Improved tracking for systems with configuration dependent dynamics by the application of robust Iterative Learning Control

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Abstract

Iterative Learning Control (ILC) is a method to improve the tracking accuracy of systems that perform the same task repetitively. This paper describes a robust ILC algorithm, which explicitly deals with uncertainty in the dynamic model of the controlled system. The algorithm is suited for systems with linear-time varying dynamics, which makes it applicable to mechanical systems with configuration dependent dynamics. The effectiveness of the algorithm is demonstrated from the application to an industrial robot.

1 Introduction

The tracking accuracy of many feedback-controlled mechanical systems is limited by the bandwidth of the closed-loop system, which is typically below the elastic resonance frequencies of the mechanical system. If the feedback-controlled mechanical system performs a repetitive task, then the frequency components of the error beyond the bandwidth of the feedback controller can be reduced by the application of Iterative Learning Control (ILC). ILC reduces the error by iteratively updating a feedforward using the measurement of the tracking error in the previous iteration. Effective ILC algorithms that reduce the tracking error in a limited number of iterations can be designed using a model of the system dynamics. However, modelling errors might result in divergence of the error over the iterations and should thus be considered carefully. Recently, robust ILC algorithms have been developed that guarantee convergence of the tracking error for a specified uncertainty in the modelled dynamics [1]. The authors extended the application of robust ILC to systems with linear time-varying (LTV) dynamics and a relatively large model uncertainty [2]. The algorithm can be applied to mechanical systems with configuration dependent dynamics, because these dynamics can be approximated as LTV for small deviations from the repetitively traced trajectory.

2 Robust Iterative Learning Control for LTV systems

The robust ILC algorithm aims at realising robust convergence of the tracking error, i.e. converge for the worst case effect of the uncertainty in the dynamic model of the controlled system. The developed robust ILC algorithm is based on a scalar objective function that should be negative to make the error converge to zero with a certain demanded convergence rate. Dynamic game theory is used to compute the feedforward that minimises the objective function for the worst case effect of the model uncertainty. The error converges robustly if the resulting value of the objective function is negative, which is thus a condition for robust convergence of the error.

The convergence condition poses an upper limit on the model uncertainty for which the error converges robustly to zero. If the model uncertainty exceeds this limit, then the convergence condition can still be satisfied by the application of a robustness filter avoiding that the ILC algorithm compensates for the part of the error corresponding to large model uncertainty. For example, if the uncertainty in the phase-response of an LTI system is larger than 90° in a certain frequency range, then the convergence condition is only satisfied by using a robustness filter that makes the ILC algorithm refrain from the compensation of the error in this frequency range. Such large phase uncertainty may exist near the resonance frequency of a system with low damping where the phase response changes with 180° in a small frequency band.

The reader is referred to [2] for an extensive discussion of the robust ILC algorithm. In this paper the practical applicability of the algorithm is demonstrated.

3 Experimental validation on an industrial robot

The robust ILC algorithm is applied to the industrial Stäubli RX90 robot, which is controlled by its standard industrial controller. This robot, depicted in figure 1, is applied for laser welding. The welding head mounted to this robot should trace a weld seam with an accuracy of about 0.1 mm to realise defect free welds. The tracking error is measured with an optical sensor that is integrated in the welding head.

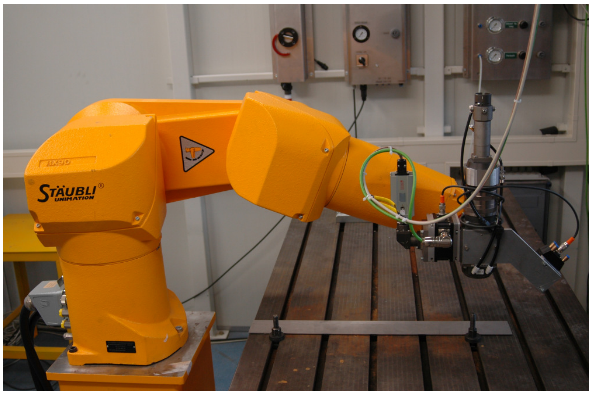

Figure 1: The industrial Stäubli RX90 robot

The performance of the ILC algorithm is demonstrated for a weld-seam with a serrated profile which should be traced while the welding head moves away from the robot base at a velocity of 400 mm/s. Initially the robot is commanded to move in a straight line, resulting in the tracking error along the weld seam shown in figure 2. The tracking error cannot be reduced to 0.1 mm using feedback control because of the large high-frequency components. Therefore the proposed ILC algorithm is applied.

Measurements of the robot’s dynamic response are used to estimate an LTI and an LTV dynamic model. The LTI model does not describe the change of the robot dynamics along the trajectory due to the change of configuration, which results in a relatively large model uncertainty. The LTV model is able to describe the varying robot dynamics, resulting in a smaller uncertainty.

It is demanded that the robust ILC algorithm reduces at least a quarter of the error in each iteration. A low-pass robustness filter is needed to satisfy the convergence condition for this convergence rate and the uncertainty in the models. The highest cut-off frequencies satisfying the convergence condition is taken for the robustness filter, resulting in 9.8 Hz for the LTI model and 14.6 Hz for the LTV model. The tracking error is thus reduced in the largest frequency band using the LTV model.

Figure 2 shows the original tracking error and the tracking error in the third iteration of ILC. The tracking error in the third iteration consists mainly of frequency components beyond the cutoff frequency of the robustness filter and thus the error is not reduced further in subsequent iterations. Clearly the tracking error is smallest for the LTV model, which demonstrates the improved performance obtained with the robust ILC algorithm [2] for a system with configuration dependent dynamics.

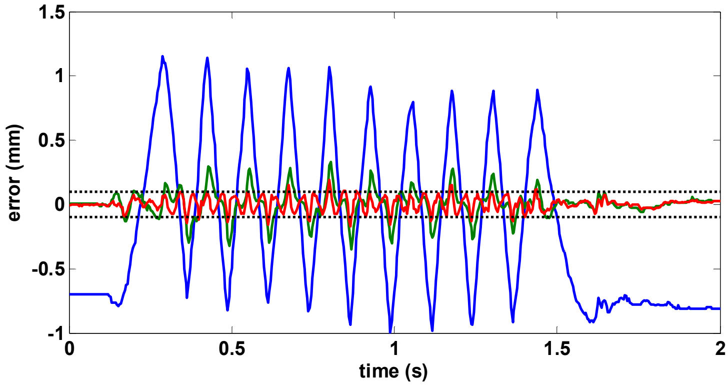

Figure 2: The tracking error without ILC (blue), in the third iteration of ILC using an LTI model (green) and using an LTV model (red).

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