A Practical PID Controller with Bounded Torques for Robot Manipulators

Víctor Santibáñez[†*], Karla Camarillo[†], Javier Moreno–Valenzuela[‡], and Ricardo Campa[†]

[†] Instituto Tecnológico de la Laguna,
Blvd. Revolución y Cuauhtémoc, Torreón, Coahuila, 27000, México
[‡] Centro de Investigación y Desarrollo de Tecnología Digital del IPN
Av. Parque 1310, Mesa de Otay, Tijuana, B.C., 22510, México
{santibanez,recampa}@ieee.org,{vsantiba,recampa}@itlalaguna.edu.mx
karla_camarillo@hotmail.com,moreno@citedi.mx
http://www.itlalaguna.edu.mx

Abstract. This paper proposes a saturated nonlinear PID controller for industrial robot manipulators. Our controller considers the natural saturation problem given by the output of the control computer, the saturation phenomenon of the internal PI velocity controller in the servo driver and the actuator torque constraints of the robot manipulators. An approach based on the singular perturbation method is used to analyze the local exponential stability of the closed–loop system. We obtain sufficient conditions that allow us to achieve local regulation at a desired joint position.

Key words: Robot Control, PID, Bounded Control, Industrial Robots

1 Introduction

It is well known that industrial robots are equipped with PID controllers, that practically assure the semiglobal asymptotic stability of the closed-loop equilibrium for the regulation case [1]–[8]. Also, it is known that the real-life actuators are unable to supply unlimited torque, and their output is bounded. This implies physical constraints which if are not taken into account in the design of the controller, can affect the stability and performance of the closed–loop system [9]–[14].

Furthermore, industrial robots are equipped with a position control computer which produces the commands of desired joint velocities. These commands are bounded in the same way than the actuators output. In this work we consider these two constraints to design our controller.

Several approaches have been proposed in the literature for the problem of regulation case of robot manipulators with bounded inputs; different analytical frameworks and control objectives are considered. Some works have been

* This work was partially supported by CONACyT and DGEST, Mexico.

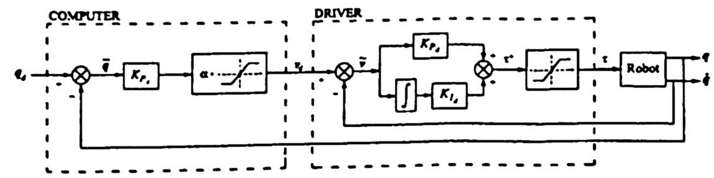

Fig. 1. Scheme of a practical nonlinear PID controller with bounded torques for robot manipulators.

reported to solve this problem [9]–[14]. Solutions without considering velocity measurements with gravity compensation are treated in [12]. A full-state (position and velocity) feedback solution with adaptive-gravity compensation is presented in [15]. More recently, new schemes dealing with the problem of robot manipulators with bounded inputs have been presented: [16]–[20]. An adaptive approach involving task-space coordinates considering the uncertainties of the kinematic model of the robot manipulator is proposed in [18].

Some works that deal with global nonlinear PID regulators based on Lyapunov and passivity theory have been reported in [21]–[24], but without considering the influence of the saturation phenomenon.

A few saturated PID controllers have been reported; for the case of semiglobal asymptotic stability, a saturated linear PID controller was presented in [19] and [20]; for the case of global asymptotic stability, saturated nonlinear PID controllers were introduced in [25] and [26].

In this paper, we propose a new saturated nonlinear PID regulator for robot manipulators. The structure of this new proposed controller is closer to the structure of the practical PID controllers used in the industry. Fig. 1 shows the scheme that we consider to design our saturated nonlinear PID controller where it clearly shows the constraints over the input and output commands of the servo driver. We use a proportional controller as external position control and a joint velocity PI controller which is intrinsic in the servo drivers of the actuators of the robot manipulators.

We employ the singular perturbation theory to analyze local exponential stability of the equilibrium of the closed-loop system.

Throughout this paper, we use the notation $\lambda_{\min}\{A(x)\}$ and $\lambda_{\max}\{A(x)\}$ to indicate the smallest and largest eigenvalues, respectively, of a symmetric positive definite bounded matrix $A(x)$, for any $x \in \mathbb{R}^n$. Also, we define $\lambda_{\min}\{A\}$ as the greatest lower bound (infimum) of $\lambda_{\min}\{A(x)\}$, for all $x \in \mathbb{R}^n$, that is, $\lambda_{\min}\{A\} = \inf_{x \in \mathbb{R}^n} \lambda_{\min}\{A(x)\}$. Similarly, we define $\lambda_{\max}\{A\}$ as the least upper bound (supremum) of $\lambda_{\max}\{A(x)\}$, for all $x \in \mathbb{R}^n$, that is, $\lambda_{\max}\{A\} = \sup_{x \in \mathbb{R}^n} \lambda_{\max}\{A(x)\}$. The norm of vector x is defined as $\|x\| = \sqrt{x^T x}$ and that of matrix $A(x)$ is defined as the corresponding induced norm $\|A(x)\| = \sqrt{\lambda_{\max}\{A(x)^T A(x)\}}$.

2 Preliminaries

2.1 Robot dynamics

The dynamics of a serial n–link rigid robot, without the effect of friction, can be written as [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 $\boldsymbol{q} \in \mathbb{R}^n$ is the vector of joint positions, $\dot{\boldsymbol{q}} \in \mathbb{R}^n$ is the vector of joint velocities, $\boldsymbol{\tau} \in \mathbb{R}^n$ is the vector of applied torques, $M(\boldsymbol{q}) \in \mathbb{R}^{n\times n}$ is the symmetric positive definite manipulator inertia matrix, $C(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in \mathbb{R}^{n\times n}$ is the matrix of centripetal and Coriolis torques and $\boldsymbol{g}(\boldsymbol{q}) \in \mathbb{R}^n$ is the 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 joints of the robot are revolute type.

2.2 Properties of the robot dynamics

We recall two important properties of dynamics (1) which are useful in our paper:

Property 1. The matrix $C(\boldsymbol{q}, \dot{\boldsymbol{q}})$ and the time derivative $\dot{M}(\boldsymbol{q})$ of the inertia matrix satisfy [28], [29]:

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

$\diamond$

Property 2. The gravitational torque vector $\boldsymbol{g}(\boldsymbol{q})$ is bounded for all $\boldsymbol{q} \in \mathbb{R}^n$. This means that there exist finite constants $\gamma_i \geq 0$ such that [30]:

$$\sup_{\boldsymbol{q}\in\mathbb{R}^n} |g_i(\boldsymbol{q})| \leq \gamma_i \qquad i = 1, \cdots, n, \tag{3}$$

where $g_i(\boldsymbol{q})$ stands for the elements of $\boldsymbol{g}(\boldsymbol{q})$. Equivalently, there exists a constant k' such that

$$\|\boldsymbol{g}(\boldsymbol{q})\| \leq k' \quad \text{for all } \boldsymbol{q} \in \mathbb{R}^n.$$

Furthermore there exists a positive constant k_g such that

$$\left\|\frac{\partial \boldsymbol{g}(\boldsymbol{x})}{\partial \boldsymbol{q}}\right\| \leq k_g,$$

for all $\boldsymbol{q} \in \mathbb{R}^n$, and

$$\|\boldsymbol{g}(\boldsymbol{x}) - \boldsymbol{g}(\boldsymbol{y})\| \leq k_g\|\boldsymbol{x} - \boldsymbol{y}\|,$$

for all $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^n$. $\diamond$

2.3 Problem formulation

Before presenting the formulation of the control problem, we recall some useful definitions.

Definition 1. The hard saturation function is denoted in this work by $\mathbf{sat}(\boldsymbol{x};\boldsymbol{k}) \in \mathbb{R}^n$, where

$$\mathbf{sat}(\boldsymbol{x};\boldsymbol{k}) = \begin{bmatrix} \mathrm{sat}(x_1;k_1) \\ \mathrm{sat}(x_2;k_2) \\ \vdots \\ \mathrm{sat}(x_n;k_n) \end{bmatrix}, \quad \boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad \boldsymbol{k} = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_n \end{bmatrix},$$

with k_i being the i–th saturation limit, $i = 1, 2, \ldots, n$, and each element of $\mathbf{sat}(\boldsymbol{x};\boldsymbol{k})$ is defined as:

$$\mathrm{sat}(x_i;k_i) = \begin{cases} x_i & \text{if } |x_i| \leq k_i \\ k_i & \text{if } x_i > k_i \\ -k_i & \text{if } x_i < -k_i \end{cases}$$

◇

Furthermore, the control scheme proposed in this paper involves special saturation functions that fits into the following definition.

Definition 2. [16] Given positive constants l and m, with $l < m$, a function $\mathrm{Sat}(x;l,m) : \mathbb{R} \to \mathbb{R} : x \mapsto \mathrm{Sat}(x;l,m)$ is said to be a strictly increasing linear saturation function for (l,m) if it is locally Lipschitz, strictly increasing, C^2 differentiable and satisfies:

1) $\mathrm{Sat}(x;l,m) = x$ when $|x| \leq l$
2) $|\mathrm{Sat}(x;l,m)| < m$ for all $x \in \mathbb{R}$. ◇

For instance, the following saturation function is a special case of a linear saturations given in Definition 2, i.e.:

$$\mathrm{Sat}(x;l,m) = \begin{cases} -l + (m-l)\tanh\left(\frac{x+l}{m-l}\right) & \text{if } x < -l \\ x & \text{if } |x| \leq l \\ l + (m-l)\tanh\left(\frac{x-l}{m-l}\right) & \text{if } x > l \end{cases} \tag{4}$$

The n–saturation functions are joined together in an $n \times 1$ saturation function vector denoted by $\mathbf{Sat}(\boldsymbol{x};\boldsymbol{l},\boldsymbol{m})$, i.e.,

$$\mathbf{Sat}(\boldsymbol{x};\boldsymbol{l},\boldsymbol{m}) = \begin{bmatrix} \mathrm{Sat}(x_1;l_1,m_1) \\ \mathrm{Sat}(x_2;l_2,m_2) \\ \vdots \\ \mathrm{Sat}(x_n;l_n,m_n) \end{bmatrix},$$

where $\boldsymbol{x}, \boldsymbol{l}, \boldsymbol{m} \in \mathbb{R}^n$, that is,

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}, \quad \boldsymbol{l} = \begin{bmatrix} l_1 \\ l_2 \\ \vdots \\ l_n \end{bmatrix}, \quad \boldsymbol{m} = \begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_n \end{bmatrix}.$$

Consider the robot dynamic model (1). Assume that each joint actuator is able to supply a known maximum torque $\tau_i^{\max}$ so that:

$$|\tau_i| \leq \tau_i^{\max}, \qquad i = 1, \ldots, n \tag{5}$$

where τ_i stands for the i–entry of vector $\boldsymbol{\tau}$. In other words, if u_i represents the control signal (controller output) before the actuator, related to the ith–joint, then

$$\tau_i = \tau_i^{\max} \mathrm{sat}\left(\frac{u_i}{\tau_i^{\max}}\right), \tag{6}$$

for $i = 1, \ldots, n$, where sat$(\cdot)$ is the standard hard saturation function. We also assume:

Assumption 1. The maximum torque $\tau_i^{\max}$ of each actuator satisfies the following condition:

$$\tau_i^{\max} > \gamma_i, \tag{7}$$

where γ_i was defined in Property 2, with $i = 1, 2, ..., n$. ◇

This assumption means that the robot actuators are able to supply torques in order to hold the robot at rest for all desired joint position $\boldsymbol{q}_d \in \mathbb{R}^n$.

The control problem is to design a controller, under model uncertainty, to compute the torque $\boldsymbol{\tau} \in \mathbb{R}^n$ applied to the joints, satisfying the constraints (5), such that the robot joint positions $\boldsymbol{q}$ tend asymptotically toward the constant desired joint positions $\boldsymbol{q}_d$.

3 The proposed control scheme

In this section we present a nonlinear PID controller which can be seen as a practical version of the classical PID control of robot manipulators.

As shown in Fig. 1, the proposed controller is formed by two loops: an outer joint position proportional P loop and an inner joint velocity proportional–integral PI loop. Without considering the actuator saturation effects, in [32], it was proven that an outer loop position P controller (according to Fig. 1, $\boldsymbol{v}_d = K_{p_c}\tilde{\boldsymbol{q}}$) together with an inner velocity PI controller (according to Fig. 1, $\boldsymbol{\tau} = K_{p_d}\tilde{\boldsymbol{v}} + K_{i_d}\int_0^t \tilde{\boldsymbol{v}}(r)dr$) conform a classical PID controller, that is:

$$\begin{aligned} \boldsymbol{\tau} &= K_p\tilde{\boldsymbol{q}} + K_i\boldsymbol{w} - K_v\dot{\boldsymbol{q}} \\ \boldsymbol{w} &= \int_0^t \tilde{\boldsymbol{q}}(r)\, dr \end{aligned}$$

where $K_p = K_{p_d}K_{p_c} + K_{i_d}$, $K_v = K_{P_d}$, $K_i = K_{i_d}K_{p_c} \in \mathbb{R}^{n\times n}$ are diagonal positive definite matrices, $\tilde{q} = q_d - q \in \mathbb{R}^n$ is the position error vector and $\tilde{v} = v_d - \dot{q} \in \mathbb{R}^n$ is the velocity error vector.

However, in the real applications the commands supplied by the computer (position P loop) are limited by intrinsic constraints of the electronic devices, and the servo–drivers (velocity PI loop) and the actuators are unable to supply unlimited torques, so we must take into account these constraints in the closed–loop stability analysis.

To this end, consider that, according to Fig. 1, the position controller implemented by the computer is given by

$$v_d = \alpha \mathrm{Sat}(K_{p_c}\tilde{q}; l_p, m_p), \tag{8}$$

where $K_{p_c} \in \mathbb{R}^{n\times n}$ is a diagonal positive definite matrix whose elements are $k_{p_{c_i}}$ with $i = 1, 2...n$, α is a small positive constant suitably selected and $\mathrm{Sat}(K_{p_c}\tilde{q}; l_p, m_p)$ is a saturation function defined in Definition 2 for some (l_p, m_p), where l_p and m_p are vectors whose elements are l_{p_i} and m_{p_i}, respectively, with $i = 1, 2, \ldots, n$.

The joint velocity PI controller, in practice, is naturally implemented into the servo–drivers as:

$$\tau^* = K_{p_d}\tilde{v} + K_{i_d}\int_0^t \tilde{v}(r)dr \tag{9}$$

where $K_{p_d}, K_{i_d} \in \mathbb{R}^{n\times n}$ are diagonal positive definite matrices, and $\tilde{v}$ is the joint velocity error vector given by

$$\begin{aligned}\tilde{v} &= v_d - \dot{q}\\ &= \alpha \mathrm{Sat}(K_{p_c}\tilde{q}; l_p, m_p) - \dot{q},\end{aligned} \tag{10}$$

Substituting (10) in (9) we obtain

$$\tau^* = \alpha K_{p_d}\mathrm{Sat}(K_{p_c}\tilde{q}; l_p, m_p) - K_{p_d}\dot{q} + K_{i_d}\int_0^t [\alpha \mathrm{Sat}(K_{p_c}\tilde{q}(r); l_p, m_p) - \dot{q}(r)]dr$$

which has the form of the nonlinear PID global regulator in [21], [23], that is,

$$\tau^* = K_p\mathrm{Sat}(K_{p_c}\tilde{q}; l_p, m_p) - K_v\dot{q} + K_i\int_0^t [\alpha \mathrm{Sat}(K_{p_c}\tilde{q}(r); l_p, m_p) - \dot{q}(r)]dr,$$

with

$$\begin{aligned}K_p &= \alpha K_{p_d},\\ K_v &= K_{p_d},\\ K_i &= K_{i_d},\end{aligned}$$

where K_p, K_v, $K_i \in \mathbb{R}^{n\times n}$ are diagonal positive definite matrices whose elements are k_{p_i}, k_{v_i}, k_{i_i} respectively, with $i = 1, 2...n$.

Finally, due to the servo–drivers and the torque actuators are physically limited, the nonlinear PID controller naturally results in a nonlinear PID controller with bounded torques given by

$$\begin{aligned} \tau &= \mathrm{Sat}\left[K_p \mathrm{Sat}\left(K_{p_c}\tilde{q}; l_p, m_p\right) - K_v\dot{q} + w\right]; l_{pi}, m_{pi}] \\ w &= K_i \int_0^t [\alpha \mathrm{Sat}(K_{p_c}\tilde{q}(r); l_p, m_p) - \dot{q}(r)]dr \end{aligned} \tag{11}$$

where $\mathrm{Sat}\left[K_p\mathrm{Sat}\left(K_{p_c}\tilde{q}; l_p, m_p\right) - K_v\dot{q} + w; l_{pi}, m_{pi}\right]$ is a vector whose elements are strictly increasing linear saturation functions such as those in Definition 2, for some (l_{pi}, m_{pi}), where l_{pi} and m_{pi} are vectors whose elements are l_{pi_i} and m_{pi_i}, respectively, with $i = 1, 2, \ldots, n$, satisfying the following assumption.

Assumption 2: The saturation limits of the P and the PI loops satisfy:

$$\gamma_i < l_{p_i} < m_{p_i} < l_{pi_i} < m_{pi_i} < \tau_i^{\max}. \tag{12}$$

◇

Remark: In the practice, the saturation constraints of the electronic devices and the actuators are in fact, hard saturations like those in Definition 1. However, with the end of carrying out the stability analysis, they can be approximated by linear saturation functions like those defined in Definition 2 with $l < m$ and l arbitrarily close to m.

In order to simplify the notation, henceforth, we will omit the limits of the saturation functions.

4 Main Result

4.1 Closed–loop system

By substituting (11) into the robot dynamics (1), we obtain

$$\frac{d}{dt}\begin{bmatrix} \tilde{q} \\ \dot{q} \\ w \end{bmatrix} = \begin{bmatrix} -\dot{q} \\ M(q)^{-1}\left[\mathrm{Sat}\left[K_p\mathrm{Sat}\left(K_{p_c}\tilde{q}\right) - K_v\dot{q} + w\right] - C(q,\dot{q})\dot{q} - g(q)\right] \\ K_i\left[\alpha\mathrm{Sat}\left(K_{p_c}\tilde{q}\right) - \dot{q}\right] \end{bmatrix} \tag{13}$$

which is an autonomous differential equation with an unique equilibrium point given by $[\tilde{q}^T \ \dot{q}^T \ w^T]^T = [0^T \ 0^T \ g(q_d)^T]^T \in \mathbb{R}^{3n}$, where we have used the Assumption 2, that is, $l_{pi_i} > \gamma_i$ to get that $\mathrm{Sat}(w) - g(q_d) = 0 \Leftrightarrow w = g(q_d)$. In order to move the equilibrium point of (13) to the origin, we apply the following change of variables $x = w - g(q_d)$. Now the new closed-loop system is given by:

$$\frac{d}{dt}\begin{bmatrix} \tilde{q} \\ \dot{q} \\ x \end{bmatrix} = \begin{bmatrix} -\dot{q} \\ M(q)^{-1}\left[\mathrm{Sat}\left[K_p\mathrm{Sat}\left(K_{p_c}\tilde{q}\right) - K_v\dot{q} + x + g(q_d)\right] - C(q,\dot{q})\dot{q} - g(q)\right] \\ K_i\left[\alpha\mathrm{Sat}\left(K_{p_c}\tilde{q}\right) - \dot{q}\right] \end{bmatrix} \tag{14}$$

The previous closed-loop system can be studied as a singularly perturbed system. To this end, by choosing the integral gain matrix as $K_i = \varepsilon K_i^*$, where K_i^* is a diagonal positive definite matrix and $\varepsilon > 0$ is a small parameter and letting $t' = \varepsilon t$ be a new time-scale (t' is slow time compared to t), the system (14) can be described as a two first-order differential equations as follows:

$$\frac{d}{dt'}\boldsymbol{x} = K_i^* \left[\alpha \mathrm{Sat}\left(K_{p_c}\tilde{\boldsymbol{q}}\right) - \dot{\boldsymbol{q}}\right] \tag{15}$$

$$\varepsilon \frac{d}{dt'} \begin{bmatrix} \tilde{\boldsymbol{q}} \\ \dot{\boldsymbol{q}} \end{bmatrix} = \begin{bmatrix} -\dot{\boldsymbol{q}} \\ M(\boldsymbol{q})^{-1}\left[\mathrm{Sat}\left[K_p \mathrm{Sat}\left(K_{p_c}\tilde{\boldsymbol{q}}\right) - K_v\dot{\boldsymbol{q}} + \boldsymbol{x} + \boldsymbol{g}(\boldsymbol{q}_d)\right] - C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q})\right] \end{bmatrix} \tag{16}$$

Our main contribution is summarized in the following

Proposition 1. Consider the robot dynamics (1) in closed-loop with the practical saturated PID control law (11). Under Assumption 2, and

$$k_{p_i} l_{p_i} > |x_i + g_i(q_d) - g_i(q_d - \tilde{q})|, \ \forall \tilde{q}_i \in \mathbb{R}, \ i = 1, 2, \ldots, n,$$
$$\lambda_{\min}\{K_p K_{p_c}\} > k_g$$
$$\lambda_{\min}\{K_p\} > k_h$$

with $k_h = \frac{2k'}{\mathrm{Sat}\left(\frac{2k'\lambda_{\min}\{K_{p_c}\}}{k_g}\right)}$, the origin of the closed-loop system (15)–(16) is locally exponentially stable, and therefore, the equilibrium point of (13) is locally exponentially stable. Besides $|\tau_i(t)| \le \tau_i^{\max}$ for all $i = 1, 2, ..., n$ and $t \ge 0$. $\diamond$

Proof. By following similar steps to those given in [20], by means of the singular perturbation theory [31], it is possible to prove Proposition 1.

5 Conclusions

In this paper, we propose a saturated nonlinear PID controller which, in fact, results from the practical implementation of the classical PID controller, by considering the natural saturations of the electronics of the control computer and of the servo drivers, and the actuator torque constraints. The stability analysis of the closed-loop system can be carried out by using the singular perturbation theory; thus, we conclude local exponential stability of the equilibrium point of the closed-loop system. It is also guaranteed that, regardless of initial conditions, the delivered actuator torques evolve inside permitted limits.

References

1. S. Arimoto, and F. Miyazaki, "Stability and robustness of PID feedback control for robot manipulators of sensory capability, in M. Brady and R.P. Paul (Ed.)",

Robotics Researches: First International Symposium, MIT press, Cambridge, MA., 783–799 (1984).

2. S. Arimoto, T. Naniwa, and H. Suzuki, "Asymptotic stability and robustness of PID local feedback for position control of robot manipulators", *Proc. International Conference on Automation Robotics and Computer Vision ICARCV '90*, Singapore. 382–386 (1990).
3. R. Kelly, "Regulation of Robotic Manipulators: Stability Analysis via the Lyapunov's First Method", *Internal report*, CICESE, Ensenada, B.C., Mexico (1995).
4. R. Kelly, "A Tuning procedure for stable PID control of robot manipulators", *Robotica*, **13** (2), 141–148 (1995).
5. R. Ortega, A. Loria, and R. Kelly, "A semiglobally stable output feedback $\mathrm{PI^2D}$ regulator for robot manipulators", *IEEE Transactions on Automatic Control*, **40** (8), 1432–1436 (1995).
6. J. Alvarez–Ramirez, I. Cervantes and R. Kelly, "PID regulation of robot manipulators: stability and performance", *Systems and Control Letters*, **41**, 73–83 (2000).
7. R. Kelly, V. Santibáñez and A. Loría, *Control of Robot Manipulators in Joint Space* (Springer–Verlag, London, 2005).
8. J. L. Meza, V. Santibañez and R. Campa, "An Estimate of the Domain of Attraction for the PID Regulator of Manipulators", *International Journal of Robotics and Automation*, **22** (3), 187–195 (2007).
9. R. Kelly, and V. Santibañez, "A class of global regulators with bounded control actions for robot manipulators", *Proc. IEEE Conf. Decision and Control*, Kobe, Japan, 3382–3387 (1996).
10. R. Colbaugh, E. Barany and K. Glass, "Global regulation of uncertain manipulators using bounded controls", *Proc. IEEE Int. Conf. Robotics and Automation*, Albuquerque, USA, 1148–1155 (1997a).
11. R. Colbaugh, E. Barany and K. Glass, "Global regulation of uncertain manipulators using bounded controls", *Proc. IEEE Int. Conf. Robotics and Automation*, Albuquerque, USA, 86–91 (1997b).
12. A. Loria, R. Kelly, R. Ortega, and V. Santibañez, "On global output feedback regulation of Euler–Lagrange systems with bounded inputs" *IEEE Trans. Automat. Contr.*, **42**, 1138–1143 (1997).
13. V. Santibañez, and R. Kelly, "On Global regulation of robot manipulators: saturated linear state feedback and saturated linear output feedback", *European Journal of Control*, **3**, 104–113 (1997).
14. V. Santibañez, and R. Kelly, "A New set-point controller with bounded torques for robot manipulators", *IEEE Transactions on Industrial Electronics*, **45**, 126–133 (1998b).
15. E. Zergeroglu, W. Dixon, A. Behal and D. Dawson, "Adaptive set-point control of robotic manipulators with amplitude-limited control inputs", *Robotica*, **18**, 171–181 (2000).
16. A. Zavala–Rio and V. Santibañez, "Simple extensions of the PD–with–gravity–compensation control law for robot manipulators with bounded inputs", *IEEE Transactions on Control Systems Technology*, **14** (5), 958–965 (2006).
17. A. Zavala-Rio and V. Santibanez, "A natural saturating extension of the PD–with–desired–gravity compensation control law for robot manipulators with bounded inputs," *IEEE Transactions on Robotics*, **23** (2), 386-391 (2007).
18. W. E. Dixon W.E., "Adaptive regulation of amplitude limited for robot manipulators with uncertain kinematics and dynamics", *IEEE Transactions on Automatic Control*, **52** (3), 488–493 (2007), *Proc. of American Control Conference*, Boston MA, 3839–3844 (2004).

19. J. Alvarez-Ramirez, R. Kelly and I. Cervantes, "Semiglobal stability of saturated linear PID control for robot manipulators", *Automatica*, **39**, 989–995 (2003).
20. J. Alvarez-Ramirez, V. Santibáñez and R. Campa, "Stability of Robot Manipulators under Saturated PID Compensation", *IEEE Transactions on Control Systems Technology*, to appear (2008).
21. S. Arimoto, "Fundamental problems of robot control: Part I, Innovations in the realm of robot servo-loops", *Robotica*, **13**, 19–27 (1995).
22. R. Kelly, "Global positioning of robot manipulators via PD control plus a class of nonlinear integral actions", *IEEE Transactions on Automatic Control*, **43** (7), 934–938 (1998).
23. V. Santibañez, and R. Kelly, "A class of Nonlinear PID Global regulators for robot manipulators", *Proc. of 1998 IEEE International Conference on Robotics and Automation*, Bélgica, 3601–3606 (1998a).
24. J. L. Meza, and V. Santibáñez, "Analysis via passivity theory of a class of nonlinear PID global regulators for robot manipulators", *Proc. of the IASTED International Conference, Robotics and Applications RA'99, U.S.A.*, 288–293 (1999).
25. R. Gorez, "Globally stable PID-like control of mechanical systems" *Systems and Control Letters*, **38**, 61–72 (1999).
26. J. L. Meza, V. Santibañez and V. Hernandez, "Saturated Nonlinear PID Global Regulator for Robot Manipulators: Passivity Based Analysis", *Proc. of the 16th IFAC World Congress*, Prague, Czech Republic, (2005).
27. M. Spong and M. Vidyasagar, *Robot Dynamics and Control* (John Wiley and Sons, 1989).
28. D. Koditschek, "Natural motion for robot arms", *Proc. IEEE Conference on Decision and Control*, Las Vegas, NV., 733–735 (1984).
29. R. Ortega, and M. Spong, "Adaptive motion control of rigid robots: a tutorial", *Automatica*, **25** (6), 877–888 (1989).
30. J. J. Craig, *Adaptive Control of Mechanical Manipulators*, (Reading, MA, Addison-Wesley 1998).
31. H. Khalil, *Nonlinear Systems*, (Prentice Hall, 2002).
32. R. Kelly and J. Moreno, "Learning PID Structures in an Introductory Course of Automatic Control", *IEEE Transactions on Education*, **44** (4), 373–376 (2001).