Iterative Learning Explicit Hybrid Force/Velocity Control for Contour Tracking

Giacomo Ziliani, Antonio Visioli and Giovanni Legnani

Abstract— **In this paper we propose an Iterative Learning Control (ILC) algorithm for the contour tracking of unknown planar objects performed by an industrial SCARA robot manipulator with an explicit hybrid force/velocity controller. Conversely to the typical applications of ILC, the employed control law does not include a time-based reference position signal (and a position control loop) and therefore a different approach has been developed in order to exploit the repetitive nature of the task. Design choices are described in this context and experimental results show the effectiveness of the technique.**

I. INTRODUCTION

DESPITE the remarkable achievements in the design of control systems for complex robotic tasks, in industrial settings there is still the need of methodologies that make robot manipulators able to adapt themselves autonomously to semi-unstructured tasks in order to cut re-programming costs and to shorten the lead to production time. A typical example of an advanced task where a high degree of autonomy is necessary is the automatic tracking of planar objects of unknown shape, here the robot end-effector has to contour the piece with a reference tangential velocity by exerting at the same time a predefined normal force. Indeed, the contour tracking task is required as a basic capability in a number of applications such as grinding [1], deburring [2], [3], shape recovery [4], polishing and kinematic calibration [5].

For this purpose, hybrid force/velocity control [6] appears to be suitable to be adopted, as it explicitly controls the end-effector force in a selected direction and the end-effector velocity in the other complementary direction. Actually, two kinds of force control can be implemented [7]: 1) *explicit force control*, where the robot end-effector is controlled by directly imposing the joint torques based on the measured force errors, and 2) *implicit force control*, where the end-effector is controlled indirectly by suitably modifying the reference trajectories of the inner position control loop based on the measured force errors. Although implicit hybrid control allows in principle to better reject disturbances that occur in the robot actuation system and it can be implemented easier starting from current industrial controllers (further, the solution to the guarded move problem is simplified) [8], it is also recognized that explicit hybrid control provides in general a better performance, because of the higher bandwidth it is capable to provide [9]. This is especially true if additional functionalities like friction compensation and gain scheduling are implemented [10].

From another point of view, Iterative Learning Control (ILC) is a well-known effective approach for the robot motion control when a repetitive task is required (see, for example, [11] and references therein contained). Despite the success of the technique in the robot free motion control, actually no investigations for the application of this concept for contour tracking have been proposed with the exception of the work of Naniwa and Arimoto [12] where, however, a reference trajectory is given (i.e. the shape of the piece to be tracked is perfectly known) and only simulation results are shown. It is worth stressing that an approach similar to ILC has been employed in [13], where the controller self-improves itself iteratively by estimating the parameters of the model of the robot and of the contour by means of a Kalman filter.

In this paper an ILC technique is applied in the context of explicit hybrid force/velocity control, for the contour tracking of a piece of unknown shape. Since a reference position signal is not present, due to the kind of the task, a standard ILC approach cannot be implemented. A different technique has therefore been devised to cope with this situation.

II. EXPERIMENTAL SETUP

We refer to a two degree-of-freedom planar industrial SCARA robot, as this is the one adopted in the experiments. The set-up available consists of an industrial manipulator with a standard SCARA architecture where the z axis has been blocked for our planar tasks. A description of its dynamic model can be found in [14]. Both links have the same length of 0.33 m. The two joints are actuated by DC motors (driven by conventional PWM amplifiers) through Harmonic Drive speed reducers whose reduction rate is 1/100. Motor rotations are measured by means of two incremental encoders (2000 pulses/rev). Velocity is estimated through numerical differentiation whose output is then processed by a low-pass 2-order Butterworth filter (100 Hz cut-off frequency and 1.0 damping ratio). An ATI 65/5 Force/Torque sensor is mounted at the manipulator wrist. The corresponding signals are processed at 7.8 kHz frequency by an ISA DSP based board and collected by the robot controller at 1 kHz. The contact is achieved by

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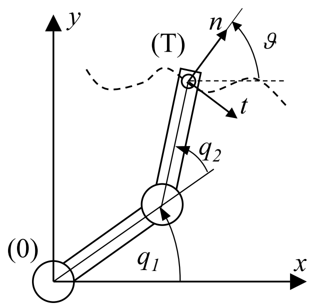

Fig. 1. Sketch of a SCARA robot following a contour.

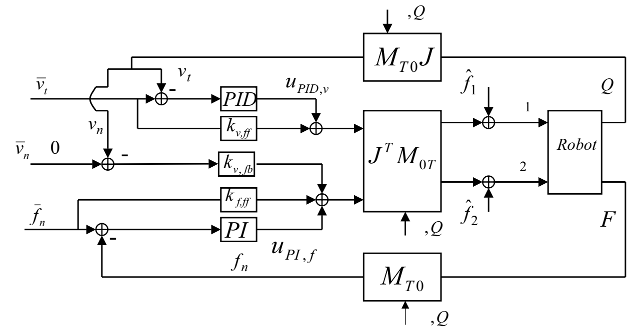

Fig. 2. Explicit hybrid force/velocity control scheme.

means of a proper 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.

III. EXPLICIT HYBRID FORCE/VELOCITY CONTROL

A. 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 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 (probe endowed with a ball bearing, see Section II), by on-line estimating the angle ϑ as:

$$\vartheta = \operatorname{atan2}(f_y, f_x) = \arctan\left(\frac{f_y}{f_x}\right) \pm \pi. \tag{1}$$

B. Control law

The explicit hybrid force/velocity control adopted is shown in Figure 2. The joint torques τ_1 and τ_2 for the first and the second joint respectively are calculated as:

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

where $R = [\bar{v}_t, \bar{f}_n]^T$ is the feedforward vector based on the force and the velocity reference signals, $K_R = diag[k_{v,ff}, k_{f,ff}]$ the corresponding diagonal matrix of gains, $\hat{f}(\dot{Q}) = [\hat{f}_1(\dot{q}_1), \hat{f}_1(\dot{q}_2)]^T$ is an available estimate of the joint friction torques [15] and

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

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.
Note that the use of a normal force derivative term has been avoided in (2) (indeed, only the proportional and the integral actions have been employed) as the derivation of such a signal is ill-conditioned [16]. 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 [17]. 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 [18]. It is worth stressing that a model of the robot is not required for the implementation of the overall control strategy.

C. Discussion

Although a good performance is achieved with the control architecture described, the following aspects are detrimental for the achievement of a high performance and they are not directly addressed with the considered explicit hybrid control law:

- there is not a rigorous methodology for tuning the control design parameters (namely, the PID gains), so that, an optimal tuning is practically impossible to achieve;
- the unavoidable backlash in the joints causes a higher error in the normal force when the joint torques changes its sign;
- although the adopted friction compensation method is effective, the accurate estimation of the static friction is indeed very difficult and it plays in any case a major role in the decrement of performances when the joint velocity changes its sign.

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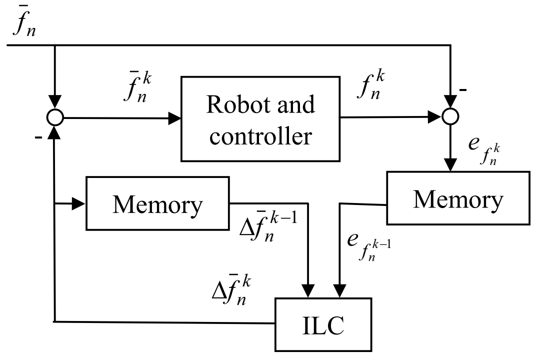

Fig. 3. The ILC based control scheme.

In this paper we propose the use of an ILC strategy capable to address these problems.

IV. The ILC strategy

We assume that the same task (*i.e.*, the contour of the same workpiece) is required to be executed repetitively. In this context, the use of ILC is appealing. However, the standard application of an ILC strategy requires a prespecified time-based reference position signal, *i.e.*, that the same robot position is predefined at the same time instants in each repetition. In a contour tracking task, since the piece to be tracked is of unknown shape (and the tangential velocity may not be the same for each repetition), there is no such reference position signal. Thus, an alternative approach has been developed.

A. General idea

The general idea is to adopt an ILC strategy to modify the normal force set-point $\bar{f}_n$ according to the normal force error measured at the previous repetition of the task. This concept is depicted in Figure 3, where the learning control law is of P-type, *i.e.*, the modification of the normal force set-point at each time instant of the kth trial is expressed as:

$$\Delta\bar{f}_n^k = \Delta\bar{f}_n^{k-1} + g \cdot e_{f_n}^{k-1} \tag{3}$$

where e_{f_n} is the measured normal force error and g is a user-chosen parameter. Note that it is fixed $\Delta\bar{f}_n^0 = 0$ and $e_{f_n}^0 = 0$, *i.e.*, the learning control law is not applied at the first repetition.

B. The new indexing

For the reasons mentioned above, it is not possible to relate directly the normal force error to a given time instant at each repetition. Thus, there is the need to relate the measured force error and the normal force set-point modification with other variables, in order to find the value of $e_{f_n}^{k-1}$ and $\Delta\bar{f}_n^{k-1}$ at each time instant. The contour tracking performances are obviously influenced by the kinematic and kinetostatic characteristics of the SCARA robot, which can be represented effectively by the force manipulability ellipsoids (examples of them are shown in Figure 4). The same reasoning applies also to the inertial and stiffness ellipsoids which have similar shapes. It appears that, due to the radial symmetry of the SCARA manipulator, the shapes of the force manipulability ellipsoids depends only on their distance from the axis origin, *i.e.*, on q_2 only. Further, if a specific pose of the manipulator is considered, in order to express the force that can be exerted in a specific direction ϑ, another variable is necessary. A possible solution is to adopt the following variable:

$$\vartheta_r = \vartheta - q_1. \tag{4}$$

Hence, it is sound to index both the measured force error and the normal force set-point modification with the two variables q_2 and ϑ_r.

In principle, when a trial of the contour tracking task is performed, at each time instant the values of both $e_{f_n}^k$ and $\Delta\bar{f}_n^k$ are associated with the values of (the measured) ϑ_r and q_2. From a practical point of view, the whole range of q_2, namely $[q_{2,min}, q_{2,max}]$ has been divided in $N_1 = 700$ equally spaced intervals, while the range of ϑ_r, namely 2π has been divided in $N_2 = 360$ intervals, so that two matrices of cells, have been created. For convenience, in both cases the range of each interval has been scaled to one. The values associated to the cells of the two matrices are initialized to zero. Two matrices are therefore actually created to store the values of the measured force errors and of the normal force set-point modifications. It has to be taken into account that, due to the nature of the task and to the non ideal repeatability of the manipulator, the trajectory followed by the manipulator is not in general the same at each iteration and therefore it might happen that in a certain trial, the trajectory of the robot is related to elements (q_2, ϑ_r) of the matrix that has not been indexed in previous trials. However, the ILC algorithm, which modifies the normal force set-point, must be able to retrieve the required information even if at each iteration the manipulator does not follow exactly the same path. Further, the set-point should vary smoothly with respect to the time in order to avoid vibrations as much as possible. For these reasons, the data that are necessary to modify the set-point value are disseminated (with a suitable weight) in a neighborhood of the path (see Figure 5). Thus, at each time instant, a two-elements by two-elements portion of the matrix is considered, that is, the element that expresses the actual manipulator configuration and the three ones (two for each dimension) that are closest to it. In this context, the distances between the centers of the elements of the matrix are adopted as a suitable measure. Then, a weight $w_{i,j}$ is calculated for each considered element (i, j) depending on the distance $d_{i,j}$ of its center from the actual position (q_2, θ_r) of the robot (see Figure 6). In particular, the following criteria has been adopted for this purpose:

- the sum of the weights has to be equal to one, in order to avoid the introduction of any gain in the data;
- the weight has to decrease when the distance of the element from the position of the manipulator increases;
- the weight has to be zero if the distance is greater than the dimension of an element (so that cells that are outside the correct two-by-two portion are not affected)

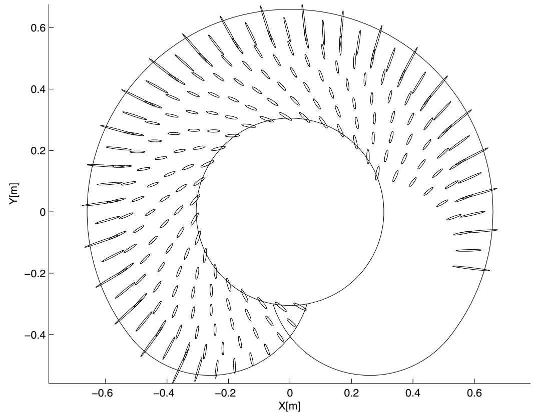

Fig. 4. Examples of force manipulability ellipsoids for the SCARA robot (positive angles q_2 are considered).

The following function, which satisfies the above requirements has been therefore selected:

$$w_{i,j} = \frac{p^+(1 - d_{i,j})}{\sum_{i,j} p^+(1 - d_{i,j})} \tag{5}$$

where $p^+(\delta)$ denotes the positive part function, i.e.:

$$p^+(\delta) := \frac{\delta + |\delta|}{2}. \tag{6}$$

It is worth noting that the positive part function sets to zero all the weights of the elements for which the distance $d_{i,j}$ is greater than the dimension of a cell, and therefore only the correct portion of each matrix is affected by the learning procedure. Thus, the values of the measured normal force error and of the force set-point modification are stored in each cell of the two-by-two portion of the matrix, but with the determined associated weight.

Actually, another aspect has to be considered. In fact, due to the discretization of ϑ_r and q_2 and due to the repetitive nature of the task, there might be different values of e_{f_n} and $\Delta\bar{f}_n$ to be considered (at different time instants) within the same cell (*i.e.*, for the same element of the matrix). However, it is obvious that only one value for each variable has to be associated to a cell. For this reason it has been chosen to store the sum of the values of each variable over the time (denoted as $\Delta\bar{F}_n$ and E_{f_n} respectively) and the sum of the corresponding weight as well (denoted as $W_{i,j}$). Then, the normal force error and the set-point modification to be actually adopted in the learning control law (3) are determined by dividing the stored sums of the variables with the sum of the weights.

C. The ILC algorithm

Based on the considerations made in the previous subsections, the proposed ILC algorithm is formulated as follows. At the kth iteration, for each time instant:

1) The position of the manipulator in the new coordinates is determined:

$$\tilde{q}_2 = \frac{q_2 - q_{2,min}}{q_{2,max} - q_{2,min}} N_1 \qquad \tilde{\vartheta}_r = \frac{\vartheta_r}{2\pi} N_2 \tag{7}$$

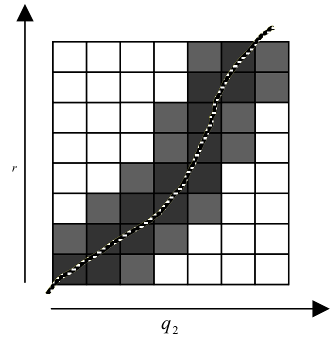

Fig. 5. Elements of the matrix (dark and pale grey) that are involved in the ILC during the execution of a trajectory.

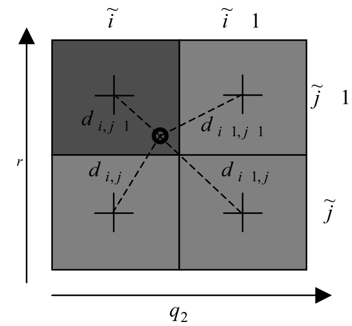

Fig. 6. Cells affected by the learning control strategy at each time instant; **O**: manipulator position; **+**: cell center.

where N_1 and N_2 are the number of discretization intervals.

2) The elements of the matrix related to the manipulator position are determined:

$$\tilde{i} = \mathrm{trunc}(\tilde{q}_2) \qquad \tilde{j} = \mathrm{trunc}(\tilde{\vartheta}_r) \tag{8}$$

where the truncation function is defined as:

$$\mathrm{trunc}(\delta) := \max\{n \in \mathbb{N} : n \leq \delta\}, \qquad \delta \in \mathbb{R}. \tag{9}$$

The elements of the matrices that are involved in the learning procedure are therefore

$$(\tilde{i}, \tilde{j}), \quad (\tilde{i}, \tilde{j}+1), \quad (\tilde{i}+1, \tilde{j}), \quad (\tilde{i}+1, \tilde{j}+1).$$

3) The distances of the manipulator position from the centers of the involved cells are determined:

$$d_{i,j} = \sqrt{(i - \tilde{q}_2)^2 + (j - \tilde{\vartheta}_r)^2} \quad i = \tilde{i}, \tilde{i}{+}1 \;\; j = \tilde{j}, \tilde{j}{+}1 \tag{10}$$

4) The weights are calculated:

$$w^k_{i,j} = \frac{p^+(1 - d_{i,j})}{\sum_{i,j} p^+(1 - d_{i,j})} \qquad i = \tilde{i}, \tilde{i}+1 \quad j = \tilde{j}, \tilde{j}+1 \tag{11}$$

5) For each of the considered four cells, the previously stored values of the sums of the normal force error and of the set-point correction are retrieved and weighted ($i = \tilde{i}, \tilde{i}+1 \quad j = \tilde{j}, \tilde{j}+1$):

$$\Delta\bar{f}^{k-1}_{n(i,j)} = \frac{\Delta\bar{F}^{k-1}_{n(i,j)}}{W^{k-1}_{i,j}} \qquad e^{k-1}_{f_n(i,j)} = \frac{E^{k-1}_{f_n(i,j)}}{W^{k-1}_{i,j}} \tag{12}$$

6) The normal force set-point change to be actually applied is calculated ($i = \tilde{i}, \tilde{i}+1 \quad j = \tilde{j}, \tilde{j}+1$):

$$\Delta \bar{f}_n^k = \sum_{i,j} (w_{i,j}^k \cdot (\Delta \bar{f}_{n(i,j)}^{k-1} + g \cdot e_{f_n(i,j)}^{k-1})) \qquad (13)$$

7) The exerted normal force is measured and the normal force error is calculated:

$$e_{f_n}^k = \bar{f}_n - f_n. \qquad (14)$$

8) The matrix elements, after being initialized at the beginning of the repetition as $\Delta \bar{F}_{n(i,j)}^k = \Delta \bar{F}_{n(i,j)}^{k-1}$, $E_{f_n(i,j)}^k = E_{f_n(i,j)}^{k-1}$ and $W_{i,j}^k = W_{i,j}^{k-1}$ are updated for the next iteration:

$$\begin{aligned} \Delta \bar{F}_{n(i,j)}^k &= \Delta \bar{F}_{n(i,j)}^k + w_{i,j}^k \cdot \Delta \bar{f}_{n(i,j)}^k \\ E_{f_n(i,j)}^k &= E_{f_n(i,j)}^k + w_{i,j}^k \cdot e_{f_n(i,j)}^k \\ W_{i,j}^k &= W_{i,j}^k + w_i^k \end{aligned} \qquad (15)$$

V. Experimental results

The ILC strategy has been applied for the contour tracking of pieces of different (unknown) shape, placed in different positions of the manipulator workspace, as shown in Figure 7 and 8. In particular, aluminium bars (A and B), an iron disk with a diameter of 90 mm (C), a wooden complex shape (D), a true diecasting aluminium piece (E) and an iron rectangular piece with sharp edges (F) have been considered. In all the cases the value of g is 0.5 and the normal force set-point is 20 N, while the reference tangential velocity is 30 mm/s for the cases A, B and F, 20 mm/s for case D, and 10 mm/s for cases C and E.

The resulting normal force at the first and at the tenth repetition, with the normal force set-point modified by the ILC strategy in the latter case are shown for each experiments in two subplots in Figure 9 (note that the ILC strategy is applied after the guarded move phase, when the tangential velocity is different from zero), while the rms error improvements along the different repetitions are plotted in Figure 10 (one subplot for each experiment). In particular, to better evaluate the role of the ILC technique, the rms errors have been reported after having filtered them both with a low-pass and a high-pass filter (the cut-off frequency in both cases is 0.25 Hz). Note that the resulting tangential velocity has not been reported for the sake of brevity. In any case the ILC strategy does not affect significantly its performance.

From the presented results it can be easily deduced that the proposed new ILC strategy is very effective in reducing significantly after just a few trials the normal force error, especially that with a relatively slow dynamics.

VI. Conclusion

In this paper we have shown how a suitably devised Iterative Learning Control strategy can be effectively adopted in conjunction with an explicit hybrid force/velocity control law for the contour tracking of (planar) objects of unknown shape. The role of the design parameters have been discussed and a large number of experimental results have been presented in order to clearly evaluate the performance that can be achieved. It appears that just a few iterations are sufficient to significantly decrease the normal force tracking error.

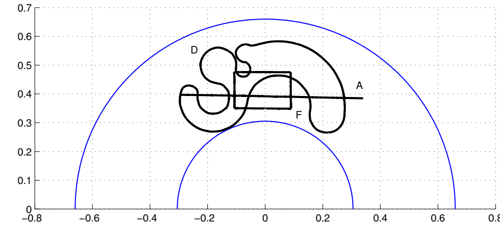

Fig. 7. Position of different workpieces in the robot workspace.

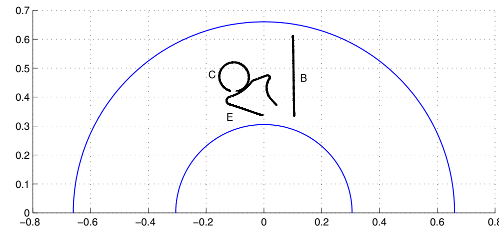

Fig. 8. Position of other workpieces in the manipulator workspace.

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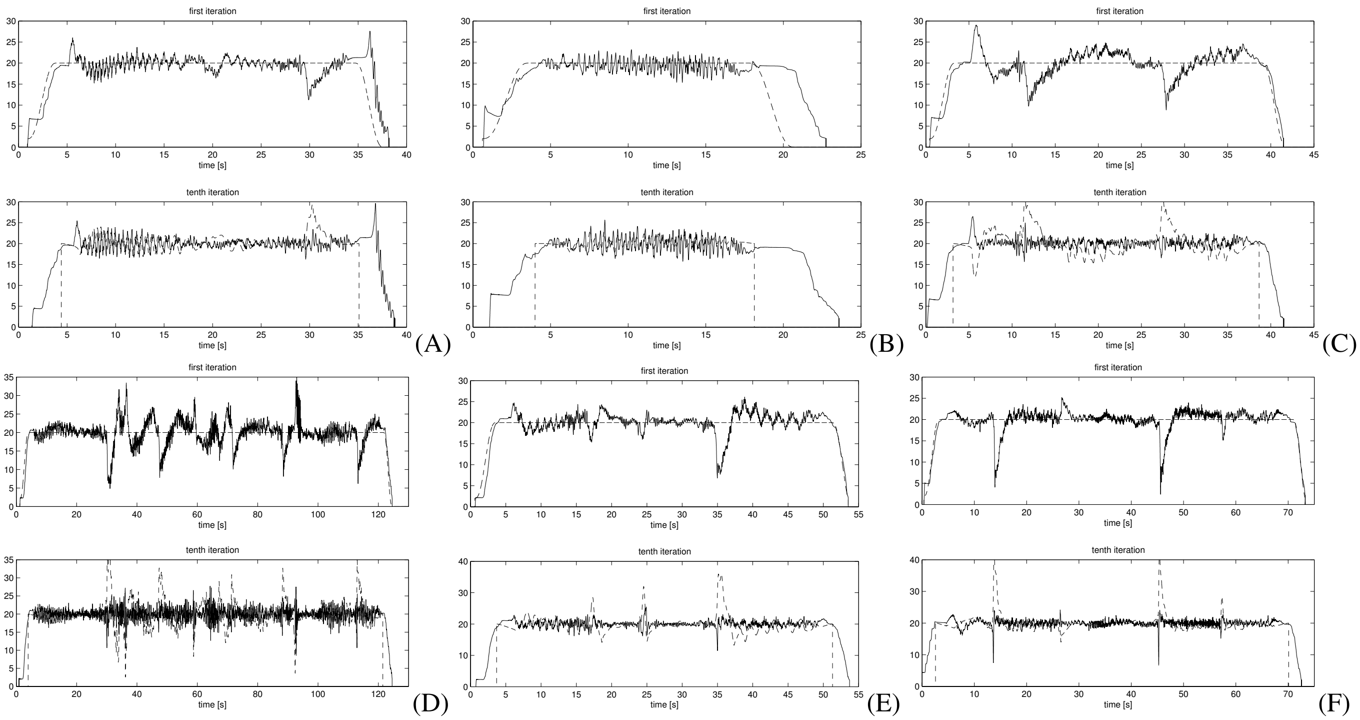

Fig. 9. Resulting normal forces (solid line) and set-point (dashed line) at the first and at the tenth iteration by applying the ILC strategy. Labels are related to the workpieces (see Figures 7 and 8)

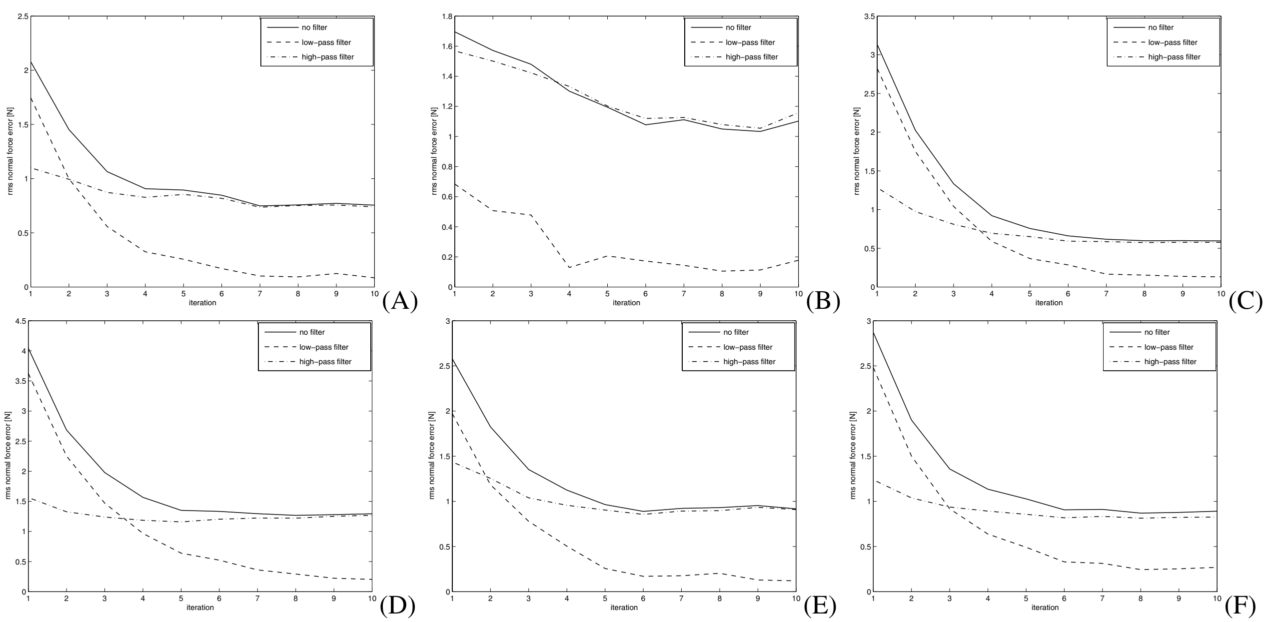

Fig. 10. Resulting rms normal force errors along the different repetitions. Solid line: non filtered errors. Dashed line: low-pass filtered errors. Dash-dot line: high-pass filtered errors.

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