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Friction Compensation in Hybrid Force/Velocity Control for Contour Tracking Tasks

Antonio Visioli, Giacomo Ziliani and Giovanni Legnani

1. Introduction

Nowadays robots in industrial settings are mainly used for repetitive tasks where they act as programmable devices reproducing previously recorded motions in a highly structured environment so that decision and initiative capability is rarely exploited. Contour tracking is, on the contrary, an example of a complex task that requires the manipulator to continuously and autonomously modify its path, coping with the uncertainties typical of unstructured environments (Siciliano & Villani, 1999). In many applications a robot is required to follow a contour while applying a normal force; these tasks include grinding (Thomessen & Lien, 2000), deburring (Ferretti et al., 2000; Ziliani et al., 2005), shape recovery (Ahmad & Lee, 1990), polishing and kinematic calibration (Legnani et al., 2001). The problem of tracking (known and) unknown contours has been studied by many researchers in the last two decades.

Hybrid force/velocity control (Raibert & Craig, 1981) appears to be suitable to be adopted in this context, because it explicitly controls the end-effector force in a selected direction and the end-effector velocity in the other complementary directions. Actually, two kinds of hybrid force/velocity control can be implemented (Roy & Whitcomb, 2002): 1) *explicit hybrid force/velocity control*, where the robot end-effector is controlled by directly imposing the joint torques based on the measured force and position/velocity errors, and 2) *implicit hybrid force/velocity control*, where the end-effector is controlled indirectly by suitably modifying the reference trajectories of the joint position/velocity inner control loops based on the measured force errors. A theoretical comparison (with experimental results) between these two approaches has been developed in (Volpe & Khosla, 1993), although the contour tracking task has not been considered.

Indeed, it is a matter of fact that these methodologies are not widely employed in industrial settings. This might be due to the fact that there is a lack of a characterisation of these techniques from an industrial point of view where the cost/benefit ratio has to be always taken into account. In order to (partially) address this fact, the implementation of an implicit and an explicit hybrid

force/velocity control law for contour tracking of objects of unknown shape performed by an industrial SCARA manipulator is discussed in this chapter. In particular, the problem of compensating joint friction effects, which have to be taken into account in the controller design in order to achieve reasonable performance in terms of normal force and tangential velocity errors, is investigated. Two model-based friction compensation methods are considered: a static method, based on a previously identified model and an adaptive method, where joint friction parameters are recursively updated.

2. Experimental Setup

The experimental set-up adopted for the experiments described in the following sections is available in the Applied Mechanics Laboratory of the University of Brescia and it consists of an industrial robot manipulator manufactured by ICOMATIC (Gussago, Italy) with a standard SCARA architecture where the vertical z axis has been blocked since a planar task is addressed. A detailed dynamic model is described in (Visioli & Legnani, 2002).

Both links have the same length of 0.33 m. The two joints are actuated by means of two DC motors that are driven by conventional PWM amplifiers and position measurements are available by means of two incremental encoders with 2000 pulses/rev. resolution. Harmonic Drive speed reducers are present and the reduction rate is 1/100 for both joints. Velocity is estimated through numerical differentiation whose output is then processed by a low-pass 2-order Butterworth filter with a 100 Hz cut-off frequency and a 1.0 damping ratio.



Figure 1. The SCARA robot during the contour tracking of a complex shape

An ATI 65/5 force/torque sensor capable of measuring forces in a range of ± 65 N and with a resolution of 0.05 N is mounted at the manipulator's wrist. The corresponding signals are processed at 7.8 kHz frequency by an ISA DSP based board.

The contact is achieved by means of a proper plastic probe endowed with a ball bearing with an 8 mm diameter whose aim is reducing tangential friction forces that may arise from the contact with the piece (see Figure 1).

The overall control law is implemented (in C/C++ language) by means of a PC-based controller based on a QNX4 real time operating system. Acquisition and control are performed at a 1 kHz frequency.

3. Hybrid Force/Velocity Control

3.1 Problem formulation

A sketch of the SCARA robot is shown in Figure 2. Frame (0) refers to the robot base, while task frame (T) has its origin on the robot end-effector with its n and t axes that are directed respectively along the normal and tangential direction of the contour of the piece, whose geometry is assumed to be unknown; ϑ denotes the angle between n axis and x axis of frame (0).

Let $Q = [q_1, q_2]^T$ be the vector of the joint positions and \dot{Q} its first time derivative. Since a suitable belt transmission keeps the end-effector with constant orientation with respect to the absolute frame, force measurements are directly available in frame (0). Let $F_{(0)} = [F_x, F_y]^T$, $F_{(T)} = [F_t, F_n]^T$ be the vector of the contact force in frame (0) and (T) respectively. They are related to each other by the equation $F_{(0)} = M_{0T}(\vartheta)F_{(T)}$ denoting with M_{ij} the rotation matrix from frame j to frame i . Note that

$$M_{0T}(\vartheta) = \begin{bmatrix} \sin \vartheta & \cos \vartheta \\ -\cos \vartheta & \sin \vartheta \end{bmatrix}. \quad (1)$$

Vector $V_{(T)} = [V_t, V_n]^T$ representing the Cartesian velocity in frame (T) can be obtained from the relation

$$V_{(T)} = M_{T0}(\vartheta)V_{(0)} = M_{T0}(\vartheta)J(Q)\dot{Q} \quad (2)$$

where $J(Q)$ is the robot Jacobian. The aim of the contour tracking task is to control the normal force and the tangential velocity of the robot probe along n and t directions of task frame (T) respectively.

These directions can be easily estimated, assuming that the contact friction force on the tangent direction is negligible with respect to the normal contact force (note that this is achieved by adopting a suitable probe endowed with a ball bearing, as described in Section 2), by on-line estimating the angle ϑ as:

$$\vartheta = \text{atan2}(F_y, F_x) = \arctan\left(\frac{F_y}{F_x}\right) \pm \pi. \quad (3)$$

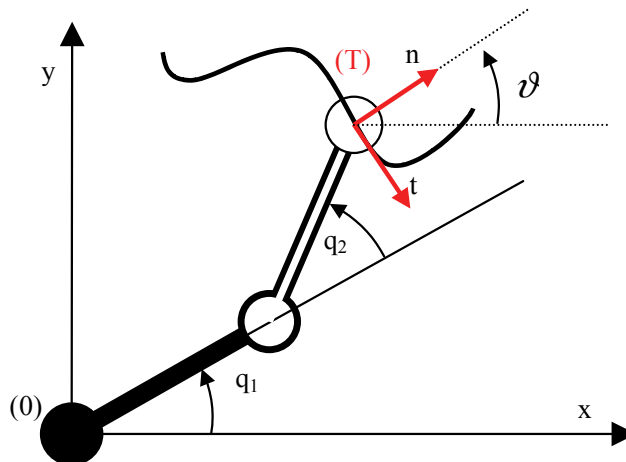


Figure 2. Sketch of a SCARA robot following a contour

3.2 Explicit hybrid force/velocity control

It is well known that the manipulator dynamics can be expressed as:

$$B(Q)\ddot{Q} + C(Q, \dot{Q})\dot{Q} + f(\dot{Q}) + G(Q) = \tau - J(Q)^T F_{(0)} \quad (4)$$

where $B(Q)$ is the inertia matrix, $C(Q, \dot{Q})$ is the matrix of centrifugal and Coriolis terms, $f = [f_1(\dot{q}_1), f_1(\dot{q}_2)]^T$ is the vector of joint friction forces, $G(Q)$ is the gravity forces term (null for the SCARA robot adopted because it works in a horizontal plane), $\tau = [\tau_1, \tau_2]^T$ is the joint torques vector, and $F_{(0)}$ was defined earlier as the vector of forces exerted from the robot on the environment. A thorough theoretical and experimental investigation of the robot identified its dynamics (Visioli & Legnani, 2002; Indri et al. 2002). It was found that, because of the low velocities and accelerations involved in conventional contour tracking tasks, the effects of the inertial and Coriolis forces can be neglected with respect to contact forces and friction terms. As a consequence of this, equation

(4) can be reduced to

$$\tau \equiv f(\dot{Q}) + J^T(Q)F_{(0)}. \quad (5)$$

In an explicit hybrid force/velocity control law the robot end-effector is controlled by directly imposing the joint torques based on the measured force and position/velocity errors (*i.e.*, no joint position/velocity inner loops are present). Based on the robot dynamic equation (5), the control scheme shown in Figure 3 can be adopted. The joint torques τ_1 and τ_2 for the first and the second joint respectively are calculated as:

$$\tau = J^T(Q)M_{0T}(U_{(T)} + K_R R) + \hat{f} \quad (6)$$

where $R = [\bar{v}_t, \bar{f}_n]^T$ is the vector of the tangential velocity and normal force reference values, $K_R = \text{diag}[k_{V,ff}, k_{F,ff}]$ is the diagonal matrix of feedforward gains, $\hat{f} = [\hat{f}_1(\dot{q}_1), \hat{f}_1(\dot{q}_2)]^T$ is an available estimate of the joint friction torques (see Section 4) and

$$U_{(T)} = [u_{PID,V}, u_{PI,F} + k_{v,fb}(\bar{v}_n(t) - v_n(t))]^T \quad (7)$$

where $u_{PID,V}$ is the tangential velocity PID output, $u_{PI,F}$ is the normal force PI output, $\bar{v}_n(t) = 0$, $v_n(t)$ is the velocity of the end-effector in the normal direction and $k_{v,fb}$ is a proportional gain.

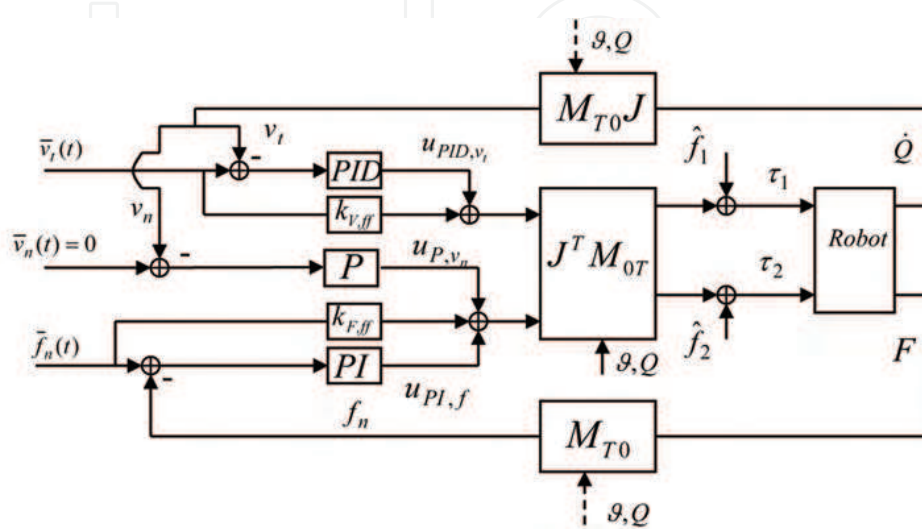


Figure 3. The explicit hybrid force/velocity control scheme

Note that the use of a normal force derivative term has been avoided in (6) (indeed, only the proportional and the integral actions have been employed) as the derivation of such a signal is ill-conditioned (Craig, 1989). Conversely, the adoption of a normal force velocity feedback loop has been proven to be effective to compensate for the large force oscillations due to the effects of link masses (and joint elasticities) in a large portion of the workspace (Jatta et al., 2006). Further, a gain scheduling approach has been adopted in order to take into account the configuration dependent dynamics of the manipulator during a constrained motion (Ziliani et al., 2006).

3.3 Implicit hybrid force/velocity control

In the considered implicit hybrid force/velocity control strategy, a hybrid force/velocity controller determines the reference input for an inner position control loop. The latter is shown in Figure 4, where $\bar{S} = [\bar{x}, \bar{y}]^T$ is the end-effector reference position in the Cartesian space and \bar{q}_1 and \bar{q}_2 are the corresponding joint reference position (which are determined by applying the inverse kinematics). In other words, a standard decentralized position control law (with friction compensation) is applied. The (outer) hybrid force/velocity controller is very similar to that of the explicit hybrid control law and it is depicted in Figure 5.

It is worth stressing at this point that it is claimed in the literature (De Schutter, 1986) that the use of an inner position control loop provides in general several advantages. In particular, the effects of the disturbances in the actuation system are reduced and the force control functionality can be simply added to the existing control architecture devoted to free motion control. Conversely, it is also claimed that the presence of an inner position loop causes a limitation of the bandwidth of the force loop.

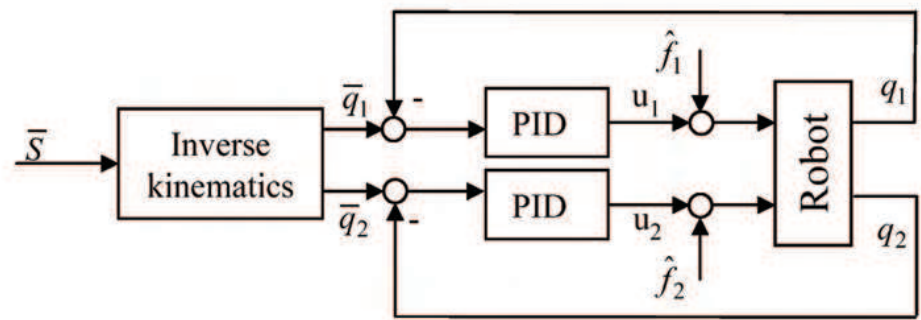


Figure 4. The inner position control loop in the implicit hybrid force/velocity control scheme

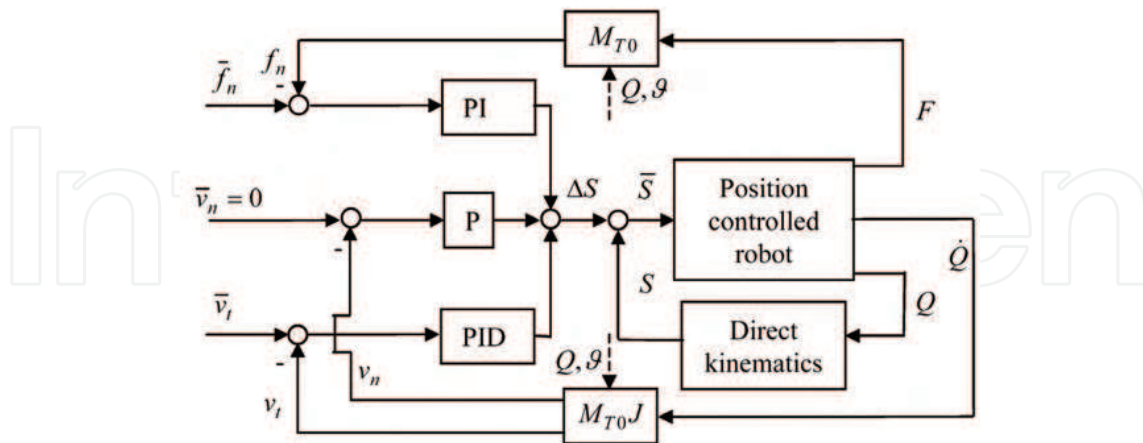


Figure 5. The implicit hybrid force/velocity control scheme

4. Joint Friction Compensation

4.1 Generalities

It is well known that friction compensation is in general very useful to improve the tracking performances of servosystems and this is indeed more significant when the task is dominated by low velocities, as in contour tracking. Actually, friction is a very complex phenomenon and different models to describe it have been proposed in the literature. Basically, they can be classified as static or dynamic models (Olsson et al., 1998). In general, when a static model is adopted, the friction force is described as a (nonlinear) function of the relative velocity of the two surfaces that are in contact. Based on these considerations, the friction terms $f_i(\dot{q}_i)$ mentioned in equations (4) and (5) can be approximated by polynomial functions of degree h (Bona et al., 2003). Positive and negative velocities might be considered separately to obtain better results in case the actual friction function is not symmetrical as might occur in industrial robots (Daemi & Heimann, 1996). Defining ($i = 1, 2$):

$$P_i := [p_{i0} \ p_{i1} \ \cdots \ p_{ih}] = \begin{cases} [p_{i0}^- \ p_{i1}^- \ \cdots \ p_{ih}^-] & \text{if } \dot{q}_i < 0 \\ [p_{i0}^+ \ p_{i1}^+ \ \cdots \ p_{ih}^+] & \text{if } \dot{q}_i > 0 \end{cases} \quad (8)$$

and

$$\Omega_i := [1 \ \dot{q}_i \ \dot{q}_i^2 \ \cdots \ \dot{q}_i^h]^T \quad (9)$$

the friction term can be modelled for the i th axis as $f_i(\dot{q}_i) = P_i \Omega_i$. If \hat{P}_i is an available estimate of vector P_i the joint friction torque can be estimated as

$$\hat{f}_i(\dot{q}_{ref,i}) = \hat{P}_i \Omega_{ref,i} \quad (10)$$

Where

$$\Omega_{ref,i} := [1 \dot{q}_{ref,i} \dot{q}_{ref,i}^2 \cdots \dot{q}_{ref,i}^h]^T \quad (11)$$

and $\dot{q}_{ref,i}$ is the i th joint velocity reference. Note that, $\Omega_{ref,i}$ was used instead of Ω_i because better experimental performance was achieved (Whitcomb et al., 1997). Since reference velocities are not directly available they have to be reconstructed from workspace references as

$$[\dot{q}_{ref,1}, \dot{q}_{ref,2}]^T = J^{-1}(Q) M_{0T} [\bar{v}_t, 0]^T. \quad (12)$$

Two methods for the determination of \hat{P}_i are considered hereafter. They will be referred as Static model-based Friction Compensation (SFC) and Adaptive Friction Compensation (AFC).

4.2 Static Friction Compensation

The first method that has been considered consists of performing suitable experiments on the robot and then of applying an off-line estimation procedure based on a recursive least squares algorithm in order to estimate all the robot parameters including friction torques ($h=3$ was used) (Indri et al., 2002). Once the (static) friction model is estimated, it can be employed in the control law both for the explicit and the implicit hybrid force/velocity control law during the contour tracking tasks. However, this technique is time consuming (as *ad hoc* experiments have to be performed) and not always appropriate as it is known that friction torques may change over time and might not be always reliably predicted (Daemi & Heimann, 1996). Thus, control performance may decrease during the robot operation and therefore it is useful to compensate for the joint friction effect using an adaptive procedure.

4.3 Adaptive Friction Compensation

The second method considered for the evaluation of \hat{P} is to employ a simple gradient descent based algorithm for each joint (Visioli et al., 1999). For this purpose, a friction error signal can be defined as

$$e = [e_1(\dot{q}_1), e_2(\dot{q}_2)]^T = f(\dot{Q}) - \hat{f} \quad (13)$$

The friction error signal can be determined suitably both for the explicit and the implicit hybrid control law. In the first case, if the model expressed by (5) represents a perfect prediction, then the output of the PID controllers in (6) would be equal to zero. Consequently the PID output can be regarded as a joint friction prediction error signal. In other words, adopting $k_{V,ff} = 0$ and $k_{F,ff} = 1$ equations (5) and (6) result in:

$$\hat{f}(Q) + u_{PID}^* + J^T(Q)F_{(0)} = f(\dot{Q}) + J^T(Q)F_{(0)} \quad (14)$$

where

$$u_{PID}^* = J^T(Q)M_{0T}U_{(T)} \quad (15)$$

is the workspace output of PID regulators transformed into the joint space. By following a similar reasoning, in case the implicit control law is employed, it is

$$\hat{f}(Q) + u_{PID}^* = f(\dot{Q}) + J^T(Q)F_{(0)} \quad (16)$$

where

$$u_{PID}^* = [u_1, u_2] \quad (17)$$

is the vector of the outputs of the joint position control loops.

The friction error signal (12) can therefore be set equal to u_{PID}^* , namely,

$$e = u_{PID}^* \quad (18)$$

where equation (15) or (17) has to be considered if the explicit or the implicit controller is adopted respectively.

Based on the value of the error signal (13), the polynomial coefficients of the friction function can be updated every control step k with the following AFC algorithm ($i=1,2$):

$$\begin{aligned} \Delta \hat{P}_i(k) &= \eta e_i(k) \Omega_i(k) + \alpha \Delta \hat{P}_i(k-1) \\ \hat{P}_i(k) &= \hat{P}_i(k-1) + \Delta \hat{P}_i(k) \end{aligned} \quad (19)$$

representing a standard least-mean-square algorithm (see (Haykin, 1999) for details and for an analysis of the convergence). The updated vector $\hat{P}_i(k)$ can then be used in model (10). Note that parameter η determines the velocity of the descent to the minimum and therefore the adaptation velocity. However, a high value of η might produce undesirable oscillations in the values of the polynomial coefficients. In any case, an appropriate value of η can be easily selected starting from a small value and increasing it until these oscillations begin to appear. Parameter α is the momentum coefficient, that helps to prevent large oscillations of the weight values and to accelerate the descent when the gradient is small. For the experiments presented in Section 5, the values $\eta = 0.005$, $\alpha = 0.9$ and $h = 1$ have been selected. Actually, choosing $h = 1$ means that a local linearization of the friction function is employed for each value of the joint velocity. The capability of modelling a complex nonlinear function, i.e. the friction phenomena is therefore due to the changing of the polynomial coefficients in order to always have an appropriate local approximation (see Figure 6). Indeed, the aim of the AFC technique is not to provide a correct global model of the friction effect, but to compensate for it. Thus, it is sufficient that the friction effect is accurately predicted just in the neighborhood of the joint velocity value in the considered time instant, since the adaptation procedure is always active to compensate for variations.

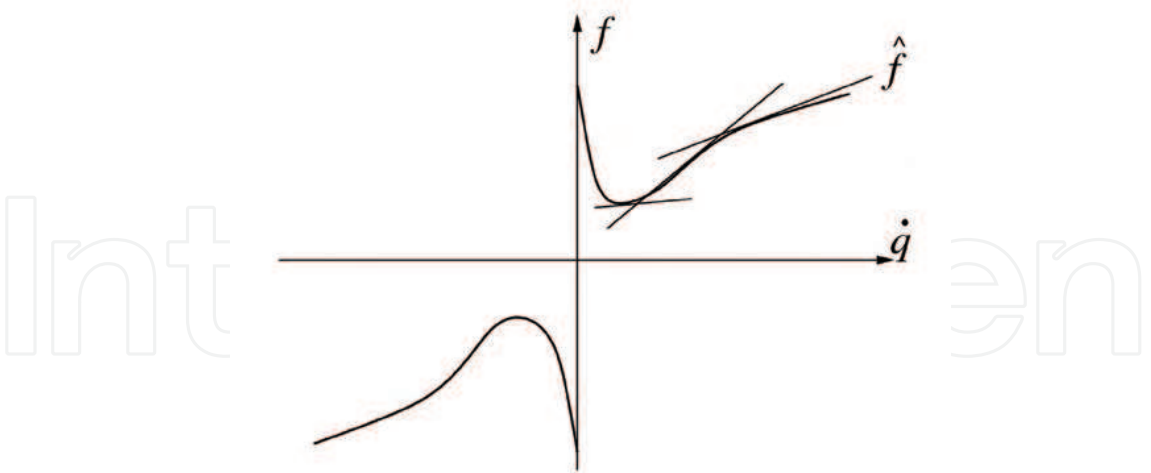


Figure 6. Local linearisation of the friction function

5. Experimental Results

Experimental results, aiming at verifying the effects of the joint friction compensation, have been obtained by considering an iron disk with a diameter of 180 mm placed in two different positions (called ‘A’ and ‘B’) of the manipulator workspace, as shown in Figure 7.

It is worth stressing again that the contour tracking task is performed by the control algorithm without any knowledge of the geometry of the workpiece. In both cases, a large set of different normal force set-points [20, 25, 30, 35, 40] N, each at different tangential velocities [10, 20, 30, 40, 50] mm/s, has been selected and the RMS force and velocity error has been calculated for both the explicit and implicit hybrid force/velocity control law, where the use of the SFC method and of the AFC method has evaluated together with the absence of joint friction compensation. The control system parameters, namely the parameters of the PID controllers in the explicit and implicit control schemes, have been selected after a careful trial-and-error procedure.

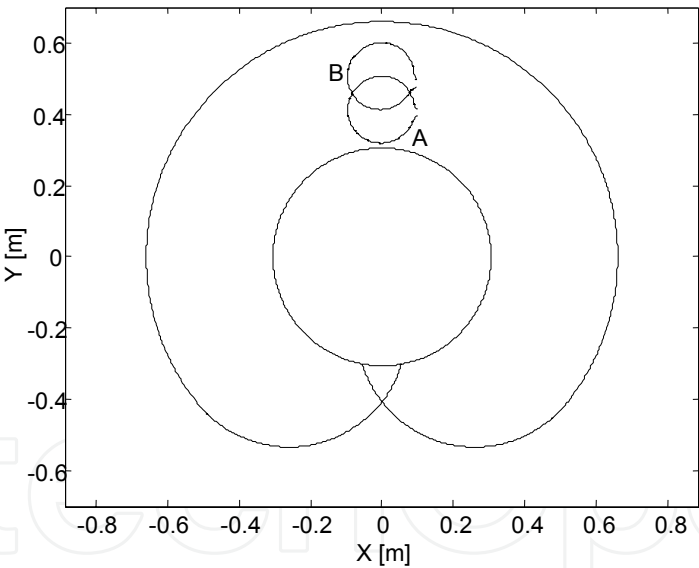
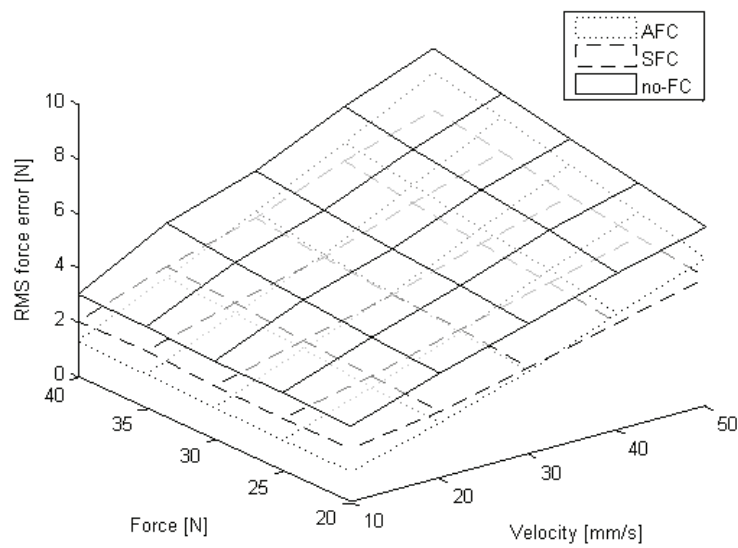


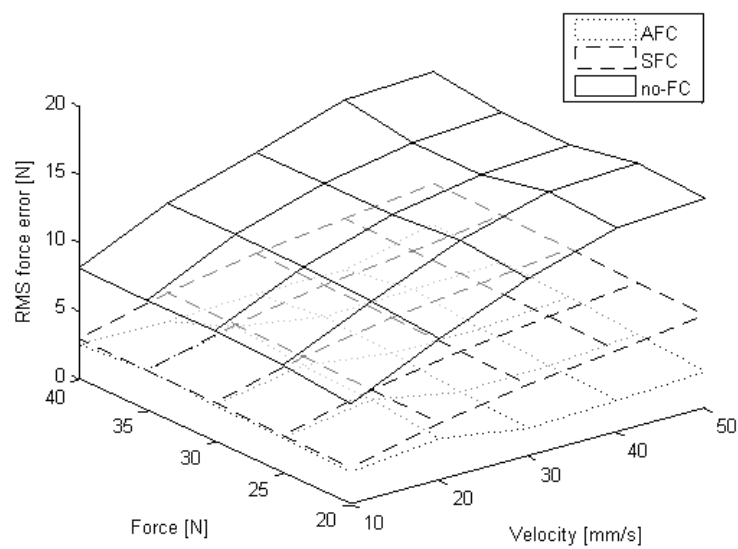
Figure 7. Positions of the workpiece in the manipulator workspace

It is worth noting that the implicit hybrid force/velocity control scheme requires a more significant tuning effort than the explicit one because of the presence of the additional position inner loop.

Results are shown in Figures 8-11. In order to understand the results better, the plots of the obtained normal force and tangential velocity signals for the considered control schemes applied to disk A when the normal force set-point is 30 N and the tangential velocity set-point is 10 mm/s are shown in Figures 12-13.



a)



b)

Figure 8. Force RMS error with no friction compensation and with SFC and AFC for the disk in the A position. a) implicit control; b) explicit control.

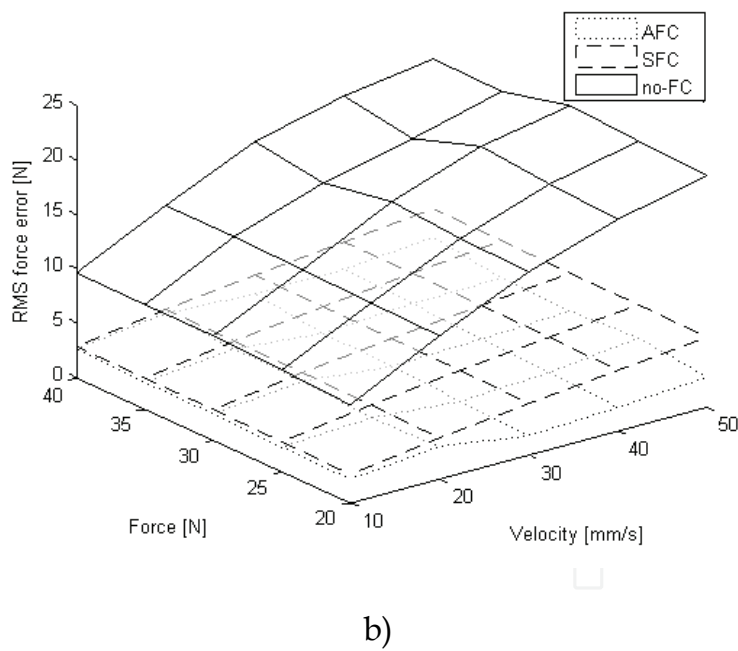
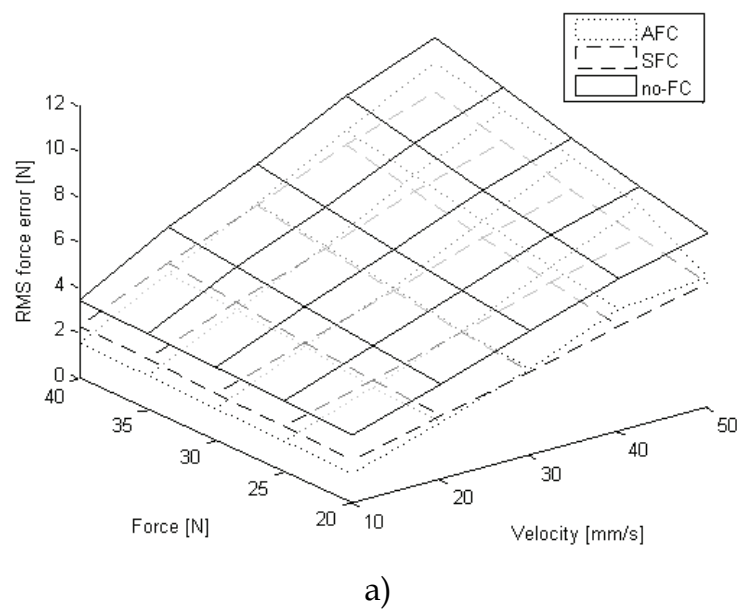


Figure 9. Force RMS error with no friction compensation and with SFC and AFC for the disk in the B position. a) implicit control; b) explicit control.

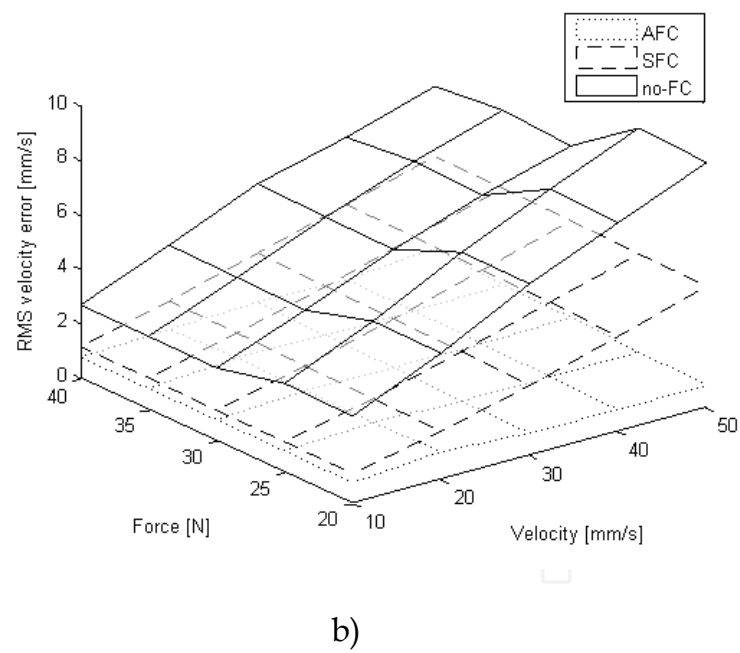
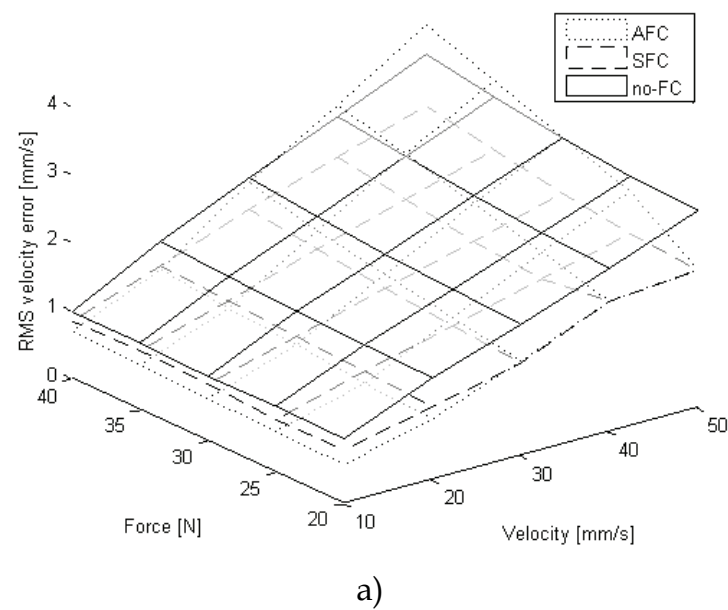


Figure 10. Velocity RMS error with no friction compensation and with SFC and AFC for the disk in the A position. a) implicit control; b) explicit control.

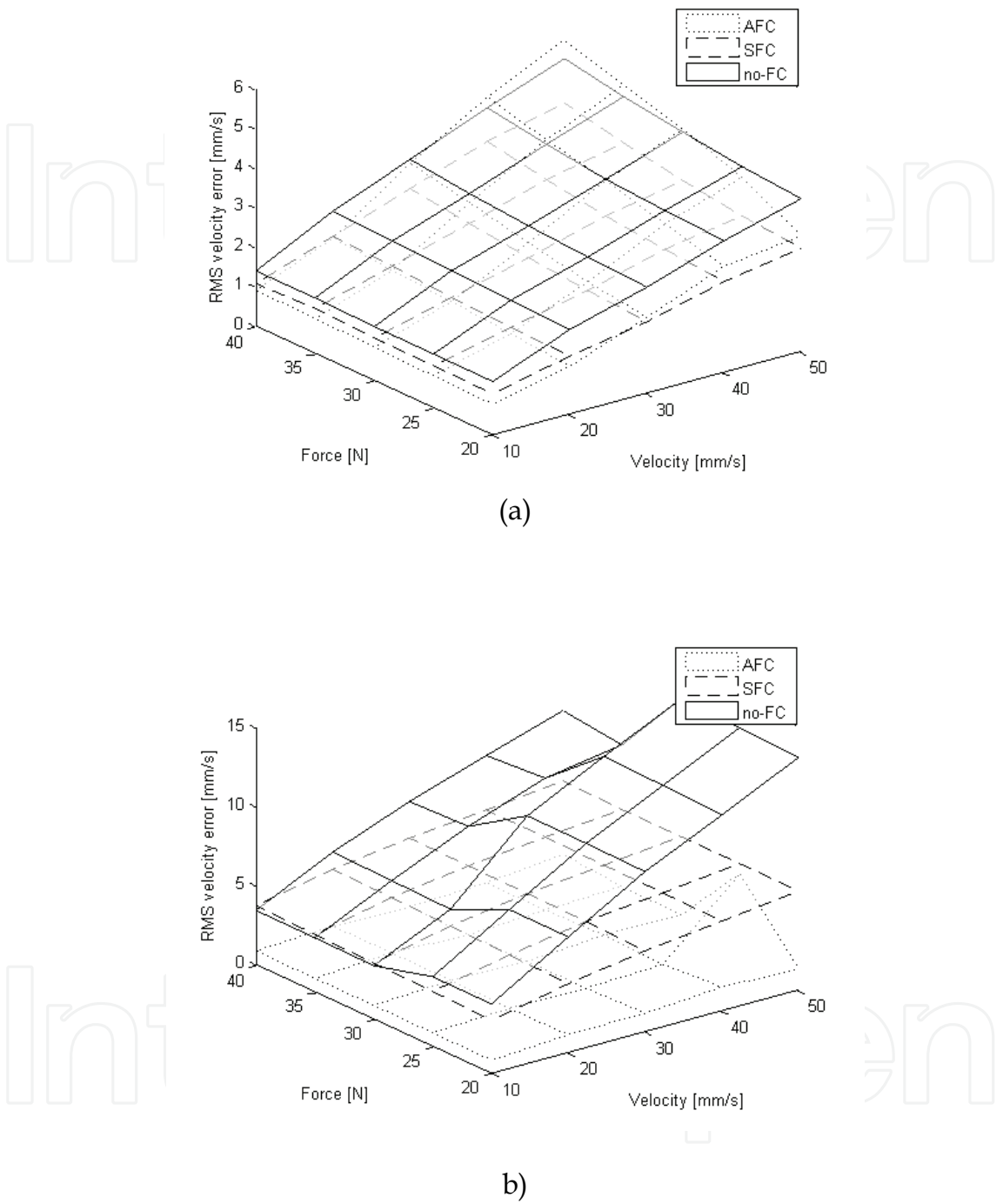


Figure 11. Velocity RMS error with no friction compensation and with SFC and AFC for the disk in the B position. A) implicit control; b) explicit control.

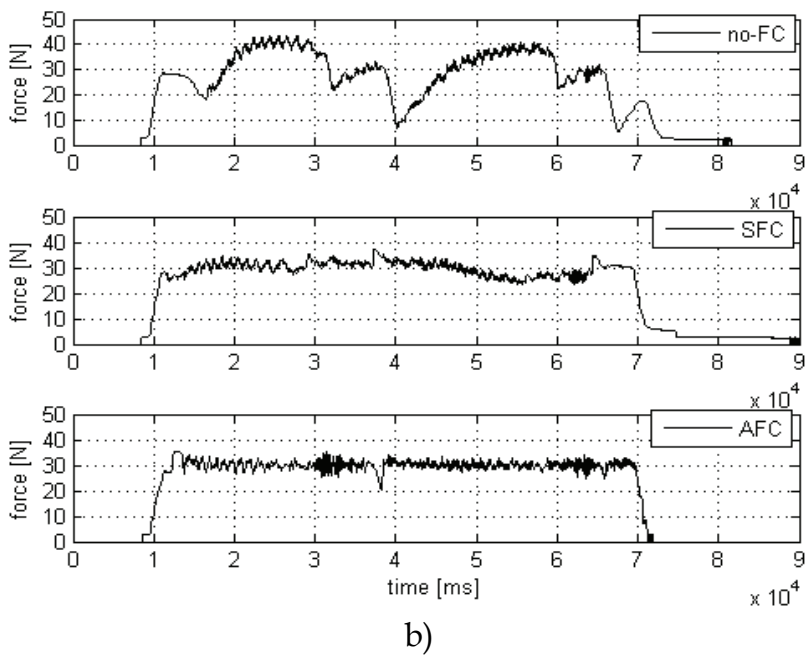
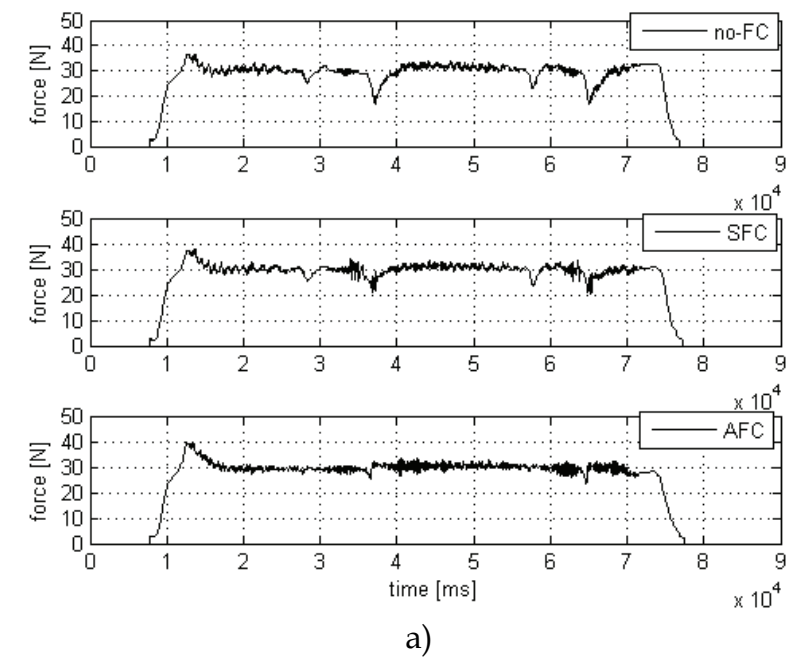


Figure 12. Normal force signals with no friction compensation and with SFC and AFC for the disk in the A position. a) implicit control; b) explicit control.

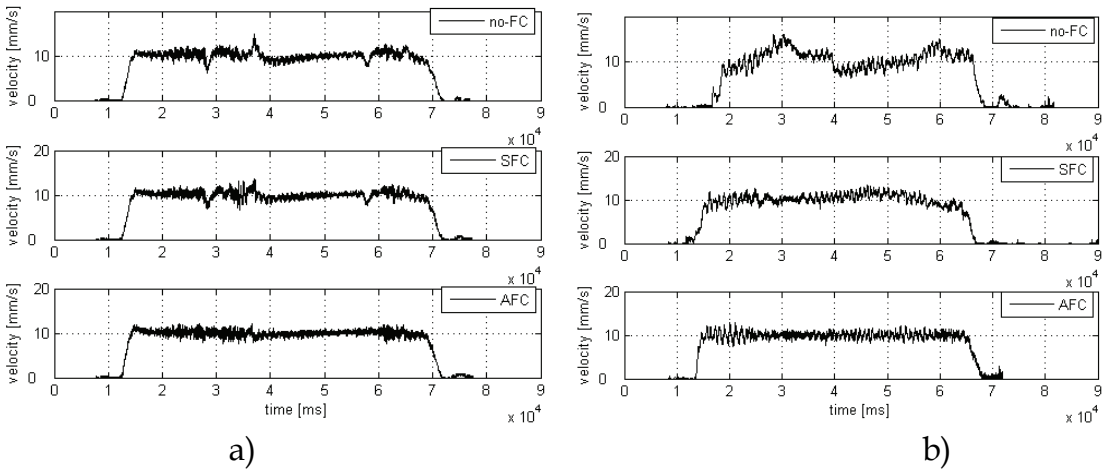


Figure 13. Tangential velocity signals with no friction compensation and with SFC and AFC for the disk in the A position. a) implicit control; b) explicit control.

The mean value of the normal force and tangent velocity RMS error for the different experiments is then reported in Table 1.

From the results presented it can be deduced that a friction compensation strategy is indeed necessary especially for the explicit control law. This is motivated by the fact that the inner joint position control loops in the implicit control law are somehow able to cope with the friction effects. However, it has to be noted again that the implicit control law requires a greater tuning effort than the explicit one (although, from another point of view, it has the advantage that it can be applied to a pre-existing motion control architecture).

The Adaptive Friction Compensation strategy provides definitely the best results for the explicit control scheme both in terms of normal force and tangential velocity, while for the implicit control law the performance obtained by the Adaptive Friction Compensation scheme and by the Static Friction Compensation scheme are similar. In any case, the great advantage for the AFC of being a model-free scheme (*i.e.*, no preliminary experiment is required to derive a friction model and robustness to variation of the friction parameters is assured) makes it more appealing to be applied in a practical context.

It is worth stressing that the AFC strategy is effective in reducing the normal force and tangential velocity errors especially when the joint velocity sign changes. This fact can be evaluated by considering the resulting two joint velocities that would be necessary in order to achieve the required tangential velocity of 10 mm/s (for disk A). They are reported in Figure 14 (compare with Figures 12 and 13, for example at time $t=3.9$ s when the velocity of the first joint changes its sign it appears that the normal force and tangential velocity errors increase significantly when no friction compensation is applied, especially for the explicit control).

Further, the explicit hybrid force/velocity controller (with AFC) provides basically the same performance (in terms of both normal force and tangential velocity errors) disregarding the different normal force and tangential velocity set-points and the different position of the workpiece in the manipulator workspace. This is indeed a remarkable issue that is due to the higher bandwidth provided by the explicit control than the implicit one.

	Normal force [N]				Tangential velocity [mm/s]			
	Position A		Position B		Position A		Position B	
	Implicit	Explicit	Implicit	Explicit	Implicit	Explicit	Implicit	Explicit
AFC	3.74	2.97	4.70	2.83	1.8	0.89	2.5	1.3
SFC	3.65	5.16	4.50	4.80	1.5	2.7	2.1	5.1
no-FC	5.26	12.32	6.27	16.05	2.0	5.5	2.9	8.7

Table 1. Mean value of the normal force and tangent velocity RMS error for the different experiments

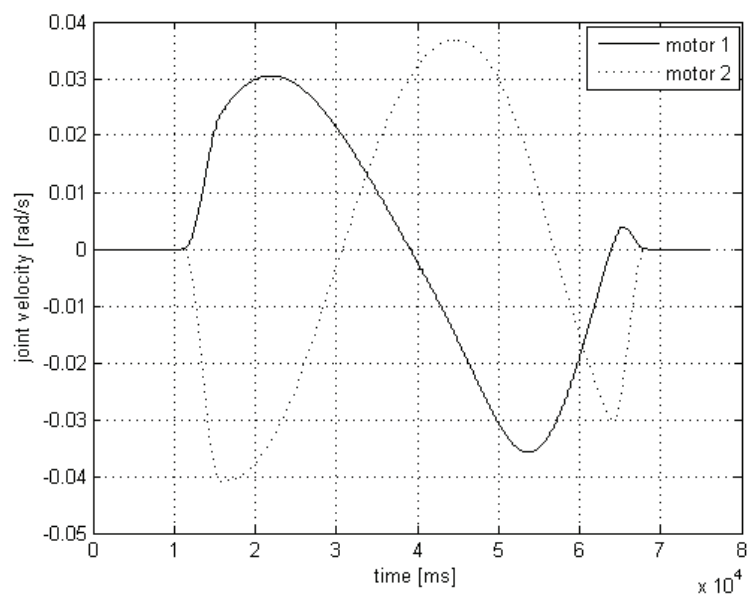


Figure 14. Required joint velocities for tracking disk A with the tangential velocity of 10 mm/s

6. Conclusions

Tasks based on force control are seldom performed by robot manipulators in industrial settings. This might be due to the lack of a thorough characterisation of the methodologies developed theoretically from an industrial point of view. Indeed, it has to be demonstrated that a proposed control strategy can be applied effectively in all the possible situations that might arise in an industrial context and, in general, the cost/benefit ratio should be clearly outlined.

In this chapter the use of hybrid force/velocity control for the contour tracking of an object of unknown shape performed by an industrial robot SCARA manipulator has been discussed. In particular, both the implicit and explicit control laws have been considered and the compensation of the joint friction effect has been addressed.

The pros and cons of the use of an inner joint position control loop have been outlined and it has been shown that the application of a friction compensation strategy is essential if the explicit control law is selected. In this context, the use of the devised Adaptive Friction Compensation strategy is advisable as it provides basically the same (high) performance in the different considered task and its application does not require any previous knowledge of the friction model, that is, no *ad hoc* experiments have to be performed.

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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