A COMPARISON BETWEEN IMPLICIT AND EXPLICIT HYBRID CONTROL FOR CONTOUR TRACKING

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Abstract: In this paper, the use of implicit (position based) and explicit hybrid force/velocity control for contour tracking task of unknown (planar) objects is discussed and compared from an industrial point of view. In particular, the joint friction compensation issue is addressed. A large number of experimental results obtained with a 2 degree-of-freedom SCARA industrial manipulator is shown to support the investigation.

Keywords: Industrial robots, contour tracking, hybrid force/velocity control.

1. INTRODUCTION

Despite the recent achievements in the design of control systems for complex robotic tasks, nowadays industrial settings still generally employ robots in fixed and highly structured environments so that reconfiguration efforts are a clear barrier to face the continuous changes required by the market demand. Indeed, robots that are able to autonomously adapt themselves to semi-unstructured tasks would be a key issue to cut re-programming costs and to shorten the lead to production time.

Automatic tracking of (unknown) planar contours (i.e. to track the contour of an object with a given reference tangential velocity and by applying a given force to the object in the normal direction) is an example of an advanced task required by many industrial applications (e.g. grinding (Thomessen and Lien, 2000), deburring (Ferretti *et al.*, 2000; Ziliani *et al.*, 2005*b*), shape recovery (Ahmad and Lee, 1990), polishing and kinematic calibration (Legnani *et al.*, 2001)) where a high degree of autonomy is needed as opposite to standard industrial operations where robots reproduce previously recorded paths with a little amount of feedback from the process under control.

For this purpose, hybrid force/velocity control (Raibert and Craig, 1981) appears to be suitable to be adopted, as it explicitly controls the end-effector force in selected directions and the end-effector velocity in the other complementary directions. Actually, two kinds of hybrid force/velocity control can be implemented (Roy and 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 and

Khosla, 1993), but 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. Actually, the cost of the design and implementation phases has to be fully addressed and many experimental results have to be provided in order to really show the practical cases where they can be successfully adopted and where they may fail.
In this paper a thorough experimental comparison between an implicit and an explicit hybrid force/velocity control law for contour tracking is performed by means of an industrial SCARA manipulator. A large number of experimental results are given and, in particular, the compensation of the joint friction effects is addressed and implementation issues are discussed.
The paper is organised as follows. In Section 2 the experimental setup is described. In Section 3 the two hybrid control laws are presented. The joint friction compensation issue is discussed in Section 4. Experimental results are shown in Section 5 and they are discussed in Section 6. Finally, conclusions are drawn in the Section 7.

2. EXPERIMENTAL SETUP

The experimental set-up available in the Applied Mechanics Laboratory of the University of Brescia 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 and 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. An ATI 65/5 force/torque sensor capable of measuring forces in a range of ± 65 N and with a resolution of 0.05N 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. 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 1. 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 is 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. Vector $V_{(T)} = [V_t, V_n]^T$ representing the Cartesian velocity in frame (T) can be obtained from the relation

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

where $J(Q)$ is the robot Jacobian matrix.
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:

$$\vartheta = \operatorname{atan2}(F_y, F_x) = \arctan\left(\frac{F_y}{F_x}\right) \pm \pi. \qquad (1)$$

3.2 Explicit hybrid force/velocity control

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). In this context, the adopted control scheme is shown in Figure 2. The joint torques τ_1 and τ_2 for the first and the second joint respectively are calculated as:

$$\tau = J^T(Q)M_{0T}(U_{(T)} + K_R R) + \hat{f} \qquad (2)$$