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Data-Based tuning of the reduced order inverse system model in a 3-DOF control structure with application to tray indexing

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Abstract

Performance of traditional model-based control replies upon accurate modelling. However, obtaining the models for unknown and complicated systems can sometimes be difficult and time consuming. Furthermore, inaccurate model-based design may not provide satisfactory performance. As a result, the data-based approaches are becoming popular in recent years, which makes use of the measurement data of closed-loop experiments to design the controller, instead of relying on an accurate system model. Such control-objective-oriented (performance-oriented) design approach is suitable for many industrial applications.

In our work, a data-based tuning procedure for tuning the inverse system model is developed within a three-degree-of-freedom (3-DOF) control structure, which is composed of a feedback controller, a feedforward controller as well as a disturbance observer. It solely makes use a measurement data to fine-tune the inverse system model parameters, aiming at achieving the best tracking performance. The gradient and hessian of the cost function is estimated in order to execute the Newton's optimization algorithm, and unbiasedness of the cost function can be proven under reasonable assumptions of stochastic properties of the perturbations. The approach is especially useful in industrial applications because quite often the control engineers are only allowed to modify the control parameters instead of the control structure. The proposed method is demonstrated through both simulation and experimental results with significantly improved tracking accuracy.

Data-Based control, Feedforward control, Disturbance observer

1. Introduction

Classical model-based control requires modelling of the system under control using first principle or identification. However, it is sometimes difficult to obtain an accurate system model and it limits the performance of traditional model-based control. On the other hand, data-based control without the intermediate step of system modelling is becoming popular recently. Iterative feedback tuning (IFT) is one of the data-based approach and it is able to generate an unbiased estimate of the gradient of certain cost function solely based on closed-loop experiment data. However, as the name suggests, it is only applicable for the feedback controller tuning.

In order to improve the tracking performance, a feedforward controller is commonly used in the industry. In addition, a disturbance observer is able to further improve the tracking accuracy by compensating for the external disturbances as well as disturbances due to model mismatch. The feedforward controller [1], disturbance observer (DOB) [2] and the traditional feedback controller forms a three-degree-of-freedom (3-DOF) controller. In this paper, a data-based iterative tuning algorithm for the inverse system model used in this 3-DOF controller is developed.

This paper is organized as follows. In Section 2, we introduce the 3-DOF controller. The data-based tuning procedure is illustrated in Section 3. The effectiveness of the proposed approach is demonstrated using a timing-belt actuation system in Section 4. Finally, conclusions are drawn in Section 5.

2. Overview of the 3-DOF control structure

The 3-DOF control structure is shown in Figure.1, where F(s), C(s), P(s), Q(s) are respectively the inverse system model, feedback controller, system under control, and the low pass filter. The key idea of the DOB is to use the inverse system model F(s) to give an estimation of the disturbance. The low pass filter Q(s) is necessary to make the DOB inner loop realizable.

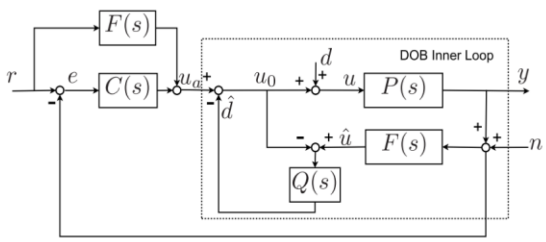

Figure 1. 3-DOF control structure

The frequency responses from r to y, r to e, d to y, and n to y are respectively

$$H_{yr} = \frac{P(C+F)}{1+PC-Q(1-PF)} \tag{1}$$

$$H_{er} = \frac{(1-PF)(1-Q)}{1+PC-Q(1-PF)} \tag{2}$$

$$H_{yd} = \frac{P(1-Q)}{1+PC-Q(1-PF)} \tag{3}$$

$$H_{yn} = \frac{P(C+QF)}{1+PC-Q(1-PF)} \quad (4)$$

In the next section, the data-based iterative tuning algorithm for the inverse system model F(s) is proposed to further improve the tracking accuracy.

3. Data-Based iterative tuning procedure

The data-based tuning approach finds the optimal parameter ρ for F(s) that can minimize certain cost function $J(\rho)$. In trajectory tracking control, it is often defined as the square of the tracking error

$$J(\rho) = e(\rho)^T e(\rho) \quad (5)$$

The gradient of J with respect to ρ can be derived as

$$\nabla J(\rho) = 2\nabla e(\rho)^T . e(\rho) \quad (6)$$

and the Hessian

$$\nabla^2 J(\rho) = 2\nabla e(\rho)^T . \nabla e(\rho) \quad (7)$$

The Newton's optimization method is given by [3]

$$^{i+1}\rho = {^i\rho} - {^i\gamma}(\nabla^2 J(\rho))^{-1}\nabla J(\rho) \quad (8)$$

Where $^i\gamma$ is the step size at iteration i. The gradient of the tracking error can be derived as

$$\nabla e(\rho) = \frac{\partial F(\rho)}{\partial \rho}\frac{QP-P}{\varphi(\rho)} r - \frac{\partial F(\rho)}{\partial \rho}\frac{\emptyset(\rho)}{\varphi(\rho)\varphi(\rho)} r \quad (9)$$

where $\varphi(\rho)$ and $\emptyset(\rho)$ are introduced to simplify the expression

$$\varphi(\rho) = QP[Q(PF(\rho)-1)+1-PF(\rho)] \quad (10)$$

$$\emptyset(\rho) = Q(PF(\rho)-1)+1+PC \quad (11)$$

By substituting (1) into the first half of (9), it can be directly generated from output y_1 as $\frac{\partial F(\rho)}{\partial \rho}.\frac{Q-1}{C+F(\rho)}.y_1$. Obtaining the second half of (9) is more difficult and requires feeding the tracking error e as the new reference to the closed-loop system. With the output y_2 from the second experiment, the second half of the gradient can be obtained as $\frac{\partial F(\rho)}{\partial \rho}.\frac{Q}{C+F(\rho)}.y_2$. Now the gradient can be solely obtained from closed-loop experiment data, and the Newton's optimization algorithm can be executed to iteratively improve the tracking performance.

4. Experiment result

In this section, the proposed data-based tuning approach is applied to a timing-belt actuation system to further improve its tracking accuracy. The plant under control can be simplified to be a second order system, but the low frequency portion is torque-dependent as shown in Figure.2, which makes it hard to find out the exact parameter for the inverse system model F(s). In this case, the parameters are initialized according to the red curve and then iteratively optimized using the proposed method.

The tracking error reduction after 4 iterations is shown in Figure.3, and it clearly shows the effectiveness of the proposed approach. The corresponding parameter convergence and cost function reduction is shown in Figure.4.

5. Conclusion

In this paper, we propose a data-based approach for tuning of the inverse system model in a 3-DOF control structure. The first advantage is that it avoids the costly processing of system modelling. Secondly, it can also fine-tune the controller parameters to further improve the performance when the system model is available. Thirdly, this approach makes no changes to the existing control structure and only the parameters are tuned. This is useful in the industry as quite often the control engineers are only allow the change the control parameters instead of the whole control structure.

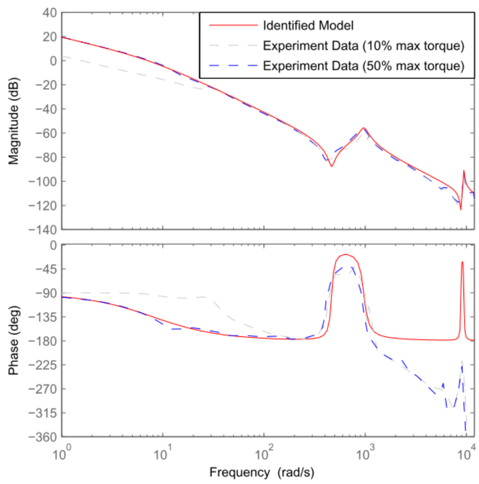

Figure 2. Bode plot of the timing-belt actuation system.

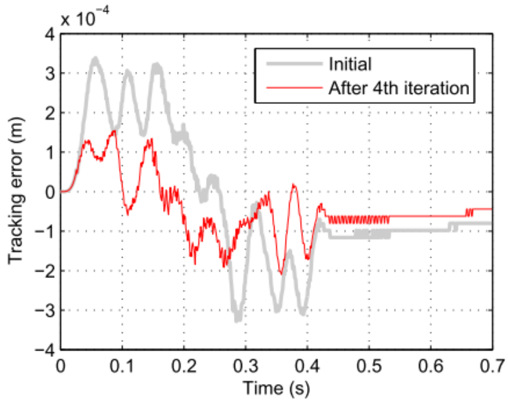

Figure 3. Tracking performance improvement by using the data-based tuning algorithm.

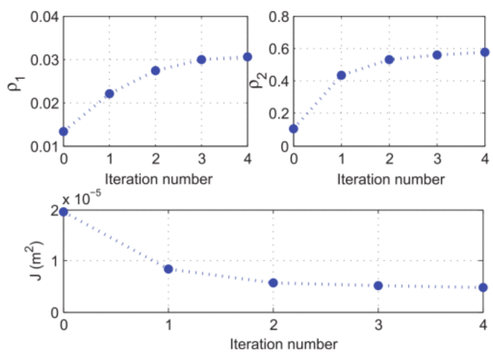

Figure 3. Parameter convergence and cost function reduction.

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