

Iterative Feedback Tuning for the joint controllers of a 7-DOF Whole Arm Manipulator

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Abstract—This paper presents the tuning of the Proportional Integral Derivative (PID) controllers of the joints of a 7 degrees of freedom (DOF) manipulator with friction using the Iterative Feedback Tuning method. In the procedure both experimental data and model simulations are used and two different approaches to the approximation of the Hessian are tested. Friction identification is also performed for the implementation of friction compensation over the pre-configured joint Proportional Derivative (PD) control of the manipulator. The responses of the system when using joint PID control and joint PD control with gravity and friction compensation are compared.

I. INTRODUCTION

In a controlled robotic system, gravity compensation with joint Proportional Derivative (PD) control eliminates the offset error in the response caused for the influence of gravity [1]. Nevertheless, the existence of other disturbances such as friction will not guarantee a zero error in the output response. Therefore, the effects of friction must be canceled separately through the implementation of a compensation strategy. In some cases the influence of friction does not affect significantly the performance of the system, so a compensation technique might not be required. The best way to determine the latter is to identify the actual friction phenomena manifested on the system.

A control strategy capable of dealing with friction, when all its parameters are conveniently selected, is the joint Proportional Integral Derivative (PID) control [2]. A suitable method for PID controller tuning is the Iterative Feedback Tuning (IFT), which is an iterative method based in the use of experimental data [3], [4]. The theory behind IFT had been developed for discrete-time linear time-invariant (LTI) systems, however its implementation has been proven to be effective on systems with non linearities [5], [6], [7], [8], [9]. The reliability of this method lies in the fact that the response of the system is recorded and used later to estimate a gradient direction for each parameter of the controller through several iterations, according to the standard of a determined performance measure. IFT is a model-free tuning method, however, when the experiments to obtain the gradient are difficult to implement on the system, the use of a model to conduct this procedure seems suitable.

In order to improve the performance of a 7 degrees of freedom (DOF) robot manipulator configured as a joint PD control with gravity compensation, two different control strategies were developed: 1) A feedforward friction compensation scheme added to the joint PD control and gravity

compensation currently configured in the system, 2) Joint PID control using IFT tuning. During the controller tuning, the response of the actual system is used to estimate a performance measure, while the gradient direction for the parameters is computed using a mathematical model of the system.

Section II describes the dynamic characteristics of the 7-DOF manipulator. Section III explains briefly the structures of the manipulator's PD/PID joint control and some theory behind PD control with gravity and feedforward friction compensation. Section IV portrays the IFT method. The process of tuning the joint PID controllers is developed in Section V, where some plots of the response of the system in experiments are also displayed. Finally, some conclusions are addressed in Section VI.

II. THE MANIPULATOR

The whole arm manipulator (WAM) is a 7-DOF system from *Barrett Technology Inc.* It is a joint torque controlled manipulator equipped with configurable PD/PID control and gravity compensation. All the joints of the manipulator are 1 DOF revolute joints with high backdriveability. The information related to the joints configuration, joint motor drives and the body part masses, centre of gravity and inertia matrix is provided by the manufacturer in the *WAM ARM User's Manual*. An image of the real system is shown in Fig. 1, consisting in a Barret 7-DOF Whole Arm Manipulator with an attached BH8-series BarrettHand.



Fig. 1. The Barret 7-DOF Whole Arm Manipulator with the BH8-series BarrettHand.

A. Dynamics of the manipulator

The 7-DOF manipulator is built by 7 mass links interconnected by 7 revolute joints and an attached grasper. The dynamics of the system may be modeled using a Lagrangian

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formulation which relates the link motion with the applied forces in the joint using generalized coordinates. Alternatively, a different formulation based on a recursive analysis of all the applied forces on each link may be implemented, this method is known as Newton-Euler formulation.

The dynamics of a n -DOF manipulator may be represented as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\dot{\mathbf{q}}, \mathbf{q})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{F}(\dot{\mathbf{q}}) = \boldsymbol{\tau} \quad (1)$$

where the n joint angles $q_1(t), q_2(t), \dots, q_n(t)$, joint velocities $\dot{q}_1(t), \dot{q}_2(t), \dots, \dot{q}_n(t)$ and joint accelerations $\ddot{q}_1(t), \ddot{q}_2(t), \dots, \ddot{q}_n(t)$ are arranged in vectors of length n : $\mathbf{q}(t)$, $\dot{\mathbf{q}}(t)$ and $\ddot{\mathbf{q}}(t)$ respectively. $\mathbf{M}(t)$ is the inertial matrix, vector $\mathbf{C}(\dot{\mathbf{q}}(t), \mathbf{q}(t))$ contains the centrifugal and Coriolis forces, $\mathbf{G}(\mathbf{q}(t))$ is a vector force constituted by the influence of gravity on the system, vector $\mathbf{F}(\dot{\mathbf{q}}(t))$ are the friction forces that affect the joints, and vector $\boldsymbol{\tau}(t)$ is the necessary torque to produce motion.

Friction force is inherent of the velocity of the joint and it is frequently represented by a mathematical model that includes the sliding friction (or Coulomb friction), the breakdown friction (or stiction) and the viscous friction. In most cases if the manipulator is expected to displace at medium or medium-high velocities, the friction can be modeled considering the effects of the viscous friction and the Coulomb friction only. This simplified representation of friction is known as classic friction model:

$$F = F_c \text{sign}(\dot{q}(t)) + \sigma_2 \dot{q}(t) \quad (2)$$

where F_c in the parameter for Coulomb friction, σ_2 is the viscous damping coefficient and $\dot{q}(t)$ is the velocity of the link. The value of the parameters for the classic friction model can be obtained from experimental data through the execution of joint rotations at different constant velocities [10].

III. CONTROL STRATEGIES

A. PD with Gravity compensation

The 7-DOF manipulator has been configured by the manufacturer with joint PD control and gravity compensation expressed as (3), where the control joint torque $\tau_c(t)$ is given as the sum of the difference between the reference and measured position $\tilde{q}(t)$, known as position error, multiplied by a constant proportional gain K_P , the derivative of the error $\dot{\tilde{q}}(t)$ multiplied by a derivative gain K_D and the compensation for gravity $g(q)$, which is a function of the joint position.

$$\tau_c(t) = K_P \tilde{q}(t) + K_D \dot{\tilde{q}}(t) + g(q(t)) \quad (3)$$

The diagram in Fig. 2 shows the configuration of a joint PD controller with gravity compensation as implemented in the real system. This control strategy successfully cancels the effects of gravity but it does not compensate the friction phenomena manifested in the joints of the manipulator. Then, the response error when executing a desired joint rotation is always nonzero.

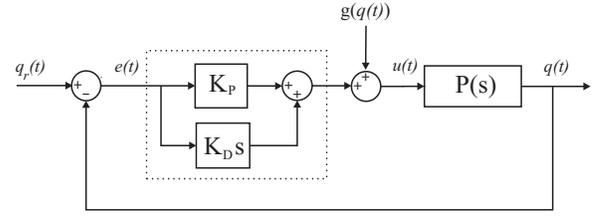


Fig. 2. Configuration of the joint PD control with gravity compensation. $q_r(t)$ is the reference trajectory, P represents the manipulator, g is the gravity compensation as a function of the joint position $q(t)$, K_D and K_P are the derivative and proportional gains, respectively.

B. PD with Gravity and Friction compensation

Feedforward compensation of systems consist in a control scheme working in parallel with the actual controller of the system. It is a desirable option for compensating relatively known disturbances due to the fact that it can be tuned individually without affecting the stability of the on system controller [11], [12], [13].

The configuration used in the development of the present work is shown in Fig. 3. In the diagram, a feedforward compensation block $C_f(s)$ is added to the joint PD control configuration shown in Fig. 2. This configuration is friendly for software implementation and its response depends on the reference signal only, the function that defines the compensation block $C_f(s)$ is explained as follows.

If each link of the manipulator is considered as a single mass in motion, the feedforward scheme must ensure that the force needed to execute the desired rotation is generated [14]. Then, the actuating force $\tau_{ff}(t)$ necessary to rotate the joint may be expressed as the sum of the mass m of the link multiplied by its reference acceleration $\ddot{q}_r(t)$, the viscous damping coefficient σ_2 multiplied by the reference velocity $\dot{q}_r(t)$ and the friction force as function of the velocity:

$$\tau_{ff}(t) = m\ddot{q}_r(t) + \sigma_2\dot{q}_r(t) + F_c(\dot{q}_r(t)) \quad (4)$$

where F_c is the Coulomb friction that affects the joint according to (2). Mathematically, the friction and gravity compensated joint PD control is defined as the sum of the contributions of the control actuating force $\tau_c(t)$ and the compensation torque $\tau_{ff}(t)$. The actuating joint torque $\tau(t)$ is

$$\tau(t) = \tau_c(t) + \tau_{ff}(t) \quad (5)$$

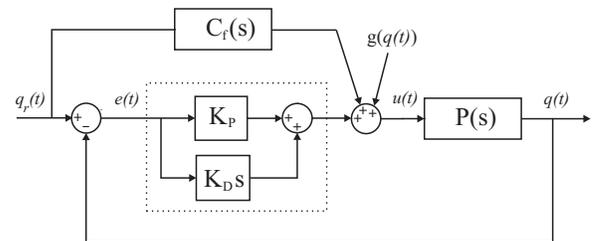


Fig. 3. Diagram of the PD control with gravity compensation, augmented with a feedforward compensation block expressed as $C_f(s)$.

C. PID control

As previously mentioned, the 7-DOF manipulator has been configured by the manufacturer with joint PD control and gravity compensation. Nevertheless, the system may be configured to perform under joint PID control by properly adjusting the gains of the joint controllers.

PID control may be considered as an extended PD control which, apart from being dependent of the position error and the derivative of the error, it considers the accumulation of the past errors through an integral term $\int_0^t \tilde{q}(\lambda) d\lambda$. The actuating torque is expressed as

$$\tau_c = K_P \tilde{q}(t) + K_D \dot{\tilde{q}}(t) + K_I \int_0^t \tilde{q}(\lambda) d\lambda \quad (6)$$

where $\tilde{q}(t)$ is the position error, $\dot{\tilde{q}}(t)$ is the derivative of the error and K_P , K_D and K_I are the proportional, derivative and integral gains respectively. The values for K_P , K_D and K_I are usually adjusted using different techniques according to the complexity of the process plant [15]. In nonlinear systems it is possible to iteratively estimate this parameters by applying an IFT method, as explained in the next section.

IV. IFT

Iterative feedback tuning is a technique used in iterative control design to find suitable controller parameters through experimental data. The method consists in the realization of several experiments where the reference signal is changing. The obtained data is then used to construct a minimizing criterion based on the error $\tilde{y}(\rho)$ of the output response. The method relies on the assumption that some disturbance v affects the performance of the system. Then

$$\tilde{y}(\rho) = y(\rho) - y_r \quad (7)$$

where y_r is the desired system response to a reference signal r , $y(\rho)$ is the actual response as a function of ρ , which is the vector that contains the controller parameters. A control objective function $J(\rho)$ can be subsequently defined as a quadratic function of the expected value of the error $\tilde{y}(\rho)$ with respect to the disturbance v of the system.

$$J(\rho) = \frac{1}{2N} \sum_{i=1}^N E[\tilde{y}(\rho)^2] \quad (8)$$

Whenever the condition of optimality $J'(\rho) = 0$ is met, the value of the parameter ρ , according to $\rho^* = \arg \min_{\rho} J(\rho)$, can be calculated iteratively by means of

$$\rho_{i+1} = \rho_i - \gamma_i R_i^{-1} \left[\frac{\partial J(\rho_i)}{\partial \rho} \right] \quad (9)$$

where R_i^{-1} is a positive definite matrix, γ_i is the iteration step and $\left[\frac{\partial J(\rho_i)}{\partial \rho} \right]$ is an estimate of the first derivative of the objective function.

The iterative feedback tuning technique is fully documented by Hjalmarsson in [16].

A. The iterative algorithm

The value of γ_i in (9) represents the size of the iteration step and it is variable through the tuning process. Generally this value is equal to 1 for the first iterations and becomes smaller as the instability point is nearly reached. The rest of the parameters that shape (9) are not straightforwardly found and its computation relies on experimental data as subsequently explained.

1) *Estimation of the gradient:* Considering equation (8) the gradient of the objective function can be expressed as

$$\frac{\partial J(\rho)}{\partial \rho} = \frac{1}{N} \sum_{i=1}^N E \left[\tilde{y}(\rho) \frac{\partial \tilde{y}(\rho)}{\partial \rho} \right] \quad (10)$$

The value of $\tilde{y}(\rho)$ can be obtained with the execution of a closed loop experiment as the one shown in Fig. 4.

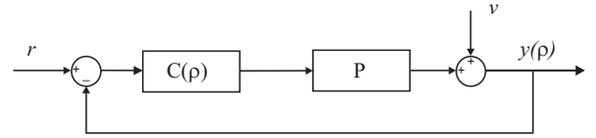


Fig. 4. Open loop experiment designed to find the value of $\tilde{y}(\rho)$. $C(\rho)$ represent the controller of the system as function of the current parameters contained in ρ , P represent the plant, r is the reference signal and $y(\rho)$ is the response of the system affected by a disturbance v .

However, the approximation of $\frac{\partial \tilde{y}(\rho)}{\partial \rho}$ requires the execution of a second experiment. The signal acquired in the previous experiment (let it be known as $y^1(\rho)$) subtracted from the reference signal r , endows the closed loop system of Fig. 4 and the output response is then filtered as shown in Fig. 5. This configuration is proposed by Hjalmarsson and colleagues in [17].

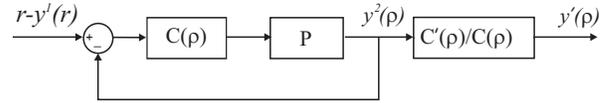


Fig. 5. Open loop experiment designed to find $\tilde{y}'(\rho)$, let $\tilde{y}^1(\rho)$ be the output of the experiment described in Fig. 4. $C(\rho)$ is the controller of the system, P is the plant and $C'(\rho)$ is the derivative of the controller with respect to its parameters.

2) *Approximation of the Hessian:* The matrix R_i in (9) indicates the update direction for the estimation of the controller parameters in each iteration i and it is usually stated as the Hessian matrix of the objective function. A common choice for the approximation of the Hessian is the Gauss-Newton gradient approach expressed by

$$R_i = \frac{1}{N} \sum_{k=1}^N \left(\left[\frac{\partial \tilde{y}(\rho_i)}{\partial \rho} \right] \left[\frac{\partial \tilde{y}(\rho_i)}{\partial \rho} \right]^T \right) \quad (11)$$

Also, a very effective technique to approximate the Hessian based on Broyden-Fletcher-Goldfarb-Shanno (BFGS) method for solving nonlinear optimization problems has been proposed in [3]. The Hessian is approximated for each iteration i as a function of a previous estimation using (12).

TABLE I
FRICTION MODEL PARAMETERS. $V + /V -$ ARE POSITIVE AND
NEGATIVE VELOCITIES RESPECTIVELY.

Joint	Coulomb friction F_c ($V + /V -$)	Viscous friction σ_2 ($V + /V -$)
1	4.4748/ 4.3609	1.3348/ 0.8266
2	2.6385/ 3.5643	3.5572/-2.3951
3	1.7399/ 2.3529	0.3944/ 1.2075
4	1.5414/ 0.7342	-2.7045/-1.0969
5	0.2798/ 0.1172	-0.1972/ 1.4670
6	0.4834/ 0.4417	0.8291/ 0.1836
7	0.0538/ 0.1370	1.0689/ 0.7954

$$B_{i+1} = B_i + \frac{z_i z_i^T}{z_i^T s_i} - \frac{B_i s_i s_i^T B_i}{s_i^T B_i s_i} \quad (12)$$

Here the Hessian $R_i = B_i$, $s_i = \rho_{i+1} - \rho_i$ and $z_i = J'(\rho_{i+1}) - J'(\rho_i)$, B_0 may be an identity matrix for the first iteration. The condition $z_i^T s_i > 0$ must be satisfied, otherwise $B_{i+1} = B_i > 0$.

V. EXPERIMENTS

A. Friction Identification for Feedforward Friction Compensation

Friction identification of the manipulator was developed using a method based on the generation of friction-velocity maps using experimental data. This data is obtained through the execution of joint rotations at different constant velocities. The friction is then shaped into a mathematical model, which parameters are estimated by applying a least squares minimization method as in

$$\sum_{i=1}^n [F(v_i) - \hat{F}(v_i)]^2 \quad (13)$$

where $F(v_i)$ is the measured torque (i.e. the friction force) at certain constant velocity v_i , and $\hat{F}(v_i)$ is the value estimated by the friction model expressed in (2). This technique has been fully documented in [10] and [18].

Table I summarizes the parameters that shape the friction for all the joints of the 7-DOF manipulator. The measured friction suited accurately the shape of the classic friction model. Therefore, the estimated friction can be used as part of the feedforward compensation block.

According to (4), the reference velocity and acceleration must be available in order to complete the compensation scheme. The real system does not provide this signals, but they may be estimated from the reference position signal. The joint velocity is approximated on line by differentiating the reference joint position. Later, the acceleration is calculated by differentiating the respective joint velocity. The compensation torque $\tau_{ff}(t)$ is added to the control loop as shown in Fig. 3.

B. IFT for the WAM joint PID control

The IFT algorithm for controllers with one degree of freedom used to tune the PID controller of every joint of the manipulator is summarized below. Each controller is tuned independently of the others.

- 1) Perform the experiment using the closed loop configuration described in Fig. 4 and define $\tilde{y}^1(\rho) = \tilde{y}(\rho)$.
- 2) Perform the experiment using the closed loop configuration described in Fig. 4 applying $r - \tilde{y}^1(\rho)$ as reference signal and define $\tilde{y}^2(\rho) = \tilde{y}(\rho)$.
- 3) Compute $\frac{\partial C(\rho)}{\partial \rho}$ for all the elements in ρ and filter $\tilde{y}^2(\rho)$ in order to obtain $\frac{\partial \tilde{y}(\rho)}{\partial \rho}$ as shown in the diagram of Fig. 5.
- 4) Estimate the gradient of the objective function with (10).
- 5) Calculate the Hessian of the objective function using the value of the gradient and update the controller parameters for the next iteration.

For this work, the IFT method was developed using both real and simulated data. Some experiments were performed in the real system while others were executed using a dynamic model of the manipulator. The dynamic model includes friction and it is very accurate regarding to the real system, then a realistic response was expected. The steps to implement the IFT method were:

- Perform step 1 of the IFT algorithm for controllers with 1-DOF in the real manipulator and use the measured position $y(\rho)$ to estimate the response error $\tilde{y}^1(\rho)$.
- Use $\tilde{y}^1(\rho)$ to perform step 2 of the IFT algorithm for controllers with 1-DOF in the model, and use the response of the model to define $\tilde{y}^2(\rho)$.
- Perform step 3, 4 and 5 of the IFT algorithm for controllers with 1-DOF.

In order to approximate the Hessian, the BFGS method and the Newton-Gauss method were implemented consecutively. It was noticed that the BFGS method gave more accurate results in the earlier iterations while the Newton-Gauss method was more accurate near the minimum. Hence, the BFGS method was used first to reduce the objective function using a fix step size of $\gamma = 0.5$. And once the objective function was near to the minimum, the Newton-Gauss method was implemented with step sizes of $\gamma = 0.5$ and $\gamma = 0.1$. The values of gamma were assigned according to the response of the system during simulations.

Table II summarizes the IFT process according to the value of the objective function for each joint controller of the manipulator. The objective function was initially estimated for the PID's parameters proposed intuitively. Then, a first iteration was computed using the BFGS method to approximate the Hessian while the final iterations were calculated using the Newton-Gauss approach.

According to Table II, 15 iterations were needed in order to tune the controllers of the whole system. Two experiments had to be executed in each iteration, one in the real system and one through simulation, then a total of 30 experiments were performed.

The value of the objective function $J(\rho)$ in (8) was estimated using the response of the real manipulator which allows a fair perspective of the performance of the controller in each iteration. Every joint of the manipulator was rotated 0.5 rad at a velocity of 0.083 rad/s, one at a time. Each rotation

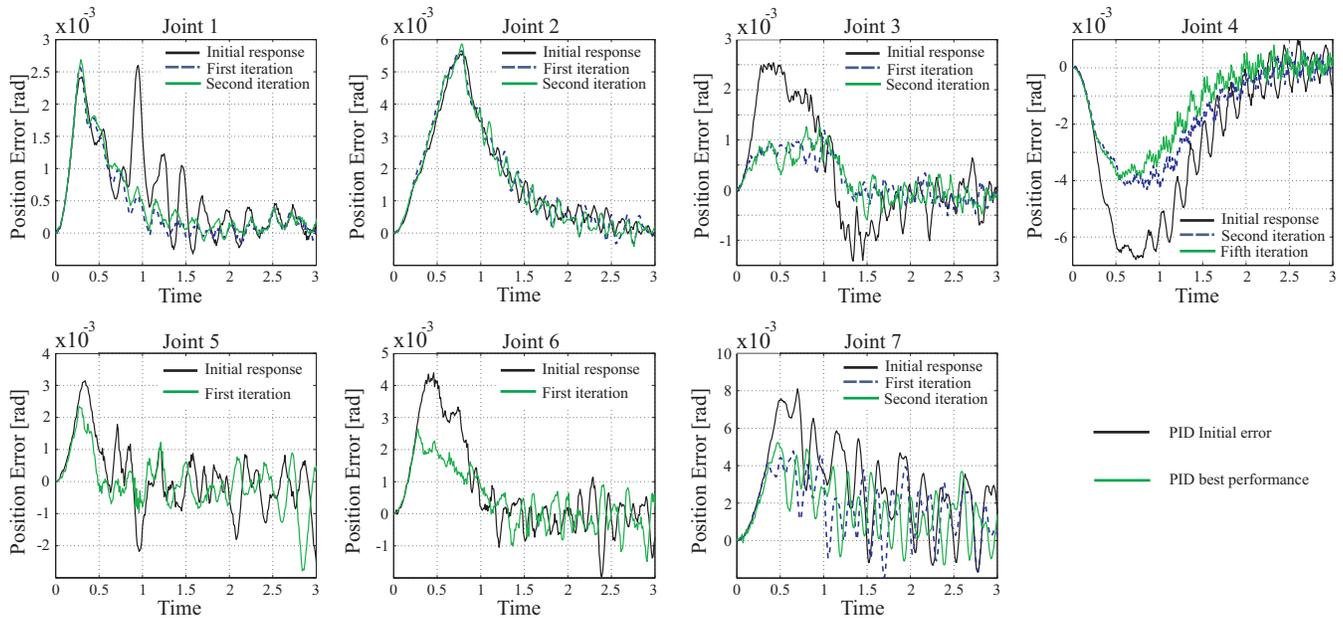


Fig. 6. Joint position error of the 7-DOF whole arm manipulator with joint PID control. The response error is shown for different iterations of the controllers parameters estimated using IFT.

TABLE II
OBJECTIVE FUNCTION $J(\rho)$ FOR THE SEVEN JOINT CONTROLLERS OF THE MANIPULATOR AT DIFFERENT ITERATIONS.

Joint	Initial PID	IFT with BFGS	IFT with Newton-Gauss			
1	0.0715	0.0321	0.0296			
2	0.5837		0.6142	0.5933		
3	0.2343	0.0105	0.0132			
4	1.5818	0.6169	0.5765	0.5235	0.4753	0.4585
5	0.3137	0.1705				
6	0.3511	0.1352				
7	2.0517	0.9095	0.8613			

lasts an approximate of 7.3s. The sampling period of the data measured in the real system is 0.01s. All simulated experiments were run using a dynamic model of the manipulator implemented in MATLAB/SimMechanics. See [10] for a description of the model.

Fig. 6 shows the position error of the seven joints of the manipulator at different iterations, during the first 3 seconds of the rotation. The improvement in the performance of the controllers of joints 1, 3, 4, and 6 is quite evident in this plots. However, in the particular case of the controllers of joints 2 and 5, a better perspective of the improvement of the controller may be obtained by referring to the values of the objective function $J(\rho)$ summarized in Table II. As seen in Table II, the use of the method helped to verify that the initial values of the PID controller parameters of the joint 2 were already the best election.

C. Performance

The performance of the manipulator was analyzed through the execution of a motion task, using each of the three

different control techniques previously described.

The task consisted in a joint rotation of 0.5 rad at a velocity of 0.083 rad/s. This experiment was executed for all the joints of the manipulator one at a time. The duration of each rotation was an approximate of 7.3s. The joint position error was used as a control performance measure.

For every rotation, the joint position was measured while the joint was in motion and the position error was estimated later using the reference trajectory. The feedforward friction compensation was implemented over the on system joint PD control with gravity compensation. The parameters of the joint PID controllers were selected according to the minimum value estimated for the objective function used in the IFT method, in order to guarantee the best performance of the manipulator during the evaluation.

Fig. 7 shows the comparison of the manipulator's response to the assigned task, each graph display the position error for every joint when executing its respective rotation. As expected, the position error of the joint PD control with gravity compensation is nonzero. The first conjecture would be to assume that the feedforward friction compensation would reduce this error, however the performance of the manipulator did no improve significantly after the compensation. On the other hand, it is evident that the manipulator performed better under joint PID control by reducing the joint position error to values notably close to zero.

VI. CONCLUSIONS

Joint PID control in manipulators is a desirable control strategy due to its capacity of successfully neglecting the effects of gravity on the system. For this work, the implementation of an IFT method for selecting the parameters of the joint PID controllers of a 7-DOF manipulator produced

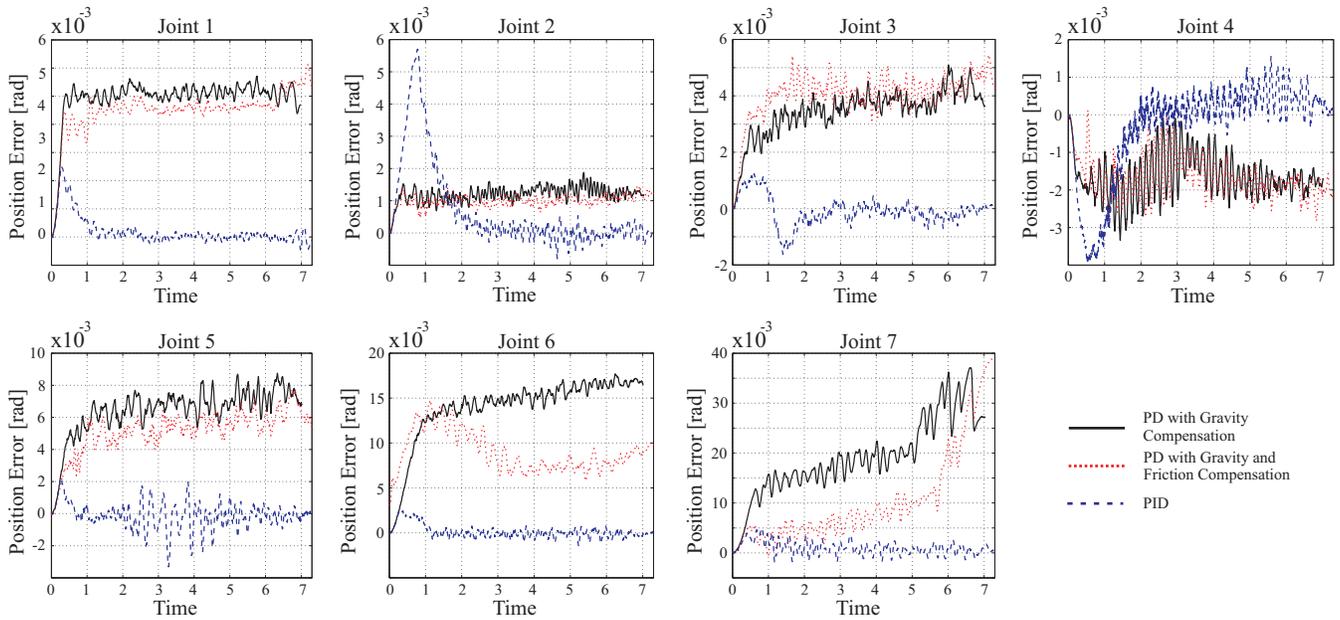


Fig. 7. Joint position error of the 7-DOF whole arm manipulator using different control strategies to execute rotations of the joints. The system is initially configured by the manufacturer with joint PD control with gravity compensation. The implementation of feedforward friction compensation and joint PID control are proposed in order to improve the performance of the manipulator.

satisfactory results. The method was able to overcome the nonlinearities of the system while dealing with friction, even when the employed process data was not 100% experimental. The use of two different techniques to calculate the gradient direction helped to monitor the iterative process and finally, by using them consecutively during the developing of the IFT method, a better approach was accomplished. The iterative feedback tuning for nonlinear systems used for the joint PID control tuning of the manipulator yielded a notorious improvement in the performance which would hardly achieved with the joint PD control and gravity compensation pre-configured in the system.

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