A VARIABLE STRUCTURE FORCE CONTROLLER FOR ROBOTIC MANIPULATORS

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Abstract. Hybrid position/force control for robotic manipulators is considered. The control is carried out in task coordinates. For the force control the non-linear variable structure controller is presented and investigated. The controller maintains the system to reach and remain at the switching hypersurfaces, consisting of internal coordinates of the force controller. The stability of the system and the existing of the sliding mode are analyzed by means of the second Lyapunov method. The developed non-linear force controller was implemented for the hybrid position/force control of a PUMA 200 manipulator. The experimental setup and obtained results are described.

Key Words. Position/force control; robot; variable structure systems; stability.

1. INTRODUCTION

Traditional control systems for robotic manipulators are being developed as the position systems, where the command trajectories are given as functions of time. To widen the application area of manipulators and to increase their accuracy, additional force control is needed. The approaches for force control can be classified into two main groups. One, the *explicit force control*, differentiates strictly between position and force control. An often used explicit approach, the hybrid position/force control (Craig and Raibert, 1979; Mason, 1981; Raibert and Craig, 1981; Volpe and Khosla, 1992), regulates some components by help of position feedback and the others - by force feedback. Due to the task requirements, the hybrid approach switches between force and position control, which may result in stability problems during the switching process. To avoid the switching problems, *implicit force control* is often used to change continuously from position control to force control. A well investigated approach to this class is impedance control (Mason, 1981; Hogan, 1985; Kazerooni, 1989; Shimura *et al.*, 1991). The major disadvantage of this scheme is its inability to track a reference contact force, because the parameters of the environment are not known exactly (Seraji and Colbaugh, 1993).

In this work we consider the hybrid position/force control. This control scheme allows to compensate or, at least, substantially decrease errors appearing while the interactions of the manipulator with the environment. In this case the manipulator receives the property to produce the desired forces during its motion along the prescribed, position controlled trajectory. For hybrid control, a force sensor, built at the wrist of the manipulator, must be used. This sensor must be able to measure the contact forces/torques during the motion. The hybrid position/force control scheme is shown in Fig. 1. Various control strategies for the explicit force control were considered by Volpe and Khosla (1992). In our paper we investigate the possibility to develop a non-linear force controller, based on the theory of the variable structure systems (VSS) (Emelyanov, 1970; Young, 1978; Utkin, 1992), and to carry out experiments with such a controller.

2. ARM/SENSOR MODEL

The dynamics of a robotic manipulator is described by means of the Lagrange equation (Fu *et al.*, 1987)

$$\mathbf{D}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{B}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{J}^{\mathrm{T}}(\mathbf{q})\mathbf{f} = \tau, \qquad (1)$$

where $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are vectors of the joint coordinates, velocities and accelerations respectively,

$\mathbf{D}(\mathbf{q})$	-	inertia matrix of the manipulator,
$\mathbf{B}(\mathbf{q},\dot{\mathbf{q}})$	-	matrix of the Coriolis and centrifugal torques,
$\mathbf{G}(\mathbf{q})$	-	vector of the gravitational torques,
$\mathbf{J}(\mathbf{q})$	-	Jacobian matrix of the manipulator,

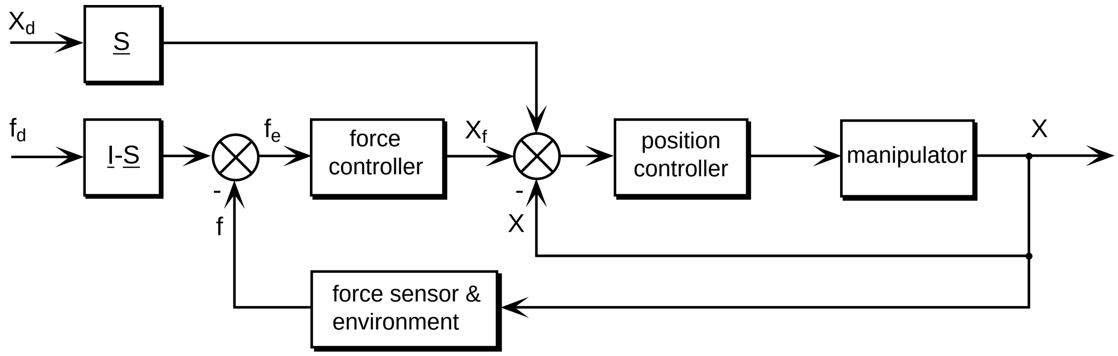

Fig. 1. Hybrid position/force control scheme

f	-	vector of the contact forces/torques in the task space,
τ	-	vector of the manipulator torques in the joint coordinates.

The (6x1) - velocity vector of the manipulator in the task space is found as

$$\dot{\mathbf{X}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}. \qquad (2)$$

From (2) one can receive the (6x1) - acceleration vector of the end point of the manipulator as

$$\ddot{\mathbf{X}} = \mathbf{J}(\mathbf{q})\ddot{\mathbf{q}} + \dot{\mathbf{J}}(\mathbf{q})\dot{\mathbf{q}}. \qquad (3)$$

Since the desired forces/torques are given in the task space of the manipulator, it is desirable that the input position vector will be given in these coordinates too. Then, using the Resolved Acceleration Position Control (Luh *et al.*, 1980), the accelerations of the manipulator in the task space should satisfy

$$\ddot{\mathbf{X}} = \ddot{\mathbf{X}}_d + \mathbf{K}_v(\dot{\mathbf{X}}_d - \dot{\mathbf{X}}) + \mathbf{K}_p(\mathbf{X}_d - \mathbf{X}), \qquad (4)$$

where $\mathbf{X}_d$ is desired position/orientation vector in the task space, $\mathbf{K}_v = \mathrm{diag}(K_{v,1}, \ldots, K_{v,6})$ and $\mathbf{K}_p = \mathrm{diag}(K_{p,1}, \ldots, K_{p,6})$ are diagonal matrices. By means of the choice of coefficients $K_{v,j}$ and $K_{p,j}$ it is possible to achieve the desirable dynamic behaviour of the manipulator. Using expressions (2) and (4), from (3) it follows:

$$\begin{aligned}\ddot{\mathbf{q}} = -\mathbf{K}_v\dot{\mathbf{q}} + \mathbf{J}^{-1}(\mathbf{q})[\ddot{\mathbf{X}}_d + \mathbf{K}_v\dot{\mathbf{X}}_d \\ + \mathbf{K}_p(\mathbf{X}_d - \mathbf{X}) - \dot{\mathbf{J}}(\mathbf{q})\dot{\mathbf{q}}].\end{aligned} \qquad (5)$$

On the base of expressions (1) and (5), using the desired and measured values, the necessary input torques for the each joint of the manipulator can be calculated.

3. VARIABLE STRUCTURE FORCE CONTROLLER

Practically, the force controller development shows that the integral control law and, perhaps, some filtering algorithms are necessary in order to receive the appropriate accuracy while the force control. The presence of an integrator in the force controller leads to a zero steady state error in the case of a constant reference force (Ohto and Mayeda, 1991; Volpe and Khosla, 1992). The filtering algorithms are necessary because of noise in the force/torque measurements. While the force controller development the mathematical models of the manipulator, its environment and the force sensor are necessary. As it is seen from expressions (1) and (5), these models are very complex; e.g. the full arm-sensor-environment dynamics is described by the differential equations of the forth order (Eppinger and Seering, 1986). It is obviously, that the accurate models are very difficult to create as well as to on-line implement.

Using the named above substantially necessary parts, we develop the non-linear force controller, based on the VSS theory. The known advantage of such systems is the possibility of their successful work without the accurate dynamic models of a manipulator and its environment; only the borders of the dynamic parameters must be known. In accordance with the VSS theory the switching hypersurfaces in the internal for the force controller coordinates are formed. The control must maintain the system to move to and, further, to stay at the switching hypersurfaces. In this case there is a sliding mode in the system, and the system is described by the hypersurface equations. The coefficients of these equations may be found so that the desired dynamic properties of the whole system are achieved.

Using the VSS theory the switching hypersurfaces are formed in the $(f_{e,j}, \dot{f}_{e,j}, \omega_j)$ - coordinates of the force controller as

$$h_j = T_{s,j}\dot{f}_{e,j} + f_{e,j} - K_{s,j}\omega_j, \quad j = 1, \ldots, 6, \qquad (6)$$

where $f_{e,j} = f_{d,j} - f_j$ is force/torque error, i.e. the difference between the desired (reference) and the real contact force/torque respectively, $\dot{f}_{e,j} = df_{e,j}/dt$, $T_{s,j} = \text{const}$, $T_{s,j} > 0$, $K_{s,j} = \text{const}$, $K_{s,j} > 0$, $\omega_j = K_{i,j}^{-1} X_{f,j}$ is internal coordinate of the force controller, $K_{i,j} = \text{const}$, $K_{i,j} > 0$ and $\dot{X}_{f,j}$ is derivative component of the output vector $\mathbf{X}_f = (X_{f,1}, \ldots, X_{f,6})^T$ of the force controller. Then, expression (6) may be written in the vector form as

$$\mathbf{h} = \mathbf{T}_s \dot{\mathbf{f}}_e + \mathbf{f}_e - \mathbf{K}_s \omega, \tag{7}$$

where:

$$\mathbf{h} = (h_1, \ldots, h_6)^T, \qquad \mathbf{T}_s = \text{diag}(T_{s,1}, \ldots, T_{s,6}),$$
$$\mathbf{f}_e = (f_{e,1}, \ldots, f_{e,6})^T, \qquad \dot{\mathbf{f}}_e = (\dot{f}_{e,1}, \ldots, \dot{f}_{e,6})^T,$$
$$\mathbf{K}_s = \text{diag}(K_{s,1}, \ldots, K_{s,6}), \qquad \omega = (\omega_1, \ldots, \omega_6)^T.$$

There are many applications where the manipulator must produce desired contact forces/torques $\mathbf{f}_d$, given in the task space, when the manipulator moves along the prescribed trajectory or when the position of the gripper is given constant. In this paper we consider the case when the desired position of the manipulator as well as the desired forces/torques are constant during contact with the environment. One should note that the proposed force control algorithm is only valid in case of contact of the manipulator with the environment. This structure is neither thought to work for all control conditions, i.e. like impedance control (Hogan, 1985) nor valid for impact control (Volpe and Khosla, 1991).

For the measured forces/torques, as it was shown by Shimura *et al.* (1991), one can write

$$\mathbf{f}_m(s) = \mathbf{W}_e(s)\mathbf{X}(s), \tag{8}$$

where $\mathbf{f}_m = (f_{m,1}, \ldots, f_{m,6})^T$ is vector of the force/torque measurements, $\mathbf{W}_e(s) = \text{diag}(D_{e,1}s + K_{e,1}, \ldots, D_{e,6}s + K_{e,6})$, $D_{e,j}$ and $K_{e,j}$ are viscosity and spring coefficients respectively. Since there is a noise in the force measurements, one should use a filter, e.g. with the transfer function of the first order

$$\mathbf{W}_f(s) = \text{diag}\left(\frac{1}{T_{f,1}s+1}, \ldots, \frac{1}{T_{f,6}s+1}\right), \tag{9}$$

as it is shown in Fig. 2. As the steady state error must be null, an integrator is introduced. It is described by the transfer function

$$\mathbf{W}_i(s) = \text{diag}\left(\frac{K_{i,1}}{s}, \ldots, \frac{K_{i,6}}{s}\right). \tag{10}$$

Then, the second filter with the transfer function

$$\mathbf{W}(s) = \text{diag}\left(\frac{1}{T_1 s+1}, \ldots, \frac{1}{T_6 s+1}\right), \tag{11}$$

is situated before the integrator. In this way, the resulting control scheme with non-linear force controller is presented in Fig. 2, where the parts of the controller with denotations

$$\mathbf{W}_h(s) = \text{diag}(T_{s,1}s+1, \ldots, T_{s,6}s+1), \tag{12}$$

$$\mathbf{F}(\mathbf{h}) = \text{diag}(u_o \text{sign}(h_1), \ldots, u_o \text{sign}(h_6)), \quad u_o = \text{const}, \; u_o > 0. \tag{13}$$

correspond with the idea of the sliding mode control. In the case of the given fixed position of the gripper in the Cartesian coordinates and the Resolved Acceleration Position Control (Luh *et al.*, 1980), the transient processes relative to the task coordinates are monotonous and are described by the second order differential equation (4) (An *et al.*, 1988). The second Lyapunov method is applied to analyze the existence of the sliding mode in the system and its stability (Utkin, 1992). The following Lyapunov function candidate is considered

$$V = \frac{1}{2}\mathbf{h}^T\mathbf{h}. \tag{14}$$

In accordance with the second Lyapunov method the system is stable when $V \geq 0$ and $\dot{V} \leq 0$. Using (14), one can receive

$$\dot{V} = \mathbf{h}^T\dot{\mathbf{h}}. \tag{15}$$

From expression (7) one can write

$$\dot{\mathbf{h}} = \mathbf{T}_s\ddot{\mathbf{f}}_e + \dot{\mathbf{f}}_e - \mathbf{K}_s\dot{\omega}. \tag{16}$$

Setting $T_{s,j} = T_{f,j}$, $j = 1, \ldots, 6$, from equation (16) one can receive for the control scheme of Fig. 2:

$$\dot{\mathbf{h}} = \mathbf{T}_f\ddot{\mathbf{f}}_d + \dot{\mathbf{f}}_d - (\mathbf{D}_e\ddot{\mathbf{X}} - \mathbf{K}_e\dot{\mathbf{X}}) - \mathbf{K}_s\dot{\omega}. \tag{17}$$

where

$$\mathbf{T}_f = \text{diag}(T_{f,1}, \ldots, T_{f,6}),$$
$$\mathbf{D}_e = \text{diag}(D_{e,1}, \ldots, D_{e,6}),$$
$$\mathbf{K}_e = \text{diag}(K_{e,1}, \ldots, K_{e,6}).$$

In the case of contact of the manipulator with the environment the desired position/orientation vector is set null (the desired contact was achieved). The position/orientation error vector of the manipulator in the task space is denoted as $\mathbf{e} = \mathbf{X}_f - \mathbf{X}$.

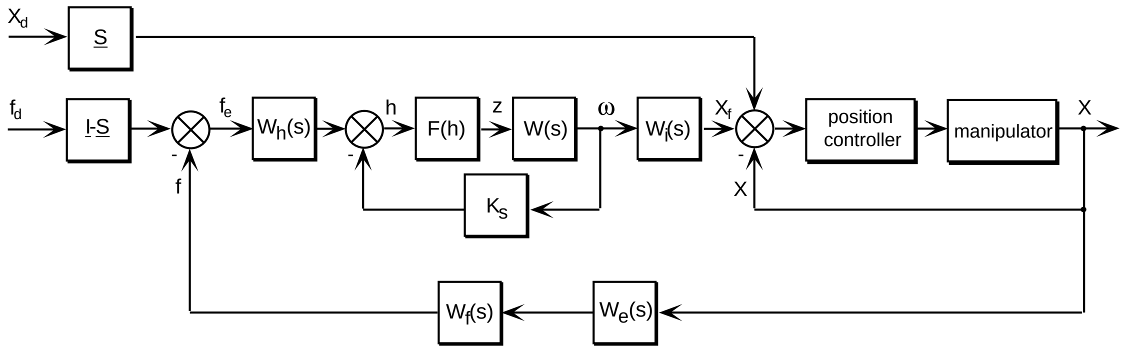

Fig. 2. Hybrid position/force control scheme with variable structure force controller

As it follows from equation (10) and Fig. 2, $\omega = \mathbf{K}_i^{-1}\dot{\mathbf{X}}_f = \mathbf{K}_i^{-1}(\dot{\mathbf{e}} + \dot{\mathbf{X}})$. Setting $\mathbf{T} = \mathbf{K}_v^{-1}$, where $\mathbf{T} = \mathrm{diag}(T_1, \ldots, T_6)$ and setting

$$\mathbf{K}_e = (\mathbf{D}_e + \mathbf{K}_s\mathbf{K}_i^{-1})\mathbf{K}_v \tag{18}$$

by means of the choice of coefficients $K_{s,j}$, expression (17) can be rewritten as

$$\begin{aligned}\dot{\mathbf{h}} = {} & \mathbf{T}_f\ddot{\mathbf{f}}_d + \dot{\mathbf{f}}_d - (\mathbf{D}_e + \mathbf{K}_s\mathbf{K}_i^{-1})\mathbf{z} \\ & - (\mathbf{D}_e + \mathbf{K}_s\mathbf{K}_i^{-1})\mathbf{K}_p\mathbf{e} - \mathbf{K}_s\mathbf{K}_i^{-1}\ddot{\mathbf{e}},\end{aligned} \tag{19}$$

where

$$\mathbf{z} = \ddot{\mathbf{X}}_f + \mathbf{K}_v\dot{\mathbf{X}}_f\,.$$

(20)

Since $\mathbf{z} = \mathbf{F}(\mathbf{h})$, from (19) with the use of (4) it follows for the constant desired forces/torques

$$\begin{aligned}\dot{\mathbf{h}} = {} & -(\mathbf{D}_e + \mathbf{K}_s\mathbf{K}_i^{-1})\mathbf{F}(\mathbf{h}) \\ & + (\mathbf{D}_e\ddot{\mathbf{e}} + \mathbf{K}_e\dot{\mathbf{e}}).\end{aligned} \tag{21}$$

Further, it is also supposed that the following conditions are provided:

$$u_o > \frac{|D_{e,j}\ddot{e}_j + K_{e,j}\dot{e}_j|}{D_{e,j} + K_{s,j}K_{i,j}^{-1}}, \quad j = 1, \ldots, 6\,. \tag{22}$$

In the case of the Resolved Acceleration Position Control for the manipulator the position/orientation, velocity and acceleration errors aspire to zero, and $D_{e,j}$, $K_{e,j}$ are limited (Shimura *et al.*, 1991). In this way, conditions (22) may be obviously provided. Then, the first derivative of the Lyapunov function is

$$\begin{aligned}\dot{V} = {} & -u_o\sum_j (D_{e,j} + K_{s,j}K_{i,j}^{-1})|h_j| \\ & + \sum_j (D_{e,j}\ddot{e}_j + K_{e,j}\dot{e}_j)h_j \le 0.\end{aligned} \tag{23}$$

In accordance with the second Lyapunov method expression (23) proves the existence of sliding mode for the system and its stability.

4. EXPERIMENTAL RESULTS

The developed variable structure force controller was implemented on the PUMA 200 manipulator system, used in the project KAMRO - Karlsruhe Autonomous Mobile Robot (Damm *et al.*, 1993). To achieve a high environmental stiffness, a metal cone was fixed to the end-effector of the manipulator and a metal contact plane was used. The experimental setup is presented in Fig. 3.

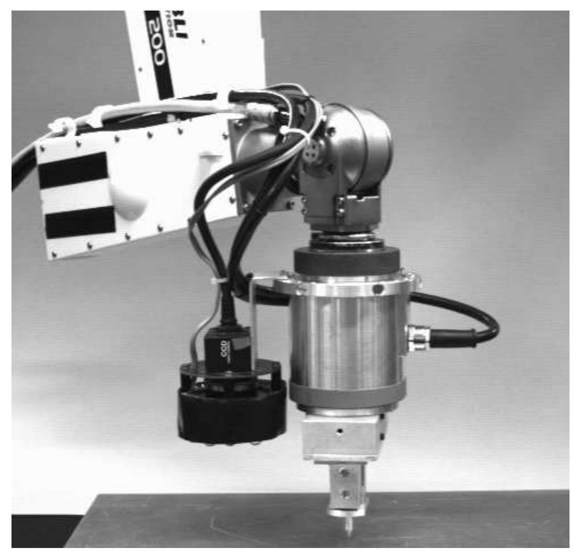

Fig. 3. Experimental setup

The control system is implemented on a VMEbus-based multiprocessor system. In its current state it consists of the following components:

- one 68040-CPU board for the Cartesian control and trajectory calculation of the manipulator,
- two 68000-CPU boards, each controlling three joints of the PUMA 200 robot,
- one sensor interface board for the interfacing to the force/torque sensor and gripper,
- one memory board for the communication and synchronisation of the CPU boards,

- one 68020-CPU board for the communication via Ethernet and BITBUS.

The sampling time of the force controller is mainly determined by the time requirements of the force/torque measurement and the computational demands, so that the Cartesian cycles take more time than cycles of the underlaying position controller. Because of the effect of the sampling period on tracking performance (Tarn *et al.*, 1993), both sampling times were individually minimised. To avoid the problems of asynchronous control, the force control period was chosen 10.6 ms, six times longer than the position control period.

One important requirement for force control is the fixed time delay of the measurement. The measuring time is determined by the force pre-processing unit and assumed to be constant. Hence, the delay depends on the moment of triggering. A constant time delay is guaranteed by accessing the hardware system clock of the joint controller to trigger the force measurement. Another demand is that the force values must be independent from the current manipulator motion. Therefore, a simplified dynamic model of the sensor with a flanged gripper is used. This model considers the actual orientation of the tool centre point relative to the gravitation vector, and the actual acceleration of the tool centre point.

The experiments were carried out when the vertical force of 3 N was preliminary given at the desired position of the environment. Then, the force was increased to 6 N in the vertical direction. The forces for the horizontal directions were given null. For the developed non-linear force controller an acceptable transient process was achieved by tuning experimentally the parameters of the switching hypersurfaces. The obtained experimental results are presented in Fig. 4.

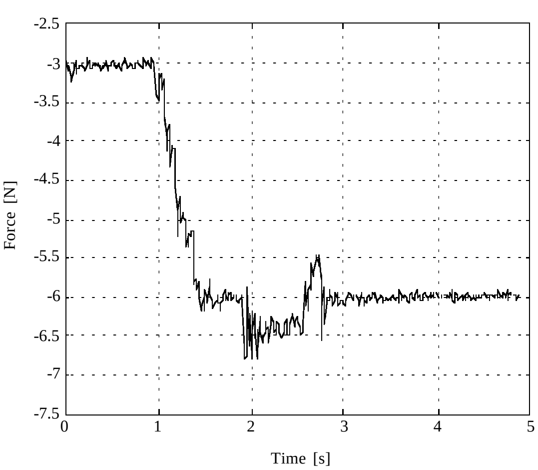

Fig. 4. Transient process for the force controller with discontinuous control

These results show that the control system is stable when the developed variable structure force controller was used for the hybrid position/force control. The parameters of the force controller were chosen to receive the fast transient process. For the case of Fig. 4 the transient period is about 2.1 s.

The possibility to decrease the "chattering" occurring during the sliding mode, because of the switching, i.e. discontinuous control, was investigated too. The discontinuous control with $\mathrm{sign}(h_j)$ functions was replaced by applying the continuous control, formed with the help of the function considered by Harashima *et al.* (1986):

$$\mathrm{cont}(h_j) = h_j / (|h_j| + \delta_j), \tag{24}$$

where $\delta_j = \mathrm{const}$, $\delta_j > 0$. Further, the following controls were applied:

$$z_j = |f_{e,j}| \mathrm{cont}(h_j). \tag{25}$$

This control algorithm was studied experimentally. The obtained results are presented in Fig. 5. As it is seen, this allowed to improve the accuracy of the system and its quickness - the transient process is about 1.4 s.

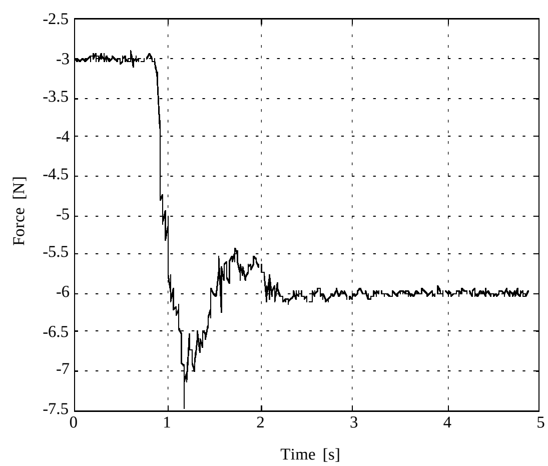

Fig. 5. Transient process for the force controller with continuous control

5. CONCLUSION

For the hybrid position/force control for robotic manipulators the development of variable structure force controller was investigated. The substantially necessary parts (integrator and filters) and the non-linear control algorithm were used to form the structure of the force controller. The stability of the developed non-linear force controller was analyzed by means of the second Lyapunov method.

It allowed to find the appropriate parameters of the controller to provide its stability. The final parameters were found by means of the experiments, when the developed non-linear force controller was implemented for the hybrid position/force control of the PUMA 200 manipulator. The obtained experimental results showed that the developed force controller allows to receive fast and accurate operation of the system.

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7. REFERENCES

An, C.H., Atkeson, C.G., and Hollerbach, J.M. (1988). *Model-Based Control of a Robot Manipulator.* MIT Press.

Craig, J.J., and Raibert, M.H. (1979). A systematic method of hybrid position/force control of a manipulator. *Proc. of the IEEE Conf. on Computer Software and Applications, Chicago*, pp. 418-432.

Damm, M., Kappey, D., Schloen, J., Rembold, U., and Dillmann, R. (1993). A multi-sensor and adaptive real-time control architecture for an autonomous robot. *Proc. of the Int. Conf. on Intelligent Autonomous Systems IAS-3, Pittsburgh, Febr. 15-18, 1993*, pp. 439-448.

Emelyanov, S.V. (1970). *Theory of Variable Structure Systems (in Russian).* Nauka, Moscow.

Eppinger, S., and Seering, W. (1986). On dynamic models of robot force control. *Proc. of the IEEE Conf. on Robotics and Automation*, pp. 29-34.

Fu, K.S., Gonzalez, R.C, and Lee, C.S.G. (1987). *Robotics: Control, Sensing, Vision, and Intelligence.* McGraw-Hill Industrial Engineering Series.

Harashima, F., Hashimoto, H., Maruyama, K. (1986). Practical robust control of robot arm using variable structure system. *Proc. of the IEEE Int. Conf. on Robotics and Automation, San Francisco, April 7-10, 1986*, pp. 532-539.

Hogan, N. (1985). Impedance control: an approach to manipulation, Part 1-3. *Transactions of the ASME, J. Dynamic Systems, Measurement, and Control*, **107,** 1-24.

Kazerooni, H. (1989). On the robot compliant motion control. *Transactions of the ASME, J. Dynamic Systems, Measurement, and Control*, **111,** 416-425.

Luh, J.Y.S., Walker, M.W., and Paul, R.P. (1980). Resolved acceleration control of mechanical manipulators. *IEEE Transaction on Automatic Control*, **AC - 25,** 268-474.

Mason, M.T. (1981). Compliance and force control for computer controlled manipulators. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC - 11,** 418-432.

Ohto, M., and Mayeda, H. A. (1991). Hybrid position/force control for robot manipulators with position controllers. *Proc. of the Int. Conf. on Industrial Electronics, Control and Instrumentation, IECON´91, Oct. 28 - Nov. 1, 1991*, pp. 1037-1042.

Raibert, M.H., and Craig, J.J. (1981). Hybrid position/force control of manipulators. *IEEE Transactions of the ASME, J. Dynamic Systems, Measurement and Control*, **102,** 126-133.

Seraji, H., and Colbaugh, R. (1993). Adaptive force-based impedance control. *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Yokohama, Japan, July 26-30, 1993*, pp. 1537-1544.

Shimura, K., Sugai, M., and Hori, Y. (1991). A novel robot motion control based on the decentralized robust servomechanism for each joint. *Proc. of the Int. Conf. on Industrial Electronics, Control and Instrumentation, IECON´91, Oct. 28 - Nov. 1, 1991*, pp. 1283-1288.

Tarn, T.J., Bejczy, A.K., Marth, G.T., and Ramadorai, A.K. (1993). Performance comparison of four manipulator servo schemes. *IEEE Control Systems Magazine*, **13,** 22-29.

Utkin, V.I. (1992). *Sliding Modes in Control and Optimization.* Springer-Verlag, Berlin.

Volpe, R., and Khosla, P. (1991). Experimental verification of a strategy for impact control. *Proc. of the IEEE Int. Conf. on Robotics and Automation, Sacramento, 1991*, pp. 1854-1860.

Volpe, R., and Khosla, P. (1992). An experimental evaluation and comparison of explicit force control strategies for robotic manipulators. *Proc. of the IEEE Int. Conf. on Robotics and Automation, Nice, France, May 12-14, 1992*, pp. 1387-1393.

Young, K.-K.D. (1978). Controller design for a manipulator using theory of variable structure systems. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-8,** 101-109.