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Settling time optimization by machine-in-the-loop data-driven tuning of nonlinear feedback controllers: application in wire bonding equipment

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Abstract

Because of the ever-increasing throughput and accuracy demands in industrial applications, the settling time (i.e., the time required for the positioning error to converge and satisfy a desired error bound in point-to-point motions) is a critical performance metric in high-end mechatronic applications. Linear time-invariant (LTI) feedback controllers, widely used in industry, face fundamental limitations such as the waterbed effect, fixed relations between gain and phase, and trade-offs between rise time and overshoot, hindering satisfaction of future accuracy and throughput demands. To overcome these limitations, we explore the use of nonlinear feedback controllers based on the so-called hybrid integrator-gain system. Performance-optimal tuning of such nonlinear controllers is challenged by the lack of well-established and intuitive design approaches. Therefore, we propose a machine-in-the-loop data-driven tuning approach aimed at optimizing the settling time, coupled with an automated data-based stability verification procedure that is solely based on measured frequency-response function data, to prevent unstable responses. In a case study on an industrial wire bonder system, a significant reduction of 21% in the worst-case settling time is achieved using the proposed approach, compared to an LTI controller tuned with industrial state-of-the-art frequency-based autotuner.

Nonlinear control, Hybrid integrator-gain system (HIGS), Hybrid control, Data-driven control, Extremum-seeking control (ESC), Settling time optimization

1. Introduction

The increasing demand for high accuracy and throughput in industrial applications motivates the need for improving transient performance in control systems. Linear time-invariant (LTI) control strategies, such as proportional-integral-derivative (PID) controllers, have long been the standard in industrial practice due to their simplicity, predictability in performance and stability, and availability of well-established and intuitive tuning techniques such as manual loop-shaping methods or frequency-based autotuners. However, LTI controllers are inherently limited by fundamental trade-offs, such as those highlighted by Bode's sensitivity integral (waterbed effect) [1] and gain-phase relationship [2]. Additionally, time-domain trade-offs between rise time and overshoot present further challenges in increasing performance and throughput.

Nonlinear and hybrid control techniques, such as variable gain control [3], reset control [4, 5], the hybrid integrator-gain system (HIGS) [6], and sliding mode control [7], offer promising solutions to these limitations. However, despite their advantages, these techniques often lack well-established and intuitive tuning methods, requiring more control engineering experience and increasing design complexity. The lack of well-established and intuitive design procedures poses a significant barrier to the adoption of nonlinear/hybrid controllers in industry, especially when performance requirements and machine-to-machine variations demand machine-specific controller designs.

Data-driven controller tuning approaches enable machine-specific controller tuning and reduce the need for expert control engineering experience. Techniques such as extremum seeking control (ESC) [8, 9], iterative feedback tuning (IFT) [10], and iterative learning control (ILC) [11] have been developed to automate such tuning processes. However, feedback controllers designed using ESC and IFT typically lack guarantees regarding closed-loop stability, which are critical in feedback control, whereas ILC addresses only the design of feedforward control. Moreover, their applicability to nonlinear controller design is often limited. To address these challenges, this work focuses on developing a data-driven tuning algorithm for HIGS-based controllers. These controllers are particularly suited for industrial applications due to their ability to overcome LTI controller limitations [12] and the availability of tools to ensure input-to-state stability (ISS[1]) based solely on measured frequency-response function (FRF) data [13]. In particular, the proposed approach aims at optimizing the settling time.

The contributions of this work are as follows. First, the development of a data-driven framework for tuning HIGS-based controllers, aimed at optimizing transient performance by minimizing the settling time. The second contribution is the experimental verification of the proposed tuning approach on an industrial wire bonder system, showcasing its effectiveness in

1 ISS implies asymptotic stability in the absence of disturbances and a bounded response in the presence of disturbances.

tuning stable HIGS-based controllers for high-precision industrial applications, while optimizing settling time.

The remainder of the abstract is structured as follows. In Section 2.1, we discuss the design of the HIGS-based controller. In Section 2.2, we elaborate on the transient performance optimization problem. The results of the industrial case study are presented in Section 3 and a conclusion is given in Section 4.

2. Methodology

2.1. HIGS-Based Controller Design

The HIGS is a nonlinear control element inspired by the Clegg integrator [14] and is mathematically defined as the piecewise linear system [13]:

$$\mathcal{H}: \begin{cases} \dot{x}_h() = \omega_h(), & \text{if } ((), (), \dot{()}) \in \mathcal{F}1, \\ x_h() = k_h(), & \text{if } ((),(),\dot{()}) \in \mathcal{F}2, \\ () = x_h() \end{cases} \quad (1)$$

with state $x_h() \in \mathbb{R}$, input $() \in \mathbb{R}$, and output $() \in \mathbb{R}$ at time $\geqslant 0$. Two modes can be identified in $\mathcal{H}$. The first mode is the integrator-mode active in the set $\mathcal{F}_1 := \{(, , \dot{}) \in \mathbb{R} \mid _h \geqslant ^2 \wedge (, , \dot{}) \notin \mathcal{F}_2\}$, in which the HIGS functions like a linear integrator with integrator frequency $\omega_h \in \mathbb{R}_{>0}$. In the second mode, active in the set $\mathcal{F}_2 := \{(, , \dot{}) \in \mathbb{R} \mid = _h \wedge \omega_h ^2 > k_h \dot{}\}$, the HIGS behaves like a static gain $k_h \in \mathbb{R}_{>0}$. Both the HIGS and the Clegg integrator aim to reduce phase lag traditionally present in LTI integrators by keeping the sign of their outputs aligned with the sign of their inputs. However, in contrast to the Clegg integrator, the HIGS avoids undesirable discontinuous jumps in the output by switching between the integrator-mode and the gain-mode. An illustration of the differences in the time responses of a linear integrator, a Clegg integrator, and the HIGS to a sinusoidal input can be seen in Figure 1.

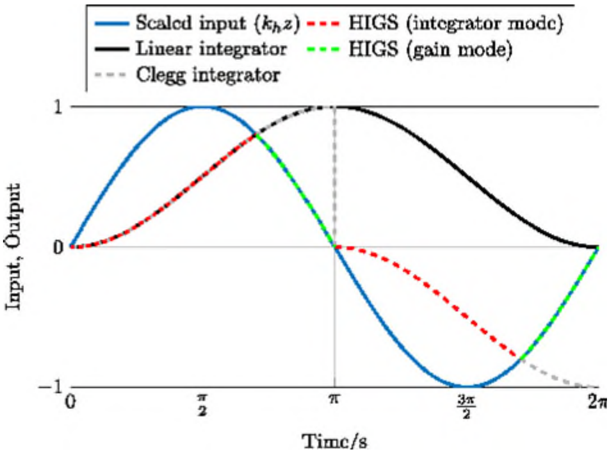

Figure 1. Comparison of time responses of a linear integrator, a Clegg integrator, and the HIGS, for a sinusoidal input $() = ()$ with $\omega_h = 1$, $k_h = 0.5$.

The phase lag reduction of the HIGS can be exploited in controller design as described in [12]. To this end, the HIGS is placed in series with an LTI pre-filter:

$$^{-1}() = \frac{+}{\omega_h} \quad (0)$$

with $\omega = |1 + (4/\pi)| \omega_h/k_h$ and an LTI post-filter $*$. The pre-filter compensates for the approximate magnitude characteristics of the HIGS determined by sinusoidal input describing function analysis [15] and, in combination with the HIGS, provides a phase lead, while the post-filter shapes the overall magnitude characteristics to match the desired magnitude characteristics. The resulting structure then has similar describing function-based magnitude characteristics as $*$ but with a reduced phase lag. To counter undesired repeated

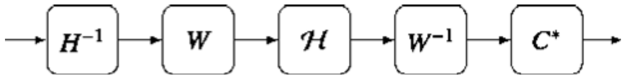

Figure 2. Full structure of a HIGS based integrator ($*() = 1/$)

rapid switching between the integrator-mode and the gain-mode, which reduces the effective control gain and thus compromises low-frequency disturbance rejection capabilities, an additional frequency-lifting pre-filter is placed between $^{-1}$ and the HIGS [16]. This pre-filter removes undesirable frequency components from the input to the HIGS. Its inverse $^{-1}$ is placed between the HIGS and $*$ to maintain the desired magnitude and phase characteristics. If we choose $*() = 1/$ the resulting structure shown in Figure 2 is a HIGS-based integrator element with describing function-based magnitude characteristics similar to a linear integrator but with a reduced phase lag of 38 instead of 90 degrees. Due to the exclusive reliance on the first harmonic, the describing function analysis neglects higher order harmonics and is an approximation. No guarantees for tuning and stability purposes can therefore be given, illustrating the importance of a time-domain tuning method as presented in this abstract. In [13], frequency-domain conditions are presented to verify whether the closed-loop system including the HIGS-based controller is input-to-state stable, which can be checked graphically using a Nyquist and Popov-like plot based on FRF-data. We have developed an automated procedure for verifying satisfaction of these conditions to facilitate a data-driven tuning method.

2.2. Problem Formulation

The developed data-driven tuning method is aimed at optimizing transient performance by minimizing the settling time in point-to-point motions. That is, the time required for the tracking error $()$ to converge until it no longer violates a predefined error bound, after the reference motion has reached the desired position at time . As shown in [17], exhibits an extreme sensitivity to changes in the controller parameters, due to its discontinuous dependence on these parameters. Therefore, inspired by [17], we decompose the settling time optimization problem into a cascade of two optimization problems with continuous cost functions, to circumvent this extreme sensitivity on changes in the controller parameters. In this cascade of optimization problems, the inner optimization loop is aimed at solving the following problem:

$$\begin{aligned} *() := \arg \min_{\in} & \ (,) \\ \text{s.t.} & \ \max_{[+,]} |(,)| \leqslant \end{aligned} \quad (3)$$

with $(,) := \int^{+} |(,)|$. Here, denotes the controller parameters, denotes all combinations of the controller parameters for which the closed-loop system is input-to-state stable, is the total duration of the point-to-point motion that is chosen sufficiently large to allow the tracking error to settle within the error bound, and is the optimization variable of the outer optimization problem. The outer optimization loop is aimed at solving the following problem:

$$\begin{aligned} * := \arg \min_{[0,-]} & \\ \text{s.t.} & \ (3) \text{ has a feasible solution} \end{aligned} \quad (4)$$

The inner problem (3) is aimed at minimizing the integral absolute error over a time interval with duration after the reference motion has finished, subject to the constraint that the error does not violate the error bound after this time interval. The outer problem (4) is aimed at searching for the smallest value of for which the inner problem can be solved, and as a result thus minimizes the settling time. The inner problem (3) is solved using the DIRECT algorithm similar to the ESC algorithm as in [17], with two modifications to include the automated procedure for guaranteeing the closed-loop system to be input-to-state stable, and to stop the optimization when the constraint in (4) is already known to be satisfied. The outer optimization problem is solved using a bisection search in which is decreased if (3) has a feasible solution, i.e., the constraint can be satisfied, and increased if this is not the case.

3. Results

The proposed data-driven tuning approach is applied to an industrial wire bonder system. Wire bonders are essential systems in semiconductor manufacturing, responsible for creating precise wired interconnections between integrated circuits and their packaging. These interconnections are achieved through rapid, point-to-point movements along the wire bonder's -, -, and -axes, as illustrated in Figure 3. To ensure the high-quality standards required in semiconductor production, the positioning error of the wire bonder must remain within a strict error bound at the moment the connection is made. Typically, this error bound is in the micrometer range to guarantee accurate wire placement and prevent undesired contact or overlap. Additionally, the manufacturing process demands high throughput, with wire bonders expected to place in the order of ten wires per second. In this case study, we focus on the -axis motion of the wire bonder. This approach is justified by the practical observation that the motion axes are sufficiently decoupled, allowing each axis to be treated as an independent single-input single-output (SISO) system. The typical controller for a wire-bonder stage is a PID with the addition of low-pass filtering and notch filters. For ease of exposition, we omit the notch-filters and use a first-order low-pass filter. The used controller is constructed by a linear lead-lag filter

$$() = \frac{\tilde{} + \tilde{}}{\tilde{} + \tilde{}} \tag{5}$$

with gain , lead frequency ω , and lag frequency ω . In addition to the lead-lag filter we use a HIGS-based integrator $\{\mathcal{H}\}$ as presented in Section 2.1. To avoid high-frequency switching, the filter is chosen as

$$() = \frac{{}^{2}(+)^{2}}{{}^{2}\tilde{} + \tilde{}^{2}} \tag{6}$$

with zeros ω_z and poles . The resulting HIGS-based controller has eight tunable parameters. These parameters are: , and of the lead-lag filter , the HIGS parameters h and h, the integrator frequency of $*$, and the zeros and poles of the frequency-lifting filter . However, h only affects the combination of $^{-1}$ and the HIGS $\mathcal{H}$ in the ratio h/h determining the corner frequency of the HIGS, meaning we can take $h = 1$ without loss of generality. Additionally, the zeros of the filter primarily ensure that is bi-proper. As a result, they can be fixed and set to sufficiently large values so as not to affect the desired low-pass behavior of . In this work, we selected $= 4\ 1$, where represents the sampling frequency in Hertz (typically in the order of several kilohertz).

The remaining parameters $= [, , , h, , \tilde{}$ are tuned using the proposed ESC approach. We compare[2] the ESC tuned HIGS-based controller against a similar LTI controller which replaces the HIGS-based integrator with a linear integrator and which is tuned using a proprietary state-of-the-art frequency-based autotuner (FBA) currently used in industry. This FBA optimizes controller parameters based on FRF data of

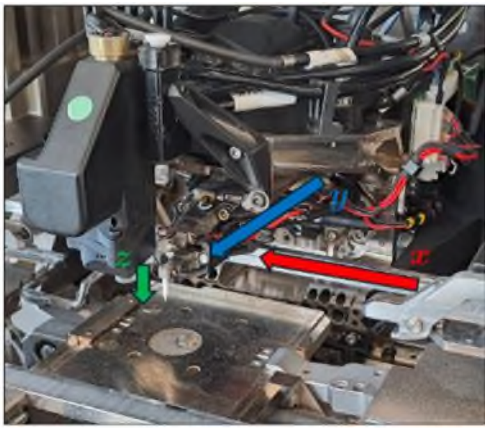

Figure 3. The wire bonder motion stage consisting of an *x*-motion axis, a *y*-motion axis, and a *z*-motion axis stacked on top of each other.

the system by using particle swarm optimization to maximize the bandwidth given a user-defined bound on the closed-loop sensitivity function. Additionally, we compare against a HIGS-based controller tuned using the FBA based on the describing function approximation of the HIGS-based controller. Note that due to the use of the describing function in the FBA, no guarantees on stability can be given and it is not possible to tune the filter , which is therefore omitted from this controller. The initial lower bound $\tilde{}$ and upper bound $\bar{}$ in the bisection search are set to 80 and 240 samples, respectively. The other parameters lower bounds have all been set to zero and the upper bounds are chosen as shown in Table 1.

Table 1. Upper parameter bounds and resulting optimized values

	Bound	ESC HIGS	FBA HIGS	FBA linear
	0.715	0.34573	0.44286	0.60369
	0.015 π	0.00639 π	0.01205 π	0.01351 π
	0.13125 π	0.05590 π	0.07542 π	0.07343 π
	0.01 π	0.00438 π	0.01036 π	N/A
	0.01 π	0.00907 π	0.01024 π	0.00595 π
	0.25 π	0.01389 π	N/A	N/A

We optimize over both the forward and backward movement of a point-to-point motion to obtain the overall lowest worst case settling time. The total optimization resulted in 34 698 function evaluations of which only 960 with parameters that result in an input-to-state stable closed-loop system, and therefore in motion experiments. With the duration of a single motion experiment being in the order of hundreds of milliseconds, the total optimization time without additional computational time is in the order of ten minutes. The resulting settling times are illustrated by Figure 4, where the black vertical dashed lines indicate the start of the settling phase (reference reached the desired position) and the colored dashed vertical lines indicate the moments the response satisfies the desired error bound. It can be seen that the HIGS leads to a slight increase in settling time in the forward motion (see interval between 300-400 samples in Figure 4), but a significant reduction in settling time in the backward motion (see between 900-1000 samples). Overall, the optimized HIGS-based controller resulted in a reduction of 21% in worst-case settling time over both motion directions compared to the other tested controllers, since in this case the backward motion is limiting in terms of the settling time. We care to stress that the settling time is an inherently discontinuous performance metric as a function of controller parameters. As a consequence, the settling time may jump to

[2]Some results in this section are normalized for confidentiality reasons.

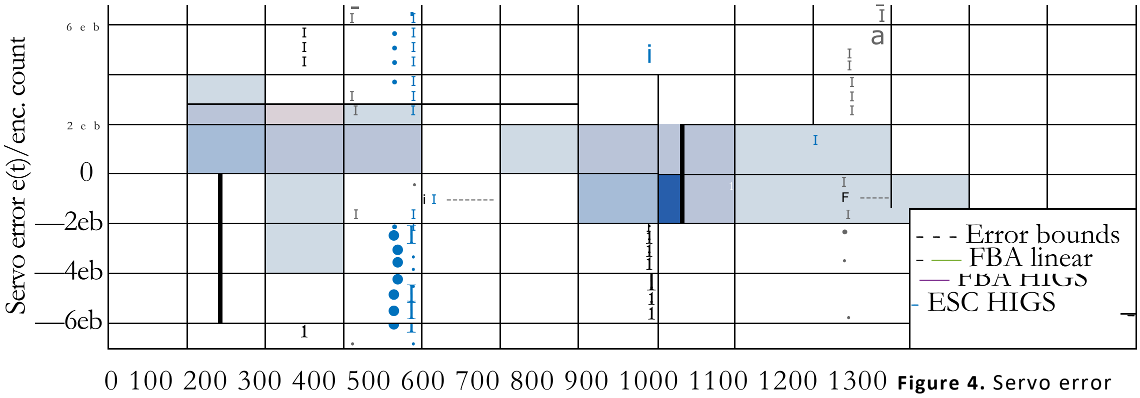

Figure 4. Servo error $e(t)$ obtained for the three controllers during five repetitions of the same motion for every controller.

higher or lower values in the presence of a (small) disturbance. To evaluate the robustness against such small changes or disturbances, we display the settling time as a function of the error bound, see Figure 5. The figure clearly shows a jump in the settling time of the ESC HIGS controller when the error bound is reduced to $0.98eb$ in the backward motion. However, despite this jump the worst-case settling time of the ESC HIGS controller remains lower than the worst-case settling time for the other controllers.

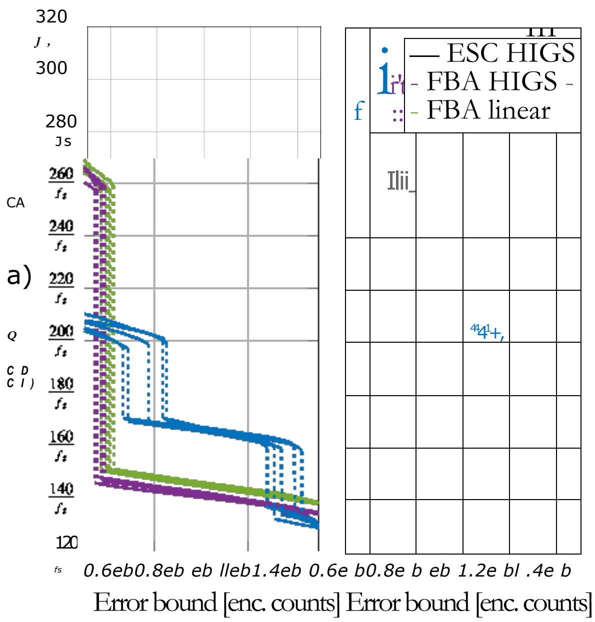

Figure 5. Settling times obtained with different error bounds e_b for the three controllers during five repetitions of the forward (left) and backward (right) motion.

4. Conclusion

We developed a data-driven approach for the automatic tuning of controllers based on hybrid integrator-gain systems, addressing the challenges posed by the complexity of nonlinear and hybrid controller design and possible machine-to-machine variations. The proposed method focuses on optimizing settling times for point-to-point tasks, while guaranteeing closed-loop stability solely based on measured FRF data of the plant. We validated the proposed method experimentally in a case study involving an industrial wire bonder system. The framework successfully tuned a HIGS-based controller, achieving stable responses with improvements in settling times of up to 21% relative to current industrial methods. Future research may explore applications to higher-order controllers or other types of nonlinear controllers such as variable-gain controllers.

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