NOVEL JOINT SPACE FORCE GUIDANCE ALGORITHM WITH LABORATORY ROBOT SYSTEM

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Abstract: This article presents the implementation of a new algorithm of force guided motions with a six axis articulated robot frequently used in research laboratories. This new approach is based on the idea of impedance control in joint space and it is implemented on a digital signal processor-based robot controller. It allows an intuitive force guidance of the robot by taking the gripper by the hand. Robot may be also guided over the singularities in this way. Behaviour of the robot is thus freely programmable in the wide range.

Keywords: Force control, Impedance control, Man/machine interaction, Robotic manipulator.

1. INTRODUCTION

Force guidance of articulated robots is an important aspect in the field of interaction between robots and humans. It means moving the robot by taking the gripper by the operator's hand and guiding it throughout the working space. This is made possible by a force/torque sensor mounted in the robot wrist or a set of torque sensors mounted in joints. From measured force and torque values suitable motions of the robot are generated.

One possible application of force guided motion is the comfortable teaching of positions and orientations without using manual teach-in pendant. With this intuitive teaching it is possible to save time while programming the robot for industrial tasks. Force guided motions may also be equally useful as assistance in tasks like drilling, grinding or the transport of heavy articles, as well as in robotic surgery, e.g..

Most of the implemented algorithms of robots force guidance are based on the Cartesian space approaches. As there are some of disadvantages with this approach, the approach presented in this work is based on the idea of impedance control in joint space. Force and torque values measured by the force/torque sensor are transformed into equivalent joint torques. The desired behaviour of the robot is then given in joint space and not in Cartesian space. It defines the kind of interaction between the man and the robot. With the algorithm presented here the complete workspace of the robot can be reached by the end-effector. It also enables to move the robot over singularities and to change position and orientation of robot's end-effector at the same time and with the same behaviour.

The new approach is implemented with a digital signal processor based controller, which controls the six axis articulated robot manipulator of the type Siemens MANUTEC r3. This laboratory test system is chosen because it offers an important advantage. As a rule, with commercial industrial robot systems the desired values of position and orientation in Cartesian space or the desired joint angle values are sent to the trajectory generator. This module then generates a smooth motion. Time delay of at least one interpolation period follows out of this between the desired and actual position which is an unfavourable fact for force guided motions or for robot force control. The choice of this laboratory robot system gives the possibility to have access to the lower level of the robot motion generation, namely to joint velocities.

2. DEVELOPMENT OF EXPERIMENTAL CONTROL SYSTEM

Development and implementation of force guidance algorithms presented in section 3 was preceded by the development of an adequate control system. This was unavoidable as control systems of common commercial robots do not still admit good working environment.

The algorithm of force guidance presented in the next chapter is tested with the following robot system based on a robot Siemens MANUTEC r3 which was often used in research laboratories all over Germany (Otter and Türk, 1988). This robot is a six axis articulated robot with a payload of 15 kg. From the original robot control rack just the joint power amplifiers have been kept. Each power amplifier includes motor current and joint velocity controller. The joint velocities can be controlled by analogue voltages (±8 V for maximum speed in positive/negative direction).

The actual joint angles are measured by incremental position encoders, therefore micro-switches to calibrate reference positions are necessary.

Forces and torques acting on the end-effector are measured with a six component force/torque sensor FT Delta SI-660-60 produced by SCHUNK. Values of voltages from strain gauges of the force/torque sensor are transformed into Cartesian force and torque values using force/torque sensor controller. The effective range of force/torque sensor used is ±660 N for forces and 60 Nm for torques. Cartesian forces and torques are represented by analogue voltages (±5V for maximum/minimum force or torque).

The new robot controller, WinDDC-Real-Time-Controller, was developed. It is based on Analog Devices ADSP 2181 digital signal processor. Robot controller is equipped with digital and analogue inputs and outputs, inputs for incremental position encoders, interfaces for industrial field busses (CAN-Bus, e.g.) and serial interfaces. Robot controller is programmed by a special language called DDC (Neumann, 1991). This programming language contains commands enabling access to the peripherals and to software elements of control technology like integrators, differentiators, etc.. This allows very comfortable and easy programming of controller. The program design is performed with a standard PC (Windows operating system) and the WinDDC software. After the program is designed, it is sent to the robot controller via serial connection. User program in the robot controller is then periodically executed in real time. It is possible during execution to keep influence on program variables by PC and supervise these variables from the robot controller by their visualization. Before running the program with the robot controller PC simulations are also possible with WinDDC. Additional parts of WinDDC are software modules for analysis and closed loop controller design. Complete structure of WinDDC software package is shown in Fig. 1.

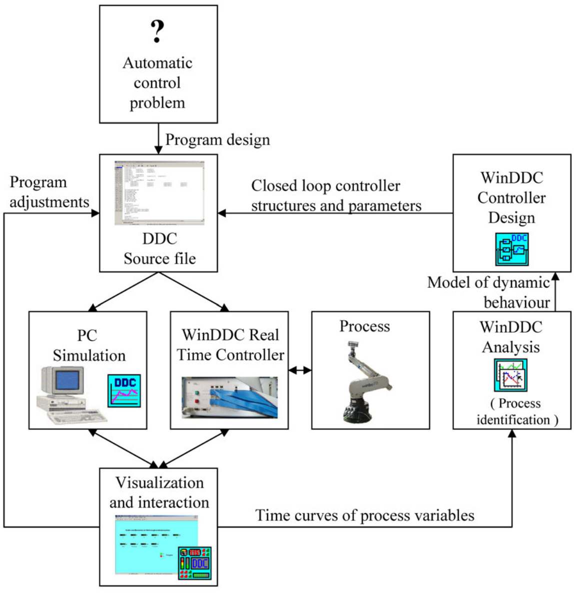

Fig. 1. Structure overview of WinDDC.

Fig. 2 shows the above described robot system together with all its main components. Major advantage of this laboratory robot system in comparison with common commercial robots is the following. As a rule, it is not possible with a commercial robot controller to have access to desired joint velocities or desired motor currents. The only possibility is to set the desired positions. However, the desired joint angles are not directly generated by the joint angle controllers, they are connected with the trajectory generator to get a smooth motion. This is the cause of a time delay between the desired and real joint angles which is unfavourable in force guided motions.

An example illustrating this point is shown in Fig. 3. The desired angle of joint No.1 is given by the sinusoid with the amplitude of 10 deg and frequency of 0.5 Hz. First, the commercial robot system STÄUBLI RX 90B was used for measurement. Time delay between desired value and current value of joint angle makes approximately 170 ms. This corresponds to the phase shift of 30 deg. Using the laboratory robot system based on a MANUTEC r3 robot the time delay is 20 ms (phase shift 3.6 deg).

3. JOINT SPACE BASED FORCE GUIDANCE

In this section the essential steps of the new approach to force guidance in joint space will be described.

3.1 Compensating of gravity influences

As the orientation of the end-effector changes, the force and torque components of gravity vector $\boldsymbol{\tau}_{\mathbf{G}}$

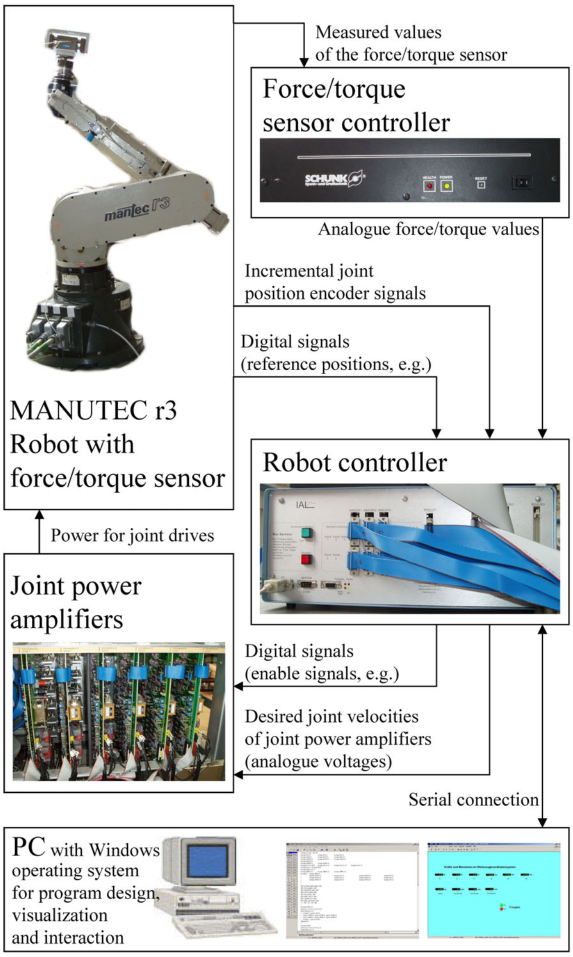

Fig. 2. Structure overview of the robot system used for force guidance.

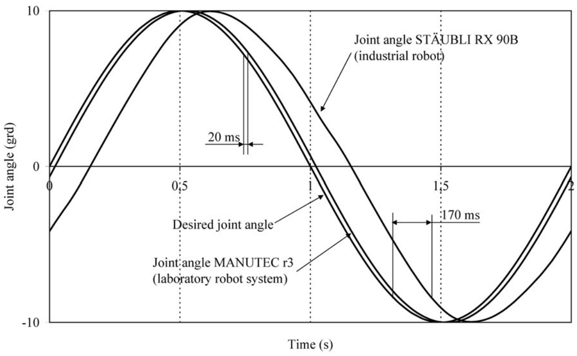

Fig. 3. Behaviour of joint No. 1 during a sinusoidal stimulation.

have to be eliminated from the measurement values of the force/torque sensor readings $\boldsymbol{\tau}_\mathbf{M}$. It is not sufficient just to tare the sensor. Usually, the force/torque sensor is mounted in robot's wrist, and then gripper or some kind of tool is attached to it. For compensation purposes it is necessary to learn the gravity force of the gripper together with the gripped object or the tool f_g and the vector of their centre of gravity $\mathbf{c}=[c_x, c_y, c_z]^T$. Determining of gravity force and of centre of gravity can be performed by different algorithms. They are very well known and will not be therefore repeated here. Orientation of robot's end-effector given by the rotation matrix **R** depends on the current values of the joint angles comprised in vector $\mathbf{q}=[q_1, q_2, q_3, q_4, q_5, q_6]^T$, $\mathbf{R}=\mathbf{R}(\mathbf{q})$. Vector $\boldsymbol{\tau}_\mathbf{T}$ which is composed of measured force and torque values free of gravity influences can be calculated as follows:

$$\boldsymbol{\tau}_\mathbf{T} = \boldsymbol{\tau}_\mathbf{M} - \boldsymbol{\tau}_\mathbf{G}$$

$$\boldsymbol{\tau}_\mathbf{T} = \begin{bmatrix} F_{x_M} \\ F_{y_M} \\ F_{z_M} \\ \hdashline M_{x_M} \\ M_{y_M} \\ M_{z_M} \end{bmatrix} - \begin{bmatrix} \mathbf{R}^\mathrm{T} \cdot \begin{bmatrix} 0 \\ 0 \\ f_g \end{bmatrix} \\ \hdashline \mathbf{c} \times \mathbf{R}^\mathrm{T} \cdot \begin{bmatrix} 0 \\ 0 \\ f_g \end{bmatrix} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_\mathbf{T} \\ \hdashline \mathbf{F}_\mathbf{T} \end{bmatrix} \qquad (1)$$

3.2 *Transformation of forces and torques*

The algorithm of force guided motions presented in this paper is based on the joint space approach, therefore the measured values of the force/torque sensor should be transformed into equivalent torques in joint space.

To calculate the equivalent joint torques from Cartesian forces and torques calculation of Jacobian matrix **J** is necessary for the particular robot manipulator used (McKerrow, 1991). In this case Jacobian matrix can be calculated by differentiation of vector **P** of position and orientation $[p_x, p_y, p_z, r_x, r_y, r_z]^T$ with respect to the vector of joint angles $\underline{q}$:

$$\mathbf{J} = \frac{d\mathbf{P}}{d\mathbf{q}} = \frac{d\left[p_x \quad p_y \quad p_z \quad r_x \quad r_y \quad r_z\right]^T}{d\left[q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6\right]^T} \qquad (2)$$

There are different possibilities to represent robot end-effector's orientation and the Jacobian (2) depends on this choice, too. In this case the three orientation angles yaw (r_x), pitch (r_y) and roll (r_z) were chosen. They represent the orientation of the tool coordinate frame by rotation around the x, y and z axes of the world coordinate system, respectively, and $\mathbf{R}=\mathbf{R}(\mathbf{q})=\mathbf{R}(r_x, r_y, r_z)$.

Within the first step the values of forces $\mathbf{F}_\mathbf{T}$ and torques $\mathbf{M}_\mathbf{T}$ measured by the force/torque sensor and free from influences of gravity force will be transformed from the tool coordinate frame to the reference coordinate system using the actual rotation matrix $\mathbf{R}(\mathbf{q})$:

$$\boldsymbol{\tau} = \begin{bmatrix} \mathbf{R} \cdot \mathbf{F}_\mathbf{T} \\ \hdashline \mathbf{R} \cdot \mathbf{M}_\mathbf{T} \end{bmatrix} \qquad (3)$$

This transformation does not take into account the additional torque generated by force $\mathbf{F}_\mathbf{T}$, it just expresses the already existing vectors of force and torque in reference coordinate frame. Now the vector of measured forces and torques in world frame $\boldsymbol{\tau}$ can be directly transformed into corresponding joint torques by using transposed Jacobian matrix $\mathbf{J}^{\mathrm{T}}$ (Sciavicco and Siciliano, 2003):

$$\boldsymbol{\tau}_{\mathbf{q}} = \mathbf{J}^{\mathrm{T}} \cdot \boldsymbol{\tau}$$
$$\boldsymbol{\tau}_{\mathbf{q}} = \begin{bmatrix} \tau_1 & \tau_2 & \tau_3 & \tau_4 & \tau_5 & \tau_6 \end{bmatrix}^T \tag{4}$$

Vector $\boldsymbol{\tau}_{\mathbf{q}}$ contains joint torques equivalent to the external forces and torques acting on robot's end-effector.

3.3 *Defining the desired behaviour*

In principle, human-robot cooperation takes place with force guiding. Under the desired behaviour the accommodation of robot properties to those acceptable by human will be understood here. They may be defined in terms of mechanical impedance. It is suitable for force guided motions to choose mass-damper system as the desired behaviour of the robot. Spring behaviour is obviously not convenient in this application. In the Cartesian space approach three mass-damper systems for position and three for orientation are selected. In the joint space approach six mass-damper systems may be selected, one for each joint. Behaviour of every joint is defined by the following differential equation:

$$\tau_i = d_i \cdot \dot{q}_{D_i} + m_i \cdot \ddot{q}_{D_i} \tag{5}$$

where dq_{Di}/dt and dq_{Di}^2/d^2t are the joint desired velocity and joint desired acceleration, respectively. From equation (5) the time evolution q_D of the desired joint angle i and its time derivations can be computed. The parameter d_i in (5) corresponds to the damping of a single joint and the parameter m_i to its inertia. These two parameters determine the complete joint behaviour. Increasing m_i leads to more inertial behaviour of the robot. The effect of the parameter d_i can be interpreted as the viscous friction.

Other choices of desired joint behaviour are also possible. Including additional term corresponding to static friction in (5) would reduce drift effect of the end-effector caused by inaccurate gravity compensation, e.g..

3.4 *Joint control*

The outputs of the desired robot behaviour model are the desired values of angle q_{Di}, corresponding rotational velocity and rotational acceleration for each joint, see also (5). The joint power amplifiers of the test system already include velocity and current controllers. Therefore only the software position controllers need to be implemented in the robot controller. The easiest way how to perform this is to design simple proportional closed loop controllers to control joint angles. To reduce static control errors the joint velocities are additionally feed forward controlled by the velocities from the desired behaviour model. The control law is given as:

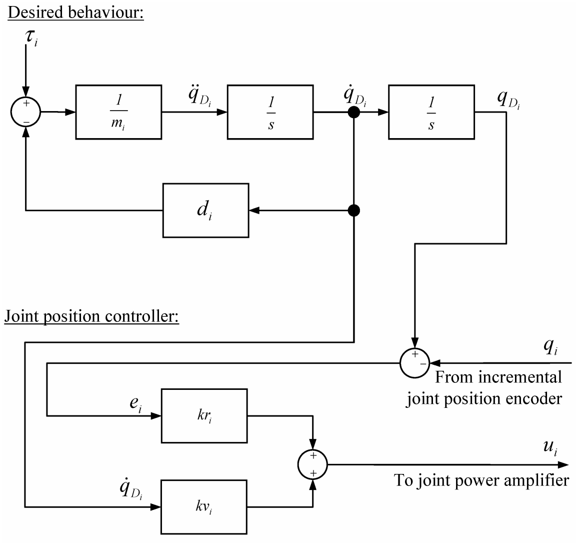

Fig. 4. Joint position controller and desired behaviour of joint *i*.

$$u_i = k_{r_i} \cdot \left(q_{D_i} - q_i\right) + k_{v_i} \cdot \dot{q}_{D_i} \tag{6}$$

where i refers to i-th joint, k_r and k_v are controller gains. Controller output u_i represents the desired joint velocity for the velocity controller within power amplifier. Fig. 4 shows the controller structure together with the desired behaviour of joint *i*.

From the practical point of view it is important to bound the calculated joint angles by limits of individual joints. Equally important is the anti windup feature of the desired behaviour. This means that integrator, which outputs joint velocity is set to zero when the joint angle reaches the limit bound.

In Fig. 5, e.g., the force acting on the robot's end-effector in the direction of y-axis in the reference coordinate frame generates the motion along this axis using the Cartesian approach. However, rotations around joint axis 1 and 4 would be expected by our natural experience.

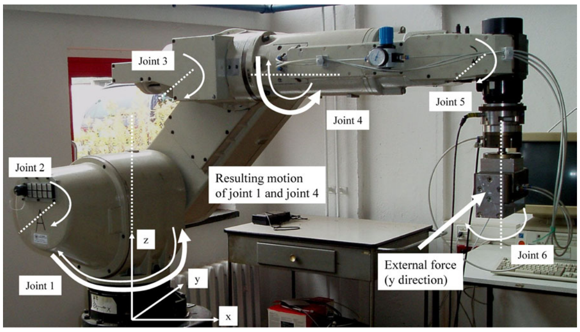

Fig. 5. Reaction of the robot to the external force within the "natural approach".

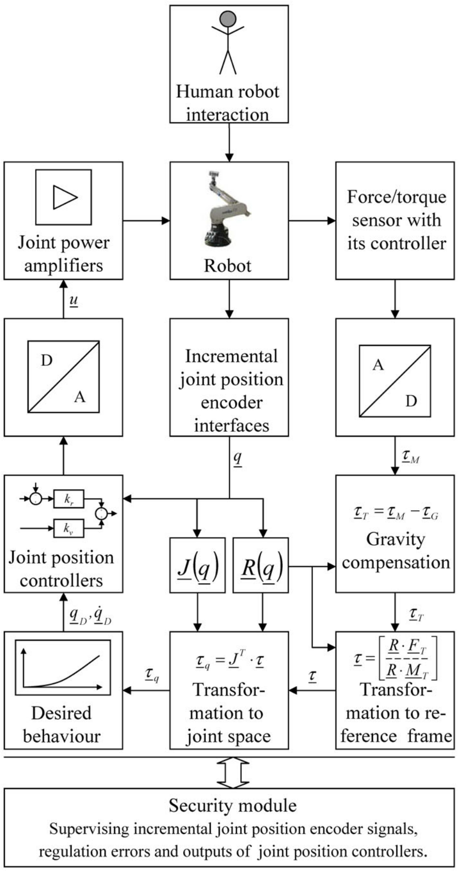

Fig. 6. Structure of the complete closed loop control.

Besides, it is not possible with force guidance in Cartesian space to move the robot over singular positions. This means a limitation of the reachable workspace to the actual configuration space. Trying to move the end-effector over a singular position would be caused unintended high joint velocities which may be dangerous for the operator. With the new joint space approach here presented this situation is not possible, because there is no inverse matrix in the new algorithm. This point is extremely important for the security of a human interacting with the robot.

4. IMPLEMENTATION AND EXPERIMENTS

The algorithm of force guidance described in the previous chapter is implemented in the robot controller using the special programming language DDC (Neumann, 1991). The complete program contains all functions from section 3 (force/torque transformation, computation of desired behaviour, e.g.). The desired behaviour of the robot has to be determined by the imaginary joint inertias and dampings. Table 1 show their values used in experiments.

Table 1 Parameters of desired joint behaviour.

Joint Number	1	2	3	4	5	6
Inertia (kgm^2)	100	100	50	25	10	5
Damping (kgm^{2}s^{-1})	200	200	100	50	20	10

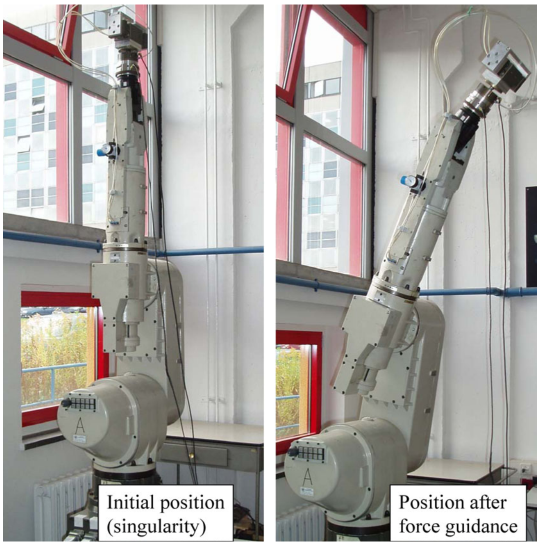

Fig. 7. Initial and final position during the force guidance experiment.

Very important issue in the implementation of the algorithm is the security of the operator. For this reason different modules are included in the program. One of them is the module for the limitation of voltages to the joint power amplifiers. This measure corresponds to the limitation of the real joint velocities. It is also inevitable to set limits to accelerations and velocities in the desired behaviour. Readings of the incremental position encoders represent the actual joint velocities. These values are monitored. Is any limit exceeded the emergency stop of the robot is executed. An important safety measure is to supervise the jittering of the incremental position encoder readings to detect if they are alive. In addition to it, some plausibility tests are implemented like supervising of control errors. If any irregularity is detected robot emergency stop is activated. Structure of the complete closed loop control is shown in Fig 6. In this case the program of the robot controller runs with the cycle time of 5 ms.

One example illustrating the advantages of the joint approach to force guidance will be presented. Initial position of the robot is given by setting all joint angles to zero (see Fig. 7). Robot is now located in the singular position. After starting force guidance algorithm operator comes into contact with the robot. Forces and torques caused by the operator and acting on robot's end-effector during the experiment (already transformed into reference frame) are shown in Fig. 8. The equivalent joint torques can be found in Fig. 9. These joint torques generate motions of joints, which are determined by the desired behaviour model. The curves of the joint angle values as a result of the external forces and torques are shown in Fig. 10. Robot was moved to its final position, which is also shown in Fig. 7. It can be seen that the robot could be successfully moved away from the singular position without any danger. Using the Cartesian approach to force guided motions this would not be possible.

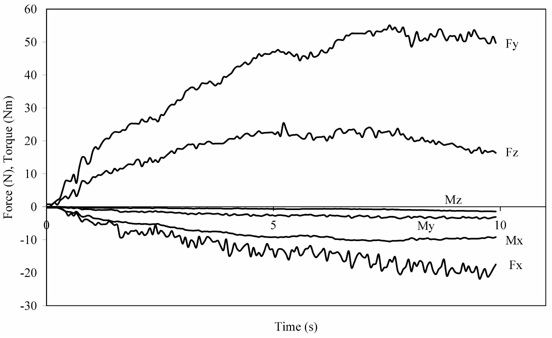

Fig. 8. Measured forces and torques caused by the operator.

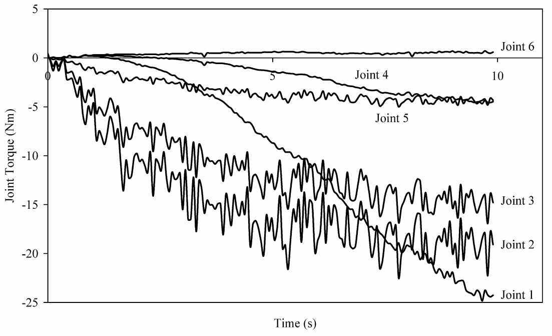

Fig. 9. Corresponding joint torques.

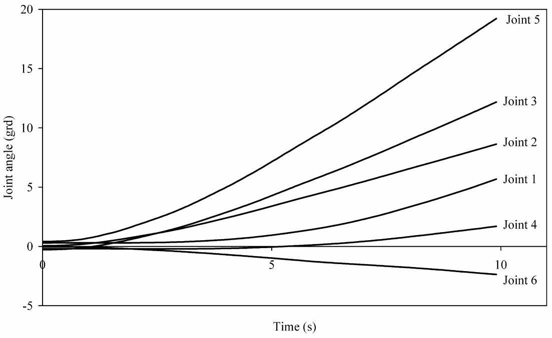

Fig. 10. Measured joint angles during force guidance.

To prove usefulness of the algorithm for industrial applications some security measures have to be additionally taken. All security-related components should be built in two-channel technique (Som, 2004). Further development of this point will be the subject of further research.

CONCLUSIONS

In this work the development of laboratory robot system for force/torque control problems was presented. Its DSP-based robot controllers have the direct access to the joint controllers which are part of joint power amplifiers. In this way improved dynamical behaviour of robot force control can be reached. With robot controller and its programming language WinDDC different controller structures can be implemented in an easy way. This arrangement considerably reduces the development time.

Further on, new algorithm of force guided motion was implemented. It is based on the idea of impedance control in joint space. This approach have some advantages is comparison with some known Cartesian algorithms. One of them is the possibility to move the robot by hand over singular positions without any danger.

To apply the algorithm of force guidance in industrial tasks, more developments in the field of operator's security are necessary. However, this seems to be only possible together with robot producer as commercial robot controllers have no access to security-related functions of control system.

Another wide field of applications of joint space impedance control algorithm is to perform contact operations. Mass-damper system in joints needs to be substituted with spring-mass-damper system in the role of desired joint behaviour. Rather then just to comply with the working environment robot can now exert forces on it. This could find use with processes like grinding or deburring. On the other hand, programmable remote centre compliance may in principle be realized for use in manufacturing tasks in this way.

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