Fuzzy Self-Tuning PID Semiglobal Regulator for Robot Manipulators

J. L. Meza, V. Santibáñez, *Member, IEEE*, R. Soto, *Member, IEEE*, and M. A. Llama, *Member, IEEE*

***Abstract*—In this paper, we present a semiglobal asymptotic stability analysis via Lyapunov theory for a new proportional-integral-derivative (PID) controller control scheme, proposed in this work, which is based on a fuzzy system for tuning the PID gains for robot manipulators. PID controller is a well-known set point control strategy for industrial manipulators which ensures semiglobal asymptotic stability for fixed symmetric positive definite (proportional, integral, and derivative) gain matrices. We show that semiglobal asymptotic stability attribute also holds for a class of gain matrices depending on the manipulator states. This feature increases the potential of the PID control scheme to improve the performance of the transient response and handle practical constraints in actual robots such as presence of actuators with limited torque capabilities. We illustrate this potential by means of a fuzzy self-tuning algorithm to select the proportional, integral, and derivative gains according to the actual state of a robotic manipulator. To the best of the authors' knowledge, our proposal of a fuzzy self-tuning PID regulator for robot manipulators is the first one with a semiglobal asymptotic stability proof. Real-time experimental results on a two-degree-of-freedom robot arm show the usefulness of the proposed approach.**

***Index Terms*—Fuzzy proportional-integral-derivative (PID), Lyapunov stability, PID control, robot control, self-tuning.**

I. Introduction

THE classical proportional-integral-derivative (PID) regulator is still widely used in industrial applications due to its design simplicity and its excellent performance, particularly in applications in which the process parameters are not well known [1]–[9]. Specifically, most of the robots employed in industrial operations are controlled by PID algorithms; in spite of this fact, there is a relative lack of theoretical results. It has been pointed out that the stability results presented in the literature are far from being conclusive [10]–[13], [15]. Moreover, it is known that, under linear PID control, the asymptotic stability is valid only in a local sense [16] or, in the best of the cases, in a semiglobal sense [14], [15], [17]. It is worth noting that the stability analysis of the closed-loop system driven by the classical PID control is usually carried out by considering a constant selection of the controller gains. This characteristic may limit the application of this controller in cases where, in addition to asymptotic stability, it is required to maintain a good performance for the control system. In order to get high performance or deal with real constraints of actual manipulators, such as actuator capabilities, it may be necessary to have variable gains for these controllers [18]. Several practical techniques have been suggested to choose adequate values for the controller gains which depend on the robot configuration, such as gain scheduling, fuzzy control, and neural network approach [19]–[24]. Our approach is inspired by a previous work presented in [18] and [25]. The structure of the fuzzy controller used in [18] is based on fuzzy tuning proportional-derivative algorithms with gravity compensation to select the proportional and derivative gains according to the actual position errors. Our first contribution is the proposal of a new PID control with variable gains. In this paper, we use the potential of fuzzy self-tuning schemes in order to design a methodology for online selection of the proportional, derivative, and integral gains for the PID controller, which improves the previous work in [18] in the fact of not using the knowledge of the gravity vector. In addition to the guarantee of Lyapunov asymptotic stability for the closed-loop system, this approach also ensures practical performances beyond the standard nonfuzzy scheme. Specifically, the proposed control scheme solves the regulation problem of robot manipulators constrained to deliver torques inside prescribed limits according to the actuator capabilities and improves the performance of the transient response. In order to illustrate the performance of this control scheme, we present experimental results on a vertical two-degree-of-freedom direct-drive robot. Also, this paper shows that the proposed tuning method yields a semiglobal asymptotically stable closed-loop system, not only for constant positive definite gain matrices but also for a class of manipulator-state-dependent gain matrices. This theoretical result is the second contribution of this paper which has useful implications to handle real constraint of robot manipulators, such as torque capability limitations of their actuators, and to improve the performance of the closed-loop system. To the best of the authors' knowledge, for the fuzzy self-tuning PID regulator problem of robot manipulators, this is the first paper with a semiglobal asymptotic stability proof. The third contribution of this paper is the real-time experimental validation of this theoretical result on a two-degree-of-freedom robot arm. The experimental results show the usefulness of the proposed approach. This paper extends our earlier work [26] with more details on the stability analysis,

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giving a more comprehensive description on the stability proof and extending the analysis from local to semiglobal stability. Furthermore, experimental results are complemented with the variable gain graphics showing their temporal evolutions. In order to make easier the comprehension of the theoretical analysis, it is necessary to keep some basic concepts of [26] in this paper.

Throughout this paper, we use the notation $\lambda_m\{A(\boldsymbol{x})\}$ and $\lambda_M\{A(\boldsymbol{x})\}$ to indicate the smallest and largest eigenvalues, respectively, of a symmetric positive definite bounded matrix $A(\boldsymbol{x})$, for any $\boldsymbol{x} \in \mathbb{R}^n$. By an abuse of notation, we define $\lambda_m\{A\}$ as the greatest lower bound (infimum) of $\lambda_m\{A(\boldsymbol{x})\}$, for all $\boldsymbol{x} \in \mathbb{R}^n$, that is, $\lambda_m\{A\} := \inf_{\boldsymbol{x}\in\mathbb{R}^n} \lambda_m\{A(\boldsymbol{x})\}$. Similarly, we define $\lambda_M\{A\}$ as the least upper bound (supremum) of $\lambda_M\{A(\boldsymbol{x})\}$, for all $\boldsymbol{x} \in \mathbb{R}^n$, that is, $\lambda_M\{A\} := \sup_{\boldsymbol{x}\in\mathbb{R}^n} \lambda_M\{A(\boldsymbol{x})\}$. The norm of vector $\boldsymbol{x}$ is defined as $\|\boldsymbol{x}\| = \sqrt{\boldsymbol{x}^T\boldsymbol{x}}$ and that of matrix $A(\boldsymbol{x})$ is defined as the corresponding induced norm $\|A(\boldsymbol{x})\| = \sqrt{\lambda_M\{A(\boldsymbol{x})^T A(\boldsymbol{x})\}}$. The vectors are denoted by bold small letters.

II. Robot Dynamics

Consider the general equation describing the dynamics of an n-degree-of-freedom rigid robot manipulator [27]

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{q}$ is the $n \times 1$ vector of joint displacements, $\dot{\boldsymbol{q}}$ is the $n \times 1$ vector of joint velocities, $\boldsymbol{\tau}$ is the $n \times 1$ vector of applied torques, $M(\boldsymbol{q})$ is the $n \times n$ symmetric positive definite manipulator inertia matrix, whose entries are $M_{ij}(\boldsymbol{q})$ with $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, n$, $C(\boldsymbol{q},\dot{\boldsymbol{q}})$ is the $n \times n$ matrix of centripetal and Coriolis torques, and $\boldsymbol{g}(\boldsymbol{q})$ is the $n \times 1$ vector of gravitational torques obtained as the gradient of the robot potential energy $\mathcal{U}(\boldsymbol{q})$, i.e.

$$\boldsymbol{g}(\boldsymbol{q}) = \frac{\partial\mathcal{U}(\boldsymbol{q})}{\partial\boldsymbol{q}}. \tag{2}$$

We assume that all the links are joined together by revolute joints. Three important properties of dynamics (1) are the following.

Property 1 [28]: The matrix $C(\boldsymbol{q},\dot{\boldsymbol{q}})$ and the time derivative $\dot{M}(\boldsymbol{q})$ of the inertia matrix satisfy

$$\dot{\boldsymbol{q}}^T\left[\frac{1}{2}\dot{M}(\boldsymbol{q}) - C(\boldsymbol{q},\dot{\boldsymbol{q}})\right]\dot{\boldsymbol{q}} = \boldsymbol{0} \qquad \forall\boldsymbol{q},\dot{\boldsymbol{q}} \in \mathbb{R}^n$$

$$\dot{M}(\boldsymbol{q}) = C(\boldsymbol{q},\dot{\boldsymbol{q}}) + C(\boldsymbol{q},\dot{\boldsymbol{q}})^T.$$

Property 2 [29]: There exists a positive constant k_g such that

$$k_g \geq \left\|\frac{\partial\boldsymbol{g}(\boldsymbol{q})}{\partial\boldsymbol{q}}\right\| \qquad \forall\boldsymbol{q} \in \mathbb{R}^n.$$

This implies that $\max_q |\partial g_i(q)/\partial q_j|$ is bounded for all $i = 1, \ldots, n$ and $j = 1, \ldots, n$.

Property 3 [29]: There exists a positive constant k_c such that, for all $\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z} \in \mathbb{R}^n$, we have

$$\|C(\boldsymbol{x},\boldsymbol{y})\boldsymbol{z}\| \leq k_c\|\boldsymbol{y}\|\|\boldsymbol{z}\|.$$

If the matrices of the dynamics are known, then the constants k_g and k_c can be obtained using the following expressions [31]:

$$k_g = n\left(\max_{i,j,q}\left|\frac{\partial g_i(\boldsymbol{q})}{\partial q_j}\right|\right) \qquad k_c = n^2\left(\max_{i,j,k,q}\left|C_{k_{ij}}(\boldsymbol{q})\right|\right)$$

where $C_{k_{ij}}(\boldsymbol{q})$ is a matrix whose element $\{i,j\}$ is the c_{ijk} Christoffel symbol of $C(\boldsymbol{q},\dot{\boldsymbol{q}})$ [31].

Finally, we present a useful Lemma.

Lemma 1 [25], [30]: Let a gain matrix $K_x(\boldsymbol{x}) : \mathbb{R}^n \rightarrow \mathbb{R}^{n\times n}$ have the following structure:

$$K_x(\boldsymbol{x}) = \begin{bmatrix} k_{x_1}(x_1) & 0 & \cdots & 0 \\ 0 & k_{x_2}(x_2) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & k_{x_n}(x_n) \end{bmatrix}. \tag{3}$$

Assume that there exist constants k_{l_i} and k_{u_i} where $k_{u_i} > k_{l_i} > 0$ such that $k_{u_i} \geq k_{x_i}(x_i) \geq k_{l_i}$ for all $x_i \in \mathbb{R}$ and $i = 1, \ldots, n$; then

$$\frac{1}{2}k_{u_i}|x_i|^2 \geq \int_0^{x_i} \xi_i k_{x_i}(\xi_i)d\xi_i \geq \frac{1}{2}k_{l_i}|x_i|^2 \tag{4}$$

$$\int_0^{x_i} \xi_i k_{x_i}(\xi_i)d\xi_i \rightarrow \infty \quad \text{as} \quad |x_i| \rightarrow \infty \tag{5}$$

which yields

$$\frac{1}{2}k_u\|\boldsymbol{x}\|^2 \geq \int_{\boldsymbol{0}}^{\boldsymbol{x}} \boldsymbol{\xi}^T K_x(\boldsymbol{\xi})d\boldsymbol{\xi} \geq \frac{1}{2}k_l\|\boldsymbol{x}\|^2 \tag{6}$$

with $k_u = \max_i\{k_{u_i}\}$ and $k_l = \min_i\{k_{l_i}\}$, and

$$\int_{\boldsymbol{0}}^{\boldsymbol{x}} \boldsymbol{\xi}^T K_x(\boldsymbol{\xi})d\boldsymbol{\xi} \rightarrow \infty \quad \text{as} \quad \|\boldsymbol{x}\| \rightarrow \infty \tag{7}$$

where, by convenience, we have introduced the following notation:

$$\int_{\boldsymbol{0}}^{\boldsymbol{x}} \boldsymbol{\xi}^T K_p(\boldsymbol{\xi})d\boldsymbol{\xi} = \sum_{i=1}^{n}\int_0^{x_i} \xi_i k_{p_i}(\xi_i)d\xi_i.$$

III. Proposed PID Control With Nonlinear Gains

The PID controller is a well-known set point control strategy for manipulators which ensures asymptotic stability for fixed symmetric positive definite gain matrices. In order to improve the performance of the closed-loop system, a possible solution could be to use variable gains [30].

We introduce a new PID controller with variable gains whose main feature is that stability holds even though the gains depend on the robot states. A generalization of the classical linear PID controller can be obtained by allowing to have nonlinear proportional $K_p(\tilde{\boldsymbol{q}})$, integral $K_i(\boldsymbol{\omega})$, and derivative $K_v(\tilde{\boldsymbol{q}})$ gain matrices as functions of the robot configuration. This leads to the following proposed control law:

$$\boldsymbol{\tau} = K_p(\tilde{\boldsymbol{q}})\tilde{\boldsymbol{q}} - K_v(\tilde{\boldsymbol{q}})\dot{\boldsymbol{q}} + K_i(\boldsymbol{\omega})\int_0^t \tilde{\boldsymbol{q}}(\sigma)d\sigma \tag{8}$$

where $K_p(\tilde{\boldsymbol{q}})$, $K_v(\tilde{\boldsymbol{q}})$, and $K_i(\boldsymbol{\omega})$ are positive definite diagonal $n \times n$ matrices, whose entries are denoted by $k_{p_i}(\tilde{q}_i)$, $k_{v_i}(\tilde{q}_i)$, and $k_{i_i}(\omega_i)$, respectively, $\tilde{\boldsymbol{q}} = \boldsymbol{q}_d - \boldsymbol{q}$ denotes the position error vector, and $\dot{\boldsymbol{\omega}} = \alpha\tilde{\boldsymbol{q}} - \dot{\boldsymbol{q}}$, with $\alpha > 0$.

For stability analysis purposes, the control law (8) can be rewritten as [31], [33]

$$\boldsymbol{\tau} = K_p'(\tilde{\boldsymbol{q}})\tilde{\boldsymbol{q}} - K_v(\tilde{\boldsymbol{q}})\dot{\boldsymbol{q}} + K_i'(\boldsymbol{\omega})\int_0^t \left(\alpha\tilde{\boldsymbol{q}}(\sigma) + \dot{\tilde{\boldsymbol{q}}}(\sigma)\right) d\sigma \tag{9}$$

where $K_p'(\tilde{\boldsymbol{q}}) = K_p(\tilde{\boldsymbol{q}}) - (K_i(\boldsymbol{\omega})/\alpha)$ and $K_i'(\boldsymbol{\omega}) = (K_i(\boldsymbol{\omega})/\alpha)$, with $\alpha > (\lambda_M\{K_i\}/\lambda_m\{K_p\})$.

This latter condition ensures that $K_p'(\tilde{\boldsymbol{q}}) > 0$. The α constant is introduced in order to make easier the stability analysis, and this will be used as a parameter of the Lyapunov function.

Assumption 1: There exist positive constants $k_{pl_i}, k_{pu_i}, k_{vl_i}, k_{vu_i}, k_{il_i}$, and k_{iu_i} such that Lemma 1 can be applied. That is

$$\frac{1}{2}\tilde{\boldsymbol{q}}^T K_{pu}'\tilde{\boldsymbol{q}} \geq \int_0^{\tilde{\boldsymbol{q}}} \boldsymbol{\xi} K_p'(\boldsymbol{\xi})d\boldsymbol{\xi} \geq \frac{1}{2}\tilde{\boldsymbol{q}}^T K_{pl}'\tilde{\boldsymbol{q}} \tag{10}$$

$$\frac{1}{2}\tilde{\boldsymbol{q}}^T K_{vu}\tilde{\boldsymbol{q}} \geq \int_0^{\tilde{\boldsymbol{q}}} \boldsymbol{\xi} K_v(\boldsymbol{\xi})d\boldsymbol{\xi} \geq \frac{1}{2}\tilde{\boldsymbol{q}}^T K_{vl}\tilde{\boldsymbol{q}} \tag{11}$$

$$\frac{1}{2}\boldsymbol{\omega}^T K_{iu}'\boldsymbol{\omega} \geq \int_0^{\boldsymbol{\omega}} \boldsymbol{\xi} K_i'(\boldsymbol{\xi})d\boldsymbol{\xi} \geq \frac{1}{2}\boldsymbol{\omega}^T K_{il}'\boldsymbol{\omega} \tag{12}$$

where K_{pu}', K_{pl}', K_{vu}, K_{vl}, K_{iu}', and K_{il}' are $n \times n$ constant positive definite diagonal matrices whose entries are $k_{pu_i}', k_{pl_i}', k_{vu_i}, k_{vl_i}, k_{iu_i}'$, and k_{il_i}', respectively, with $i = 1, 2, \ldots, n$.

Assumption 2: In an ϵ-neighborhood $N(\boldsymbol{\omega}, \epsilon) = \{\boldsymbol{\omega} \in \mathbb{R}^n : \|\boldsymbol{\omega}\| < \epsilon\}$ of $\boldsymbol{\omega} = 0$, the integral gain matrix is constant, that is, $K_i'(\boldsymbol{\omega}) = K_{il}'$, where $K_{il}' \in \mathbb{R}^{n\times n}$ is a diagonal positive definite constant matrix.

Remark 1: The practical usefulness of this control strategy (8) will become clear later when a fuzzy self-tuning algorithm will be introduced. Assumptions 1 and 2 are naturally fulfilled in fuzzy self-tuning approaches; hence, they are not restrictive.

The closed-loop system is obtained substituting the control law (9) into the robot dynamics (1). This can be written as

$$\frac{d}{dt}\begin{bmatrix} \tilde{\boldsymbol{q}} \\ \dot{\boldsymbol{q}} \\ \boldsymbol{\omega} \end{bmatrix} = \begin{bmatrix} -\dot{\boldsymbol{q}} \\ M^{-1}\left[K_p'(\tilde{\boldsymbol{q}})\tilde{\boldsymbol{q}} - K_v(\tilde{\boldsymbol{q}})\dot{\boldsymbol{q}} - C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) \right. \\ \left. + K_i'(\boldsymbol{\omega})\boldsymbol{\omega} + \boldsymbol{g}(\boldsymbol{q}_d)\right] \\ \alpha\tilde{\boldsymbol{q}} - \dot{\boldsymbol{q}} \end{bmatrix} \tag{13}$$

where $\boldsymbol{\omega}$ is defined as

$$\boldsymbol{\omega}(t) = \int_0^t \left[\alpha\tilde{\boldsymbol{q}}(\sigma) + \dot{\tilde{\boldsymbol{q}}}(\sigma)\right] d\sigma - K_{il}'^{-1}\boldsymbol{g}(\boldsymbol{q}_d)$$

and we have used the Assumption 2 in such a way that (13) becomes an autonomous nonlinear differential equation whose origin

$$[\tilde{\boldsymbol{q}}^T \quad \dot{\boldsymbol{q}}^T \quad \boldsymbol{\omega}^T]^T = \boldsymbol{0} \in \mathbb{R}^{3n} \tag{14}$$

is the unique equilibrium point.

IV. Semiglobal Asymptotic Stability Analysis

In this section, we show that the stability also holds for a class of nonconstant state-depending proportional, integral, and derivative gain matrices; specifically, we consider the control law (9) corresponding to a PID control scheme with nonlinear gain matrices. The stability analysis is based on a preliminary version described in [26]. The semiglobal stability is established in the sense that the region of attraction can be arbitrarily enlarged with an adequate selection of the controller gains.

A. Lyapunov Function Candidate

In order to study stability of equilibrium point (14), we propose the following Lyapunov function candidate:

$$\begin{aligned} V(\tilde{\boldsymbol{q}}, \dot{\boldsymbol{q}}, \boldsymbol{\omega}) = &\int_{\boldsymbol{0}}^{\tilde{\boldsymbol{q}}} \boldsymbol{\xi}^T K_p'(\boldsymbol{\xi})d\boldsymbol{\xi} - \mathcal{U}(\boldsymbol{q}_d) + \mathcal{U}(\boldsymbol{q}) + \boldsymbol{g}(\boldsymbol{q}_d)^T\tilde{\boldsymbol{q}} \\ &+ \frac{1}{2}\dot{\boldsymbol{q}}^T M(\boldsymbol{q})\dot{\boldsymbol{q}} - \alpha\tilde{\boldsymbol{q}}^T M(\boldsymbol{q})\dot{\boldsymbol{q}} \\ &+ \alpha\int_{\boldsymbol{0}}^{\tilde{\boldsymbol{q}}} \boldsymbol{\xi}^T K_v(\boldsymbol{\xi})d\boldsymbol{\xi} + \int_{\boldsymbol{0}}^{\omega} \boldsymbol{\xi}^T K_i'(\boldsymbol{\xi})d\boldsymbol{\xi} \end{aligned} \tag{15}$$

which is different to that presented in [17] and [34], in the fact that the gain matrices are dependent on the states $\tilde{\boldsymbol{q}}$ and $\boldsymbol{\omega}$. By using Assumption 1 and following similar steps given in [34], we can conclude that (15) is a globally positive definite and radially unbounded function under the condition

$$k_{pl_i} > \sum_{j=1}^{n} \max_q \left|\frac{\partial g_i(q)}{\partial q_j}\right| \tag{16}$$

and α is chosen in such a way that it satisfies

$$\frac{k_{vl_i}}{\sum_{j=1}^{n}\max_q |M_{ij}(q)|} > \alpha > \frac{k_{il_i}}{k_{pl_i} - \sum_{j=1}^{n}\max_q |\partial g_i(q)/\partial q_j|}. \tag{17}$$

B. Time Derivative of the Lyapunov Function Candidate

The time derivative of the Lyapunov function candidate (15) along the trajectories of the closed-loop equation (13) is

$$\begin{aligned} \dot{V}(\tilde{\boldsymbol{q}}, \dot{\boldsymbol{q}}, \boldsymbol{\omega}) = &-\dot{\boldsymbol{q}}^T\left[K_v(\tilde{\boldsymbol{q}}) - \alpha M(\boldsymbol{q})\right]\dot{\boldsymbol{q}} - \alpha\tilde{\boldsymbol{q}}^T C(\boldsymbol{q},\dot{\boldsymbol{q}})^T\dot{\boldsymbol{q}} \\ &- \alpha\tilde{\boldsymbol{q}}^T\left[K_p(\tilde{\boldsymbol{q}}) - K_i(\boldsymbol{\omega})/\alpha\right]\tilde{\boldsymbol{q}} - \alpha\tilde{\boldsymbol{q}}^T\left[\boldsymbol{g}(\boldsymbol{q}_d) - \boldsymbol{g}(\boldsymbol{q})\right] \end{aligned}$$

where we have used the Leibnitz' rule for differentiation of integrals and Property 1. Again, following similar steps given in [34], we can assure that $\dot{V}(\tilde{\boldsymbol{q}}, \dot{\boldsymbol{q}}, \boldsymbol{\omega})$ is negative semidefinite in the domain D defined as an open ball whose radius is η

$$D = \left\{ \boldsymbol{x} := [\tilde{\boldsymbol{q}}^T \ \dot{\boldsymbol{q}}^T \ \boldsymbol{\omega}^T]^T \in \mathbb{R}^{3n} : \|\boldsymbol{x}\| < \eta \right\}$$

provided that (16)

$$\frac{k_{vl_i}}{\sum_{j=1}^{n} \max_q |M_{ij}(q)|} > \alpha, \qquad i = 1, \ldots, n \tag{18}$$

$$\frac{\lambda_m\{K_v\}}{k_c \eta} > \alpha > \frac{k_{il_i}}{k_{pl_i} - \sum_{j=1}^{n} \max_q |\partial g_i(q)/\partial q_j|} \tag{19}$$

are satisfied. By using the LaSalle invariance principle [32], we can ensure asymptotic stability of the origin of the closed-loop system (13) provided that (16)–(19) are satisfied.

C. Semiglobal Asymptotic Stability

To establish semiglobal asymptotic stability, we must prove that, with a suitable choice of the controller gains, we can arbitrarily enlarge the domain of attraction. In [34], it was proven that, respecting always the conditions demanded by (17)–(19) over α, the estimate of the domain of attraction

$$\Omega_{c'} = \left\{ \boldsymbol{x} \in \mathbb{R}^{3n} : \|\boldsymbol{x}\| \le r = \sqrt{\frac{\alpha_1}{\alpha_2}} \eta \right\} \tag{20}$$

can be enlarged, where α_1 and α_2 are given by

$$\alpha_1 = \min \left\{ \frac{1}{2} \lambda_m \left\{ M(\boldsymbol{q}) \right\} \lambda_m\{Q\}, \frac{1}{2} \lambda_m \left\{ M(\boldsymbol{q}) \right\} \lambda_m\{Q\}, \frac{1}{2} \lambda_m\{K_i/\alpha\} \right\} \tag{21}$$

with

$$Q = \begin{bmatrix} 1 & -\alpha \\ -\alpha & \alpha^2 + \frac{\alpha\gamma_2 + \gamma_1}{\lambda_m\{M(\boldsymbol{q})\}} \end{bmatrix}$$

$$\gamma_1 = \min_i \left\{ K_{p_i} - \left(\frac{1}{\alpha} K_{i_i} + \sum_{j=1}^{n} \max_q \left| \frac{\partial g_i(q)}{\partial q_j} \right| \right) \right\} - \varepsilon > 0$$

$$\gamma_2 = \min_i \left\{ K_{v_i} - \alpha \sum_{j=1}^{n} \max_q |M_{ij}(\boldsymbol{q})| \right\} - \varepsilon > 0$$

$$\alpha_2 = \max \left\{ \frac{1}{2}\gamma_3 + \frac{\alpha}{2} \lambda_M\{K_v\} + \frac{1}{2}, \frac{1}{2} \lambda_M \left\{ M(\boldsymbol{q}) \right\} + \frac{\alpha^2}{2} \lambda_M^2 \left\{ M(\boldsymbol{q}) \right\}, \frac{1}{2} \lambda_M\{K_i/\alpha\} \right\}$$

$$\gamma_3 = \max_i \left\{ K_{p_i} - \left(\frac{1}{\alpha} K_{i_i} - \sum_{j=1}^{n} \max_q \left| \frac{\partial g_i(q)}{\partial q_j} \right| \right) \right\} + \varepsilon > 0 \tag{22}$$

for small $\varepsilon > 0$.

Thus far, we have proved the following.

Proposition 1: Consider the robot dynamical model (1) together with the control law (8). Let the gain matrices $K_p(\tilde{\boldsymbol{q}})$, $K_v(\tilde{\boldsymbol{q}})$, and $K_i(\boldsymbol{\omega})$ have the structure given in (3). Under conditions (16)–(19), there always exist appropriate proportional $K_p(\tilde{\boldsymbol{q}})$, derivative $K_v(\tilde{\boldsymbol{q}})$, and integral $K_i(\boldsymbol{\omega})$ gain matrices, such that the equilibrium $[\tilde{\boldsymbol{q}}^T \ \dot{\boldsymbol{q}}^T \ \boldsymbol{\omega}^T]^T = \boldsymbol{0} \in \mathbb{R}^{3n}$ of the closed-loop system (13) is semiglobal asymptotically stable, in the sense that the estimate of the domain of attraction given by

$$\Omega_{c'} = \left\{ \boldsymbol{x} \in \mathbb{R}^{3n} : \|\boldsymbol{x}\| \le \sqrt{\frac{\alpha_1}{\alpha_2}} \eta \right\}$$

with α_1, α_2, and $\eta > 0$, given by (21), (22), and (19), can be arbitrarily enlarged with an appropriate selection of the controller gains. A Lyapunov function to prove this is given by (15).

Remark 2: The main difference of this new proposed PID controller with respect to that PID, analyzed in [34], is the fact of using variable gains depending on the states $\tilde{\boldsymbol{q}}$ and $\boldsymbol{\omega}$. This nice feature allows us to take advantage of fuzzy logic techniques to self-tune the gains in order to obtain better performance in the transient response of robots controlled by PID schemes. Previous works using the technique of variable gains, [18] and [25] in control of robot manipulators, need the knowledge of the robot dynamics model and its parameters. In contrast, in our new proposal, we employ a PID structure with variable gains self-tuned by fuzzy techniques; such a structure does not use explicitly the robot dynamics model.

V. Fuzzy Approach for Self-Tuning the PID Controller Gains

Freedom to select the proportional, integral, and derivative gain matrices in a nonlinear manner for the PID control scheme may be of worth in real applications where manipulators are under effects of disturbances and constraints. Fuzzy logic is a suitable approach as a mechanism to determine the nonlinear gains of the PID control scheme according to previous practical specifications. This is because the input–output characteristics of fuzzy logic systems could be easily suited in order to fulfill the stability requirements established in Proposition 1.

In order to tune the proportional gains $k_{p_i}(\tilde{q}_i)$, the integral gain $k_{i_i}(\omega_i)$, and the derivative gains $k_{v_i}(\tilde{q}_i)$ according to the states $|\tilde{q}_i|$ and $|\omega_i|$, in this paper, we define one conceptual fuzzy logic tuner (FLT). In summary, $3n$ elementary FLT will be involved in the computation of n proportional gains $k_{p_i}(\tilde{q}_i)$, n integral gains $k_{i_i}(\omega_i)$, and n derivative gains $k_{v_i}(\tilde{q}_i)$.

A. Basic FLT

Having in mind the real-time implementation of the fuzzy self-tuning algorithm, a quite simple approach to design the FLT has been adopted [25]. Let the conceptual FLT have one input x and its corresponding output y. The FLT can be seen as a static mapping H defined by

$$H : \mathbb{R}_+ \to \mathbb{R}$$

$$x \mapsto y$$

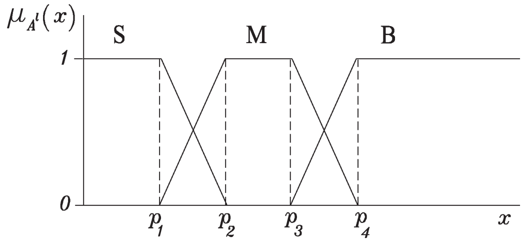

Fig. 1. Input membership functions.

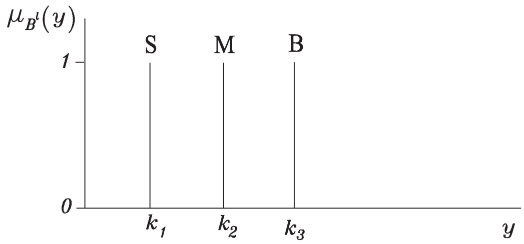

Fig. 2. Output membership functions.

where, in our case, the input x will be the state $|\tilde{q}_i|$ or $|\omega_i|$ and the output y will be the gain k_{p_i}, or k_{v_i}, or k_{i_i}.

B. Rule Base and Inference Engine

A fuzzy rule base for the case of each $3n$ Mamdani-type elementary FLT with one input x and one output y is given by the general canonical IF-THEN rule form [35]

$$\text{IF } x \text{ } is \text{ } A^l \text{ THEN } y \text{ } is \text{ } B^l \tag{23}$$

where A^l and B^l are fuzzy sets and $l = 1, \ldots, m$ is the number of rules. We define three positive trapezoidal fuzzy sets, namely, big (B), medium (M), and small (S), to cover the input variable, whose membership functions are shown in Fig. 1, and three positive singleton fuzzy sets, namely, big (B), medium (M), and small (S) to cover the output variable, whose membership functions are shown in Fig. 2; hence, the number of rules m is three.

The designed fuzzy rule base is given as follows:

$$\texttt{IF } x \text{ is } S \texttt{ THEN } y \text{ is } B$$

$$\texttt{IF } x \text{ is } M \texttt{ THEN } y \text{ is } M$$

$$\texttt{IF } x \text{ is } B \texttt{ THEN } y \text{ is } S$$

where x is either $|\tilde{q}_i|$ or $|\omega_i|$ and y is either k_{p_i} or k_{v_i} or k_{i_i}, $i = 1, \ldots, n$.

The first rule specifies that, for a small position error, we should apply a big k_p in order to reduce still more this error. The second one specifies that, for a medium position error, we must apply a medium k_p, and the last rule specifies that, for a big position error, we need to apply a small k_p in order to avoid torque saturation. With regard to derivative gain k_v, a similar criterion is used taking into account that, for big position errors, it is suitable to have small damping, to avoid an oscillatory response. For the case of integral gains, a similar criterion is used taking into account that, for big $|\omega_i|$, it is suitable to have small k_i to avoid undesirable oscillations. Table I summarizes the fuzzy rules applied to each proportional, derivative, and integral tuner.

Evaluation of the rules is realized by using Mamdani's product inference engine [35].

TABLE I
LOOKUP TABLE FOR THE FUZZY RULE BASE $i = 1, \ldots, n$

$\lvert\dot{q}_i\rvert \setminus \lvert\tilde{q}_i\rvert$	S	M	B
Don't care	$k_{p_i} = B$ $k_{v_i} = B$	$k_{p_i} = M$ $k_{v_i} = M$	$k_{p_i} = S$ $k_{v_i} = S$
$\lvert\dot{q}_i\rvert \setminus \lvert\omega_i\rvert$	S	M	B
Don't care	$k_{i_i} = B$	$k_{i_i} = M$	$k_{i_i} = S$

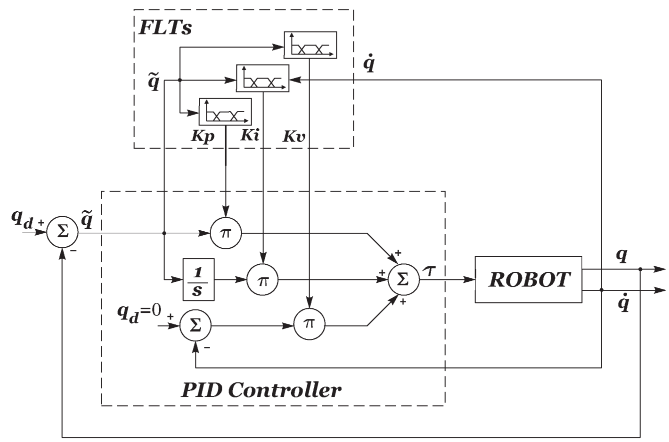

Fig. 3. Block diagram fuzzy self-tuning PID control.

C. Defuzzification Method

The defuzzification strategy chosen in this paper is the center average method [35]. Therefore, the output y can be computed as

$$y = \frac{\sum_{l=1}^{m} \bar{y}^l \mu_{A^l}(x)}{\sum_{l=1}^{m} \mu_{A^l}(x)} \tag{24}$$

where $\bar{y} = \{k_1, k_2, k_3\}$ denotes the centers of the output membership functions B^l.

Therefore, for a given input x, the output y can be computed straightforward from (24) as it was pointed out in [25]. This FLT has the feature that, under simple conditions, its output y is upper and lower bounded by strictly positive constants. This feature allows to fulfill completely Assumptions 1 and 2. A block diagram of the self-tuning PID control scheme is shown in Fig. 3.

D. Tuning of the Gains

As previously described, the basic FLT is invoked to determine the proportional, integral, and derivative gains. Thus, a set

Fig. 4. Experimental robot arm.

of $3n$ FLTs for $i = 1, \ldots, n$ is defined, that is

$$\begin{aligned} H_{k_{p_i}} &: \mathbb{R}_+ \to \mathbb{R} \\ &|\tilde{q}_i| \mapsto k_{p_i} \\ H_{k_{i_i}} &: \mathbb{R}_+ \to \mathbb{R} \\ &|\omega_i| \mapsto k_{i_i} \\ \text{and} \quad H_{k_{v_i}} &: \mathbb{R}_+ \to \mathbb{R} \\ &|\tilde{q}_i| \mapsto k_{v_i}. \end{aligned}$$

The tuning of the gains must take into account the stability conditions given in Proposition 1, which we can summarize in the following tuning procedure:

1) $k_{pl_i}(\tilde{q}_i) > \sum_{j=1}^{n} \max_q |\partial g_i(\boldsymbol{q})/\partial q_j|$, for all $\tilde{q}_i \in \mathbb{R}$, and $i = 1, \ldots, n$;
2) $k_{il_i}(\omega_i) > 0$, for all $\omega_i \in \mathbb{R}$, and $i = 1, \ldots, n$;
3) $k_{vl_i}(\tilde{q}_i) > \sum_{j=1}^{n} \max_q |M_{ij}(q)| K_{il_i}/(K_{Pi} - \sum_{j=1}^{n} \max_q |\partial g_i(q)/\partial q_j|)$, for all $\tilde{q}_i \in \mathbb{R}$, and $i = 1, \ldots, n$.

Moreover, the tuning of the gains must consider, in addition to the theoretical conditions of stability, the human knowledge rules given in the rule base of Table I.

VI. Experimental Results

In order to illustrate the performance of the proposed fuzzy self-tuning approach with respect to the fixed parameters of the PID control scheme, some experiments were carried out on a well-identified robot arm [36]. The system corresponds to a direct-drive vertical robot arm with two degrees of freedom moving in the vertical plane as shown in Fig. 4, where

$$M(\boldsymbol{q}) = \begin{bmatrix} 2.35 + 0.16\cos(q_2) & 0.10 + 0.08\cos(q_2) \\ 0.10 + 0.08\cos(q_2) & 0.10 \end{bmatrix}$$

$$C(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \begin{bmatrix} -0.168\sin(q_2)\dot{q}_2 & -0.084\sin(q_2)\dot{q}_2 \\ 0.084\sin(q_2)\dot{q}_1 & 0 \end{bmatrix}$$

$$\boldsymbol{g}(\boldsymbol{q}) = 9.81 \begin{bmatrix} 3.921\sin(q_1) + 0.186\sin(q_1 + q_2) \\ 0.186\sin(q_1 + q_2) \end{bmatrix}.$$

According to the actuator manufacturer, the direct-drive motors are able to supply torques within the following bounds: $|\tau_1| \leq 200$ [N · m] and $|\tau_2| \leq 15$ [N · m]. With the end of supporting the effectiveness of the proposed controller, we have used a squared signal whose amplitude is increased or decreased in magnitude every 2 s. More specifically, the robot task is coded in the following desired joint positions:

$$q_{d1}(t) = \begin{cases} 45^\circ & \text{if } 0 \leq t < 2 \text{ s} \\ 90^\circ & \text{if } 2 \leq t < 4 \text{ s} \\ 45^\circ & \text{if } 4 \leq t < 10 \text{ s} \end{cases}$$

$$q_{d2}(t) = \begin{cases} 90^\circ & \text{if } 0 \leq t < 2 \text{ s} \\ 45^\circ & \text{if } 2 \leq t < 4 \text{ s} \\ 90^\circ & \text{if } 4 \leq t < 10 \text{ s.} \end{cases}$$

The aforementioned position references are piecewise constant and really demand large torques to reach the amplitude of the respective requested step. In order to compare and evaluate the effectiveness of the proposed controller, the experiment was conducted for two controllers: the proposed fuzzy self-tuning PID control scheme and the classical PID control scheme. Fuzzy partitions of the universe of discourse of the errors $|\tilde{q}_1|$ and $|\tilde{q}_2|$ are characterized, respectively, by the sets

$$p(|\tilde{q}_1|) = \{2, 4, 10, 30\} \text{ [deg]}$$
$$p(|\tilde{q}_2|) = \{2, 4, 10, 30\} \text{ [deg]}$$

where $p(|\tilde{q}_i|) = \{p_1, p_2, \ldots, p_4\}$ denotes the supports of the membership function of $\tilde{q}_i$, while fuzzy partitions of the state variables $|\omega_1|$ and $|\omega_2|$ are characterized, respectively, by the sets

$$p(|\omega_1|) = \{0.573, 5.73, 14.325, 28.65, \} \text{ [deg]}$$
$$p(|\omega_2|) = \{5.73, 28.65, 57.3, 114.6\} \text{ [deg].}$$

The fuzzy partitions of the universe of discourse of the proportional, integral, and derivative gains are determined taking into account the desired accuracy and stability conditions given in Proposition 1. The partitions of the universe of discourse for the proportional gains were

$$\boldsymbol{k}_{p_1} = \{2.97, 10.47, 17.45\} \text{ [N · m/deg]}$$
$$\boldsymbol{k}_{p_2} = \{0.15, 0.87, 1.75\} \text{ [N · m/deg]}$$

where $\boldsymbol{k}_{p_i} = \{k_1, k_2, k_3\}$ denotes the supports of the membership function of output k_{p_i}. Following similar criteria, the partitions of the universe of discourse for the integral and derivative gains k_{i_i} and k_{v_i} were chosen as follows:

$$\boldsymbol{k}_{i_1} = \{1.57, 1.92, 2.36\} \text{ [N · m/(deg s)]}$$
$$\boldsymbol{k}_{i_2} = \{0.0087, 0.035, 0.087\} \text{ [N · m/(deg s)]}$$
$$\boldsymbol{k}_{v_1} = \{1.66, 2, 2.5\} \text{ [N · m s/deg]}$$
$$\boldsymbol{k}_{v_2} = \{0.041, 0.26, 0.5\} \text{ [N · m s/deg].}$$

The aforementioned fuzzy partitions ensure that the fuzzy self-tuners deliver proportional, integral, and derivative gains in agreement with the conditions of Proposition 1; thus, the

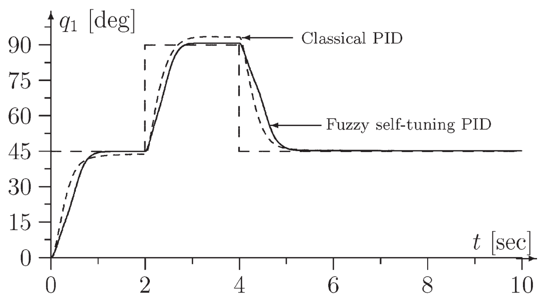

Fig. 5. Desired and actual positions 1 for the fuzzy self-tuning PID control and classical PID.

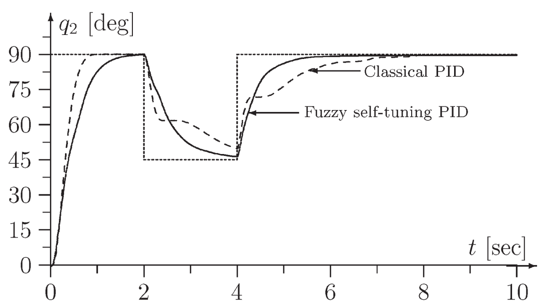

Fig. 6. Desired and actual positions 2 for the fuzzy self-tuning PID control and classical PID.

origin of the state space of the closed-loop system is semiglobal asymptotically stable.

With the end of getting a fair comparison, we have tuned the fixed gains of the classical PID controller in accordance with the conditions given in Proposition 1, and we have chosen those gains that yield the best performance in the sense of minimum rise time, without overshoot, and avoiding the possibility to saturate the actuators. The best tuning for the fixed PID gains is obtained with

$$\begin{aligned} \boldsymbol{k}_{p_1} &= \{3.5\}\ \ [\mathrm{Nm/deg}] \\ \boldsymbol{k}_{p_2} &= \{0.16\}\ \ [\mathrm{Nm/deg}] \\ \boldsymbol{k}_{v_1} &= \{0.96\}\ \ [\mathrm{Nm\ sec/deg}] \\ \boldsymbol{k}_{v_2} &= \{0.35\}\ \ [\mathrm{Nm\ sec/deg}] \\ \boldsymbol{k}_{i_1} &= \{2.09\}\ \ [\mathrm{Nm/(deg\ sec)}] \\ \boldsymbol{k}_{i_2} &= \{0.105\}\ \ [\mathrm{Nm/(deg\ sec)}]\,. \end{aligned}$$

Even so, we have permitted the fixed gains of the PID scheme to have an initial peak in the torque command of the elbow actuator slightly above of the torque limits during $2.5 \cdot 10^{-3}$ s. Indeed, the control equipment is protected by software in order to not demand, in the practice control, actions above the actuator torque constraints, which means that, in fact, we have permitted that the torque 2 is saturated initially during two sample times.

The experimental results are shown in Figs. 5–8. They show the desired and actual joint positions and the applied torques for the fuzzy self-tuning PID control and the classical PID control. From Figs. 5 and 6, one can observe that the transient responses of the links for the classical PID control are acceptable for the first step, but for the following changes of the step magnitude,

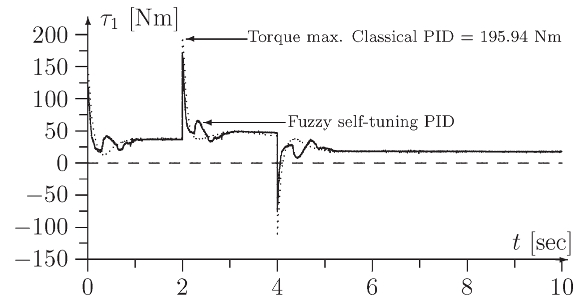

Fig. 7. Applied torque to the joint 1 for the fuzzy self-tuning PID control and classical PID.

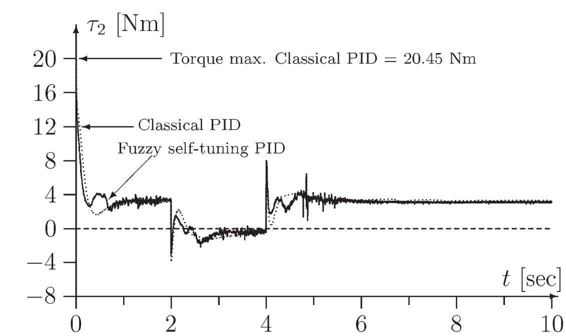

Fig. 8. Applied torque to the joint 2 for the fuzzy self-tuning PID control and classical PID.

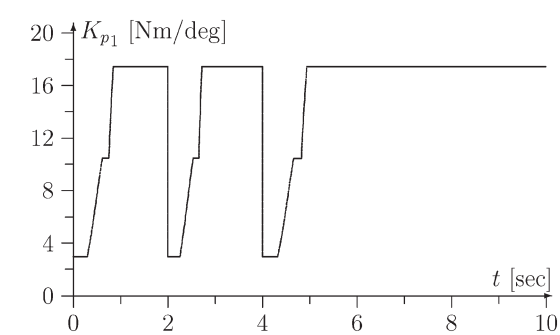

Fig. 9. Proportional gain k_{p1}.

transient responses are not really good and the accuracy of positioning is not satisfactory. This is due to the fact that the control gains are constant, and they cannot be changed in accordance with the values of the states.

The proposed fuzzy self-tuning PID controller was tested under the same desired task. The transient responses q_1 and q_2 are shown in Figs. 5 and 6; by comparing these position errors with those obtained for the case of fixed gains, we see that the accuracy and the transient are improved by using the fuzzy self-tuning algorithm. Applied torques τ_1 and τ_2 are shown in Figs. 7 and 8; these figures show the evolution of the applied torques; both remain within the torque actuator limits. The applied torque τ_2 presents high-frequency fluctuations of small magnitude which are imperceptible for the mechanical system; this can be seen in the position response in Fig. 6.

The improvement in the performance of the fuzzy self-tuning responses is mainly due to the variable nature of the gain matrices, whose evolution during the experiment can be seen in Figs. 9–14.

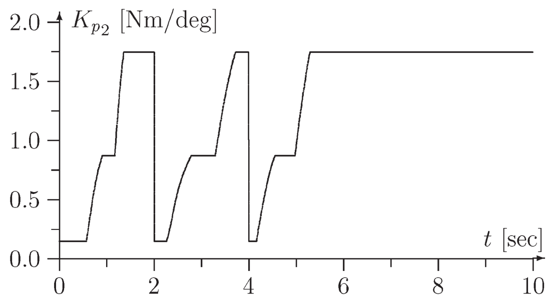

Fig. 10. Proportional gain k_{p2}.

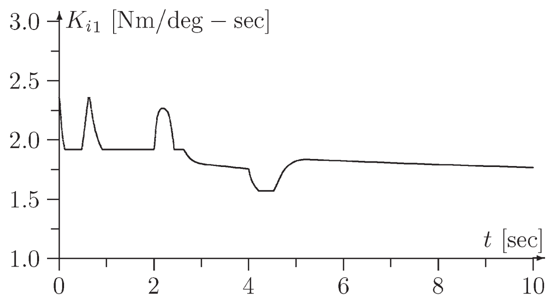

Fig. 11. Integral gain k_{i1}.

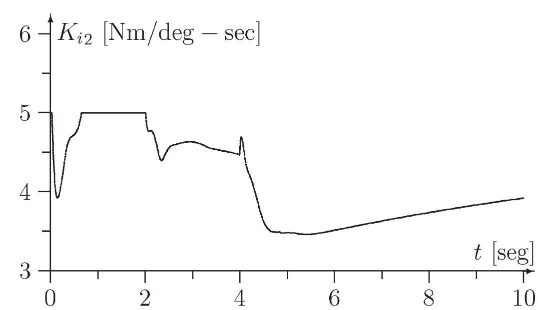

Fig. 12. Integral gain k_{i2}.

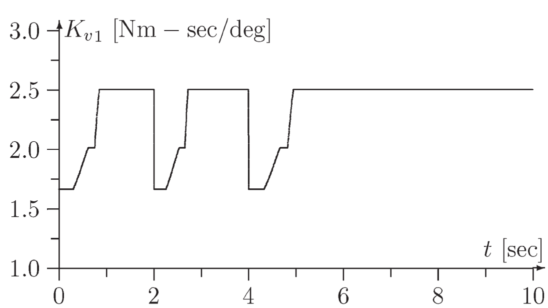

Fig. 13. Derivative gain k_{v1}.

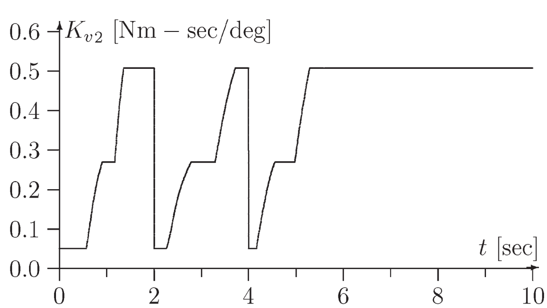

Fig. 14. Derivative gain k_{v2}.

VII. CONCLUSION

In this paper, we have proposed a fuzzy adaptation scheme for tuning the proportional, integral, and derivative state-dependent gains of a PID controller for robot manipulators. Moreover, a semiglobal asymptotic stability proof for the proposed fuzzy self-tuning PID controller for robot manipulators is presented. The proposed approach allows to consider important practical features in real robots, such as achievement of desired accuracy and avoidance of working of the actuators' torques beyond their capabilities. The performance of the proposed fuzzy scheme has been verified by means of real-time experimental tests on a two-degree-of-freedom direct-drive robot arm.

In summary, we have extended the stability analysis presented in [34] from PID controllers with fixed gains to PID controllers with variable gains for robot manipulators. Furthermore, we have applied such an analysis in order to self-tune, via fuzzy logic, the proportional, derivative, and integral gain matrices. The new resulting control scheme is superior to that shown in [34] due to the use of variable gain matrices and is also superior to control schemes introduced in [18] and [25], because the new proposed controller does not employ explicitly the knowledge of the robot dynamics model. Our result is a synergy of [34] and [25].

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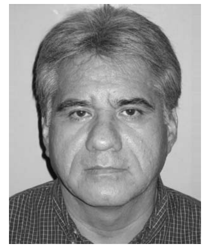

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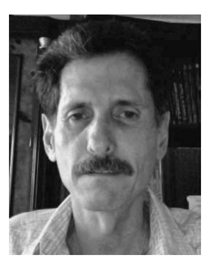

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