The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Multi-Loop Model Based Parallel Control Systems

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***Abstract*— The paper presents robust control systems based on the Model-Following Control concept. There are analyzed three control structures extended to the general n-loop case. The parallel way in which the proposed structures are built reduces the time the signal is propagated in the loops, which outperforms the well-known serial cascade structure. Additionally, employing forward dynamical models relieves one of having to find the compensator, unlike feedforward or IMC(Internal Model Control)/(2DOF)IMC systems. The robustness of the proposed structures is significantly higher than that offered by the most commonly used control systems, i.e. the single-loop PID control. An example of implementing the n-MFC structure for position control of a directly driven two-joint serial manipulator is also given in the paper.**

I. INTRODUCTION

Direct use of the control process model is a well-known and frequently employed way [1] to counteract the adverse effect produced by process nonlinearity and/or time-variability or output disturbances. One of the many solutions from among the general Model-Based Control (MBC) group is the Model-Following Control (MFC), which appeared in literature in the 1990s [2]. It is a simple 2DOF (Degree-of-Freedom) structure based on a forward plant model, which employing initially two classic PID controllers. Its theoretical analysis and interesting robust properties are described in [3][4]. One of the features displayed by the structure is that the model loop is not affected by disturbances, which not necessarily should be regarded as an advantage. In [5] there was presented the first modification called MFC-p (plant feedback), which consisted in a feedback interchange. This made it possible, amongst others, to actively employ the both controllers to suppress disturbances. The deterioration of MFC-p stability gave rise to the next modification consisted in using a double feedback that resulted in combining advantages offered by MFC and MFC-p without their limitations at the same time. In this way a three-loop MFC-mp (model/plant feedback) system came into being [6]. Although the modifications described in [5][6] presented an interesting alternative to MFC, they did not ameliorate the greatest limitation in using these structures, namely the necessity of simplifying the process model.

Conceptually, the MFC systems are tracking the model output, hence it is essential that the control performance within the model loop be as good as possible. Since the classic PID controller of moderate robustness [7] is a component of MFC, therefore this circumstance forces one to reduce the model complexity. To obviate the need for it, a concept has been presented in [8] to extend MFC to the n-loop case. The idea makes use of gradual complexity of models, for which finding the nonlinear manipulated variables is carried out concurrently. In this paper the remaining two systems MFC-p and MFC-mp are extended to the n-loop case, for which a simple theoretical analysis has been made. Additionally, the n-MFC system has been presented as applied to control the two-joint EDDA (Experimental Direct Drive Arm) manipulator.

This work was supported by Institute for Robotics and Process Control at the Technische Universität Braunschweig, Germany

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II. PROPOSED MULTI-LOOP CONTROL SYSTEMS

Three control systems are depicted in a single Fig. 1 by employing switches s_1 and s_2. So for different combinations of s_1 and s_2 we get: n-MFC-m $(s_1 = 1, s_2 = 0)$, n-MFC-p $(s_1 = 0, s_2 = 1)$ and n-MFC-mp $(s_1 = 1, s_2 = 1)$. The structure is composed of the following blocks: R_i and R_k are the classic PID controllers; C is a compensator needed only for a particular case discussed further;

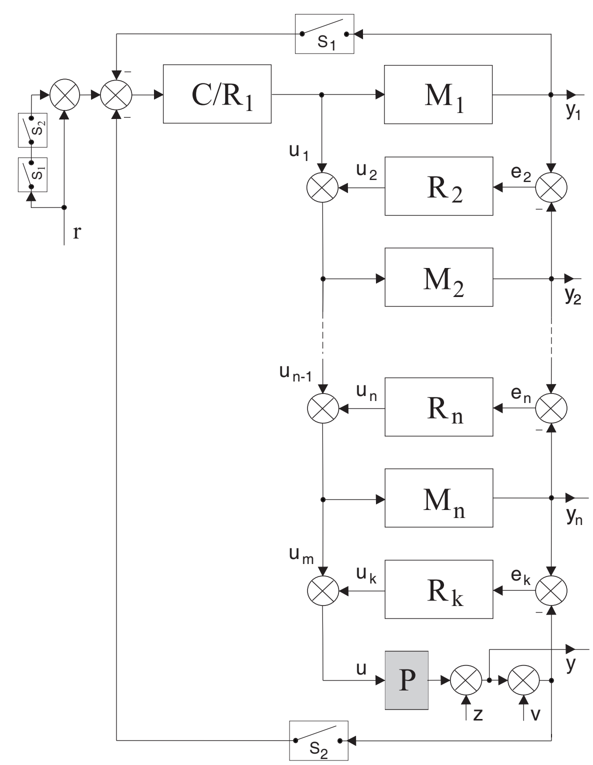

Fig. 1. General block diagram for three control structures: n-MFC-m (model feedback), n-MFC-p (plant feedback) and n-MFC-mp (model/plant feedback).

$$
\begin{aligned}
y_{n-mfc-x} \quad &= \quad \underbrace{\frac{TPR_1M_1(1+R_kM_i)(s_1s_2+1)}{M_i(1+R_kP)+M_iR_1M_1s_1(1+R_kP)+TPR_1M_1s_2(1+R_kM_i)}}_{F_{n-mfc-x}}\,r+ \\
&+ \quad \underbrace{\frac{M_i(1+R_1M_1s_1)}{M_i(1+R_kP)+M_iR_1M_1s_1(1+R_kP)+TPR_1M_1s_2(1+R_kM_i)}}_{S_{n-mfc-x}}\,z- \\
&- \quad \underbrace{\frac{TPR_1M_1s_2(1+R_kM_i)+R_kPM_i(1+R_1M_1s_1)}{M_i(1+R_kP)+M_iR_1M_1s_1(1+R_kP)+TPR_1M_1s_2(1+R_kM_i)}}_{W_{n-mfc-x}}\,v
\end{aligned} \tag{1}
$$

P is the process to be controlled; s_1 and s_2 define the type of the structure; M_i represents the process model of gradual complexity, which may be given in the following general way:

$$
\begin{cases}
M_1 = m_1 \\
M_2 = m_1, m_2 \\
... \\
M_i = m_1, m_2, ..., m_i \\
... \\
M_n = m_1, m_2, ..., m_i, ...m_n
\end{cases} \tag{2}
$$

where: m_i are nonlinear parts of the process model M_n.

No matter what structure is selected its general operation principle is much the same. It consists in finding component nonlinear manipulated variables in individual loops; the components are then added up to give the resultant nonlinear manipulated variable u_m, which after having been corrected by u_k delivered by the R_k controller, is applied directly to the process. Hence, choosing appropriately the model complexity M_i we can utilize the robustness exhibited by the single-loop PID structures, which enable strongly nonlinear processes to be controlled effectively by systems depicted in Fig. 1.

An analysis of three MFC systems shown in Fig. 1 for the simplest configuration $i = 1$ has been carried out in [4]. In this case, a further system arises for the switch combination $(s_1 = 0, s_2 = 0)$, namely the known 2DOF IMC structure, along with three different two-loop MFC systems. Therefore, a compensator C determined most commonly through minimization of a functional [1] is used here, instead of the controller R_1.

To carry out a simple analysis in the frequency domain the proposed systems are described above in terms of their transfer functions with the switches s_1 and s_2 taken into account.

III. Properties of the MFC structures

Properties exhibited by n-MFC systems are compared always with those offered by the classic single-loop PID structure. It is pertinent to ask why the comparison is not made with the 2DOF IMC control. Although the n-MFC systems resemble 2DOF IMC in structure, they have much more in common with the single-loop PID control in respect of synthesis. Additionally, it seems to be interesting to compare the n-MFC structures to that single-loop one most frequently encountered in industry [9].

A. Reference tracking and disturbance suppression

Equation (1) gives the transfer function of the structure Fig. 1, i.e. a universal description of three control systems n-MFC-m, n-MFC-p and n-MFC-mp depending on how the switches s_1 and s_2 are set. Equation (1) comprises three parts: $F_{n-mfc-x}$ - defining tracking the reference r, $S_{n-mfc-x}$ - defining suppression of system disturbances z and $W_{n-mfc-x}$ - defining suppression of output-related disturbances v. For the simplest case described in [4] the transfer function $T_{i=1}$=1 and reduces all three systems to the classic form, i.e. based on a single model M. Should the multi-loop solution be employed, the transfer function T takes the form:

$$
T_{i\geq 2} = \frac{M_i \prod_{i=2}^{n}(1+R_iM_{i-1})}{M_1 \prod_{i=2}^{n}(1+R_iM_i)} \tag{3}
$$

Equation (1) is fairly complicated, and drawing inferences from its form about reference tracking or disturbance suppression is quite difficult. For this reason a simple analysis has been carried out in the frequency domain. Fig. 2, Fig. 3 and Fig. 4 presents frequency responses that illustrate the quality of reference r tracking, and suppression of system/output disturbances in the case of all n-MFC structures and the classic single-loop PID one. For the cases shown in Fig. 2 and Fig. 3 a substantial improvement compared to the single-loop control may be observed. On the other hand, an impaired suppression of output disturbances (Fig. 4) for the proposed systems also deserves mention. The reason is that the controller R_k significantly increases the resultant gain in the process loop, which implies an increase in amplification of output disturbances. This is an obvious drawback of n-MFC, which limits the usefulness of these systems if they are strongly noise affected.

The double negative feedback existing in the n-MFC-mp system has an interesting repercussion for the relation existing between the process output y and the reference r value in steady-state. Furnishing a general proof of this statement

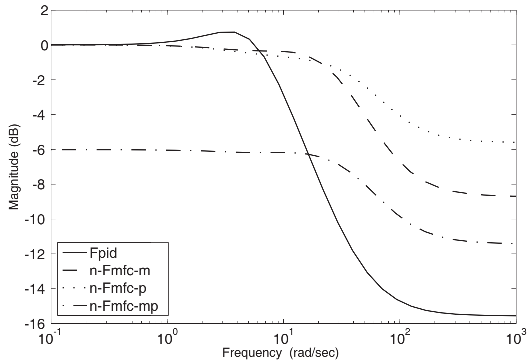

Fig. 2. Reference tracking performance offered by the proposed n-MFC systems and the single-loop PID control.

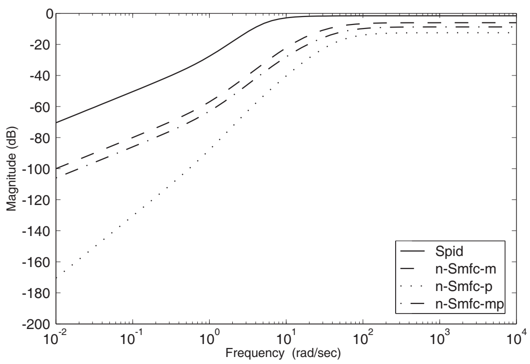

Fig. 3. Suppression performance of system disturbances z offered by the proposed n-MFC systems and the single-loop PID control.

is quite troublesome due to complicated formulas involved. However, the relation between y and r in steady-state may be easily found under certain simplifying assumptions. Let the control system of Fig. 1 $(s_1 = 1, s_2 = 1)$ be stable, and the controllers R_i and R_k contain integration terms, hence: $\lim_{t\to\infty} e_1(t) = \lim_{t\to\infty} e_k(t) = 0$, where: $e_1 = r - y_1 - y$. Assuming the reference r is a unit step, we have for the steady state $y_1 = y = y'$, whence $y' = \frac{r}{2}$. As follows, the output in the steady state is equal to half the reference signal. This circumstance does not present any disadvantage, however it should be taken into account when choosing

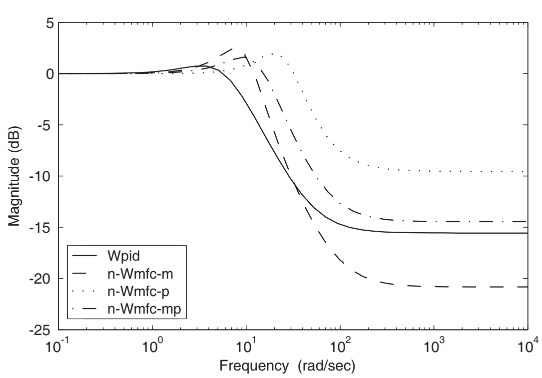

Fig. 4. Suppression performance of output disturbances v offered by the proposed n-MFC systems and the single-loop PID control.

the reference magnitude. The phenomenon was corroborated by simulation experiments, and its results are displayed in Fig. 2. For $F_{n-mfc-mp}$ a suppression of low and medium frequencies at $-6dB$, which corresponds to the half of the reference, may be observed there. These feature has been reflected in Fig. 1. The reference is dependant on the control structure in the following way: $(1 + s_1 s_2)r$.

B. Robustness and Stability

The notion of sensitivity is applicable to situations, where parameter perturbations are of minor nature, i.e. where the system stability is not impaired. As an example the "ageing" of processes [10] may be given here. However, the effect is much more detrimental if changes occur in the process structure caused by plant nonlinearity, time-variability or by conscious or unconscious disregarding of plant dynamics components while designing the control system. Hence, beside the relative sensitivity also the notion of robustness is defined, as the ability to preserve the system stability if some of plant dynamics components are omitted at the stage of controller synthesis.

The plant variability may be modeled in several ways [11] as a multiplicative uncertainty, an additive uncertainty or a product uncertainty. All of them can be related to both the plant input and the plant output. Assuming Δ_p represents parameters change of the actual process P, the multiplicative output-related model of uncertainty, called also the relative error, is defined by: $P = [1 + \Delta_p]\tilde{P}$. To carry out the robustness analysis of the n-MFC systems, use has been made of the condition valid for the classic PID system, owing to the possibility to reduce the multi-loop structures to a single-loop one:

$$|\Delta_p|_{pid} < \left| \frac{1 + R\tilde{P}}{R\tilde{P}} \right| \tag{4}$$

In [4] the allowable process perturbations Δ_p for the single model loop case (i=1) for three structures 1-MFC-m, 1-MFC-p and 1-MFC-mp have been determined:

$$|\Delta_p|_{1-mfc-x} < \left| \underbrace{\underbrace{\underbrace{\frac{(1+R_k\tilde{P})}{R_1\tilde{P}}}_{1-mfc-m}(1+R_1\tilde{P})}_{1-mfc-p}+(1+R_k\tilde{P})}_{1-mfc-mp} \right| \tag{5}$$

The greater the magnitude of the right-hand side of the inequality (4) or (5) is, the higher the robustness of the control system will be. As may be noted, the robustness of the single-loop structure is the higher, the smaller is the magnitude $|R|$ is, (4). This means that the robustness to plant perturbations is achieved at the expense of quality of tracking the reference

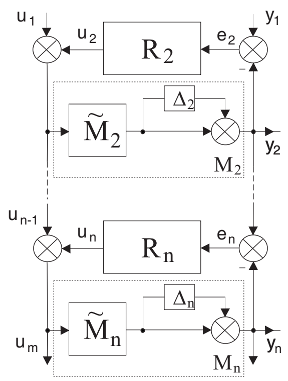

Fig. 5. Block diagram with a multiplicative uncertainty for the purpose of robustness analysis.

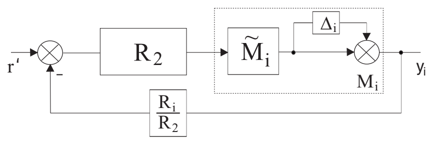

Fig. 6. Reduction of n-loops to the classic PID structure.

signal or of suppression of disturbances. This adverse effect does not occur in n-MFC systems. The numerator of the inequality (5) contains the transfer function of the corrective controller R_k. By increasing the magnitude of $|R_k|$ we also increase the allowable process perturbations, thus improving tracking and suppression properties of the system [3].

It still remains to examine the model loops designed to generate the global nonlinear manipulated variable u_m. This objective has been met by utilizing the robustness of a single feedback loop. Each of the models M_i by assumption is burdened (Fig. 5) by uncertainty Δ_i, which is attributable to the static/dynamic nonlinearity or inaccuracy of modeling.

To utilize the ready to use condition for the PID system (4) for the purpose of robustness analysis, the output of the i-th model y_i has been rearranged to get:

$$y_{i_{|i\geq 2}} = \frac{R_2 M_i}{1+R_i M_i} \underbrace{\frac{\prod_{i=3}^{n}(1+R_i M_{i-1})}{\prod_{i=3}^{n}(1+R_{i-1} M_{i-1})} y_1}_{r'} \tag{6}$$

To determine the robustness condition for the model loops, the structure Fig. 6 may be helpful, which leads eventually, in view of (4), to the sought inequality:

$$|\Delta_i| < \left| \frac{1+R_i \tilde{M}_i}{R_2 \tilde{M}_i} \right| \tag{7}$$

Fig. 7 displays results of stability tests carried out for a process that will be used in the subsequent discussion. The curves obtained give an account of allowable perturbations for the classic PID system and the n-MFC systems under consideration as a function of frequency. Additionally, the robustness of n-MFC systems can be improved by utilizing an appropriate number of model loops, which linearize in a simple way the process that is difficult to control.

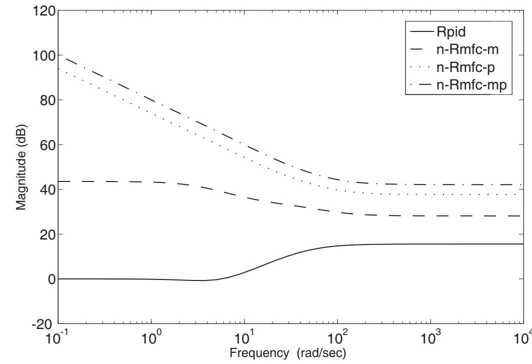

Fig. 7. Robustness to process parameters variations offered by the proposed n-MFC systems and the single-loop PID control.

IV. Experimental verification

To demonstrate implementation of the multi-loop control systems considered above in actual practice, the n-MFC-m structure has been employed $(s_1 = 1, s_2 = 0)$ for position control of the two-joint EDDA (Experimental Direct Drive Arm) manipulator. The EDDA manipulator (Fig. 8) is an open kinematic chain, in which effects produced by dynamic couplings or static moments become highlighted due to the lack of transmission gear [12]. By this means a complex MIMO (Multiple Input Multiple Output) plant has been developed, best suited to test new concepts of robust control. Test results are given for three control structures, namely the classic PID, 1-MFC-m (classic MFC) and 2-MFC-m.

The manipulator represents a control plant strongly non-linear both statically and dynamically [13]. Conceptually, it is also a time-variant system, because the prime task of any manipulation is to transfer objects from point A to point B. Here process parameters vary not only with the operating point, but also are time-dependent.

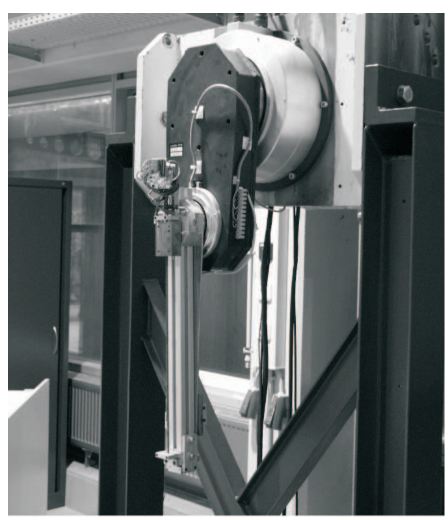

Fig. 8. EDDA (Experimental Direct Drive Arm).

To simplify the mathematical description let us assume that we have to do with a "pure" kinematic chain. Without going into details the forward model of the robot manipulator is defined by the following equation [14]:

$$\ddot{q} = M^{-1}(q)[\tau - C(q,\dot{q}) - B(q,\dot{q}) - G(q) - F(\dot{q})] \quad (8)$$

where: $M(q)$ - manipulator inertia matrix, $C(q,\dot{q})$ - matrix of Coriolis forces, $B(q,\dot{q})$ - matrix of centrifugal forces, $G(q)$ vector of gravitational forces and $F(\dot{q})$ - vector of friction force.

Each of components (8) is nonlinear and taking account of them in the model contributes significantly to the model comprehensiveness. Hence, (8) may be presented in the form of gradual complexity defined in (2) with some of its components being abandoned:

$$\begin{array}{lll} M_1 & -> & \ddot{q} = M^{-1}(q)[\tau] \\ M_2 & -> & \ddot{q} = M^{-1}(q)[\tau - C(q,\dot{q})] \\ M_3 & -> & \ddot{q} = M^{-1}(q)[\tau - C(q,\dot{q}) - B(q,\dot{q})] \\ & ... & \\ M_n & -> & \ddot{q} = M^{-1}(q)[\tau - C(q,\dot{q}) - B(q,\dot{q}) - ...] \end{array} \quad (9)$$

By this means the models $M_1 ... M_n$ may be utilized directly to implement the proposed control systems n-MFC. The classic PID control has been tested first. The tests have been carried out for the second joint of the manipulator only, with the first joint being at a standstill (the simplest case). Even in such a situation the controller parameterization requires a compromise because of static nonlinearities. For the position $\pm\pi i$ $\{where : i = 0, 1, ..., n\}$ no energy supply to the system is required to track the reference in contrast to the position $\pm(\frac{\pi}{2} + \pi i)$, where the greatest amount of energy is needed to compensate the effect produced by the acceleration of gravity g. So, the process can exhibit self-regulation or not for different configurations.

For the classic structure the controller has been parameterized for the position 0 (self-regulation), therefore a significant control error may be noticed in position pi/2 (lack of self-regulation). *Unfortunately, as it turned out, the control stability could not be provided for the entire working area of the joint Fig. 9 (e.g. if the position is changed 0 $->$ $\frac{3}{2}\pi$), which makes the classic PID structure unsuitable to control the chosen process.*

Next, the two-loop 1-MFC-m system has been implemented. Employing the complete manipulator model (8) in the first MFC loop turned out to be impossible. Too complicated nonlinear relationships to be found in the dynamic model precluded one from obtaining a satisfying control performance in the model loop of 1-MFC-m. So, the model (8) has been simplified to the form M_1:

$$\ddot{q} = M^{-1}(q)[\tau - F(\dot{q})] \quad (10)$$

Based on the above model the two-loop 1-MFC-m structure has been implemented for a MIMO system. Fig. 10 and

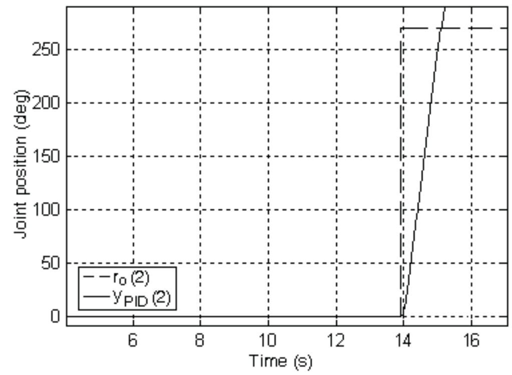

Fig. 9. Loss of stability while changing the operating point (PID control).

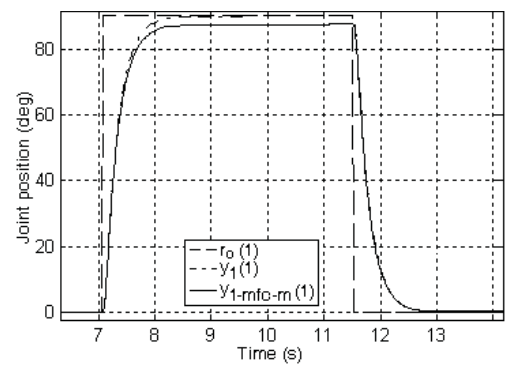

Fig. 10. Results of the position control experiment for the first joint (1-MFC-m control).

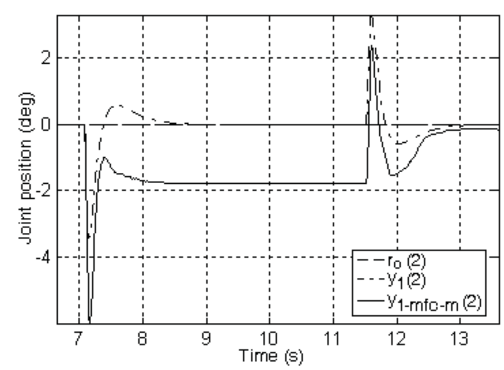

Fig. 11. Results of the position control experiment for the second joint (1-MFC-m control).

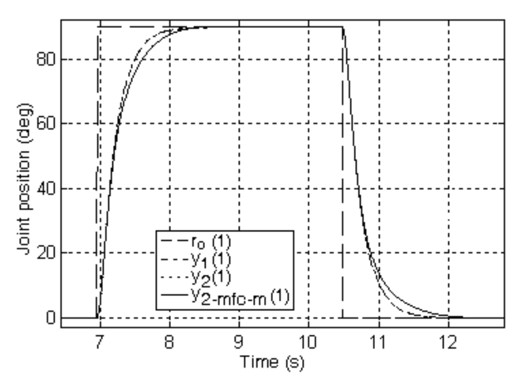

Fig. 12. Results of the position control experiment for the first joint (2-MFC-m control).

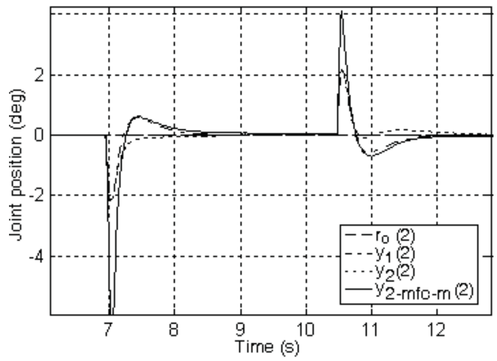

Fig. 13. Results of the position control experiment for the second joint (2-MFC-m control).

Fig. 11 illustrate the obtained control performance for the joint 1 and 2 respectively. Fig. 11 also shows the effect produced by dynamic couplings occurring at the instant the neighboring joint accelerates. Also in this case the obtained control performance leaves much to be desired because of the steady-state error. *However, this control technique makes it possible to keep the system stability if the operating point is changed, i.e. for an arbitrarily chosen set-point.*

The drastically reduced model M_1 disregarding, amongst others, the effect of gravitation, when applied to the 1-MFC-m structure, has presented a too great simplification for the corrective controller R_k to cope with. To utilize the full mathematical model to determine nonlinear manipulated variables, the three-loop 2-MFC-m structure has been used, for which the M_1 model has been of the form (10), and M_2 has presented a full description of the manipulator dynamics (8). By this means two components of the nonlinear manipulated variable have been generated in two model loops, namely u_1 associated with the manipulator inertia and viscous friction and u_2 associated with centrifugal/Coriolis velocities and gravitation.

As may be noticed in Fig. 12 and Fig. 13, the control performance has been considerably improved. On the one hand, the system stability has been provided for the whole working area, and on the other hand the steady-state error has been eliminated. This objective has been met by utilizing the natural robustness exhibited by PID control, which enables one to control effectively complex dynamic processes owing to the proposed structures (Fig. 1) and gradual model representation (2).

V. Conclusions

Three generalized systems of the MFC family, which feature interesting robustness properties have been presented in the paper. Utilizing the forward model in the control structures makes it possible to implement n-MFC for a variety of processes. In addition, the presented systems are characterized by constant parameters, which renders the controller tuning easy to perform.

Although the two-loop 1-MFC-x structure is sufficient for practical applications in the majority of cases (1-MFC-m in temperature control [15], 1-MFC-p in steam boiler control [16], 1-MFC-mp in position/force control [6]) the paper shows the way of increasing the number of model loops in order to improve the control performance. The two-joint experimental manipulator has served as a control plant. It is apparent that using the Newton/Euler or Euler/Lagrange method the inverse manipulator equation can be arrived at, which may be utilized directly for control employing, for example, a feedforward system. Here the model has been reduced to the forward form only to test the properties of the systems under discussion.

VI. Acknowledgments

The paper is a result of collaboration with the Institute for Robotics and Process Control, Technical University of Braunschweig, Germany. The author wishes to express his appreciation to the people of the Institute for providing assistance in a rapid project execution.

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