Position control under simultaneous limited torque and speed of a torque-driven nonlinear rotational mechanism

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Abstract: This paper deals with shaft displacement regulation (position control) of a torque-driven nonlinear gravity unbalanced mechanism under both prescribed bounded torque and speed. This is a novel control objective formulation for mechanisms. A nonlinear dynamic controller to resolve this control formulation is proposed. This controller aims to take care of the actuator/plant by keeping them within a safe operating torque–speed zone. An experimental study complements the proposed theory. Potential applications of the proposed approach are in safe control of robots.

1. Introduction

From an automatic control point of view, it is recognized that most physical actuators (electric motors included) have limited capabilities (see e.g. Åström & Murray, 2008; Dorf & Bishop, 2008; Tarbouriech, Garcia, Gomes da Silva Jr., & Queinnec, 2011). In order to ensure proper safe operation of actuators like electric motors, they must operate inside prescribed “safe operating zones”—delimited by their torque–speed curve—where motors may be constrained to “medium/high” torque but “low” speed (Hughes & Drury, 2013). When this kind of actuators is applied to handle mechanisms such as robots (see Figure 1), the control system should take care of retaining the actuators within their safe prescribed torque and speed limits.

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PUBLIC INTEREST STATEMENT

This paper proposes a solution to position control of a gravity unbalanced shaft driven by a torque actuator by respecting prescribed safe desired torque and speed bounds. This is a first step toward the more challenging self hardware-protecting safe control of robot manipulators.
The position control of robot manipulators (also called regulation or point-to-point robot control) can be defined as “commanding the robot to go from an initial configuration to a desired final configuration without regard to the intermediate path to be followed by the end effector” (Kelly, Santibánez, & Berghuis, 1997) and it has been the subject of several researches.

Regarding the position control of robot manipulators, studies which consider some type of restrictions in the actuators have been reported, such as Kelly et al. (1997) where torque limits are considered (without taking into account velocity constraints) and Ngo and Mahony (2006) where joint velocity constraints and bounded torque were taken into account. In the latter paper, torque is bounded in norm but no specific values of torque limits were stated in the control objective. The position control for other classes of robots such as nonholonomic mobile robots subject to input limits has been addressed (see for example Chen, 2014). Other studies where the system to be controlled presents input constraints have been reported in the literature such as Su, Chen, Wang, and Lam (2014), where the problem of consensus for a multiagent system subject to input saturations was addressed.

As a first approach toward the safe control of robot manipulators required that the torque actuators remain operating within their prescribed torque and speed limits, this paper considers the position control of a torque-driven nonlinear rotational mechanism.

The torque-driven nonlinear rotational mechanism is a rotational mechanical system whose input is provided by a torque actuator. The rotational mechanical system is modeled by a nonlinear differential equation (a physical example of such system is a pendulum, while a brushed DC motor is assumed to be a torque actuator (see Figure 2)).
The control of linear and nonlinear servomechanisms is an active research topic. For example, in Kelly (1987) an adaptive control for DC motors is proposed for position control, in Kelly and Moreno-Valenzuela (2001) a study on shaft position regulation for DC motors was made using Proportional-Integral-Derivative controllers. Adaptive controller for the speed control of a servomechanism is proposed by Chen, and Cheng (2012). In those papers, neither input torque nor speed limits were considered.

For recent approaches to servomechanisms control under constrained input, see for example Aghili (2013), where a study on torque control taking into account voltage and current limits is presented; Guzmán-Guemez and Moreno-Valenzuela (2013) and Moreno-Valenzuela and Guzman-Guemez (2016) where the voltage control is addressed by considering limitation of the duty cycle percentage.

The contribution of this paper is to address the position control of a torque-driven mechanism but by respecting prescribed simultaneous torque and speed bounds of the actuator. To the best of the authors’ knowledge, this is the first time that the issue of keeping the overall control system operating within both torque and speed bounds is addressed.

This paper is organized as follows: In Section 2, plant model and control objective are presented. The proposed controller is stated in Section 3. The analysis is given in Section 4. An experimental study to complement the proposed theory is provided in Section 5. Finally, the conclusion is presented in Section 6.

2. Problem statement

2.1. Plant model: gravity unbalanced shaft driven by a torque actuator

This paper considers an “unbalanced rotational device driven by a torque actuator” (see in Figure 2 a picture of a laboratory setup) modeled by the normalized nonlinear second-order ordinary differential equation:

\[ J \ddot{q} + f_v \dot{q} + mgl \sin(q) = \tau, \tag{1} \]

where \( J > 0 \) is the rotor–shaft–load moment of inertia, \( m > 0 \) is its mass assumed to be concentrated at a distance \( l > 0 \) from the rotation axis (gravity unbalanced load like a hanging pendulum shaped one), \( f_v \geq 0 \) is the viscous friction coefficient, and \( g > 0 \) is the gravity acceleration; variables \( q, \dot{q} \) and \( \ddot{q} \) are, the shaft angular position, speed and acceleration, respectively, and \( \tau \) is the “input”—torque—provided by a motor–electronic driver actuator setup in torque–mode.

Plant model (Equation 1) may be seen as a particular simple case of more complex and challenging systems like torque-driven robot manipulators (Kelly, Santibánez, & Loria, 2005).

With regard to the system (Equation 1) to be controlled, in this paper, the following assumptions are made:

Assumption 1: The plant model (Equation 1) related parameters: \( J, f_v \) and \( mgl \) are known.

Assumption 2: Shaft position \( q \) and speed \( \dot{q} \) measurements are available from system (Equation 1).

Assumption 3: The “safe operating zone” of the motor–electronic driver actuator is defined by the region delimited by the torque-speed characteristic curve corresponding to “medium / high” absolute value torque \(|\tau|\) bounded by \( \tau_{\text{max}} > 0 \), and “small” speed \(|\dot{q}|\) bounded by \( \text{Vel}_{\text{max}} > 0 \). This is shown by the green left bottom rectangle in Figure 3.
2.2. Actuator model

In this paper, we use the following ideal identity actuator model:

\[ \tau = u. \]  

(2)

No torque limit is assumed for the actuator.

2.3. Control objective

The control objective is shaft displacement regulation by respecting prescribed simultaneous torque and speed limits:

\[ \lim_{t \to \infty} q(t) = q_d, \]  

(3)

and

\[ |q(t)| \leq \text{Vel}_{\text{max}} \forall t \geq 0, \]  

(4)

and

\[ |	au(t)| \leq \tau_{\text{max}} \forall t \geq 0, \]  

(5)

where \( q_d \) is the known desired shaft displacement (arbitrary but constant), \( \text{Vel}_{\text{max}} > 0 \) is the known safe operational speed limit of the actuator/controlled system, and \( \tau_{\text{max}} > 0 \) is the known maximum safe torque from the actuator.

Although no torque limit was assumed for the actuator, as a safety matter, a safe desired bound \( \tau_{\text{max}} < \infty \) is given to maintain the actuator/controlled system into the “safe operating zone.”

According to Assumption 1, knowledge of some plant model parameters is required. If the plant model parameters are unknown, it would be necessary to explore alternative control methods, such as adaptive control (e.g. Kelly, 1987; Loria, Kelly, & Teel, 2005; Slotine & Li, 1988).

Assumption 4: The prescribed desired bounds \( \tau_{\text{max}} \) and \( \text{Vel}_{\text{max}} \) are supposed to satisfy the following condition:

\[ \tau_{\text{max}} > f_q \text{Vel}_{\text{max}} + mgl. \]  

(6)

Figure 3 shows a plot of \(|\tau| \) versus \(|\dot{q}|\). The red outer zone represents the prohibited unsafe operating area; meanwhile the “safe operating zone” is represented by the green left bottom inner rectangle. In this “safe zone,” speed and torque constraints (Equations 4 and 5) hold simultaneously.
3. Proposed controller

This paper proposes the following control law:

\[
\begin{align*}
    u &= J_1 sech^2 \left( k_2 \xi \right) k_2 \tanh(\dot{q}) \\
    &- J_2 sech^2 \left( k_1 \dot{q} \right) k_1 \dot{q} \\
    &+ f_v \dot{q} + mgl \sin(q), \\
    \dot{\xi} &= \tanh(\dot{q}),
\end{align*}
\]

where the position error \( \dot{q} \) is defined as

\[
\dot{q} = q_d - q.
\]

Controller parameters \( \gamma_1 \) and \( \gamma_2 \) are chosen to satisfy the following conditions:

\[
\begin{align*}
    &\gamma_1 < \gamma_2 < 0, \\
    &\gamma_1 + \gamma_2 \leq \text{Vel}_{\text{max}}.
\end{align*}
\]

The initial velocity \( \dot{q}(0) \) is assumed to be “small” in the sense:

\[
|\dot{q}(0)| < \gamma_1 - \gamma_2,
\]

which in virtue of (Inequalities 9) trivially satisfies (Equation 4) at \( t = 0 \).

The remaining controller parameters \( k_s \) and \( k_p \) are positive and are chosen to satisfy the tuning inequalities:

\[
\begin{align*}
    &k_p < \frac{\tau_{\text{max}} - (f_v \text{Vel}_{\text{max}} + mgl)}{J_2 \text{Vel}_{\text{max}}}, \\
    &k_s \leq \frac{\tau_{\text{max}} - (f_v \text{Vel}_{\text{max}} + mgl) - J_2 k_p \text{Vel}_{\text{max}}}{J_2 \gamma_1},
\end{align*}
\]

Note that the right-hand side of (Inequality 11) is positive due to \( \tau_{\text{max}} \) was assumed to satisfy condition (Inequality 6) and the right-hand side of (Inequality 12) is positive due to \( k_p \) satisfies condition (Inequality 11).

And finally the initial condition \( \xi(0) \) considered here as a parameter of the controller is obtained through the formula:

\[
\xi(0) = \frac{1}{k_s} \arctanh \left( \frac{\dot{q}(0) - \gamma_2 \tanh \left( k_p \dot{q}(0) \right)}{\gamma_1} \right),
\]

which is well defined because \( \dot{q}(0) \) satisfies (Inequality 10).

Inequality 10 ensures that the speed initial condition satisfies the control objective (Equation 4) at \( t = 0 \). However, given the (Condition 9) the value \( |\dot{q}(0)| \) is restricted to \( |\dot{q}(0)| < \text{Vel}_{\text{max}} \), i.e., the initial velocities \( \dot{q}(0) = -\text{Vel}_{\text{max}} \) and \( \dot{q}(0) = \text{Vel}_{\text{max}} \) are not permissible values. In other words, the system (Equation 1) should not be started at the prescribed speed limits. The larger the difference \( \gamma_1 - \gamma_2 \), the larger the values of \( |\dot{q}(0)| \) that are allowed but always under restriction \( |\dot{q}(0)| < \text{Vel}_{\text{max}} \).
To choose the parameters of the controller in (Equation 7), it is required to satisfy conditions (Inequalities 9, 11 and 12) and (Equation 13). The fulfillment of these conditions guarantees the achievement of the control objective in (Equation 3) and (Conditions 3 and 5) provided that initial speed is small enough in the sense of (Condition 10).

4. Analysis
The remaining of this section is devoted to prove that the proposed controller in (Equation 7) achieves the control objective in (Equation 3) and (Conditions 3 and 5).

4.1. Speed boundedness
Using torque actuator model in (Equation 2), control action $u$ in (Equation 7), and replacing into the plant model (Equation 1) yields:

$$\frac{dq}{dt} = \gamma_1 \text{sech}^2(k_s \xi) \tan(h(q)) - \gamma_2 \text{sech}^2(k_p \dot{q}) \dot{k}_p q, \tag{14}$$

whose integral produces:

$$\dot{q} = \gamma_1 \tanh(k_s \xi) + \gamma_2 \tanh(k_p \dot{q}) + \left[q(0) - \gamma_1 \tanh(k_s(0)) - \gamma_2 \tanh(k_p(0))\right]. \tag{15}$$

By replacing (Equation 13) into (Equation 15), it becomes:

$$\dot{q} = \gamma_1 \tanh(k_s \xi) + \gamma_2 \tanh(k_p \dot{q}). \tag{16}$$

Note that controller in (Equation 7) is very convenient, such that the value of the velocity $\dot{q}$ can be determined by (Equation 16). The resultant velocity depends on the position error $\dot{q}$ and the integral of a nonlinear function of the position error. The obtained (Equation 16) is useful in the proof of the three parts of the control objective in (Equation 3) and (Conditions 4 and 5).

From (Equation 16), the velocity $\dot{q}$, can be bounded as follows:

$$|\dot{q}| = |\gamma_1 \tanh(k_s \xi) + \gamma_2 \tanh(k_p \dot{q})|,$$

$$\leq |\gamma_1 \tanh(k_s \xi)| + |\gamma_2 \tanh(k_p \dot{q})|,$$

$$= \gamma_1 |\tanh(k_s \xi)| + \gamma_2 |\tanh(k_p \dot{q})|,$$

$$\leq \gamma_1 + \gamma_2,$$

$$\leq \text{Vel}_{\text{max}}, \tag{17}$$

where (Condition 9) on parameters $\gamma_1$ and $\gamma_2$ have been used.

Note that (Inequality 17) means that the desired speed boundedness (Condition 4) is achieved.

4.2. Torque boundedness
In this part of the paper, it is demonstrated that the requested torque $u$ to the actuator by the proposed controller in (Equation 7) is within the prescribed bound (Condition 5).

The requested torque $u$ to the actuator by the controller in (Equation 7) is bounded by:
\[ |u| = |J_{1}\text{sech}^2(k_s\xi)k_s \tanh(q)| \]
\[ - J_{2}\text{sech}^2\left(k_p\dot{q}\right)k_p \dot{q} \]
\[ + f_s \dot{q} + mg \sin(q)|, \]
\[ \leq |J_{1}\text{sech}^2(k_s\xi)k_s \tanh(q)| \]
\[ + |J_{2}\text{sech}^2\left(k_p\dot{q}\right)k_p \dot{q}| \]
\[ + |f_s \dot{q}| + |mg| \sin(q)|, \]
\[ = J_{1}k_s|\text{sech}^2(k_s \xi) \tanh(q)| \]
\[ + J_{2}k_p|\text{sech}^2\left(k_p \dot{q}\right)| |q| \]
\[ + f_s |q| + mg |\sin(q)|, \]
\[ \leq J_{1}k_s|\text{sech}^2(k_s \xi) \tanh(q)| \]
\[ + J_{2}k_p|\text{sech}^2\left(k_p \dot{q}\right)| |\text{Vel}_{\text{max}}| \]
\[ + f_s |\text{Vel}_{\text{max}}| + mg |\sin(q)|, \]
\[ \leq J_{1}k_s + J_{2}k_p |\text{Vel}_{\text{max}}| + f_s |\text{Vel}_{\text{max}}| + mg |, \]
\[ \leq \tau_{\text{max}}, \]
where (Inequalities 9, 12 and 17) have been used.

Since the control action \( u \) satisfies (Inequality 18), it follows from the actuator model (Equation 2) that
\[ |\tau| \leq \tau_{\text{max}}. \]

The obtained (Inequality 19) means that the desired torque boundedness objective (Equation 5) is guaranteed.

4.3. Shaft displacement regulation

Taking into account (Equations 7, 8 and 16), a closed-loop system state representation in terms of \( \dot{q} \) and \( \xi \) can be written as follows:
\[
\frac{d}{dt} \begin{bmatrix} \dot{q} \\ \xi \end{bmatrix} = \begin{bmatrix} -\gamma_1 \tanh(k_s \xi) - \gamma_2 \tanh(k_p \dot{q}) \\ \tanh(q) \end{bmatrix},
\]
which is a nonlinear autonomous dynamic system having one unique equilibrium at \( [\dot{q} \; \xi]^T = 0 \in \mathbb{R}^2 \).

Let us consider the following continuously differentiable function:
\[ V(\dot{q}, \xi) = \frac{k_s}{\gamma_1} \ln[\cosh(q)] + \ln[\cosh(k_s \xi)]. \]

Furthermore, function \( V(\dot{q}, \xi) \) above is also globally positive definite and radially unbounded. So, \( V(\dot{q}, \xi) \) qualifies as a Lyapunov function candidate. Figure 4 depicts a typical shape of \( V(\dot{q}, \xi) \).
The time derivative of $V(\tilde{q}, \xi)$ in (Equation 21) is:

$$\dot{V}(\tilde{q}, \xi) = \frac{k_s}{\gamma_1} \tanh(\tilde{q}) \dot{\tilde{q}} + \tanh(k_s \xi) k_s \dot{\xi},$$

$$= \frac{k_s}{\gamma_1} \tanh(\tilde{q}) \left[ -\gamma_1 \tanh(k_s \xi) - \gamma_2 \tanh(k_p \tilde{q}) \right] + \tanh(k_s \xi) k_s \tanh(\tilde{q}),$$

$$= -\frac{k_s}{\gamma_1} \gamma_2 \tanh(\tilde{q}) \tanh(k_p \tilde{q}).$$

(22)

Since $k_s$, $\gamma_1$, and $\gamma_2$ are all positive constants, then $V(\tilde{q}, \xi)$ is a globally negative semidefinite function:

$$\dot{V}(\tilde{q}, \xi) \leq 0 \quad \text{for all } \tilde{q}, \xi \in \mathbb{R}. \quad (23)$$

In virtue of the Lyapunov's direct method (see e.g. Kelly et al., 2005), this implies that the equilibrium $[\tilde{q} \xi]^T = \mathbf{0} \in \mathbb{R}^2$ of the closed-loop system (Equation 20) is stable in the Lyapunov's sense, and it can be shown that both state variables $\tilde{q}$ and $\xi$ are bounded.

In order to prove achievement of the shaft displacement regulation objective (Equation 3), Barbalat's Lemma (Slotine & Li, 1991) shall be invoked.

Taking again the time derivative of $V$ in (Equation 22), it follows that

$$\ddot{V}(\tilde{q}, \xi) = \frac{k_s \gamma_2}{\gamma_1} \left[ \text{sech}^2(\tilde{q}) \tanh(k_s \tilde{q}) \right]
+ k_p \tanh(\tilde{q}) \tanh(\xi) \tilde{q},$$

$$\leq \frac{k_s \gamma_2}{\gamma_1} \left[ 1 + k_p \text{Vel}_{\text{max}} \right] \dot{\tilde{q}},$$

(24)

which allows the conclusion that $\dot{V}$ is a bounded function. By invoking the Barbalat’s Lemma (Slotine & Li, 1991) it leads to $V \to 0$ as $t \to \infty$. Therefore, from Equation (22) it follows that the position error $\tilde{q}$ tends to zero:

$$\lim_{t \to \infty} \tilde{q}(t) = 0,$$

(25)

which is equivalent to the shaft displacement regulation objective (Equation 3).
5. Experimental study
A pendulum-like torque-driven gravity unbalanced mechanism located at Instituto Politécnico Nacional-CITEDI was used to illustrate through experiments the theoretical results. A diagram of the system is depicted in Figure 5.

The measurement data are obtained with the DAQ Sensoray 626 which has input ports for optical encoders, bidirectional input/output digital ports and analog input/output ports. This DAQ allows interacting with Matlab/Simulink and performs real-time experiments through Real-Time Windows Target libraries. The control algorithm in (Equation 7) was executed at a sampling period of $1 \times 10^{-3}$ [s].

As actuator, a brushed direct current motor model 14207S-008 from Pittman was used with output torque limit

$$
\tau_{\text{max}} = 0.35 [\text{Nm}].
$$

The value of the motor speed limit $\text{Vel}_{\text{max}}$ was set to

$$
\text{Vel}_{\text{max}} = 5 [\text{rad/s}].
$$

The motor constant is

$$
k_{m} = 0.0706 [\text{Nm/A}].
$$

Position measurement is carried out by an optical encoder with resolution of 2000 pulses per revolution (ppr). The motor is powered by the servoamplifier Advanced Motion Controls model 30A20AC configured in current mode with relation

$$
i = k_{sa} v,
$$

where $v \in \mathbb{R}$ is differential voltage input of the servoamplifier, $i \in \mathbb{R}$ is the delivered current to the load and

$$
k_{sa} = 1 [\text{A/V}]
$$

is the servoamplifier gain. Finally, the delivered torque is given by the relation

$$
\tau = k_{m} i = k_{m} k_{sa} v = 0.0706 v.
$$

(26)
Considering actuator model (Equation 2) and Equation (26), the requested torque $u$ and the voltage $v$ are related by the following equation:

$$v = \frac{u}{0.0706}. \quad (27)$$

Estimate of the plant parameters (obtained by off-line least squares method) are:

$$J = 0.01204,$$
$$f_v = 0.004,$$
$$mgl = 0.1569.$$

To select the controller parameters, first choose $\gamma_1$ and $\gamma_2$ in order to satisfy (Condition 9). Choose $k_p$ according to (Condition 11). Then choose a large value of $k_s$ (which will be restricted by the previous selection of controller parameters $\gamma_1$, $\gamma_2$ and $k_p$, and by the plant parameters, and by the given speed and torque limits) that satisfy (Condition 12), and finally use (Equation 13) to compute $q(0)$.

Two experiments were performed. Parameters of the controller in (Equation 7) and desired joint positions of the experimental study were set as in Table 1.

The initial conditions of the system model (Equation 1) were:

$$q(0) = 0,$$
$$\dot{q}(0) = 0. \quad (28)$$

The controller parameters $\gamma_1$ and $\gamma_2$ selected as in Table 1, ensure that (Condition 9) are satisfied. On the other hand, the controller parameters $k_p$ and $k_s$, hold the tuning rules (Inequalities 11 and 12). The null initial speed $|\dot{q}(0)|$ in (Equation 28) satisfies (Inequality 10). Thus, all tuning rules: (Conditions 9, 11 and 12) and (Equation 13) are satisfied, so according to the closed-loop system analysis, it is expected that the control objective in Equations (3–5) are achieved.

Results of Experiment 1 are presented in Figures 6–9.

Figure 6 shows the shaft position $q(t)$ in blue continuous line and its desired position $q_d = 2$ in horizontal red dashed line.

Figure 7 depicts the estimation of shaft velocity $\dot{q}(t)$. Figure 8 shows the computed control action $u(t)$. Finally, Figure 9 shows $u(t)$ vs. $\dot{q}(t)$ evolving inside the “safe zone” as specified by the control objectives (Conditions 4 and 5).

| Table 1. Parameters of the controller in (7) and desired joint positions of the experimental study |
|---------------------------------------------------------------|
| Parameter       | Experiment 1 | Experiment 2 |
|------------------|--------------|--------------|
| $q_d$            | 2            | 5            |
| $\gamma_1$      | 4            | 4            |
| $\gamma_2$      | 1            | 1            |
| $k_p$            | 1            | 2.5          |
| $k_s$            | 2.3          | 0.4          |
| $\dot{q}(0)$     | -0.1069      | -0.6385      |
Figure 6. Experiment 1. Shaft position \( q(t) \). The desired value \( q_d = 2 \) is represented by the horizontal red dashed line.

Figure 7. Experiment 1. Estimation of shaft velocity \( \dot{q}(t) \). The limit values \( \text{Vel}_{\text{max}} \) and \( -\text{Vel}_{\text{max}} \) are in red dashed lines and the values of \( \gamma_1 - \gamma_2 \) and \( -(\gamma_1 + \gamma_2) \) in green dashed lines.

Figure 8. Experiment 1. Computed control action \( u(t) \). The limit values of \( f_{\text{max}} \) and \( -f_{\text{max}} \) are in horizontal red dashed lines.
Figure 9. Experiment 1. Plot of computed \( u(t) \) versus \( q(t) \) within the inner “safe operating zone”.

Figure 10. Experiment 2. Shaft position \( q(t) \). The desired value \( q_d = 5 \) is represented by the horizontal red dashed line.

Figure 11. Experiment 2. Estimation of shaft velocity \( \dot{q}(t) \). The limit values \( \text{Vel}_{\text{max}} \) and \( -\text{Vel}_{\text{max}} \) are in red dashed lines and the values of \( r_1 - r_2 \) and \( -(r_1 - r_2) \) in green dashed lines.
Results of Experiment 2 are presented in Figures 10–13, with the shaft position $q(t)$, estimation of velocity $\dot{q}(t)$, computed control action $u(t)$ and computed $u(t)$ versus $\dot{q}(t)$ in Figures 10, 11, 12, and 13, respectively. Note from Figure 13 that $u(t)$ vs. $\dot{q}(t)$ evolve inside the “safe zone”.

Steady-state errors of position $q(t)$ in Figures 6 and 10 are observed, which may be due to: (1) unmodelled static friction present at the shaft-bearing of the DC motor actuator; (2) the implementation of the continuous controller in (Equation 7) as a discrete controller for the experimental study; (3) the velocity $\dot{q}$ is not being directly measured, instead of that, a velocity estimation based in position numerical differentiation is being used; and (4) the quantization noise in the digital-to-analog converter.

6. Conclusion
The control objective of shaft position regulation with simultaneous desired bounds of both torque and speed of an electro-mechanical system has been introduced in this paper. A nonlinear dynamic controller for the case of a torque-driven gravity nonlinear unbalanced device model was proposed. This research is a first step toward the formulation and design of “self–protecting” control system for more general, complex and challenging systems like robot manipulators where protection of motor–actuators is mandatory.
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