & 0 & 0 & n_x & s_x & a_x \\ 0 & 0 & 0 & n_y & s_y & a_y \\ 0 & 0 & 0 & n_z & s_z & a_z \end{bmatrix} \cdot \begin{bmatrix} F_{T_x} \\ F_{T_y} \\ F_{T_z} \\ M_{T_x} \\ M_{T_y} \\ M_{T_z} \end{bmatrix} \tag{3}$$

This transformation does not take into account the additional torque components generated by F_{Tx}, F_{Ty} and F_{Tz}. It just expresses the already existing vectors of forces and torques in base coordinate frame. Now, the desired impedance behaviour $\underline{I}$ is introduced as the relationship between robot velocities and interaction forces/torques. It is used to compute a suitable motion of the robot end-effector. In general the motion is described by its velocity vector $\underline{v}$ including the linear and angular velocity components:

$$\underline{v} = \begin{bmatrix} \dot{p}_x & \dot{p}_y & \dot{p}_z & \omega_x & \omega_y & \omega_z \end{bmatrix}^T = \underline{I}(\underline{F}, \quad t) \tag{4}$$

Usually the desired impedance behaviour is described by differential equations, the velocity values are time dependent. To command the robot motion, from the current desired velocities in task space the corresponding joint velocities have to be calculated. For this purpose the inverse of the Jacobian matrix $\underline{J}^{-1}$ may be used. Another possibility is to calculate the desired location of the end-effector in Cartesian coordinates via integration of the velocity values. If the inverse kinematics of the robot is known from the Cartesian location the desired joint coordinates can be computed and sent to the joint position control loops.
The properties of force guidance in task space are analysed and compared with the joint space approach in section 2.3.

2.2 Force guidance in joint space

Another possibility to guide the manipulator with forces and torques acting on its end-effector is the joint space approach to force guidance (Winkler & Suchý, 2006b). For this purpose it is necessary to compute from the interaction forces/torques free of gravity influences and orientate in base coordinate frame (see Eq. 3) the equivalent joint torques and/or forces represented by vector $\underline{\tau}$, where m is the number of joints of the robot. To achieve this, the transposed Jacobian matrix $\underline{J}^T$ is used (Sciavicco & Siciliano, 2004):

$$\underline{\tau} = \begin{bmatrix} \tau_1 & \tau_2 & \dots & \dots & \dots & \tau_m \end{bmatrix}^T = \underline{J}^T \cdot \underline{F} \tag{5}$$

Eq. (5) is only valid if $\underline{J}$ is the geometric Jacobian matrix. In the case that $\underline{J}$ is calculated by way of differentiation of the end-effector location $\underline{P}$ with respect to the joint positions $\underline{q}$, the torque values in vector $\underline{F}$ have been brought into the orientation of the orientation representation chosen in $\underline{P}$. Here is an example: The location of the end-effector is given by the position coordinates p_x, p_y, p_z and its orientation is represented by the zy'z'' Euler angles ϕ, θ, ψ:

$$\underline{P} = \begin{bmatrix} p_x & p_y & p_z & \phi & \theta & \psi \end{bmatrix}^T \tag{6}$$

The vector $\underline{F}$ has to be transformed into vector $\underline{F}_{zy'z''}$, (Sciavicco & Siciliano, 2004) by:

$$\underline{F}_{zy'z''} = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_z \\ M_{y'} \\ M_{z''} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 0 & \cos(\phi)\sin(\theta) & \sin(\phi)\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \underline{F} \tag{7}$$

The force components F_x, F_y, F_z keep unchanged. Of course the torque M_z is directed around the z axis of the original coordinate frame. $M_{y'}$ is directed around the new y′ axis arising by rotation around z. Eventual $M_{z''}$ is directed around the new z′′ axis arising by rotation around z and y′. Now it is possible to compute the joint torques and/or forces by an analytical Jacobian matrix $\underline{J}_A$:

$$\underline{\tau} = \underline{J}_A^T \cdot \underline{F}_{zy'z''} = \left[\frac{d\underline{P}}{d\underline{q}}\right]^T \cdot \underline{F}_{zy'z''} \tag{8}$$

In this case the desired impedance behaviour is given in joint space. It defines the relationship between joint torques and/or forces caused by the operator and the desired joint velocities:

$$\underline{\dot{q}} = \begin{bmatrix} \dot{q}_1 & \dot{q}_2 & \ldots & \ldots & \ldots & \dot{q}_m \end{bmatrix}^T = \underline{I}(\underline{\tau}, \quad t) \tag{9}$$

If the robot controller provides the access to the joint velocity control loops the desired impedance behaviour may be connected directly to their inputs. Otherwise, the velocities have to be integrated to get the desired joint positions which can be sent to the joint position control loops or to the trajectory generation module.

2.3 Comparison of both approaches to force guidance

First, for comparison of the task space approach to force guidance with the joint space approach a manipulator with very simple kinematics was chosen. It will be called Planar Two Link Manipulator here. It consists of only two links of lengths L_1 and L_2 equipped with rotational joints. The joint angles are denoted as q_1 and q_2. As the manipulator has only two degrees of freedom vector $\underline{P}$ from Eq. (6) can be reduced and written as follows (Stadler, 1995):

$$\underline{P} = \begin{bmatrix} p_x & p_y \end{bmatrix}^T = \begin{bmatrix} L_1\cos(q_1) + L_2\cos(q_1+q_2) & L_1\sin(q_1) + L_2\sin(q_1+q_2) \end{bmatrix}^T \tag{10}$$

The end-effector orientation has not been taken into consideration because it can not be given independently of the position coordinates. For the experiment it will be assumed an external force acts on the end-effector described by vector $\underline{F}=[F_x\ F_y]^T=[-1\ 1]^T$. The desired impedance behaviour of the task space approach is given by Eq. (11) as the linear relationship between velocity and force components:

$$\begin{bmatrix} \dot{p}_x \\ \dot{p}_y \end{bmatrix} = \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix} \cdot \underline{F} \tag{11}$$

It will be assumed there is no time lag in the transfer behaviour because the dynamics of the system is not important when analysing the kinematics of the robot motion. In the same case for the desired impedance behaviour in joint space it follows:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} c_3 & 0 \\ 0 & c_4 \end{bmatrix} \cdot \left(\underline{J}^T \cdot \underline{F} \right) \tag{12}$$

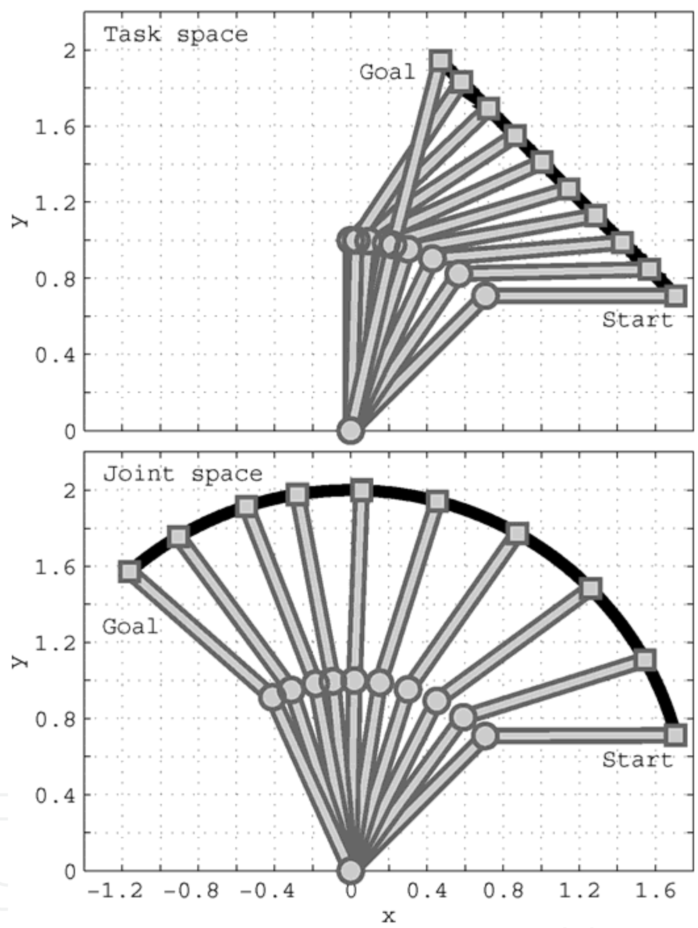


Figure 2. Paths of the force guided Planar Two Link Manipulator

Fig. 2 shows the two paths of the Planar Two Link Manipulator end-effector as the reaction to the external force $\underline{F}$. In the first case (force guidance in task space) robot stops at the singular position where joint angle q_2 becomes equal to 0. From this position it can never be moved away using this algorithm. The inverse kinematics is ambiguous and the inverse Jacobian matrix is not defined. The path resulting from the joint space approach is different.

The kinematical structure of the robot is taken into consideration by this algorithm. This feature may be an advantage in some applications because the operator associates the expected behaviour with the robot kinematics.
It can be also seen that the singularity is crossed. The singularities may also be understood as the boundaries between different configurations of the robot. The configuration defines how the manipulator reaches a location given in Cartesian coordinates. In the case of the Planar Two Link Manipulator there are two possibilities to reach the position described by vector $\underline{P}$. They are distinguished by the sign of the joint angle q_2. One preferred kinematical structure of industrial robots is the kinematics of the six axes articulated robots. It has the property to be able to reach a Cartesian location with 8 variants selectable by 3 configuration parameters (Craig, 2005). During force based human robot interaction in task space the posture of the manipulator is restricted to unique configuration. The change of robot arm configuration is only possible while performing the joint space approach to force guidance. The teach-in application, e.g., may require a particular posture due to restriction caused by the environment.

	Task Space	Joint Space
Dependence of robot behaviour on kinematics	No	Yes
Admissibility of singularities	No	Yes
Workspace	Restricted	Full
Separation of position and orientation changes of the end-effector	Possible	Not possible
Applicability to redundant manipulators	Restricted	Yes
Applicability to parallel manipulators	Yes	Not expedient

Table 1. Properties of both approaches to force guidance

Besides the six axes articulated robots there are some other popular robot kinematics. SCARA robots have one singular position similar to the Planar Two Link Manipulator. Guiding a SCARA robot in joint space it is easy possible to cross its singularity. One special case is the Cartesian robot. Its behaviour during force guidance in task space is identically equal to the joint space approach. Thinking of redundant manipulators the problem of configuration management becomes extremely important. Generally speaking infinite many solutions of the inverse kinematics problem may exist. In this case Cartesian motions are only possible with some constraints laid on certain joints. With force guidance in joint space this task would be easier realizable.
Different from serial manipulators are parallel robots with respect to kinematics. It is relatively easy to compute their inverse kinematics. In general the direct kinematics can be solved only by successive approximation. So it is proposed to use the Cartesian interaction forces and torques to guide the parallel robot directly in task space.
As a conclusion of this section some properties of both algorithms to force guidance are compared in Table 1.

3. Dynamics in force based human robot interaction

3.1 Desired impedance behaviour

In the previous section the kinematics of the robot motion during force based human robot interaction was detailed discussed. For comparison of the task space with the joint space approach the desired impedance behaviour, introduced as the relationship between interaction forces/torques and desired velocities, was simplified to direct proportional dependency, see (11) or (12). In this case all acceleration and deceleration processes have to be performed infinitely fast which is not feasible for the real robot manipulator. Applied to a mechanical system it would mean that the mass of the system is zero. Hence, the desired impedance behaviour has to be extended. One suitable choice is the behaviour of a simple mass damper system. It is described by two parameters mass m and damping d. Applied to joint space the particular desired joint velocity can be calculated from the interaction joint torque or force τ by:

$$\tau = m \cdot \ddot{q}_D + d \cdot \dot{q}_D \tag{13}$$

The desired joint velocity can be integrated to get the desired joint position q_d which may be connected to the joint position control loop.

It is possible to extend the desired impedance behaviour with some additional features. One very important feature is the dead zone nonlinearity within the interaction force branch to prevent unintentional drifts of the manipulator arm. The undesirable robot motions during force guidance, e.g., are the result of force/torque measurement inaccuracies or imprecise gravity compensation of the tool. For several applications, except the force based teach-in process, it may be convenient to insert the spring into the desired impedance behaviour. This will result in spring mass damper behaviour which will bring the robot end-effector back to starting position. It is described by Eq. (14) where k represents the spring constant:

$$\tau = m \cdot \ddot{q}_D + d \cdot \dot{q}_D + k \cdot q_D \tag{14}$$

Very important for the operator security is to bound the desired joint velocity of the desired impedance behaviour. However, in the robot controller also the current joint velocities and the current Cartesian end-effector velocities have to be supervised and limited according to valid standards (Deutsches Institut für Normung, 1993). For the direct human robot interaction in the automatic mode without deadman button it may be necessary to use a two-channel safety controller to supervise the robot controller (Som, 2004). Besides velocity limitation of the joint its position should also be bounded. This can be realized by a limiting nonlinearity in the desired velocity branch together with an anti-wind-up feature. Apart from this hard limit stop a comfortable alternative is the soft position limit stop. For this purpose the damping d of the desired impedance behaviour may be increased in the neighbourhood of the joint position boundary or an additionally spring behaviour can be activated. The just introduced feature allows the operator to feel the joint boundaries intuitive during force based human robot interaction.

3.2 Intuitive collision avoidance

Besides the implementation of the virtual joint boundaries already mentioned while thinking of the desired impedance behaviour, a lot of features are imaginable to make the force based human robot interaction more comfortable. One of these features is the intuitive collision avoidance. In contrast to the joint boundaries it is realized in task space. The aim which should be achieved is that the operator guiding the robot will be detained to bring the end-effector in contact with an obstacle located within the robot workspace. Such functionality may be important in particular when obstacles are present after the teach-in process is finished. It is possible to use, e.g., the CAD data of the robot work cell to generate the intuitive collision avoidance.

There are a lot of possibilities to implement virtual restrictions of the robot workspace during force guidance. One very interesting approach are force potential fields, (Choset et al., 2005). Virtual forces act on the robot end-effector against the operator near obstacles, so that the operator feels these obstacles. Nevertheless, if the end-effector is located in a close distance to the obstacle, which could be somewhat dangerous, as a result of the virtual force the robot will be moved automatically away from it.

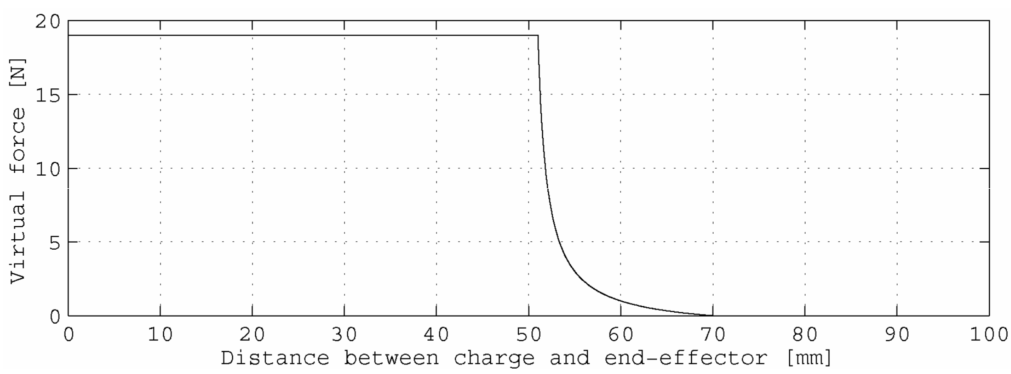


Figure 3. Proposal of the virtual force in the neighbourhood of one charge

A very convenient approach to generate the force potential field is the idea of using virtual force charges. These charges may be seen as electric charges which generate an electrostatic field in their neighbourhood. Between two charges the electrostatic force acts. Its value is reciprocally proportional to the square of the charges distance. However, for the realization of a virtual force potential field this kind of dependency is not obligatory. One possible proposal of the force potential function F_v of single virtual charge acting on the robot end-effector is shown in Fig. 3.

From the virtual force value F_V the force vector $\underline{F}_V$ orientated from charge position $\underline{e}=[e_x\, e_y\, e_z]^T$ to the end-effector position $\underline{p}=[p_x\, p_y\, p_z]^T$ can be computed as follows:

$$\underline{F}_V = F_V\left(\left\|\underline{p}-\underline{e}\right\|\right)\cdot\frac{\underline{p}-\underline{e}}{\left\|\underline{p}-\underline{e}\right\|} \tag{15}$$

For the generation of a virtual force field surrounding an obstacle several charges are necessary. It is favourable to place these on the object surface. The number of charges be denoted with n. Now for the calculation of the virtual force acting on the robot end-effector the principle of superposition can be used:

$$\underline{F}_V = \sum_{i=1}^{n}\left(F_V\left(\left\|\underline{p}-\underline{e}_i\right\|\right)\cdot\frac{\underline{p}-\underline{e}_i}{\left\|\underline{p}-\underline{e}_i\right\|}\right) \tag{16}$$

Fig. 4 shows an example of realization the intuitive collision avoidance system for its validation. Robot STÄUBLI RX90B is located close to an obstacle. On its surface certain number of charges has been placed, some of them are visible in the figure. In the robot controller the algorithms of force guidance in task and in joint space are implemented. For this goal, in the robot wrist a 6D F/T sensor is mounted. Additional to the operator the virtual force $\underline{F}_V$ caused by the charges acts on the end-effector and tries to move the robot away from the obstacle. $\underline{F}_v$ is computed within every interpolation cycle taking the current end-effector position $\underline{p}$ and the positions of the charges $\underline{e}_i$ into consideration.
After starting the program in the robot controller the robot is guided by the operator around the object via force/torque interaction. The virtual force field emitted by the obstacle is being felt by the human operator. The smaller the distance between end-effector and object the higher the force acting against the operator. As a result of the experiment, the end-effector path during force based human robot interaction and the corresponding virtual force vectors are shown in Fig. 5. It was possible to move the robot intuitively around the obstacle without danger of any collision.
This approach which is based on the virtual force field generated by fictive charges may be understood as an active collision avoidance system. Robot is accelerated by the force field in direction away from the obstacle. Another possibility is the passive approach. For this purpose near the object the damping parameters of the desired impedance behaviour have to be increased, e.g. as follows:

$$d = d_{const} + d_V(\underline{p}) \tag{17}$$

Consequently, the operator has to increase its force applied to the end-effector to generate an adequate motion of the robot and the force guidance is hindered. Also the combination of the active and the passive approach seems to be possible for intuitive collision avoidance.

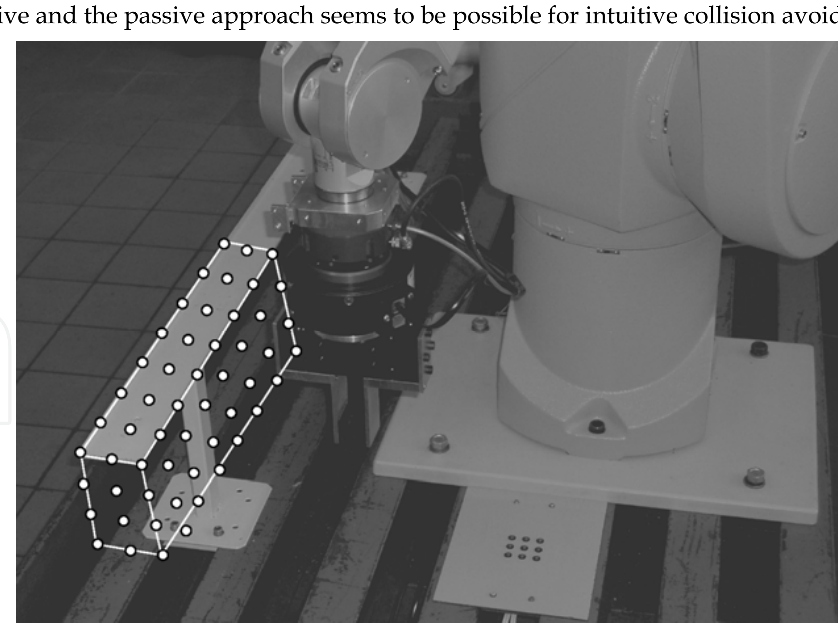


Figure 4. Experimental setup for the validation of the intuitive collision avoidance

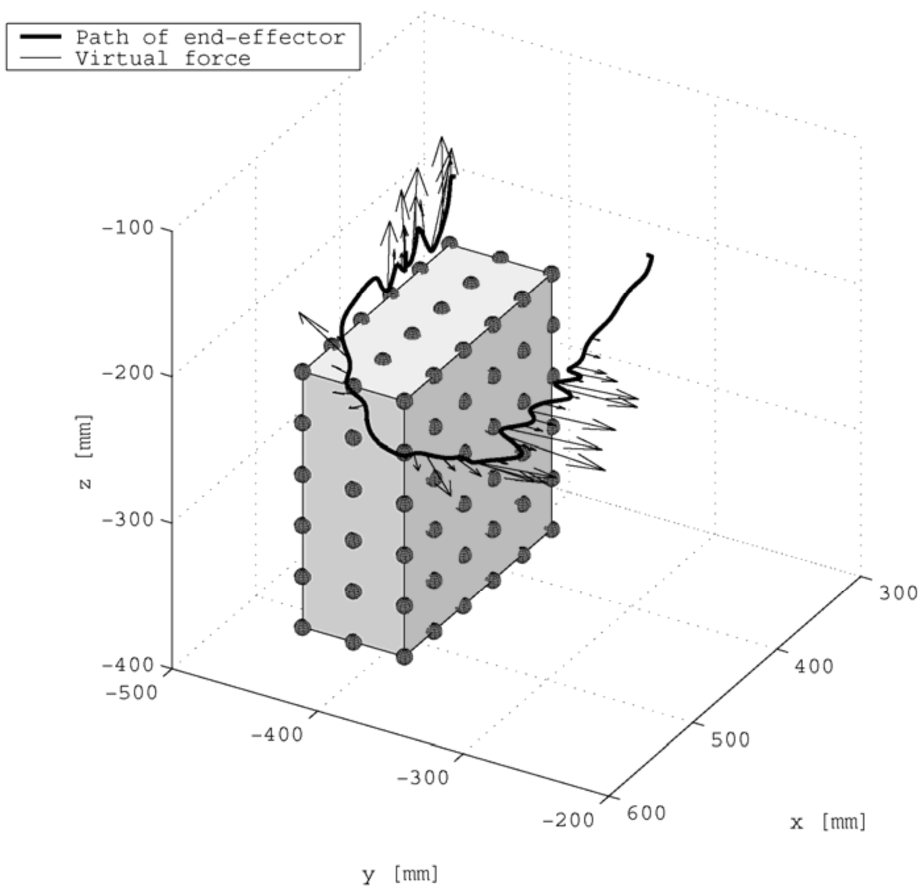


Figure 5. Virtual forces acting on the end-effector during its motion around the obstacle

3.3 Dynamics of the controlled robot manipulator

The task of the manipulator and its controller is tracking the path given by the desired impedance behaviour. Therefore, it is necessary to take also the dynamics of the robot together with its controller into consideration. Generally the dynamics of the robot arm can be described by the following equation (Angeles, 2003):

$$\underline{\tau}_M = \underline{M}(\underline{q})\underline{\ddot{q}} + \underline{C}(\underline{q}, \underline{\dot{q}}) + \underline{G}(\underline{q}) + \underline{V}(\underline{q}, \underline{\dot{q}}) \tag{18}$$

Matrix $\underline{M}$ is the inertia matrix, vectors $\underline{C}$, $\underline{G}$ and $\underline{V}$ represent the Coriolis/centrifugal, gravitational and frictional forces and/or torques, respectively. The elements in vector $\underline{\tau}_M$ are the torques/forces provided by the drives to the particular joints.

Most commonly used robots are equipped with AC servo motors connected via gears to the links. The motors are controlled by joint power amplifiers including usually power converters, current and velocity controllers. The desired joint velocities are sent to the joint power amplifiers, e.g., by analogue voltage signals or by digital bus interface. The closed loop controllers of the joint power amplifiers are adjusted by the robot manufacturer. In some cases it is possible to modify the controller parameters or to even replace the complete power amplifier. This would be justifiable in research laboratories but not in industrial applications. Thus the dynamics of the manipulator is significantly affected by the joint power amplifiers. Because it is not possible to manipulate the motor currents on an industrial robot system Eq. (18) need not been regarded any longer here.

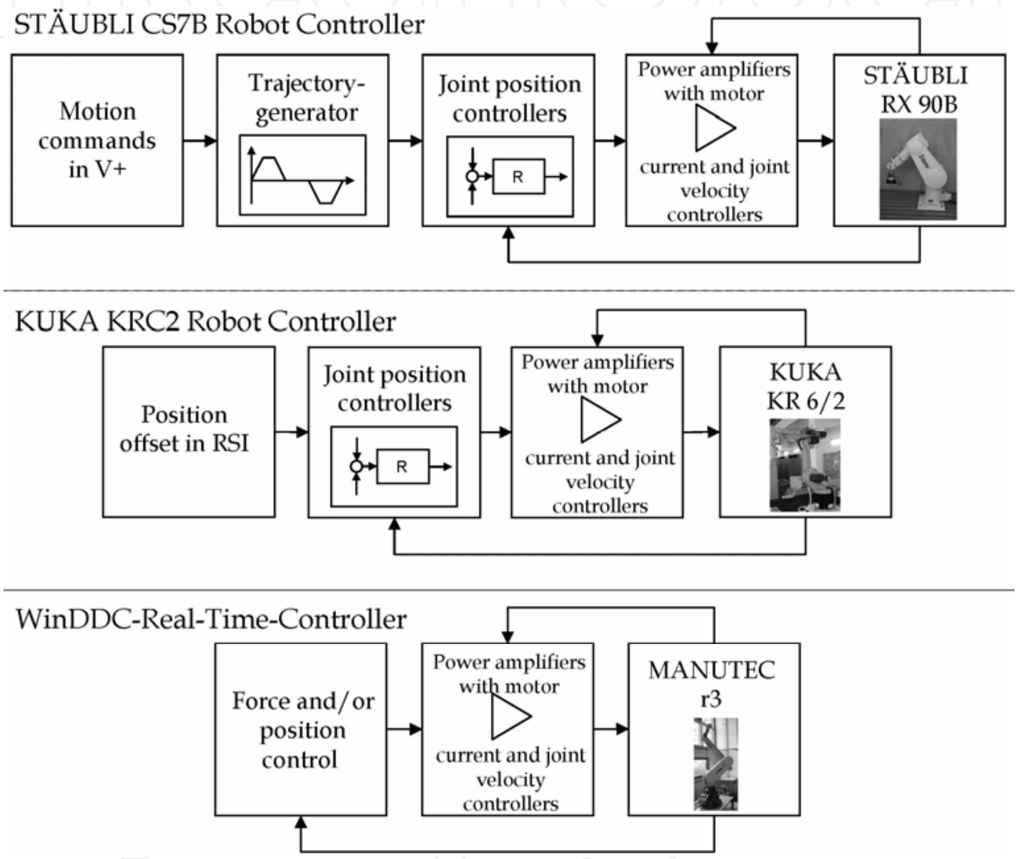


Figure 6. Robot systems for dynamic comparison

Generally, the user of an industrial robot system can program the motion of the end-effector with commands for joint, linear and circular interpolation. The path of the end-effector and the time series of joint positions and velocities are computed by the so called trajectory generator every interpolation cycle. It is a part of the robot controller. The trajectory generator is assigned to the joint position control loops which are part of the robot controller, too. Robot motion generated in this way is a motion without jerk. That means the time courses of desired joint positions, velocities and accelerations are continuously differentiable. In spite of setting the acceleration and speed parameters to 100% the trajectory generator results in a large time delay between desired and current positions.
Some industrial robot controllers provide the possibility of direct access to the position control loops. Thereby a desired position offset may be added to the current commanded

variable. It can be performed in joint or in task space. This kind of motion control is suitable in particular for sensor guided motion of an industrial robot, e.g. for robot force control.
For the realization of improved control algorithms it could be necessary to command the desired joint velocities to the joint power amplifiers. For this purpose the original robot controller may be replaced by a self developed robot controller. It will be increase the freedom in robot programming, e.g. the closed loop joint position controllers can be designed individually.

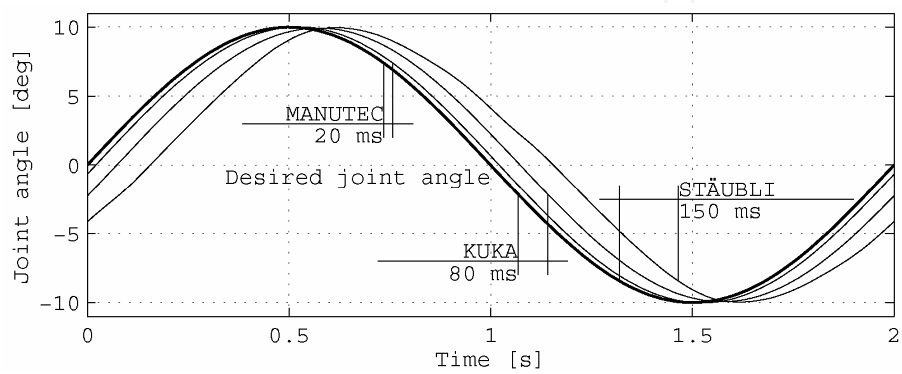


Figure 7. Dynamical behaviour of robots with different possibilities of motion generation

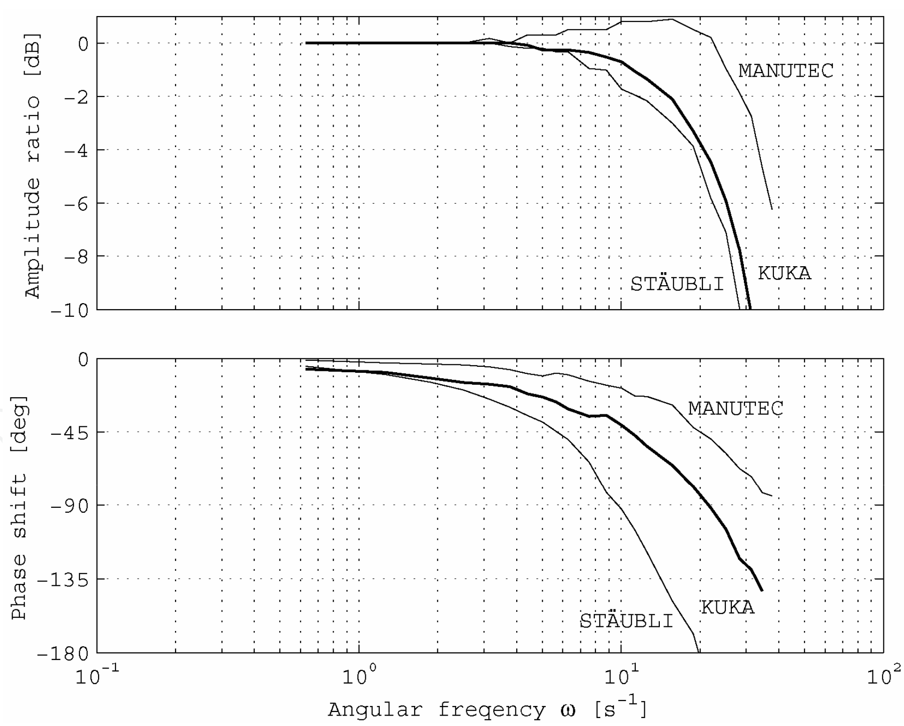


Figure 8. Frequency responses of joint No. 1

Thus, three variants to influence the robot motion have been presented. They are different with respect to their implementation level. It goes from the trajectory generator over the joint position controller to the velocity controller. The possibility to command the desired motor current was not taken into consideration. The effects will be demonstrated using three robot systems. Every of them consist of one low payload robot equipped with different robot controller. The detailed configuration of these different robot systems are shown in Fig. 6. Realization of sensor guided motions with the STÄUBLI robot controller is only possible on the level of the trajectory generator without additional software options. KUKA enables the access to the joint position controllers. For this purpose it is necessary to install the so called Robot Sensor Interface (RSI). Using RSI different controller structures can be programmed. They consist of RSI objects for signal processing. Afterward this controller structure is executed in real time in the interpolation cycle. The WinDDC-Real-Time-Controller is an universal controller with analogue/digital inputs and outputs based on a digital signal processor (DSP). It can be programmed by a special programming language called WinDDC. The analogue output signals to command the motions of the MANUTEC r3 robot represent the desired joint velocities for the joint power amplifiers. The WinDDC-Real-Time-Controller has also digital inputs for incremental position encoders measuring the current joint angles.
First, one very simple experiment will show the differences in robot dynamics caused mainly by robot controllers. The desired joint angle of joint No. 1 is commanded by the sinusoidal signal with the amplitude of 10deg and the period time of 2s. The current joint angle values were recorded for every of the three robot systems. The lag between desired and current joint angle time curves is shown in Fig. 7 and may be analyzed.
It can be seen that the maximum phase shift occurs with the STÄUBLI robot system where the desired position was sent to the trajectory generator via motion commands for joint interpolation. To get this sinusoidal series the motion was divided into a lot of small parts and the mode of the continuous motion was used. Having access to the desired values of the joint position control loops may reduce the phase shift. An example is the KUKA robot controller programmed by RSI. The minimum phase shift can be reached if it is possible to design the control loops individually which can be seen e.g. with the WinDDC-Real-Time-Controller connected to the robot MANUTEC r3. However, for this purpose only a simple proportional controller with additional feed forward control of the desired joint velocity was implemented. To get more information about the dynamics of the different robot systems the frequency responses were recorded. Their amplitude and phase responses are shown in Fig. 8. It can be seen that the system dynamics depends decisively on the level of motion generation. If the level is low the bandwidth will be high. It has to be taken into consideration while specifying the parameters of the desired impedance behaviour. Its bandwidth should be lower then the bandwidth of the robot to guarantee following the desired impedance behaviour.

4. Sensorless force based human robot interaction

The algorithms and features of force based human robot interaction presented in the previous section require that the robot is equipped with a 6D F/T sensor. The cost of such a sensor is of the order of some thousand Euros at present. Therefore, it would be favourable to find a way to do without F/T sensor. One possibility is to estimate the interaction forces and torques from the motor currents.

4.1 Estimation of interaction forces and torques

Most commonly used robots are driven by AC servo motors. Fig. 9 shows the signal flow diagram of single joint which is position controlled in cascade control mode.

The position controller is a proportional controller whereas velocity and motor current are controlled by proportional plus integral controllers. The electrical time constant of the motor is very small in comparison to the mechanical response time. It will be assumed that there are no losses due to magnetisation and internal friction. Hence, there is a linear dependency between motor current i and joint driving torque τ_M determined by motor constant k_M and gear ratio k_G ($k_{MG}=k_M k_G$). Besides the driving torque acting in the joint, robot is also influenced by Coriolis and centrifugal torque C, gravitational torque G, frictional torque V and the interaction torque τ caused by the operator or the environment. The joint acceleration torque τ_A is given according to (19):

$$\tau_A = k_{MG} \cdot i - C - G - V - \tau \tag{19}$$

Assuming the response time of the motor current control loop is very small and its static control error goes to zero due to the proportional plus integral controller structure, for the calculation of the interaction torque τ the desired value of the motor current i_D can be used instead of its current value i. The joint torque τ_A accelerates the particular robot link taking its inertia M into consideration. For operator security the velocity and acceleration values of all joints have to be small. As a result the joint torque and the Coriolis/centrifugal torque may be neglected. The interaction torque can then be approximately calculated as follows:

$$\tau = k_{MG} \cdot i_D - G - V \tag{20}$$

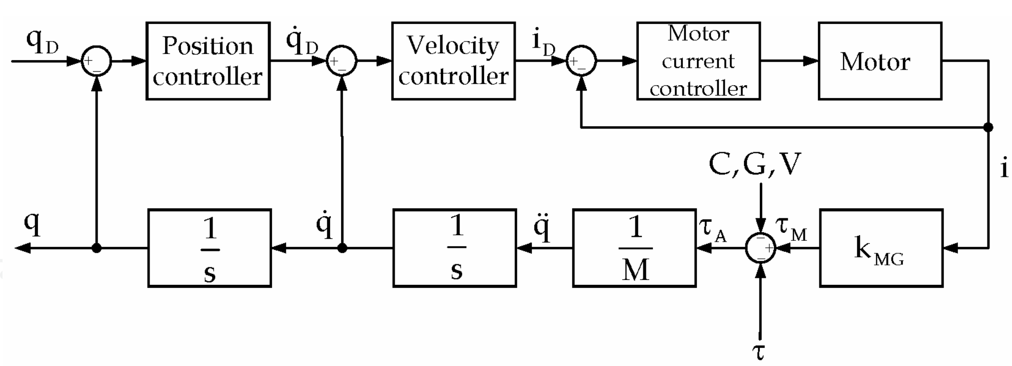


Figure 9. Signal flow diagram of one joint

To perform this calculation it is necessary to learn the vector of the gravitational torques of the robot. It is a function of the joint angle vector $\underline{q}$ and can be calculated from the dynamic model of the robot. The dynamic models of some manipulator arms are published, see e.g. (Türk & Otter, 1987) for the model of robot MANUTEC r3. The calculation of the frictional torques is difficult. Friction is speed dependent consisting of Coulomb friction, stiction and speed proportional friction. Furthermore, the particular friction components are dependent e.g. on position, temperature and aging of the robot. Especially at low velocity motions where Coulomb friction and stiction are dominant it is very difficult to calculate feasible values and at robot standstill it is nearly impossible because of the PI-structure of the velocity controller the portion of Coulomb friction and stiction can not be separated from the motor current. An example of robot joint friction is shown in Fig. 10. Here the robot MANUTEC r3 was used. It was equipped with the WinDDC-Real-Time-Controller mentioned earlier in section 3 (Winkler & Suchý, 2005). The desired values of motor currents are provided by the joint power amplifiers via analogue voltages which are connected to the analogue inputs of the robot controller for signal processing according to Eq. (20).

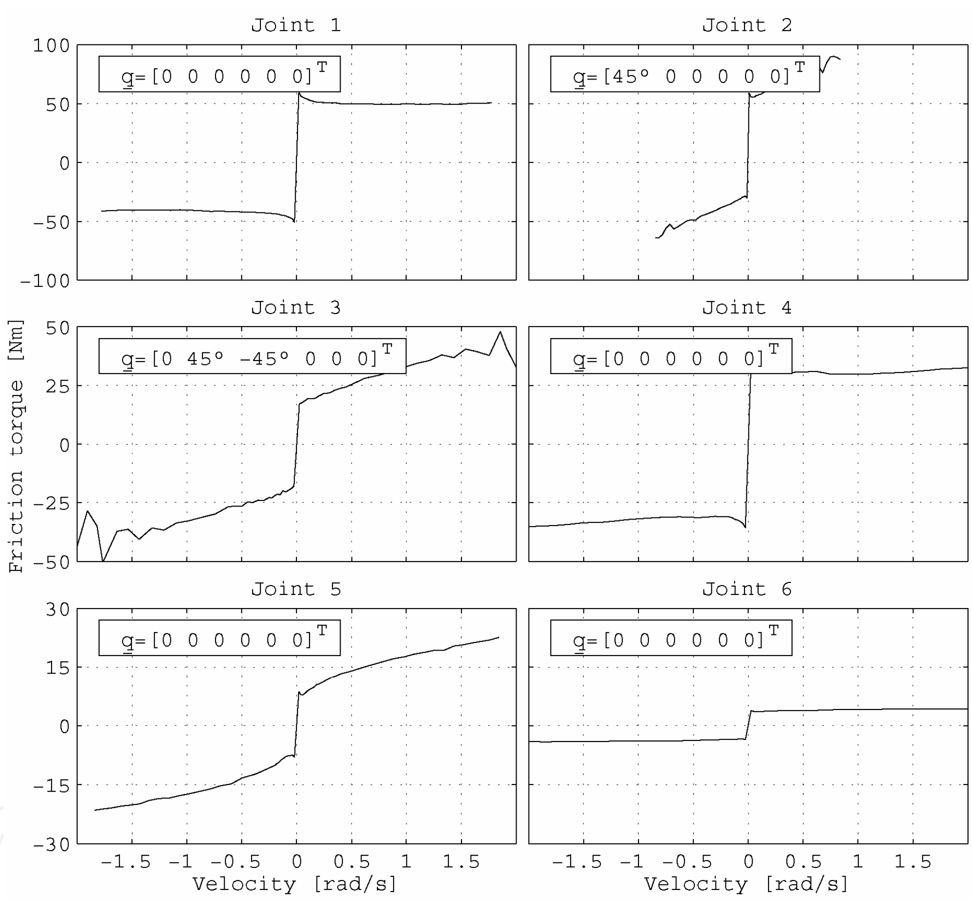


Figure 10. Joint friction torques determined for a robot of type MANUTEC r3

Fig. 10 shows clearly that during low velocity motion generated future by force based human robot interaction stiction and Coulomb friction are prevailing. Therefore, the proposed model for friction estimation is simplified to the form in Fig. 11. It consists of the dead zone nonlinearity in the neighbourhood of robot standstill described by velocity parameter $\dot{q}_A$ to prevent oscillations. In the range between $\dot{q}_A$ and $\dot{q}_B$ the friction increases to its maximum value V_c. When computing friction torques for the estimation of the interaction torques it is absolutely necessary to avoid the case that the value of any estimated friction torque is higher than its real value. Otherwise it may be happen that the force guided robot becomes unstable during human robot interaction which could be a very dangerous situation to the operator.

Verification of the proposed algorithm to estimate the interaction torques of an industrial robot from its motor currents was performed on the MANUTEC r3 robot equipped with the open WinDDC-Real-Time-Controller. For comparison of the estimated values with the real interaction forces/torques 6D-F/T sensor was additional mounted into robot wrist. For that reason the operator should touch the robot only on its end-effector behind the sensor. Pushing and polling the robot on its links would result in faulty measurements. However, it is also possible to guide the robot by means of motor currents when the operator acts on arbitrary location of the manipulator arm. The comparison is performed in joint space. From the interaction forces and torques measured by F/T sensor the corresponding joint torques can be computed using the transposed Jacobian matrix, see e.g. (5). Different postures of the robot arm were chosen to validate the estimation of the gravitational torques from the dynamic model. They are described by the joint angle vectors q_A=[0 0 90° 0 0 0]^T, q_B=[-30° 45° 30° 0 0 0]^T and q_C=[0 0 90° 0 -90° 0]^T. The operator acted in a random way with forces and torques on the robot end-effector for a certain time period and the time series of actual and estimated interaction joint torques were recorded. They are compared in Fig. 12.

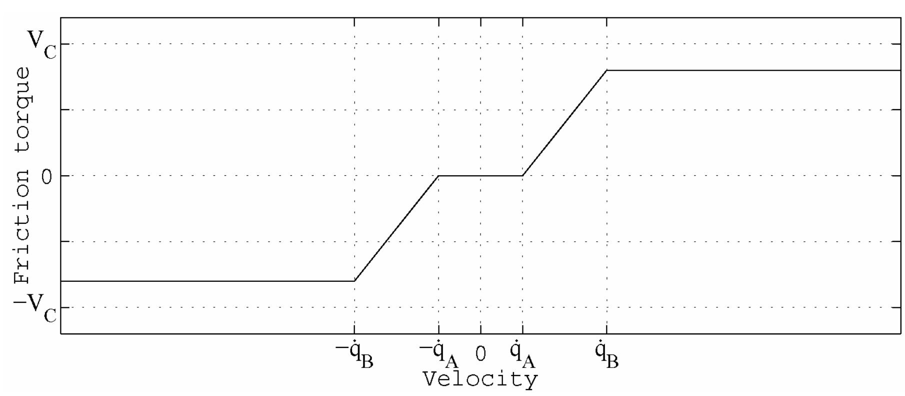
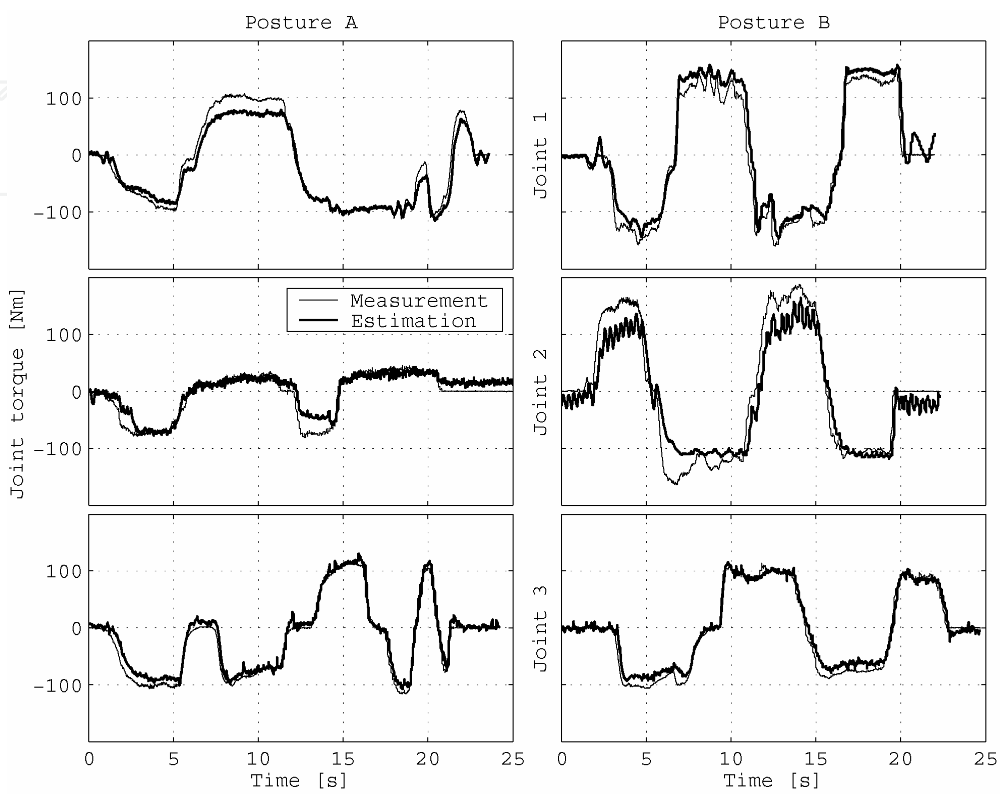


Figure 11. Proposal of friction torque model at low joint velocities

Because the signals which represent the desired motor currents sent from the velocity control loops to the motor current control loops are noisy, they have to be low pass filtered before signal processing. For this purpose a first order system was used which results in a time lag between the plot of the estimated time series and the measured time series. Furthermore, some more differences can be seen. They may result from inaccuracies of the dynamic model of the robot used for the calculation of the gravitational torques. Another source of error comes from the frictional torques. It was already mentioned that during robot standstill the proportional plus integral joint velocity controller outputs a control signal within the range of stiction. This motor current therefore is not able to generate a motion and may be misunderstood as interaction torque. This effect is shown in Fig. 12, e.g. in joint No. 1 when the robot is located at posture A.



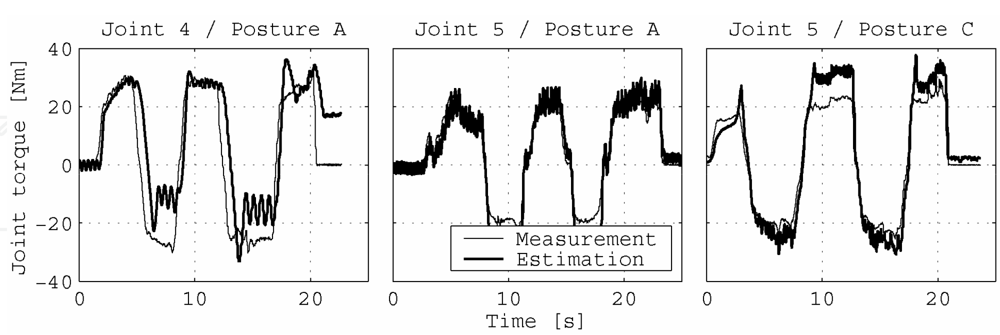


Figure 12. Comparison between interaction torques estimated from motor currents and values measured by F/T sensor at different postures of the manipulator arm

In spite of some differences the time series of measured and estimated interaction joint torques match quite well. It may thus be possible to use the desired values of the motor currents for robot force control or force based human robot interaction.

4.2 Human robot interaction based on motor currents

After estimating the interaction torques from the motor currents that values can be used for force guidance without F/T sensor. Because the forces and torques caused be the operator and estimated by the algorithm developed in the previous section are present in joint space, it will be convenient to perform the force guidance in joint space, too. Otherwise the interaction joint torques ought to be transformed into coressponding Cartesian forces/torques using the inverse of the Jacobian matrix which will result in problems in and near singularities.

$$\underline{F} = \underline{J}^{-T} \cdot \underline{\tau} \tag{21}$$

Another point why the Cartesian space approach may be unfavourable is the following: Unlike to the robot equipped with F/T wrist sensor the operator is able to move the motor current guided robot by pushing or pulling the manipulator arm at arbitrary location. Transforming such interaction forces into Cartesian forces/torques of robot tool frame the resulting robot motion may become anomalous. It is therefore proposed to perform human robot interaction based on motor currents in joint space.

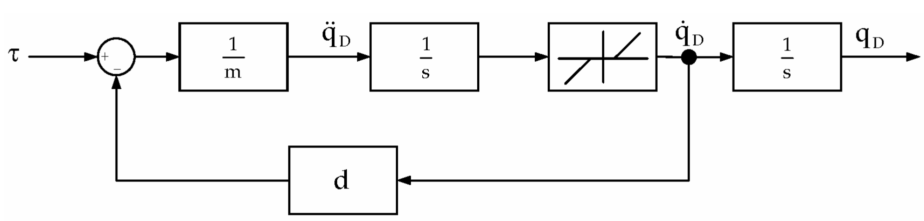


Figure 13. Mass damper desired behaviour with additionally dead zone nonlinearity

Because the estimated interaction torques differ somewhat from the measured values which are more accurate it is extremely important to implement the dead zone nonlinearity in the desired impedance behaviour. Besides its integration into the branch of the estimated joint torque very convenient place is also the branch of the desired joint velocity. Than the desired impedance behaviour based on the suggested mass damper system results in the signal flow diagram shown in Fig. 13. The dead zone nonlinearity prevents undesired motions of the robot caused by inaccurate estimation or measurement of the interaction forces and/or torques. A disadvantage of the implemented nonlinearity is that it distorts the specified parameters of the desired impedance behaviour, e.g. the value of damping will be increased.

For validation of force guidance without F/T sensor the pertaining algorithm was implemented in the WinDDC-Real-Time-Controller. Robot MANUTEC r3 was located at starting position given by $\underline{q}$=[0 0 90° 0 0 0]^T. Force guidance was activated for all joints. The operator acts on the manipulator arm to guide it throughout the work space. Fig. 14 shows the estimated interaction joint torques caused by the operator. From these values the desired joint angles are calculated using the desired behaviour proposed in Fig. 13. The desired joint angles are connected to the joint position control loops which consist of simple proportional controllers with additional feed forward control of the joint velocities. The plots of the joint angle values as a result of robot force guidance based on motor currents are shown in Fig. 15. The diagram is subdivided into parts numbered by lower case letters. These letters can be found again in Fig. 16 where some snapshots of robot posture during force guidance are presented. It can be seen that it is possible to guide the robot throughout the workspace by the operator without F/T sensor. During the experiment also some singularities were crossed without any problem.

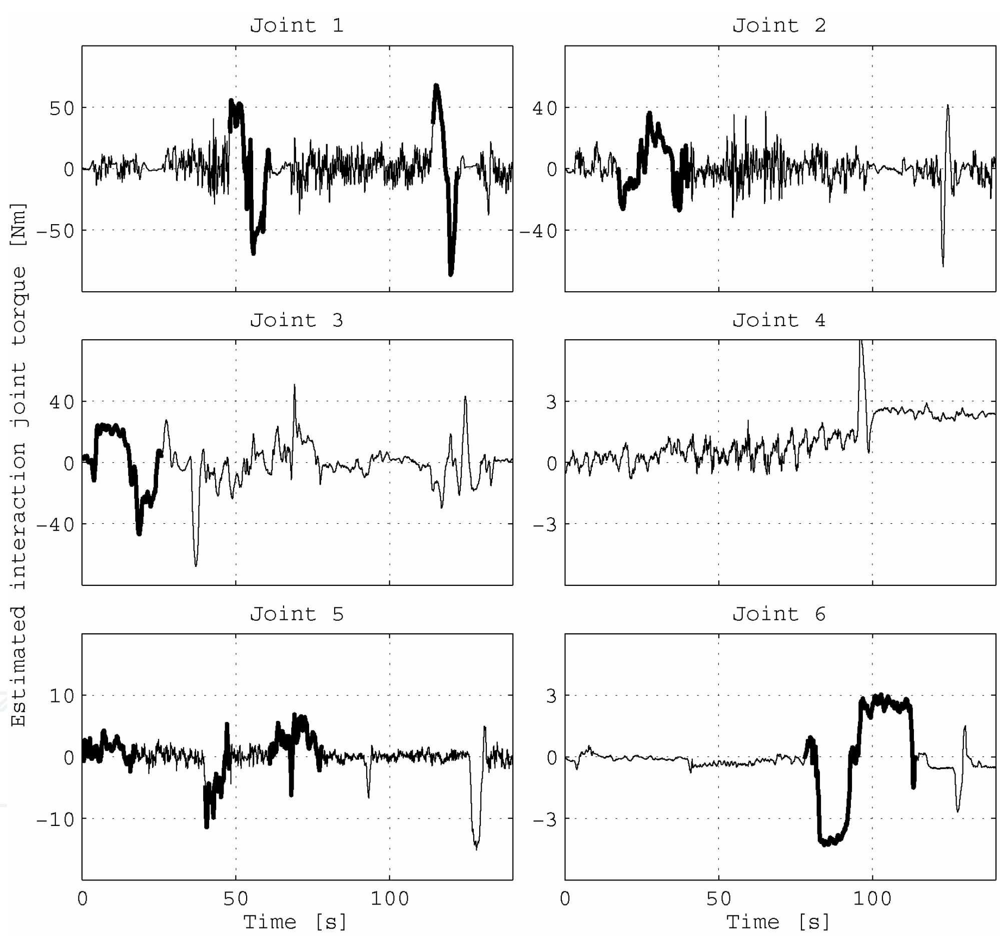


Figure 14. Estimated interaction joint torques during force guidance

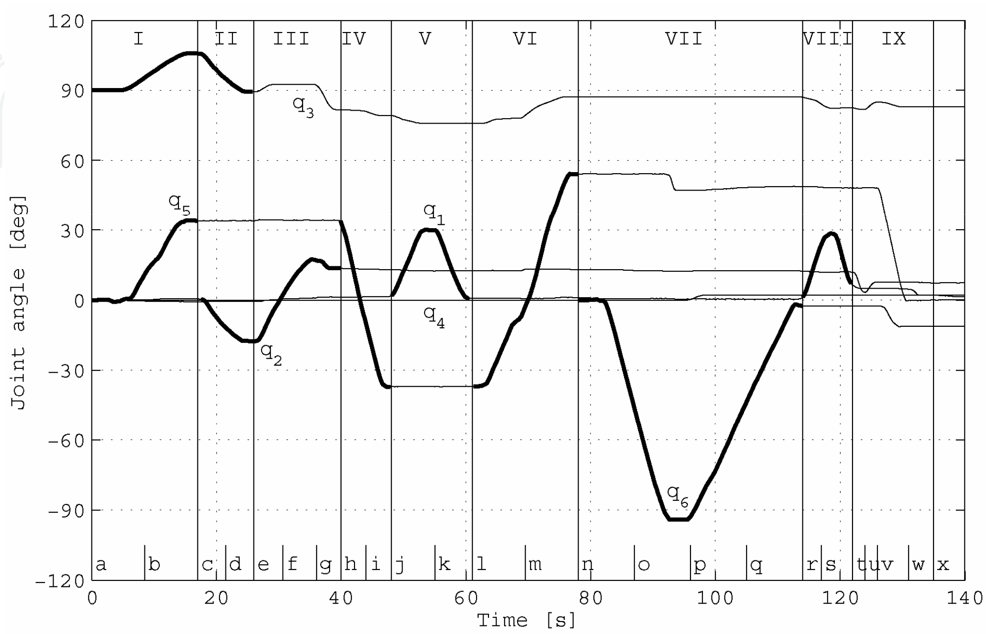


Figure 15. Joint angles during sensorless force guidance

4.3 Sensorless approaches to force guidance with industrial robot controllers

The just proposed approach to force based human robot interaction without F/T sensor requires the access to the actual or desired values of the joint motor currents. Using industrial robot controllers its functionality is often restricted to industrial applications like handling or assembly. Robot programmer can not expect that in the particular programming language any command is available which returns the motor currents or the joint torques. Nevertheless, some industrial robot controllers provide this functionality. An example is the RSI programming mode of the KUKA robot controller, already mentioned in the previous section, which enables sensor guided robot motion in real time. One special RSI object provides the values of the motor currents. They may be integrated into the corresponding controller structure consisting of RSI objects (Winkler & Suchý, 2006a).

Another functionality is the so called soft servo. It is available in several robot controllers, possibly under different name. Using the soft servo feature the stiffness of particular joints can be reduced. Commonly it is implemented by limiting the output signal of the velocity control loop in the joint position cascade controller. The soft servo is useful in some industrial applications to reduce high contact forces. However, soft servo is not favourable in force based human robot interaction. If the robot is moved and the motion is followed by change of the gravitational torques acting on the joints the robot can become unstable. Another disadvantage is that it is not possible to define the desired impedance behaviour. It is caused by robot mechanics with open joint brakes and without motor power. So it may be difficult to move a heavy payload robot by human force interaction.

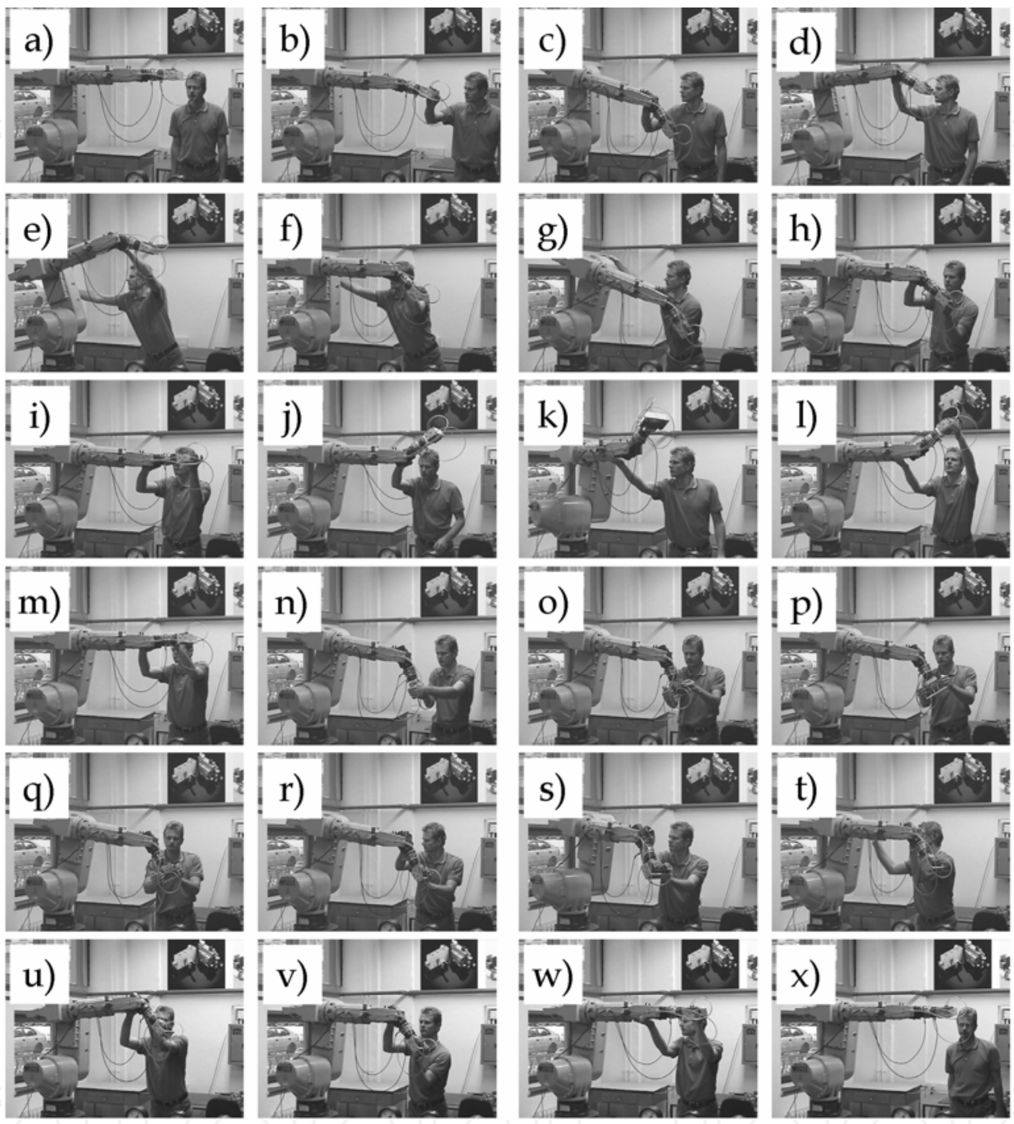


Figure 16. Snapshots of robot posture during sensorless force guidance

5. Robot teleoperation with force feedback

One special kind of human robot interaction may be developed in robotic teleoperation. Teleoperation means the remote control of a robot manipulator by an operator. Fields of applications for such a system are in hazardous environments like nuclear power plants or chemical plants. Robot teleoperation becomes more and more important also in medicine or astronautics. The basic idea is to remotely control the slave robot by master which can be implemented as control panel, joystick, phantom robot or haptic interface. Operator on the

master side may be supported by audio-visual or haptic feedback from the slave side. If the robot is controlled by the so called haptic interface the operator gets a feedback of the contact forces/torques of the slave robot. The force feedback may be essential for some tasks.
Many structures of teleoperation systems were already published (Hirzinger et al., 1997; Sheridan, 1989; Sheridan, 1995). For the realization of a teleoperation system with force feedback it is also possible to use a force guided master robot instead of haptic interface. One proposed configuration is shown in Fig. 17.

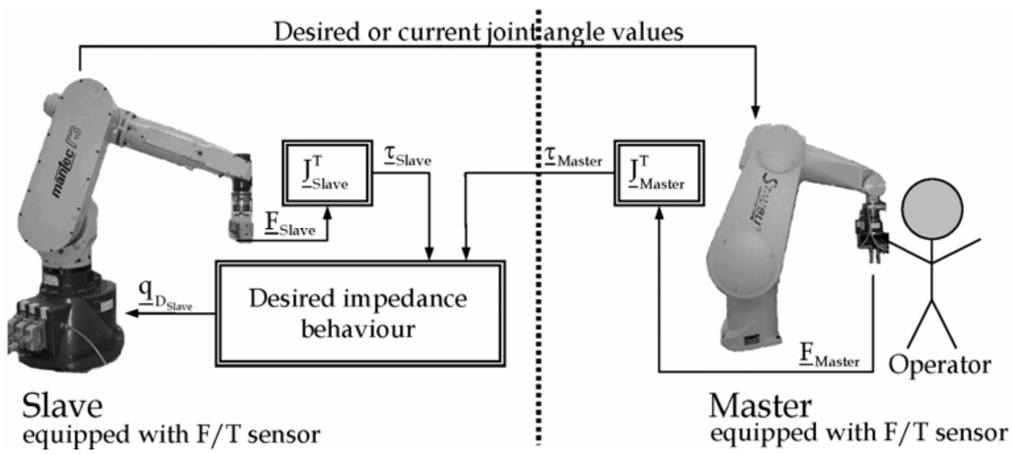


Figure 17. Proposal of a teleoperation system controlled in joint space by a force guided master robot

Both robots are equipped with F/T wrist sensors. On the other side, joint torque sensors or the schemes for estimation of the interaction or contact forces using the motor currents are also conceivable. The interaction forces of the master robot caused by the operator are transformed into joint space according to Eq. (5). The interaction joint torques are transmitted to the slave robot controller, e.g. by Ethernet connection. From the values of $\underline{\tau}_{Master}$ and the contact joint torques of the slave robot $\underline{\tau}_{Slave}$ the desired impedance behaviour computes the desired joint angle values of the slave robot $\underline{q}_{DSlave}$. The components of vector $\underline{q}_{DSlave}$ or the current joint positions are sent to the controller of the master robot where the corresponding motion will to be performed. The joint angle values have to be contingently adjusted to the particular master robot.
Very important for the stability of a teleoperation system is the time delay of data transmission. A lot of publications are dealing with this problem (Sheridan, 1989; Sheridan, 1995). One approach is based on predictive algorithms.

6. Conclusion

In this paper some possibilities and features of force based human robot interaction were presented. First, it was assumed that the robot manipulator is equipped with a six component force/torque wrist sensor to measure the interaction forces and torques caused by an operator. He or she tries to guide the robot throughout the work space by taking the gripper and pushing or pulling it. It was distinguished between the task and the joint space approach to force guidance which resulted in different behaviour with respect to the robot motion. This was shown in particular with the kinematics of the Planar Two Link Manipulator.

For the specification of the robot dynamics during force guidance the desired impedance behaviour was introduced. Using force guidance for the comfortable teach-in, e.g., the behaviour of a simple mass damper system was proposed as the basis for the desired impedance behaviour. Of course, for the implementation of these ideas in the robot controller additional features had to be realized. Besides some standard features like robot velocity limits and the joint limit stops a very extensive functionality is the intuitive collision avoidance. It is based on the force potential fields around obstacles generated by virtual charges. For this purpose the corresponding algorithm was described. However, some more research activities seem to be necessary on this field. Apart from the desired impedance behaviour the dynamic behaviour of the robot manipulator together with its controller is important for the stability of the whole robot system for force based human robot interaction. Therefore, some common robot systems were regarded with respect to their possibilities of motion generation. This aspect is also crucial for robot force control in general and seems to be important for further research as only few robot controllers admit to set the desired joint torques and/or forces by programmer. On the other side this property is assumed by most of the published approaches to robot force control.

Because a six component force/torque sensor may be very expensive, an alternative approach for the determination of the contact forces/torques between robot and environment was suggested. It is based on the motor currents of the joint drives. From these values provided by the joint power amplifiers it was possible to estimate the forces and torques acting on the whole manipulator arm. The algorithm is especially suitable for low payload robots where the relationship between interaction and gravitational forces is high. In particular the estimation of frictional joint torques from the motor currents, which is very difficult, has to be investigated in more detail. Besides application of this approach to force based human robot interaction it may be also used in standard robot force control.

One special application of force based human robot interaction is robot teleoperation with force feedback. It may be e.g. realized with the joint space approach to force guidance. In this paper the basic structure of a teleoperation system is proposed. It consists of a slave and a master robot each equipped with force/torque sensor. The force guided master robot represents the input device for the operator and the slave robot works in the target environment.

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Human Robot Interaction

Edited by Nilanjan Sarkar

ISBN 978-3-902613-13-4
Hard cover, 522 pages
Publisher I-Tech Education and Publishing
Published online 01, September, 2007
Published in print edition September, 2007

Human-robot interaction research is diverse and covers a wide range of topics. All aspects of human factors and robotics are within the purview of HRI research so far as they provide insight into how to improve our understanding in developing effective tools, protocols, and systems to enhance HRI. For example, a significant research effort is being devoted to designing human-robot interface that makes it easier for the people to interact with robots. HRI is an extremely active research field where new and important work is being published at a fast pace. It is neither possible nor is it our intention to cover every important work in this important research field in one volume. However, we believe that HRI as a research field has matured enough to merit a compilation of the outstanding work in the field in the form of a book. This book, which presents outstanding work from the leading HRI researchers covering a wide spectrum of topics, is an effort to capture and present some of the important contributions in HRI in one volume. We hope that this book will benefit both experts and novice and provide a thorough understanding of the exciting field of HRI.