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Hybrid model-based force/position control: theory and experimental verification

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Summary

Force/position control is a relatively young and rapidly developing branch of robotics. Its practical implementation faces many difficulties due to inherent process complexity. Despite this, the majority of contributions in this field use the classic approach to force control, i.e. single-loop PID control. In this paper, two model-based control structures are proposed, yielding much better results of force control as compared to the classic approach, to be achieved. These are two-loop model-following control (MFC) structures that guarantee interesting disturbance suppression behaviour by an additional degree of freedom. Tests carried out with a Manutec r2 manipulator with six degrees of freedom have shown clear advantages of the control structures under study.

KEYWORDS: Force/Position Control; MBC Model-Based Control; MFC Model-Following Control; Single-Loop Structure.

1. Introduction

This paper deals with force control applied to robot manipulators and with the control problems resulting from the complexity of the control process itself. The general control concept has been taken from reference [1], where a well-known formalism of the hybrid force/position control is presented. For such a control structure, the force control part has been modified by replacing the classic Proportional-integral-derivative control by model-based control structures, i.e. MFC-m[6,8,11] and MFC-p.[10,12]

The manipulator itself represents a control plant with varying parameters that may fluctuate depending on both time and the operating point. Its nonlinearity and non-stationarity causes many difficulties for position control.[14] In the case of force/position control, the adverse control properties of the manipulator are accompanied by non-linearities caused by the stiffness of the environment, with which a physical contact is made. Of course, there are possibilities to prevent such phenomena, e.g. by limiting the workspace of the manipulator, or choosing an environment with identical stiffness. Such an approach, however, imposes significant limits on the practicality of the control algorithm.

The limited robustness of the best-known control structure, i.e. the single-loop PID system, may account for its impracticality if applied to processes that are difficult to control, or when stringent requirements on control performance are of critical importance. Admittedly, an increase in robustness may be obtained at the cost of controller dynamics[7,13]; this, however, has a detrimental effect on the process rise time, which is an essential quality criterion if force control is dealt with. For these reasons, more sophisticated control systems are pursued that would ensure fulfilment of the imposed requirements. A reasonable alternative are two-loop model-following control (MFC) structures that offer significantly greater robustness to plant parameter variations (as compared with PID)[10,12] on the one hand, and ease of design and practical implementation on the other.

A new open robot control architecture based on *M*i*ddleware for *R*obotic and *P*rocess Control *A*pplications (MiRPA)[2] has been used to implement the proposed control structures. The obtained results have been compared with those yielded by a classic PID control. In addition, a number of tests have been carried out to examine the effect produced by a change in the stiffness of the environment. The results obtained give a good indication of the potential offered by the MFC systems with respect to robustness.

2. Classic force/position control structure

If a manipulator moves along a given trajectory in free space, then position control is fully sufficient. However, if the effector comes into contact with the environment, then the control system should be extended to force control. The purpose of this paper is to present model-based control structures and discuss the advantages that they offer if applied to the control of processes with varying parameters. With this aim in mind a decision was made to simplify the experimental task in favour of force/position control by regarding the manipulator with six degrees of freedom as a Cartesian manipulator with three degrees of freedom. Hence, in what follows, changes in position or force along the x-, y-, or z-directions will be discussed.

In every problem, where manipulators are involved, natural or artificial constraints determined by mechanical and geometric conditions come into play. In the case of force/position control, we additionally have to deal with position constraints and force constraints. These separate the degrees of freedom of potential movements an end-effector can make into two orthogonal sets that have to be controlled in accordance with different criteria.[1] For a simple case where

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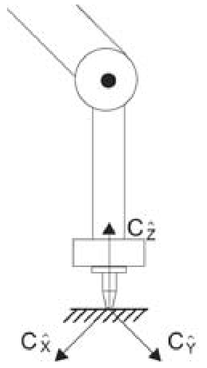

Natural constraints	
position	force
$v_z=0$	$f_x=f_y=0$
Artificial constraints	
position	force
$v_x=v_y=0$	$f_z=f_o$

v – velocity
f – force

Fig. 1. Constraints occurring in the example given.

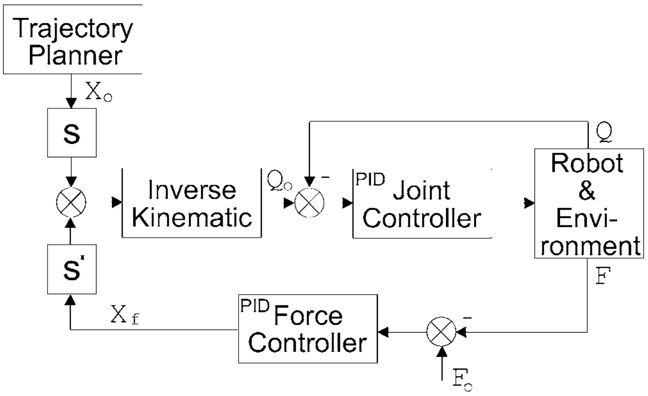

Fig. 2. Known hybrid force/position control implemented in configuration space.

force is applied in the z-direction, the constraints for a three-degree-of-freedom manipulator are given in Fig. 1.

The force/position controller, if implemented as a switching system, enables one to select which DOFs are to be controlled in which motion state. The structure of such a controller may be realized in Cartesian as well as in the configuration space (Fig. 2).

In Fig. 2, a general structure of the hybrid force/position control that has been used in our experiments is depicted. Since the position control has been implemented in configuration space, the inverse kinematic equations have been used to represent Cartesian displacements of the effector. Matrices S and S′ select along which DOFs the position or force control is applied. Matrix S is diagonal with zeros and ones on the diagonal. For example, a one in matrix S and a zero in matrix S′ means that force control is chosen. Hence, matrices S and S′ here are used as switches defining the control procedure for each manipulator's DOF depending on a selected threshold of the initial contact force.

3. Model-based force/position control structures

Ease of parameterisation, which is given by the classic PID control in a single-loop, is a major advantage offered by this control algorithm. Also, PID applied to force/position control for robot manipulators may yield satisfactory results under certain assumptions.[1,16] However, if a higher system robustness with respect to parameter changes, caused by process nonlinearities or nonstationarities is expected, then more sophisticated solutions have to be sought for. Examples are adaptive systems[5,15] with their advantages and disadvantages (such as great theoretical complexity, stability problems, high design costs, etc.). An interesting alternative is offered by two variants of time-invariant MFC systems, which are depicted in Fig. 3.

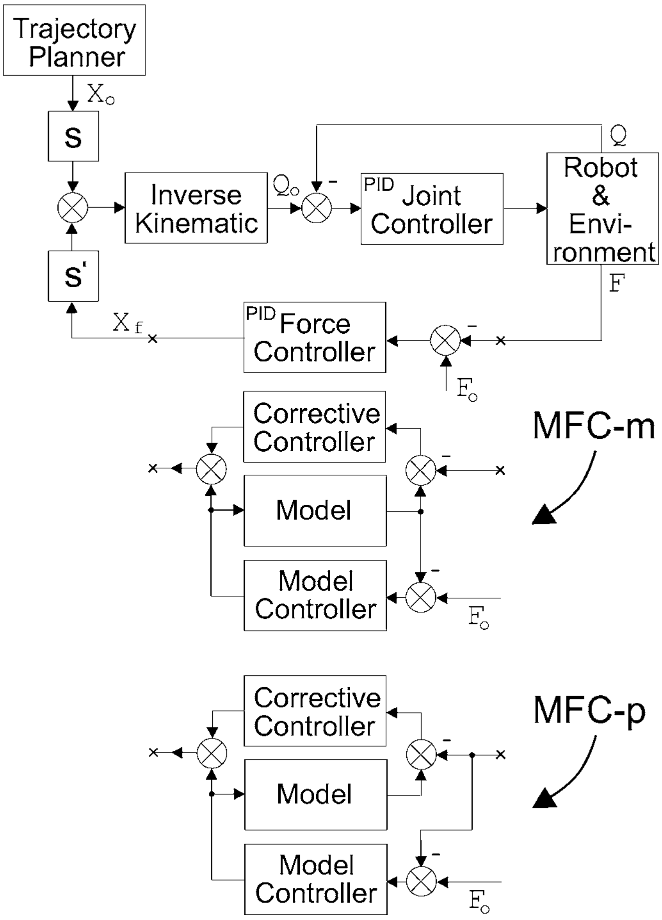

Fig. 3. Proposed model-based hybrid control. The classic PID control (top) is replaced by MFC-m or MFC-p control.

The shown MFC-m and MFC-p structures include two control loops. The difference between the structures consists in the feedback that exists in the model loop. As it turns out, this small structural modification entails substantial changes with respect to the robustness exhibited by both the structures. A theoretical analysis of the proposed solutions in comparison with the commonly known single-loop PID control will be made later.

3.1. Single-loop PID control

Undoubtedly, the classic single-loop PID feedback system is the control structure most often used in process automation. Of concern to us is the question: To what extent are the properties exhibited by the single-loop feedback structure suitable for force/position control applied to motion control of a robot manipulator? Variations in parameter values dependent on the manipulator operating point, and variations in the stiffness of the environment with which the manipulator comes into contact, may be considered as system disturbances z acting on the control system. Hence, suppression of disturbances in a single-loop system is a

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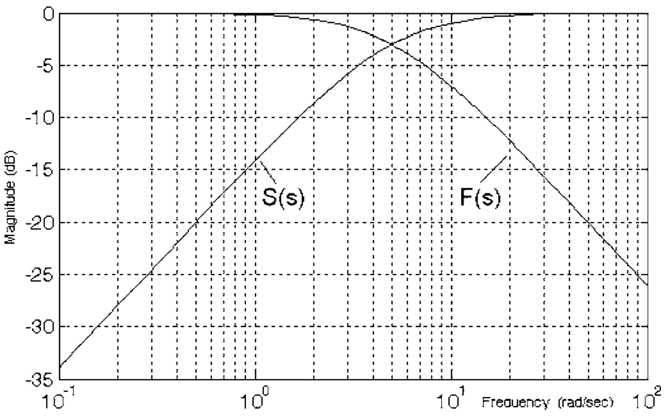

Fig. 4. Frequency responses for tracking the reference variable $F(s)$ and for disturbances $S(s)$ obtained for a single-loop PID system.

property of fundamental importance to us. The system output with due regard for disturbances may be defined in the following form:

$$y_{\text{PID}} = \frac{R_m P}{\underbrace{1 + R_m P}_{F}} y_o + \frac{1}{\underbrace{1 + R_m P}_{S}} z, \qquad (1)$$

where R_m is the controller, P is the process, and y_o is the reference variable.

As may be inferred from Eq. (1), the following equality holds true:

$$F + S = 1. \qquad (2)$$

Equation (2) illustrates the substantial restriction of the single-loop system. An ideal tracking of the reference variable within a range of frequencies determines simultaneously the range of frequencies within which the system disturbances z are suppressed. Making both the properties independent of each other in a single-loop control system is impossible due to the fact that it is a 1-DOF structure. Frequency responses for both tracking and system disturbance suppression are given in Fig. 4. The simulation has been carried out for a PI controller and a linear first-order time-lag plant.

Besides suppression of disturbances, the system robustness with respect to variations in parameters or process structure is another important property that is of further concern to us. Assuming that the process perturbations are given in a multiplicative form $P = (1 + \Delta)M$ (where M is the process model), the condition to be met by perturbation for the PID system to be stable is[8]

$$|\Delta|_{\text{PID}} < \frac{|1 + M R_m|}{|M R_m|}. \qquad (3)$$

As may be inferred from Eq. (3), the robustness of the single-loop control system depends on the reciprocal of the controller dynamics R_m. Hence, increasing the robustness of the PID structure will be achieved at the cost of longer settling time, which may be found to be unacceptable for force control. The problem may be remedied by employing the proposed control structures MFC-m and MFC-p.

3.2. Two-loop MFC-m control

Figure 3 shows, among other things, the MFC-m structure. Here, the following designations are used: R_m is the model controller, M is the process model, R_k is the corrective controller, and P is the process plant. The MFC-m output with due regard for acting system disturbances z may be defined in the following form:

$$y_{\text{MFC-m}} = \frac{R_m P\,(1 + R_k M)}{\underbrace{1 + R_m M + R_k P + R_m R_k M P}_{F_m}} y_o + \cdots + \frac{1}{\underbrace{1 + R_k P}_{S_m}} z. \qquad (4)$$

Essentially, MFC-m control consists in utilizing the linear process model to generate the basic constituent of the manipulated variable, thus ‘taking some burden’ from the corrective controller. This concept enables one to parameterise R_k with respect to the frequency and amplitude of disturbances and, possibly, to the model inaccuracy. This feature is illustrated by the following equation:

$$F_m + S_m = 1 - \frac{P\,[R_k - R_m]}{[1 + P R_k][1 + M R_m]}. \qquad (5)$$

It can be seen from Eq. (4) that $F_m = F$ if $P = M$. With appropriately parameterised controllers R_m and R_k, stronger system disturbance suppression by MFC-m may be expected for $F_m + S_m < 1$. This property is illustrated in Fig. 5, where results of simulations carried out for the case $P = M$ and $|R_m| < |R_k|$ are illustrated. As in the case illustrated in Fig. 4, the controllers R_m and R_k have been PI ones with different gains, and the process P has been assumed as first-order time-lag. With reference to Fig. 5, it can be seen that disturbances over the range of low frequencies are strongly suppressed here. The frequency response of S_m may be shaped over a wide range by appropriately chosen differentiation and integration terms in the corrective controller R_k.

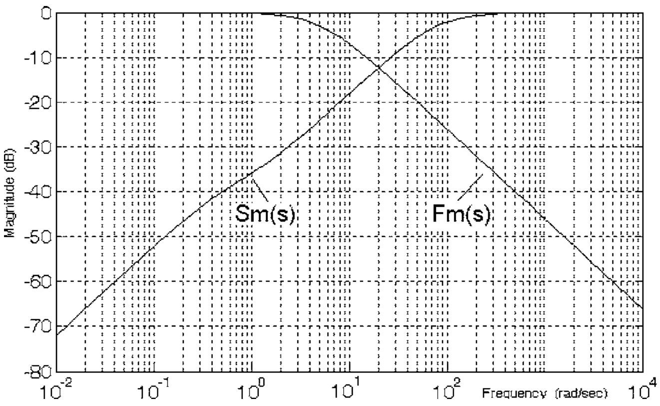

Fig. 5. Frequency responses for tracking the reference variable $F(s)$ and for disturbances $S_m(s)$ obtained for an MFC-m system.

The stability condition for MFC-m under multiplicative perturbations has been derived in references [10] and [12], and is given by

$$|\Delta|_{\text{MFC-m}} < \frac{|1 + MR_\text{k}|}{|MR_\text{m}|}. \tag{6}$$

From Eq. (6), it may be inferred that the stronger the inequality $|R_\text{m}| < |R_\text{k}|$, the higher the robustness exhibited by the MFC-m system and the more strongly suppressed the system disturbances are. Such an advantage is not exhibited by the classic single-loop feedback structure.

3.3. Two-loop MFC-p control

Figure 3 shows the structural difference between the MFC-m and MFC-p systems. In MFC-p, the feedback in the model loop is related to the process output, whereas in MFC-m, this is related to the model output. Such a modification produces a significant effect on system properties. The MFC-p system output is defined here by

$$y_{\text{MFC-p}} = \underbrace{\frac{R_\text{m}P\,(1 + R_\text{k}M)}{1 + R_\text{m}P + R_\text{k}P + R_\text{m}R_\text{k}MP}}_{F_\text{p}}\,y_\text{o} + \cdots$$
$$+ \underbrace{\frac{1}{1 + R_\text{m}P + R_\text{k}P + R_\text{m}R_\text{k}MP}}_{S_\text{p}}\,z. \tag{7}$$

It follows from Eq. (7) that

$$F_\text{p} + S_\text{p} = 1 - \frac{R_\text{k}P}{1 + R_\text{m}P + R_\text{k}P + R_\text{m}R_\text{k}MP}. \tag{8}$$

A comparison between transfer functions F_p and F_m shows that the stability condition for MFC-p differs distinctly from that for MFC-m, and is much more complicated.[10] Also, S_p is worth noticing here. The form of S_p suggests that MFC-p offers stronger suppression of system disturbances as compared to MFC-m. To verify this, simulations for identical transfer functions of P, M, R_m and R_k, as in the case of MFC-m, have been carried out. The ability of MFC-p to suppress system disturbances is illustrated in Fig. 6.

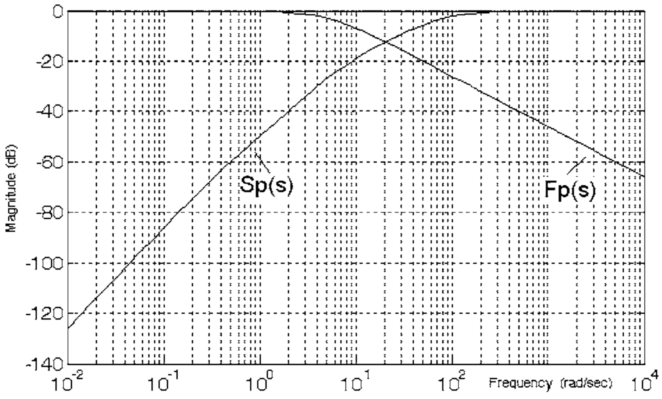

Fig. 6. Frequency responses for tracking the reference variable $F(s)$ and for disturbances $S_\text{p}(s)$ obtained for an MFC-p system.

The stability condition for MFC-p under multiplicative perturbations has been derived[10,12] and is given by

$$|\Delta|_{\text{MFC-p}} < \frac{|(1 + MR_\text{m})\,(1 + MR_\text{k})|}{|MR_\text{m}|}. \tag{9}$$

When this result is compared with that of Eq. (6), it is apparent that MFC-p tolerates greater values of $|\Delta|$ for its operation to be stable.

In the MFC-m system, there exists a distinct separation between the model loop and the process loop. In the MFC-p system, such a separation is less pronounced. Since the model controller is error-driven, both the controllers R_m and R_k are involved actively in the control of the actual process. This peculiarity leads to very interesting practical results[10] that have been observed when MFC-p was applied to force control in a robot manipulator.

4. Manipulator and environment dynamics

Equations describing manipulator dynamics are strongly nonlinear in their generalized coordinates. In the literature, many solutions for manipulator position control can be found, which linearize this difficult control plant to a larger or smaller extent. In many industry applications, the simplest PID control or cascade structures are still preferred. This is also the case with the Manutec manipulator used in our experiments. Its control is based on a three-loop cascade structure shown in Figs. 2 and 3 in a simplified way with one loop.

In case force/position control is accomplished in configuration space (Fig. 2), the position control occurs independent of the form of the selection matrix S. Therefore, the manipulator nonlinearity is compensated by the position control loop, whereas the force controller has to provide, among others, robustness with respect to variable environment stiffness.

However, this separation of tasks is only apparent, because disturbances occurring in the position control loop are also compensated by the force controller. Such a solution seems to be easier for practical implementation than the control accomplished in Cartesian space.[1]

As a preliminary step towards multi-DOF force/position control, we have implemented and tested a stable 1-DOF force control law for the force control problem shown in Fig. 7.

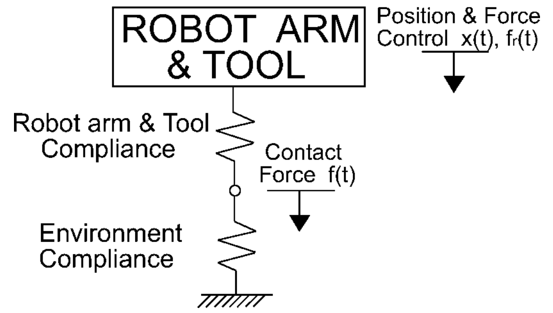

Fig. 7. One-DOF force control problem.

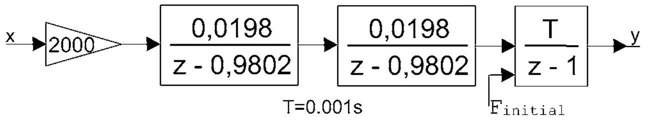

Fig. 8. Process model adopted in both the MFC structures.

For MFC-p purposes, the process has been modelled as a second-order time-lag with integration. This results from observations made with an actual classic force/position PID control. For selected optimal PID settings, a model has been sought that would ensure settling times comparable with those provided by the actual plant, assuming high stiffness of the environment (aluminium-made plate). The process model has been taken in the form shown in Fig. 8.

Modelling the phenomenon when the manipulator tip comes in contact with the environment is very difficult. Therefore, a simple linear process model has been used for our experiments (Fig. 8). Since the instant when the contact occurs has not been modelled, the model requires initialisation. The initial value of the force F_{initial} has been entered into the integration block at the instant the selection matrix S was switched over to force control. The initial value has been equal to the assumed force value that would induce changes in the selection matrix S.

5. Experimental setup

In order to implement the suggested force/position control approach, an open robot control architecture is required, which allows the integration of additional user-defined software modules. It must be possible to execute these modules under hard real-time conditions. The cycle time, the allowed latency and its jitter have to be very short. These requirements are met by the modular robot control architecture based on MiRPA, which has been mentioned in Section 1. It can easily be expanded by any control module, which may be implemented even in different programming languages. Here, we have used the MATLAB/Simulink environment to realize the investigated control structure and to observe the control results. All connections and communication steps to the robot control system are established and managed by MiRPA. The unique programming interface, the so-called Manipulation Primitive, of the control system allows the logical integration of these additional modules into robot programs on the programming level. Further details of this interface and the architecture approach are described elsewhere.[2,3]

6. Experimental results

The algorithms proposed in this paper have been tested with a Manutec r2 manipulator (Fig. 10) equipped with a force/torque sensor. In order to protect the expensive sensor and the manipulator itself, a collision protection system that is triggered by excessive forces has been used. Moreover, an additional restriction has been put on the approach velocities developed of the manipulator in Cartesian space. The tests have started with measuring the disturbances in the open control loop.

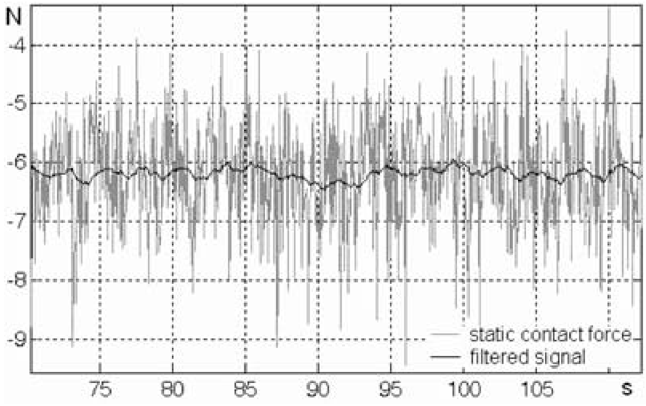

Fig. 9. Disturbed output. Contact with stiff environment (open loop).

Fig. 10. Experimental setup with stiff environment (aluminium-made plate).

Figure 9 shows the occurrence of disturbances when a static contact is made with an environment of high stiffness (aluminium-made), as illustrated in Fig. 10. The disturbances shown are due to many phenomena, the most important being substantial backlashes existing in transmissions of the manipulator. It should also be noted that the amplitude of disturbances is highly dependent on both the pressure, and the stiffness of the environment with which the contact is made.

For legibility, the obtained output has been filtered by a second-order time-lag for purposes of observation only, and not for purposes of control (Fig. 9).

6.1. One-DOF robot movement

After implementation, the proposed MFC-m and MFC-p systems, and also the classic single-loop feedback structure have undergone rigorous tests. Initially, the simplest case of

Table I. Controller settings adopted in the experiment.

	PID	MFC-m		MFC-p	
	R	R_m	R_k	R_m	R_k
K_p	0.001	0.0025	0.0005	0.0025	0.002
T_i	–	–	–	–	–
T_d	–	0.01	0.0005	0.01	–

1-DOF for a stiff environment, as shown in Fig. 10, has been considered.

Controller tuning for each control structure has been performed by experiment. For the classic single-loop system, it has turned out that the best results are yielded, if a P-type controller is employed. This is because the presence of strong disturbances precludes using numerical differentiation, if a smooth control function (manipulator displacement) should be preserved. On the other hand, the manipulator is a final control element with properties of an integrator; thus, additional integration turns out to be superfluous. For the controller chosen in such a way, the dynamic process model has been defined as mentioned in Section 4. Controller settings for the MFC-m and MFC-p structures also have been chosen on the basis of the required control performance. Eventually, the adopted controller settings have taken on values given in Table I.

For the adopted controller settings, an experiment for force control has been performed that consisted in recording the step responses provided by the systems under study. The results obtained are depicted in Figs. 11 and 12.

The results yielded by MFC-m and MFC-p are close to each other; therefore, a step response only for MFC-p is shown in Fig. 12. Comparing the results depicted in Figs. 11 and 12, it is apparent that MFC-p provides a shorter settling time, which can be additionally improved by choosing a faster process model or model controller R_m. An improvement in control performance is also noticeable in Figs. 13 and 14, where a time response to a sinusoidally varying reference value of the PID and MFC-m system is recorded.

In case of the static contact, a certain improvement in control performance when MFC is used may be noticed. However, the principal advantage of MFC is most conspicuous if a dynamic contact of the manipulator with its environment is considered.

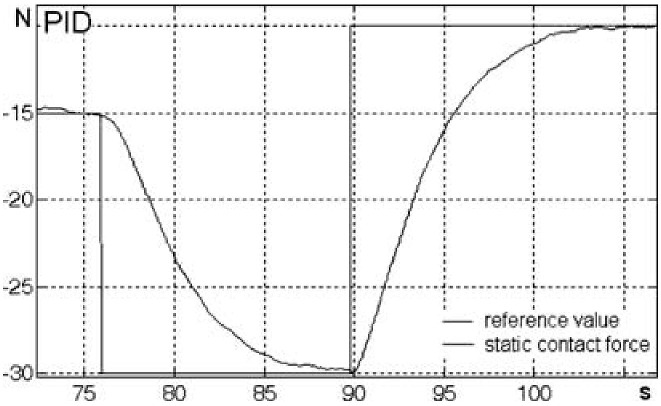

Fig. 11. Force control at static contact (PID control; low stiffness).

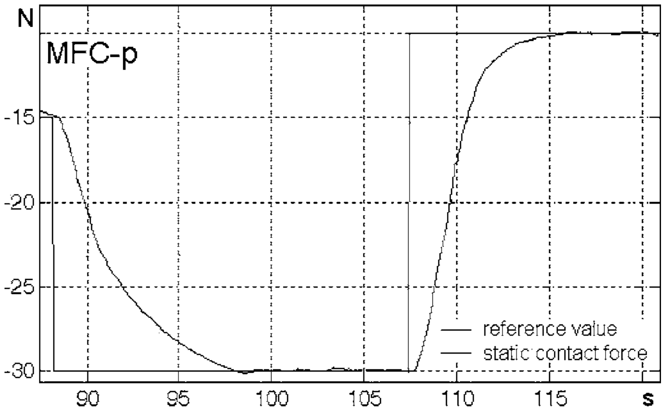

Fig. 12. Force control at static contact (MFC-p control; low stiffness).

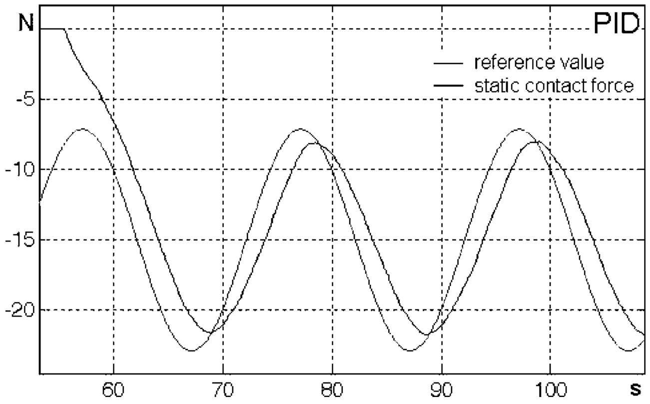

Fig. 13. Force control at static contact (PID control). Sinusoidal reference value.

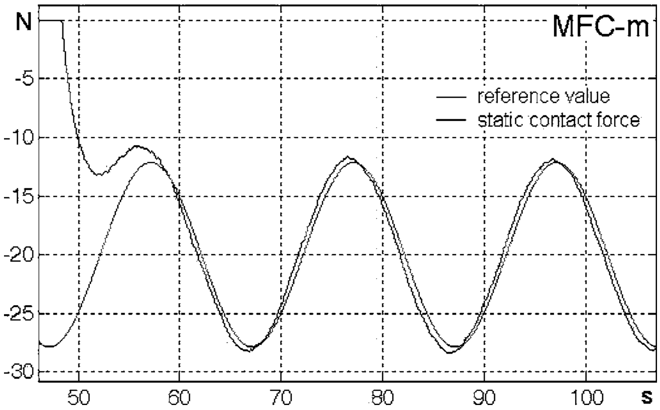

Fig. 14. Force control at static contact (MFC-m). Sinusoidal reference value.

6.2. Two-DOF robot movement

The pointwise force control defined in Fig. 1 does not involve severe practical difficulties. This is understandable when one considers that force control takes place at a strictly determined point, in the vicinity of which the controller(s) is (are) tuned. However, difficulties arise when force control is accompanied by manipulator position control, i.e. the

Table II. Constraints adopted in the experiment.

Position	Force
Natural constraints	
$v_z = 0$	$f_x = f_y = 0$
Artificial constraints	
$v_x = 0,\ v_y = v_o$	$f_z = f_o$

v: Velocity; f: force.

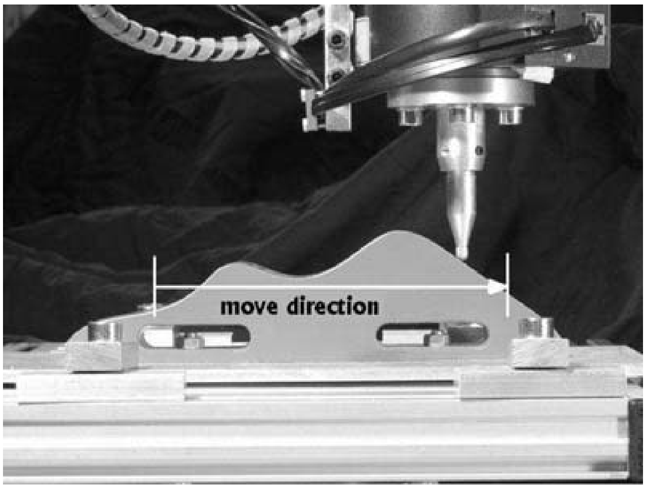

Fig. 15. Attempt to maintain a constant pressure while the effector is moved across a wavy surface.

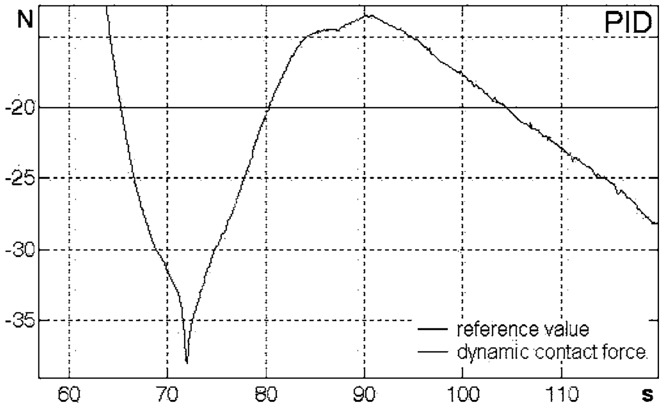

Fig. 16. Results of PID control at 1 mm/s for the experiment illustrated and pictured in Fig. 15.

manipulator is simultaneously displaced in a given direction. Therefore, let us define the constraints given in Table II.

To make the control task more difficult, a wavy surface was chosen across which the movement has been performed in the y-direction (Fig. 15). Despite small contact areas the occurring friction caused higher disturbance amplitudes, which have been higher the smaller the force set point has been.

The results obtained during tests carried out for different reference values and different speeds for the classic PID control loop are depicted in Figs. 16 and 17. The control performance there leaves much to be desired. In addition, a loss of stability takes place here at 5 mm/s (Fig. 17), with the manipulator tip losing its contact with the environment.

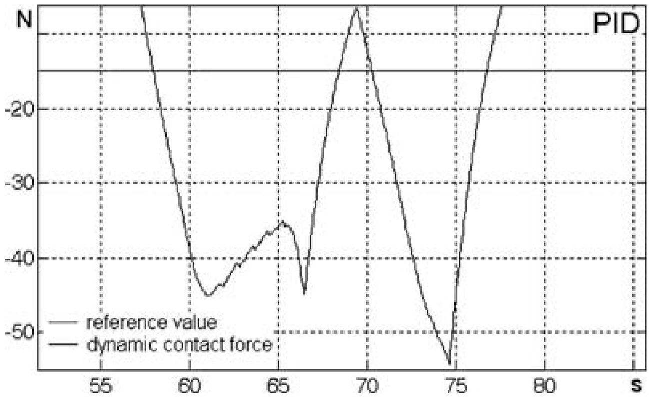

Fig. 17. Results of PID control at 5 mm/s for the experiment illustrated in Fig. 15.

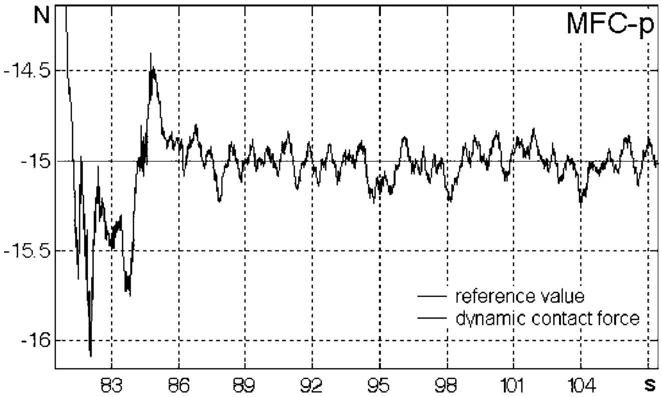

Fig. 18. Results of MFC-p control at 5 mm/s for the experiment illustrated in Fig. 15.

Next, the task illustrated in Fig. 15 has been carried out by employing the MFC-p structure. The task has been made more difficult by choosing a small reference force (15 N). As indicated in Fig. 18, the control performance provided by MFC-p is incomparably better than that offered by the classic single-loop feedback structure. It should be emphasised here that only MFC-p is able to ensure the desired control performance for the control task defined in such a way. The MFC-m structure would be appropriate, if the reference value varies. If it is constant, the control performance offered by MFC-m (depending on R_k settings) is comparable with that of a classic single-loop feedback structure.

In Section 3, the problem of robustness of the structures under consideration has been mentioned. To verify our predictions, an experimental setup has been constructed as shown in Fig. 19.

A PVC-made plate has been supported on two points. By displacing the effector from the middle of the plate towards the point of support, a substantial change in the environment elasticity has been obtained. Tests have been carried out on both the classic single-loop structure and the MFC-p one. The latter yields satisfactory results if the reference value is constant.

The intentionally introduced dependence of environment stiffness on the manipulator displacement makes the process nonstationary. This has resulted in significant plant gain fluctuations, which have had a detrimental effect on the

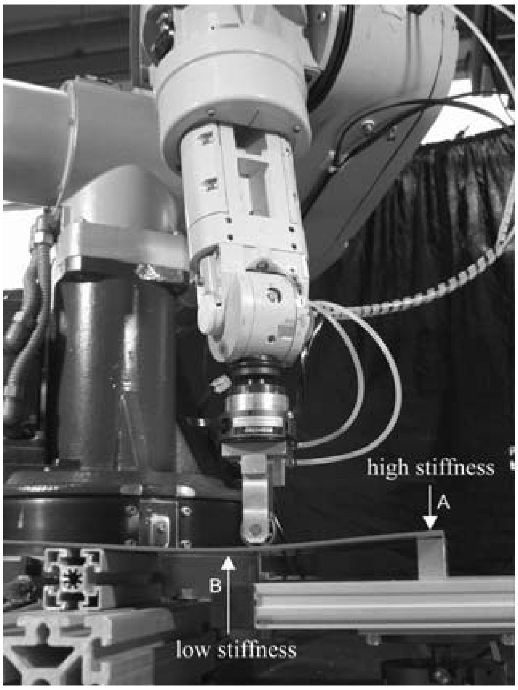

Fig. 19. Experimental setup with a varying environment stiffness (PVC-made plate).

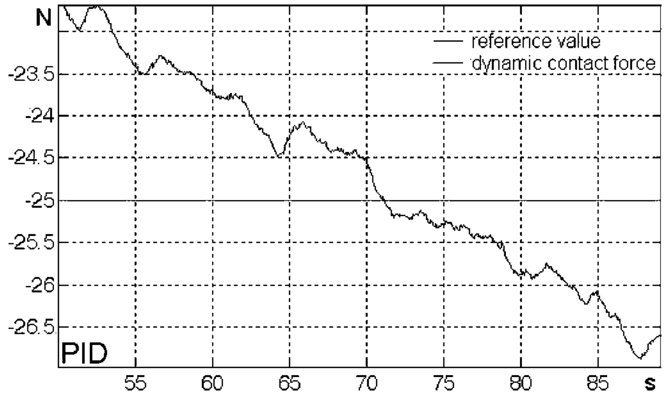

Fig. 20. Results yielded by PID control under varying environment stiffness.

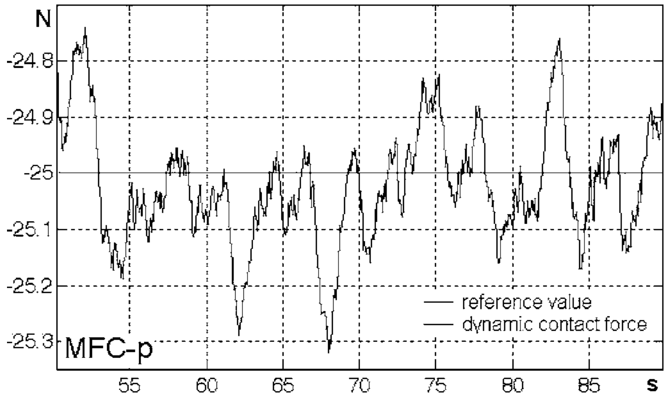

Fig. 21. Results yielded by MFC-p under varying environment stiffness.

control performance. As may be easily inferred from Fig. 20 and Fig. 21, MFC-p provides much better reference tracking than that offered by the single-loop structure.

7. Conclusions

In this paper, two control structures based on the process model applied to hybrid force/position control are presented. The structures studied provide more or less satisfactory control performance in different control tasks, which is always better than that offered by a single-loop PID control. An essential property exhibited by MFC systems is that they are time-invariant. Additionally, the basic component of the manipulated variable is generated in the model loop. This makes the design process much easier to carry out, because, unlike the well-known internal model control (IMC) systems, no compensator has to be found here. A detailed theoretical analysis of MFC-m and MFC-p structures has been given elsewhere.$^{8-12}$ Also, it has been proposed to employ these structures with the advantage to control both, a manipulator and an electrothermal process. The MFC-m structure has been extended in reference [9] to n control loops, the so-called n-MFC. As it has been shown, n-MFC is suitable to cope with strongly nonlinear control plants.

In our paper, the application of conventional PID controllers has also been discussed. This circumstance simplifies the design process; however, it entails some restrictions put on the system robustness. Although the MFC structures feature much greater robustness to variations in process parameters or structures than the single-loop systems, employment of controllers based on fuzzy logic could additionally improve the system robustness.

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