NONLINEAR CONTROL TAKES OVER?

The ever increasing demands on precision and throughput in semiconductor manufacturing machines challenge today's linear control designs. For that reason, the industry is slowly starting to witness a shift toward more flexible, but also more complex nonlinear control methods. This article discusses the use of nonlinear integrators that can boost the performance of high-precision motion systems such as wafer scanners and wire bonders.

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Introduction

Developments in technological areas such as artificial intelligence create a need for microchips with smaller feature sizes, whereas the growing number of electronic devices that are used worldwide fuels the need for producing more and more chips. To facilitate the production of microchips, both front- and back-end semiconductor manufacturing machines such as wafer scanners and wire bonders are equipped with several high-precision motion stages.

To give an indication of the extreme operating conditions: a wafer scanner achieves positioning accuracies in the nanometer-range with accelerations up to tens of g's, whereas a wire bonder achieves micrometer-range accuracies with accelerations of more than 100 g. In meeting the specifications on accuracy, throughput and robustness, these machines hinge on the use of feedforward and feedback control.

Feedforward control deals with the problem of reference tracking, and is crucial for bringing stage-positioning errors within their required levels of accuracy. However, the feedforward controller is never perfect, meaning that a tracking error will always remain. Furthermore, unpredictable external disturbances that act on the system will also cause positioning errors. Therefore, to further minimise the positioning error, feedback control is used in addition to feedforward control. The majority of feedback controllers in industrial motion systems are of a (linear) Proportional-Integral-Derivative (PID) form:

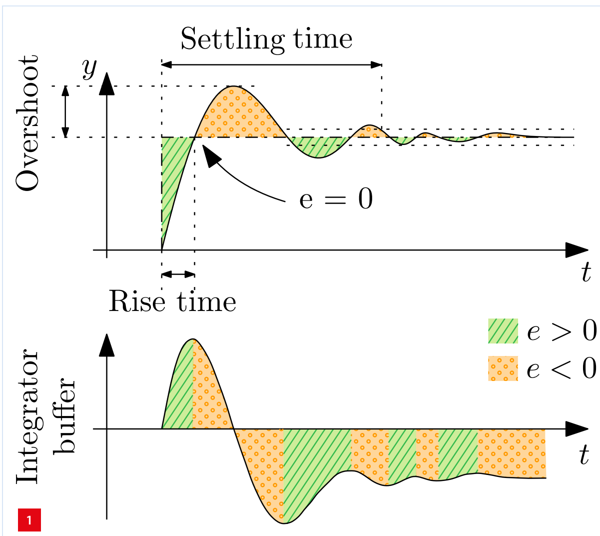
$$u(t) = \underbrace{k_p e(t)}_{\text{Proportional}} + \underbrace{k_i \int_0^t e(\tau)\,\mathrm{d}\tau}_{\text{Integral}} + \underbrace{k_d \frac{de(t)}{dt}}_{\text{Derivative}} \qquad (1)$$

In (1), e typically represents the stage positioning error and u is the controller output, for example, a desired motor force or current. The reason for the widespread application of PID control seems attributed to its ease of use and simplicity in design. That being said, linear control designs in general suffer from inherent performance trade-offs [1].

An example of such a performance trade-off relates to the integral action in the PID controller (1). This trade-off is illustrated in Figure 1 and can be understood as follows. An integrator sums the positioning error over time to push the system toward zero steady-state error, which is necessary for counteracting static disturbances.

However, when the error first crosses zero, the integrator has the summation of passed errors as a stored value in its buffer, thereby pushing the system away from zero error. It takes some time before the buffer is sufficiently emptied and the controller is able to push the system toward zero error again.

This subsequent emptying and filling of the integrator buffer lags behind changes in the feedback error signal, which compromises settling time and machine throughput.



1 *Illustrating the limitations of linear integral control.*

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Besides, this lag has a detrimental effect on the robust stability of the system: more lag means less robustness, and at some point the amount of lag can even cause the system to become unstable.

In light of the tightening requirements on speed, accuracy and robustness of high-precision machines, it is natural to ask whether linear control still presents the way forward. This question has kept researchers and control practitioners busy since the early 1950s, and has spurred many different nonlinear control approaches, some of which have been proven to outperform any linear controller [2] [3].

The potential of nonlinear control is also being noticed by industry. However, a viable alternative to the existing practice requires an analysis and design framework for nonlinear controllers that is in line with what is currently used for linear controllers. This means that intuitive frequency-domain-based tuning methods are highly preferred, and that the design can be done based solely on frequency-response data of the plant instead of the need for using a parametric model.

Although some basic understanding of nonlinear controllers was obtained over the past years, a user-friendly and complete analysis and design framework was never realised. However, several scientific breakthroughs have been recently made in this direction, making nonlinear control technology currently more accessible to engineers. In this article, we showcase two nonlinear integrators that are finding their way into various industrial applications: resetting integrators and hybrid integrators.

Nonlinear integrators

In order to overcome the aforementioned trade-off in linear integrators due to lag in emptying the integrator buffer, we exploit nonlinear mechanisms for making this process faster. Two strategies are:

1. The buffer of the integrator is emptied instantaneously by resetting its value to zero upon a zero-crossing detection of the input. This is known as a reset element; its time-response to a sinusoidal input is shown in Figure 2 in black.
2. The buffer of the integrator is emptied gradually before a zero crossing occurs by switching from an integrator mode to a gain mode. This is called a hybrid integrator-gain system (HIGS), for which the time-response to a sinusoidal input is shown in Figure 2 in red.

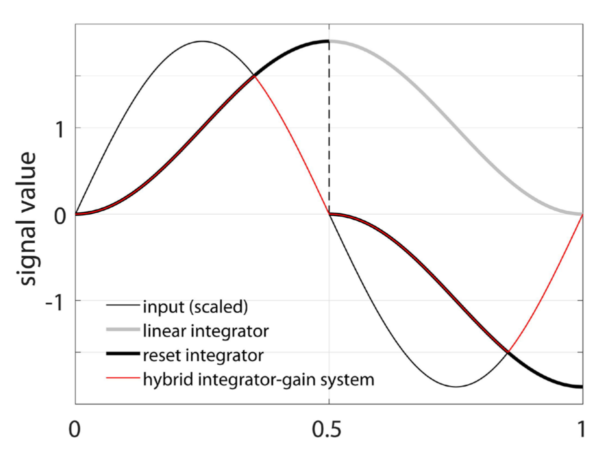
Both strategies offer the improvements we aim for in terms of emptying the integrator buffer fast (compare the non-linear responses in Figure 2 to that of the linear integrator), but two potential issues remain:

1. The discontinuous/non-smooth nature coming from resetting and switching introduces the risk of exciting high-frequency modes in the system.
2. The elements cannot maintain a non-zero integrator buffer if the input (positioning error) becomes zero. Namely, in that case the output of the nonlinear elements will be zero, i.e., the possibility to counteract static disturbances is lost.

To resolve these issues, in nonlinear stage control design we pre- and post-filter the reset and HIGS element with carefully designed linear filters. As an example, for reset integrators we can use a lead filter in front to enforce a reset earlier, and a lag filter in the back to smoothen the jump in the control output [4], resulting in the response depicted in Figure 3a. For HIGS, we typically choose a lead filter in front and an integrator at the back. The lead filter in front is used to condition the switching moments, and the linear integrator at the back allows the controller to maintain a non-zero integrator buffer when the positioning error is zero. The time-response is depicted in Figure 3b. These filtered structures lead to effective practical nonlinear integrators.

To relate nonlinear integrator properties to that of a linear integrator in terms of 'gain' and 'phase', a quasi-linear approximation of the nonlinear integrators is obtained in the frequency-domain using the method of harmonic linearisation (see text box for details). The harmonic linearisations of the pre- and post-filtered reset and hybrid integrator are shown in Figure 3 (light red). Note the significant reduction in output delay (phase lag) as compared to a linear integrator with the same 'gain'.

Amplitude and phase of the harmonic linearisations for different input frequencies are shown in the Bode plot in Figure 4, which clearly shows a –20 dB/decade amplitude decay, similar to a linear integrator, paired with a reduction in phase lag from 90° to at most 38°. This significant phase-lag reduction is seen as the enabler for breaking away from the limitations of linear control.



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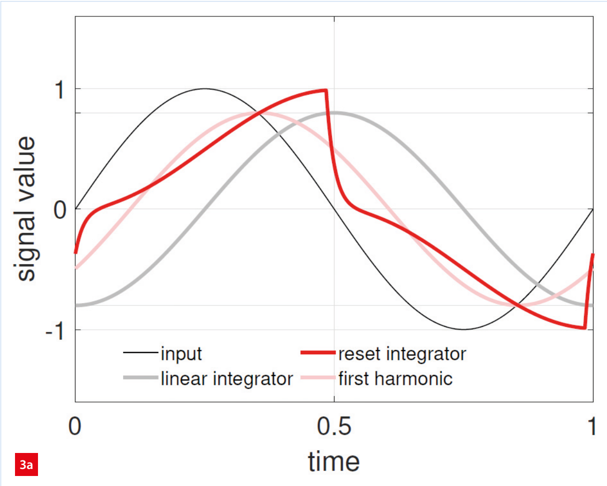
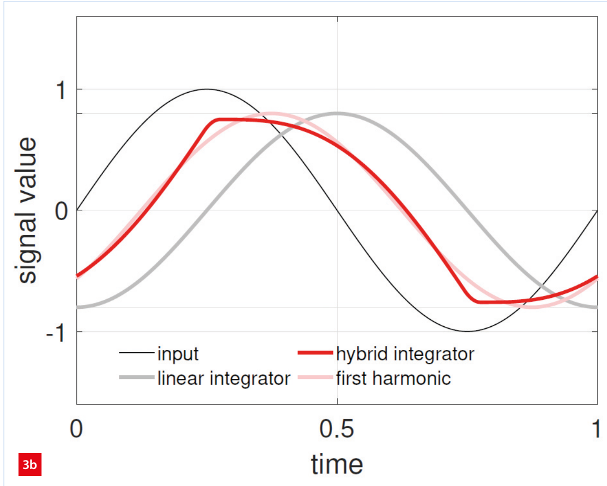
Time-domain responses of linear and nonlinear integrators.





Time-domain responses of nonlinear integrators including linear pre- and post-filters.
(a) Reset integrator.
(b) Hybrid integrator.

Harmonic linearisation

The idea underlying the method of harmonic linearisation is as follows. When injecting the nonlinear integrator with a sinusoidal input $e(t) = \sin(\omega t)$, the corresponding output will be periodic with the same period as the input. Such a periodic signal can be written as an infinite sum of harmonics (Fourier series), that is:

$$u(t) = A_0 + \sum_{k=1}^{\infty} A_k \sin(k\omega t + \phi_k) \qquad (2)$$

Here, A_0 is an offset, and A_k and φ_k are the amplitude and phase shift of the k-th harmonic. For reset elements and HIGS, the offset term is zero, i.e., $A_0 = 0$, due to symmetry of their responses. By neglecting all higher harmonics in (2) we obtain a first-order harmonic approximation:

$$u(t) \approx A_1 \sin(\omega t + \phi_1)$$

By relating the amplitude A_1 and the phase φ_1 to that of the input signal for each input frequency ω, we obtain magnitude and phase information as a function of the excitation frequency ω, which can be depicted in a Bode plot.

It is important to know whether the higher harmonics in (2) can indeed be neglected, i.e., whether the first-order approximation is valid. For this purpose, frequency-domain tools have been developed for reset elements and HIGS in [5], [6] that allow a visualisation of the magnitude of each harmonic. In this way we can predict whether the higher harmonics will have a significant contribution in the overall control output.

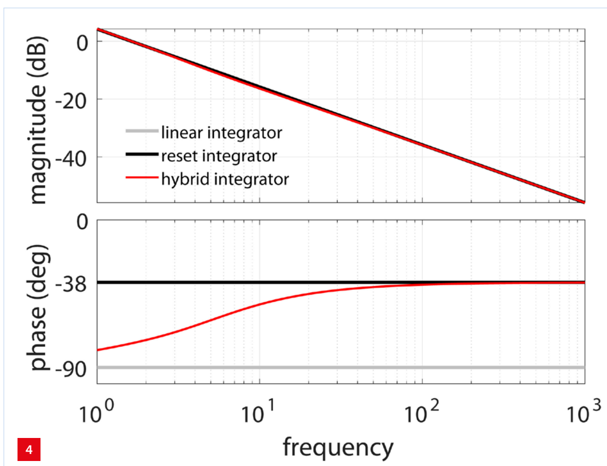
Beyond the limitations of linear control?

At this point, one may wonder what the above integrator designs can truly offer. Before showing this shortly hereafter for an industrial use case, we will first emphasise this in a simple example.
Consider the feedback configuration in Figure 5, where the plant is given by:

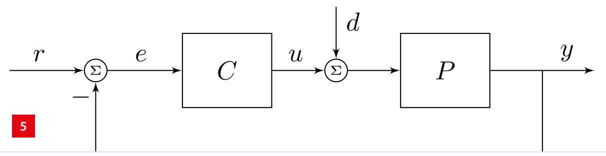
$$P(s) = \frac{1}{ms^2} \qquad (3)$$

This represents (simplified) stage dynamics with $m = 1$ kg. We aim to design a stabilising feedback controller C such that the following two control objectives are met:

- Objective 1: For $r(t) = 0$, the closed-loop system has zero steady-state output, i.e., $\lim_{t\to\infty} y(t) = 0$ in the presence of a constant input disturbance $d(t) = 0.1$ N.
- Objective 2: For $d(t) = 0$, the closed-loop system tracks a unit-step input $r(t) = 1$ for $t \geq 0$ and $r(t) = 0$ otherwise, without overshoot.



Frequency-domain characteristics of nonlinear integrators based on harmonic linearisation.



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Closed-loop system configuration with plant P and feedback controller C.

The first objective of constant disturbance rejection necessitates (according to the internal model principle) integral action in the controller C. However, as the plant is a double integrator, the resulting closed-loop system will always have overshoot in the step-response when linear integral control is used [1, Chapter 1]. This is a mere consequence of the introduced phase lag and results in longer settling times. Note that overshoot can be avoided at the cost of losing constant disturbance rejection (e.g., with PD control). Hence, we face the following trade-off:

> Given the motion system in (3), there does not exist a stabilising linear feedback controller C that can meet objectives 1 and 2 simultaneously.

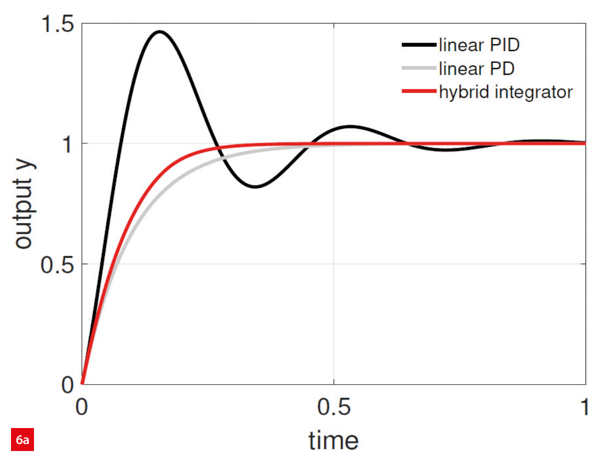
This trade-off reflects the discussed limitations in integral control. That is, on the one hand integral control is required for counteracting static disturbances, but on the other hand it results in overshoot due to phase lag. As an example of demonstrating this trade-off in linear systems, we take the PID controller in (1) with k_p = 1,000, k_i = 3,000, and k_d = 1,000, for which the closed-loop system tracking and disturbance rejection properties are shown in black in Figure 6. For the purpose of comparison, we also show the response of a linear PD controller (i.e., with k_i = 0) in grey. As expected, both the PID and PD design do not meet the control objectives simultaneously.

We now replace the linear integrator in the above PID design with a hybrid integrator combined with linear pre- and post-filters (for details on the hybrid integrator structure see [3]). This controller stabilises the system (see the text box on stability analysis for details), and the resulting tracking and disturbance rejection properties are shown in Figure 6 in red. Clearly, both control objectives are met simultaneously as the steady-state output in the presence of the disturbance is zero, and the system tracks the step input without overshoot. Moreover, the nonlinear system settles much faster as compared to its linear counterpart. This simple example demonstrates the potential of nonlinear control in terms of moving beyond classical trade-offs in linear control designs.

Industrial use case: wire-bonding machine

From here, we put theory into practice, and demonstrate the performance potential of nonlinear integrators on an industrial wire bonder manufactured by ASMPT – for an industrial case study of hybrid integral control in wafer scanners, see, e.g., the results in [10]. Wire bonders make electronic interconnections (wires) between an integrated circuit (IC) and the package or substrate that it is mounted on; see Figure 7 for an impression. Wire-bonding machines play a crucial role in the production of a wide range of microchips and other electronic devices.

The most important component of a wire bonder is its motion platform, which is illustrated in Figure 9. This platform consists of stacked X-, Y-, and Z-stages. The X-stage (red) is connected to the base frame of the machine (green) by means of a roller guide. The Y-stage (purple) is connected to the X-stage, also with a roller guide. Together, the XY-stage can move in the horizontal plane. Finally, the Z-stage (blue), which contains the capillary tip that pulls the wires, is connected to the Y-stage by means of leafsprings functioning as a pivot mechanism. In this way, the Z-stage allows for a movement in the vertical direction. Each stage is controlled by an advanced feedforward controller and a linear feedback controller.



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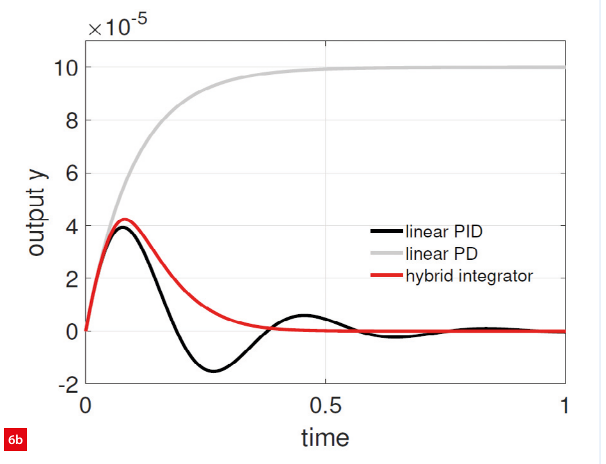

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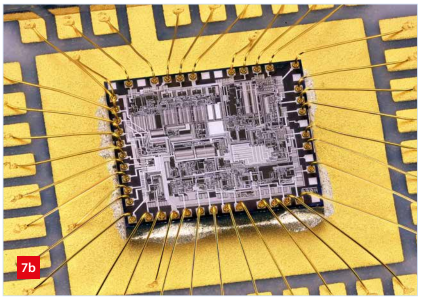
Linear and nonlinear closed-loop system responses.
(a) Step-response.
(b) Disturbance rejection.



Illustrations of the wire-bonding process.
(a) ASMPT wire-bonding machine.
(b) IC wire-bonded to a substrate [12].

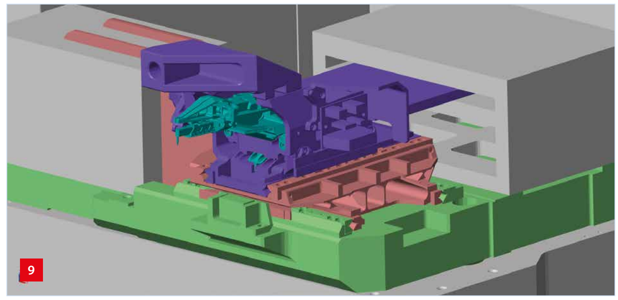
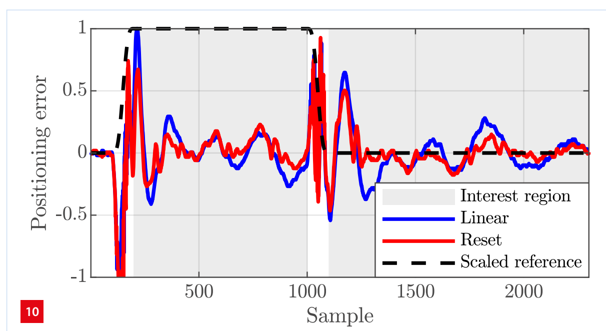


Illustration of the wire-bonder motion platform with base-frame (green), X-stage (red), Y-stage (purple), and Z-stage (blue).

Roughly speaking, a wire bonder can bond in the order of ten wires per second while maintaining positioning accuracies in the micrometer range. During motion, it is important to accurately follow the reference setpoint, in order to prevent neighbouring wires touching each other, resulting in short circuiting. After the trajectory is finished and a new bonding pad has been reached, fast settling is required to rapidly start a new bonding procedure.

If we would be able to decrease the positioning error by improving the motion controller, we could in turn decrease the settling time or speed up the motion, which allows for higher machine throughput (more bonded wires per second). To improve the positioning accuracy beyond what is possible with linear control, we incorporated a reset integrator in the X-stage controller design. Design of the reset controller was done using an intuitive frequency-domain loopshaping approach using frequency-response data of the plant, similar to what is done in linear control design (for more details on this method, the interested reader is referred to [5]).

Figure 10 compares the (normalised) positioning errors measured during motion-control experiments for the linear controller and the reset controller. During the experiments, a forward and a backward movement is made (dashed black). The goal was to further suppress the error during the parts at which the system is at a bond location and needs to settle, as indicated in grey. The positioning error obtained with the linear controller is shown in blue, whereas the error obtained with the reset controller is shown in red.

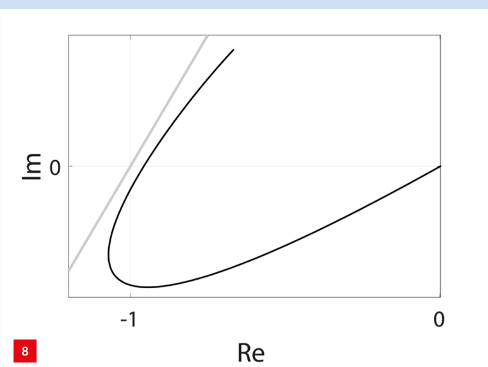


Positioning errors (normalised) achieved during motion-control experiments on a wire-bonder motion stage.

Stability analysis

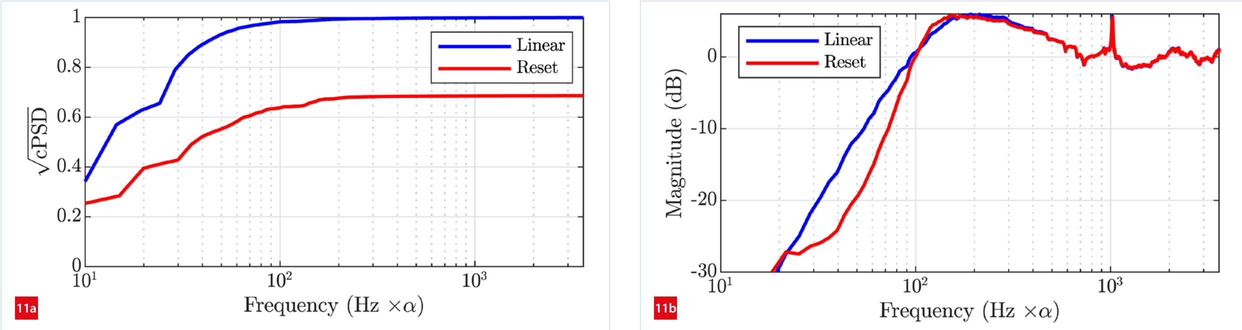
Stability analysis of systems with nonlinear integrators is not straightforward. But formal stability checks that match with graphical (frequency-domain-based) methods for linear systems through Nyquist-like plots do exist for reset integrators and hybrid integrators. For example, to check stability of the previously discussed system containing a hybrid integrator, we can use the test in [7, Section 4].

This test is illustrated in Figure 8, which is reminiscent of a classical Popov plot [11]. The black line in this figure represents a Nyquist-like curve of the linear portion of the system, i.e., it is a combination of the plant *P* and linear filters in the controller (see [7] for more details). The grey line can be interpreted as a worst-case input-output property of the nonlinear element in the controller. For example, a vertical line corresponds to a maximum input-output gain of the nonlinearity.



Popov-like stability test with the black line representing a Nyquist-like curve of the linear portion of the system, while the grey line characterises the nonlinearity.

The resulting test is simple: the black Nyquist-like curve must remain to the right of the tilted grey line. Not only does this test give rigorous stability guarantees, but the minimum distance between the Nyquist plot and the grey line indicates a robustness margin. Similar tests for reset systems can be found in [8], [9].



Frequency-domain analysis of motion-control experiments on the wire-bonder motion stage.
(a) Normalised cPSD of positioning errors.
(b) Sensitivity function.

Performance is measured in terms of the root mean square (RMS) error after the end of motion. With reset control, an RMS improvement of 32% as compared to the linear controller is achieved, showing the performance potential of this nonlinear method. The cumulative power spectral density (cPSD) is shown in Figure 11a, where it can be seen that especially in the low-frequency range the energy in the error signal has been reduced. This corresponds well with what was expected from the frequency-domain-based tuning of the reset controller.

To illustrate this result, the sensitivity functions (ratio between maximum amplitude of error and reference) of both controllers are depicted in Figure 11b. Note that for the reset controller, this sensitivity function also includes the effect of higher-order harmonics, which we can predict using the closed-loop prediction tools presented in [5]. It can be observed that we predict more suppression of the error in the low-frequency range. As visible in Figure 11a, the measurement results confirm our expectations, showcasing the strength of the developed frequency-domain design tools for the nonlinear integrators.

Concluding remarks

This article highlights two nonlinear integrator strategies: reset integrators and hybrid integrators. These integrators are able to overcome certain fundamental trade-offs in linear control design, and have the potential to enable future performance improvements in high-precision motion systems. We showcased the potential performance improvements on an industrial wire-bonding machine.

Now, we close this article with the statement that nonlinear controllers are not presented as a universal solution to every control problem, but rather as another useful 'tool' in the control engineer's toolbox.

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