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Repetitive Control for Intermittently Sampled Data: Convergence, Design, and Applications

Johan Kon, Nard Strijbosch, Sjirk Koekebakker, Leonid Mirkin, and Tom Oomen, *Senior Member, IEEE*

***Abstract*—The standard assumption that exact measurement data is available at equidistant time instances in repetitive control (RC) is not always justified, e.g., when exploiting time-stamped data from incremental encoders or in systems with data dropouts. The aim of this article is to develop an RC framework that is capable of exploiting intermittently sampled measurement signals. Stability conditions for the intermittent RC framework are provided that can be verified using the frequency response function (FRF) data. This condition results in a frequency-domain design procedure for repetitive controllers in this intermittent setting. The intermittent RC framework is validated on an industrial print belt setup for which nonequidistant measurement data are available.**

***Index Terms*—Incremental encoders, intermittent data, repetitive control (RC).**

I. Introduction

COMPENSATION of repetitive disturbances via learning methods, including repetitive control (RC) [18] and strongly related iterative learning control (ILC) approaches [4], can achieve the major performance improvements up to the sensor resolution for periodic tasks [3], [16]. Both RC and ILC exploit the reproducibility of the error. More specifically, RC addresses periodic errors caused by, for example, rotating components, while ILC addresses the reproducible part of the error in batch-to-batch operation. The key idea of these techniques is to exploit the internal model principle (IMP) [8], which exploits the past error data to determine a control input that compensates for the reproducible part of the error. Many successful applications have been reported, including hard disk drives, which are vulnerable to periodic disturbances due to eccentricities on the disk [9], and printing systems that exhibit periodic disturbances due to eccentricities in the rollers [2].

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Successful RC design methods typically rely on: 1) a stability test that can be verified using nonparametric models in the form of frequency response function (FRF) data and 2) an intuitive frequency-domain design framework based on loop shaping to explicitly address uncertainty [13]. A common RC structure consists of an internal model for a periodic disturbance based on a buffer in positive feedback interconnection with itself [11], [27], complemented by a learning and robustness filter. This approach can be extended to accommodate uncertain period length [19], [24] and multiple periods [2], [29]. The buffer can be replaced by other types of internal models as long as a periodic signal is generated, see [23]. Each of these frameworks rests on the assumption that exact equidistantly sampled measurement data is available, allowing for a linear-time invariant (LTI) RC framework, with corresponding tools such as Nyquist and Bode diagrams.

The assumption in RC that exact measurement data is available equidistant in time, i.e., at all sample instances, is not always valid. For example, the common approach to use quantized data from incremental encoders leads to performance degradation [7], since the estimation of the disturbance in the internal model is based on the inexact data. However, the measurement of an incremental encoder is exact at the time instant of a line transition [20]. These time instants are referred to as timestamps and are nonequidistant in time. Moreover, package losses in networked control systems similarly result in intermittently sampled measurements [1]. In the low-performance feedback control, intermittent sampling effects and resulting quantization can be neglected as they are insignificant compared with the magnitude of the converged error. Due to the increased performance up to the sensor resolution in RC, these effects are no longer negligible and if left unaddressed, deteriorate performance [24].

Despite the fact that ILC approaches are very similar to RC, the research directions pursued in ILC to address intermittently the sampled measurement data, including [1], [22], and [26] and do not extend well to the domain of RC. These include different methods to model the availability of data through a known probability distribution [1], [22]. Since this probability distribution is typically unknown in many applications, a worst-case analysis that yields guarantees for each possible realization of measurement instance is preferred, see [26]. All of these intermittent ILC frameworks rely on a stability analysis that exploits the identical initial condition and finite-time duration of an iteration, thereby preventing a direct extension to RC, which requires an infinite-time analysis.

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Although RC has been substantially developed for a large range of applications, at present, an RC approach that can exploit intermittently sampled measurement data, as in, e.g., systems that exploit incremental encoders or networked control systems, is not yet available. The aim of this article is to design an RC framework that can asymptotically reject periodic disturbance when the measurement data are available at nonequidistant samples.

The main contribution of this article is an intermittent RC framework that guarantees convergence when limited error information is available at arbitrary time-varying measurement points. A unified intermittent RC framework is presented that encompasses a large number of applications, including systems that exploit incremental encoders or that are subject to data dropouts. This is achieved through the following subcontributions.

- C1: Stability conditions based on the frequency response data that provide guarantees in a worst case sense (see Section III).
- C2: Guidelines for design that the guarantee stability through the frequency-domain loop-shaping techniques based on the measured FRF data (see Section IV).
- C3: Experimental validation of the developed framework on an industrial print belt setup with intermittently sampled measurements of the belt position (see Section V).

Very preliminary results related to this article are presented in [15]. This article substantially extends these results in the form of an underlying theoretical framework based on integral quadratic constraints that allows for deriving more specialized stability results that distinguish between different sampling characteristics.

Notation, definitions, and setting: All systems are considered to be discrete time, single-input–single-output (SISO). The set of real, rational, proper, and stable transfer functions is denoted by $\mathcal{RH}_\infty$. The sets $\mathbb{N}$ and $\mathbb{Z}$ indicate the set of all positive integers, and the set of all integers, respectively. Given $c \in \mathbb{C}$, c^* denotes its complex conjugate. $\mathbb{S}^n_{++}$ denotes the set of positive definite matrices. Finally, the notion of global uniform (asymptotic) stability (GUAS) is stated [14, Definition 4.4].

Definition 1: The origin $x = 0$ of a time-varying system $x(k+1) = f(x(k), k)$ with state $x(k) \in \mathbb{R}^{n_x}$ and initial value $x(k_0)$ at time k_0 is said to be globally uniformly stable (GUS) if for each $\varepsilon > 0$ there exists $\delta = \delta(\varepsilon) > 0$ not a function of k_0 such that for all $k_0 \in \mathbb{Z}$, it holds that

$$\|x(k_0)\|_2 \leq \delta \implies \|x(k)\|_2 \leq \varepsilon \ \forall k \geq k_0. \tag{1}$$

The origin is said to be globally uniformly asymptotically stable if additionally for all $k_0 \in \mathbb{Z}$, $x(k_0) \in \mathbb{R}^{n_x}$ it holds that

$$\lim_{k\to\infty} \|x(k)\|_2 = 0. \tag{2}$$

II. Problem Formulation

In this section, the intermittently sampled RC framework is introduced. First, the RC setup is introduced, after which the intermittently sampled RC problem is formulated. Finally, several application examples, including incremental encoders with time-stamped data, are shown to fit this formulation.

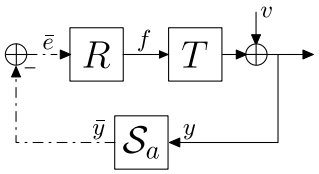

Fig. 1. Intermittently sampled RC setup with repetitive controller R, system T, and available data sampler $\mathcal{S}_\text{a}$.

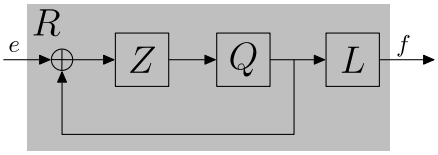

Fig. 2. Traditional repetitive controller with buffer $Z = z^N$, robustness filter Q, and learning filter L to mitigate the periodic disturbance with a period length of N samples.

A. Intermittent Repetitive Control Setup

In this article, the repetitive control setup, as depicted in Fig. 1, is considered. Here, the output of the discrete-time LTI system $T \in \mathcal{RH}_\infty$ is affected by a periodic disturbance v to produce signal y. The system T can represent either an open-loop or closed-loop system. The signal y is intermittently sampled by the sampler $\mathcal{S}_\text{a}$, which is defined next.

Definition 2: The available data sampler $\mathcal{S}_\text{a}$ samples its input at a given set of timestamps, and 0 elsewhere, i.e.,

$$\mathcal{S}_\text{a} : \bar{y}(k) = \begin{cases} y(k), & \text{if } k \in \mathcal{T} \\ 0, & \text{elsewhere} \end{cases} \tag{3}$$

where $\mathcal{T}$ is a sequence of timestamps according to

$$\mathcal{T} = \{\ldots, \tau_{-1}, \tau_0, \tau_1, \ldots\}, \tau_i \in \mathbb{Z}, \tau_i < \tau_{i+1}. \tag{4}$$

There could be various sources that cause this intermittent sampling and thereby dictate $\mathcal{T}$, as is exemplified below. In the traditional RC setting, data are available at each sampling instance, i.e., $\mathcal{T} = \mathbb{Z}$.

A repetitive controller R aims to mitigate the periodic disturbance v, exploiting the available measurement data y. A typical repetitive controller is based on the IMP [8], which states that an internal model of the disturbance v has to be included in a feedback controller to asymptotically reject the influence of the disturbance on the T, i.e., obtaining

$$\lim_{k\to\infty} e(k) = 0. \tag{5}$$

Remark 1: Note that by definition of the IMP, RC can only be used to compensate disturbances of which the time evolution can be described through a model, usually in the form of an autonomous system such as $d(k+1) = Ad(k)$. This class of disturbances encompasses constant and periodic disturbances, but excludes stochastic disturbances.

An example of a traditional repetitive controller that attenuates disturbances that have a period of N samples is given in Fig. 2 and is given by [17]

$$R = LZQ(1 - ZQ)^{-1}. \tag{6}$$

In this repetitive controller, the internal model is formed by a periodic signal generator consisting of a buffer Z which

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Fig. 3. Experimental print belt setup with a belt, rollers, and quad sensors.

delays the input with N samples, i.e., $Z = z^{-N}$. The aim of this memory loop is to generate a signal with period N such that this signal filtered with L compensates for the periodic disturbance v. The filter L is typically chosen as the inverse or an approximation of the inverse of the system T. The optional filter Q is added for robustness and is typically designed to be as close to 1 as possible, i.e., $|1 - Q| \approx 0$. In this setup, the error is given by

$$e = \frac{1}{1 + RT} v = \frac{1 - z^{-N} Q}{1 - z^{-N} Q\,(1 - TL)} v. \tag{7}$$

The key idea of the intermittent RC framework is to exploit *only* the intermittently available data to construct an internal model of the periodic disturbance v. When employing the traditional repetitive controller structure of Fig. 2, this would mean that only the elements in the buffer that are observed get updated, while the other elements remain unchanged. Intuitively, as long as new measurement data is available, updating the buffer leads to a correct model to compensate for the periodic disturbance v. This is in contrast to interpolating the intermittent measurements through a zero-order hold, which biases the internal model.

B. Applications

The RC setup of Fig. 1 encompasses a large number of applications. Systems vulnerable to data dropouts [1], [22] or stealth attacks [5] fit naturally in the RC setup given in Fig. 1, as the sampler $\mathcal{S}_\mathrm{a}$ determines which data points are available. Moreover, systems for which data are only available based on their position can also be captured by the RC setup of Fig. 1, e.g., systems that exploit incremental encoders to measure position [25].

An industrial example of a system that fits into the RC setup of Fig. 1 is a print belt system similar to the one in the Canon Varioprint i300, see Figs. 3 and 4. This print belt module consists of a motor, which is connected to a drive roller through a drive train, and a print belt, which is guided along three other rollers. A high-resolution optical encoder is attached to a measurement roller. In addition, the belt is perforated approximately every 10 mm such that an optical sensor, named a quad-sensor, provides the time interval between two subsequent hole observations. The quad sensor provides a direct measurement of the true performance variable, namely, the belt velocity close to the inkjet array.

The system is operated in the discrete time with a sampling frequency of 500 Hz. The belt is controlled using a stabilizing feedback controller on the high-resolution encoder such that the belt travels with an approximately constant velocity. The closed-loop system consisting of the motor and its feedback controller is the system T in Fig. 1.

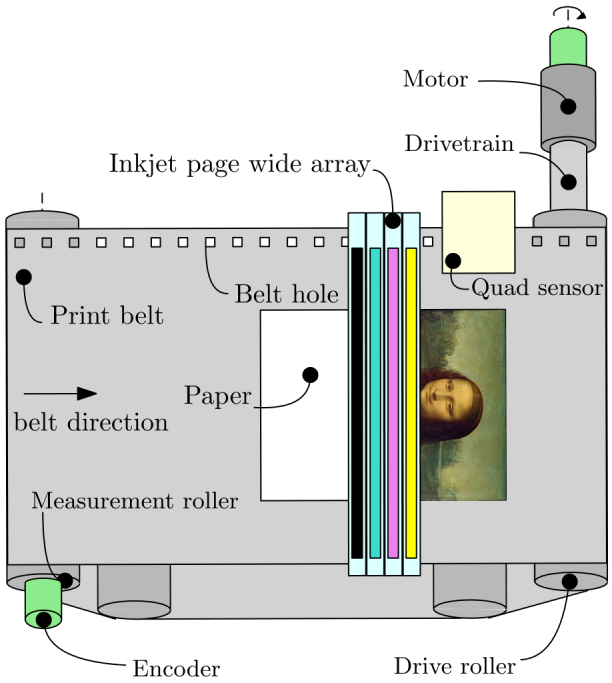

Fig. 4. Schematic top view of the print belt setup.

The rollers introduce periodic disturbances on the belt velocity that are not fully attenuated by the feedback controller. A repetitive controller that exploits the data from the quad-sensors can be used to reduce the effect of these periodic disturbances on the belt velocity. Since the distance between the holes in the belt is large, the measurements of the belt velocity are intermittently sampled and can be considered exact at their timestamps. The RC setup, as depicted in Fig. 1, encompasses the RC setup that only uses the intermittently sampled data from the quad-sensors.

C. Problem Formulation

The goal of this article is to design R that is able to asymptotically reject the influence of a periodic disturbance v on the system T, i.e., (5), using only the available error $\bar{e}(k)$ sampled at arbitrary timestamps $\mathcal{T}$ by sampler $\mathcal{S}_\mathrm{a}$, see Fig. 1. To enable this intermittent RC design, the following must be developed.

1) A stability test based on an FRF data that guarantees that the feedback interconnection of TR and $\mathcal{S}_\mathrm{a}$ is GUAS.
2) A design procedure along the lines of traditional frequency-domain RC designs based on this stability test.

III. Stability Analysis

In this section, the stability criteria for the intermittently sampled RC setup of Fig. 1 are developed, constituting contribution C1.

A. Standard Feedback Interconnection

To derive stability conditions, the intermittently sampled RC setup, see Fig. 1, is rewritten as an interconnection between

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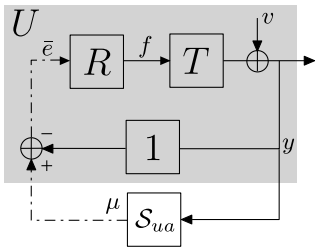

Fig. 5. Intermittently sampled RC setup with available data sampler $\mathcal{S}_{\text{a}}$ split as $\mathcal{S}_{\text{a}}(y) = y - \mathcal{S}_{\text{ua}}(y)$.

an LTI system, representing the nominal RC setup, and a memoryless LTV function representing the complement of the available data sampler $\mathcal{S}_{\text{a}}$, see Fig. 5.

Consider that T has a minimal state-space representation described by A_T, B_T, C_T, and D_T with state x_T. Similarly, R has a minimal state-space representation described by A_R, B_R, and C_R with x_R. Note that R has no direct feedthrough as most repetitive controllers either are strictly proper or can be designed to be [6], [18]. Then, the intermittently sampled RC setup, see Fig. 1, is described by

$$\begin{aligned}\begin{bmatrix} x_R(k+1) \\ x_T(k+1) \end{bmatrix} &= \begin{bmatrix} A_R & 0 \\ B_T C_R & A_T \end{bmatrix} \begin{bmatrix} x_R(k) \\ x_T(k) \end{bmatrix} - \begin{bmatrix} B_R \\ 0 \end{bmatrix} \bar{y}(k) \\ y(k) &= \begin{bmatrix} D_T C_R & C_T \end{bmatrix} \begin{bmatrix} x_R(k) \\ x_T(k) \end{bmatrix} + v(k) \\ \bar{y}(k) &= \mathcal{S}_{\text{a}}(y(k)) \end{aligned} \tag{8}$$

which can be recognized as a feedback interconnection between an LTI system representing TR and $\mathcal{S}_{\text{a}}$, see Fig. 1. For the stability analysis in such a setting, it is required that the LTI component of the intermittently sampled RC setup of Fig. 1 is stable, i.e., A_R and A_T cannot have poles on the unit circle. While A_T is stable by assumption, the internal model of R has poles on the unit circle by design, see Fig. 2. To obtain a stable LTI component, $\mathcal{S}_{\text{a}}$ is split into identity and its complement, the unavailable data sampler $\mathcal{S}_{\text{ua}}$ defined as follows.

Definition 3: The unavailable data sampler $\mathcal{S}_{\text{ua}}$ samples its input at any point, except for the set of timestamps, where its output is 0, i.e.,

$$\mathcal{S}_{\text{ua}} : \mu(k) = \begin{cases} 0, & \text{if } k \in \mathcal{T} \\ y(k), & \text{elsewhere} \end{cases} \tag{9}$$

where $\mathcal{T}$ is the sequence of timestamps.

Consequently, the intermittent output $\bar{y}(k)$ can be written as follows:

$$\bar{y}(k) = y(k) - \mathcal{S}_{\text{ua}}(y(k)) \tag{10}$$

allowing to rewrite (8) as follows:

$$\begin{aligned} x(k+1) &= Ax(k) + B\mu(k) - Bv(k) \\ y(k) &= Cx(k) + v(k) \\ \mu(k) &= \mathcal{S}_{\text{ua}}(y(k)) \end{aligned} \tag{11}$$

with state-space matrices

$$A = \begin{bmatrix} A_R - B_R D_T C_R & -B_R C_T \\ B_T C_R & A_T \end{bmatrix} \quad B = \begin{bmatrix} B_R \\ 0 \end{bmatrix} \tag{12}$$

$$C = \begin{bmatrix} D_T C_R & C_T \end{bmatrix}$$

and associated LTI mappings $U : \mu \mapsto y$ and $V : v \mapsto y$. By the standard realization theory, $U = C(zI - A)^{-1}B$ and $V = -C(zI - A)^{-1}B + 1$. Onward, it is assumed that given minimal $(A_R, B_R, C_R, 0)$ and (A_T, B_T, C_T, D_T), also the resulting $(A, B, C, 0)$ is minimal. If it is not, a minimal realization can be considered without the loss of generality.

For the purpose of presenting stability tests based on the frequency-domain data of T, it is of particular interest to represent U equivalently as a function of T. The signal balance in Fig. 5 reads as $\bar{e} = -TR\bar{e} - v + \mu$, and with $y = TR\bar{e} + v$ it holds that

$$y = TR(1 + TR)^{-1}\mu + (1 + TR)^{-1}v \tag{13}$$

such that U is given by

$$U = TR(1 + TR)^{-1}. \tag{14}$$

The introduction of $\mathcal{S}_{\text{ua}}$ transforms the setup of (8) in Fig. 1 into the setup of (11) in Fig. 5. In this setting, U represents the nominal RC system, where all data are available, which can be designed to be stable [18]. Under stability of the nominal RC system U, stability of the intermittently sampled RC setup is equivalent to stability of the feedback interconnection between the nominal RC setup U and memoryless time-varying function $\mathcal{S}_{\text{ua}}$. This can be analyzed using standard stability arguments, as is described next.

B. Stability Analysis

In this section, a frequency-domain stability condition of the intermittently sampled RC setup of Fig. 5 is presented, constituting contribution C1.

The main challenge in determining the stability of (11) and (12) is that the repetitive controller R receives the measurement information only at the timestamps in $\mathcal{T}$, while it operates in open-loop conditions outside these timestamps. For example, in the extreme case that $\mathcal{T}$ is empty, R maintains its initial condition forever by the structure of its internal model, such that it is impossible to guarantee the asymptotic stability for this $\mathcal{T}$. More generally, the following types of $\mathcal{T}$ are distinguished.

Definition 4: A timestamp sequence $\mathcal{T} = \{\ldots, \tau_{-1}, \tau_0, \tau_1, \ldots\}$, $\tau_i \in \mathbb{Z}$, $\tau_{i+1} > \tau_i$ is said to be persistent if for every $\tau_i \in \mathcal{T}$, there exists $\tau_{i+1} \in \mathcal{T}$.

Definition 5: A timestamp sequence $\mathcal{T}$ is said to be informative if it is persistent, and there is no $k_0 \in \mathbb{Z}$ such that $\bar{y}(\tau_i) = y(\tau_i) - \mathcal{S}_{\text{ua}}(y(\tau_i)) = 0\ \forall \tau_i > k_0,\ \tau_i \in \mathcal{T}$ while $y(k) \neq 0$ for some $k > k_0,\ k \notin \mathcal{T}$.

Intuitively, a persistent $\mathcal{T}$ is infinitely long, i.e., there is always a next sampling moment in the future. An informative $\mathcal{T}$ entails that the sampling moments τ_i are such that if zero output is observed for all timestamps τ_i after some time k_0, it must hold that $y(k) = 0$ also outside these timestamps. This rules out, e.g., sequences $\mathcal{T}$ for which samples are exactly located at the zeros of a sine response $y(k) = \sin(\omega k)$. Since T consists of a closed-loop system with a controller on a different nonintermittent sensor that keeps the print belt moving, for the print belt setup it holds that $\mathcal{T}$ is informative.

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Given these classes of $\mathcal{T}$, a Lyapunov-based stability criterion is posed next.

Theorem 1: Consider the intermittently sampled RC setup in (11) and (12) for $v = 0$ with (A, B, C) minimal and A Schur. If there exists a $P = P^\top \succ 0$, $\kappa \in \mathbb{R}$ such that

$$\begin{bmatrix} A^\top PA - P & A^\top PB \\ B^\top PA & B^\top PB \end{bmatrix} + \kappa \begin{bmatrix} 0 & C^\top \\ C & -2 \end{bmatrix} + \begin{bmatrix} 2C^\top C & -C^\top \\ -C & 0 \end{bmatrix} \preceq 0 \tag{15}$$

Then, the intermittently sampled RC setup is GUS. If additionally $\mathcal{T}$ is informative or (15) is strict, then, it is GUAS.

Proof: The proof is based on a Lyapunov function that uses quadratic constraints describing the behavior of $\mathcal{S}_{\text{ua}}$ as S-procedure relaxation terms. Define $X(x) = x^\top Px$ and

$$\begin{aligned} \Delta X\left(x\left(k\right)\right) &= x\left(k+1\right)^\top Px\left(k+1\right) - x\left(k\right)^\top Px\left(k\right) \\ &= \begin{bmatrix} x\left(k\right) \\ \mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) \end{bmatrix}^\top \begin{bmatrix} A^\top PA - P & A^\top PB \\ B^\top PA & B^\top PB \end{bmatrix} \times \begin{bmatrix} x\left(k\right) \\ \mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) \end{bmatrix}. \end{aligned} \tag{16}$$

Now note that by definition of $\mathcal{S}_{\text{ua}}$ in (9), it holds that

$$\mathcal{S}_{\text{ua}}\left(y\left(k\right)\right)\left(\mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) - y\left(k\right)\right) = 0 \ \forall y\left(k\right) \tag{17}$$

$$y\left(k\right)\left(-\mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) + y\left(k\right)\right) = \begin{cases} y\left(k\right)^2, & \text{if } k \in \mathcal{T} \\ 0, & \text{otherwise.} \end{cases} \tag{18}$$

Since (17) is 0, it can be multiplied by 2κ with any $\kappa \in \mathbb{R}$ and remain 0. Similarly, (18) is always nonnegative. Then, adding (17) and (18) to (16), it must hold that.

$$\begin{aligned} \Delta X\left(x\left(k\right)\right) \leq \begin{bmatrix} x\left(k\right) \\ \mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) \end{bmatrix}^\top \left(\begin{bmatrix} A^\top PA - P & A^\top PB \\ B^\top PA & B^\top PB \end{bmatrix} \right. \\ \left. + \kappa \begin{bmatrix} 0 & -C^\top \\ -C & 2 \end{bmatrix} + \begin{bmatrix} 2\,C^\top C & -C^\top \\ -C & 0 \end{bmatrix} \right) \times \begin{bmatrix} x\left(k\right) \\ \mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) \end{bmatrix}. \end{aligned} \tag{19}$$

Consequently, if (15) is satisfied, there exists P, κ such that $\Delta X(x(k)) \leq 0 \ \forall x(k)$. This immediately implies GUS by a standard Lyapunov argument [12], which is given for completeness. Specifically, summing

$$x\left(k+1\right)^\top Px\left(k+1\right) - x\left(k\right)^\top Px\left(k\right) \leq 0 \ \forall x\left(k\right) \tag{20}$$

from $k = k_0$ to $k = \bar{k} - 1 \geq k_0$ reveals

$$x\left(\bar{k}\right)^\top Px\left(\bar{k}\right) - x\left(k_0\right)^\top Px\left(k_0\right) \leq 0 \tag{21}$$

for any k_0, or equivalently

$$\left\|x\left(\bar{k}\right)\right\|^2 \leq \frac{\lambda_{\max}\left(P\right)}{\lambda_{\min}\left(P\right)} \left\|x\left(k_0\right)\right\|^2 \tag{22}$$

i.e., (11) and (12) is GUS.

In addition, if (15) is satisfied, it also holds that

$$\Delta X\left(x\left(k\right)\right) + 2\ y\left(k\right)\left(-\mathcal{S}_{\text{ua}}\left(y\left(k\right)\right) + y\left(k\right)\right) \leq 0 \tag{23}$$

since $\kappa\mathcal{S}_{\text{ua}}(y(k))(\mathcal{S}_{\text{ua}}(y(k)) - y(k)) = 0 \ \forall y(k)$. In particular, this implies that

$$\Delta X\left(x\left(\tau_i\right)\right) \leq -2\ y\left(\tau_i\right)^2 \text{ if } \tau_i \in \mathcal{T} \tag{24}$$

i.e., the Lyapunov function $X(x(k))$ is strictly decreasing at every τ_i at which a nonzero measurement is fed to the repetitive controller. Simultaneously, $\Delta X(x(k)) \leq 0$ for $k \notin \mathcal{T}$. Thus, it must hold that $\lim_{k\to\infty} X(x(k)) = c \geq 0$ for sure. Moreover, $c > 0$ can only be if $y(\tau_i) = 0 \ \forall \tau_i > k_0$. In all other cases, i.e., if $\mathcal{T}$ is informative, it must hold that $\lim_{k\to\infty} X(x(k)) = 0$, such that also $\lim_{k\to\infty} x(k) = 0$, i.e., (11) and (12) is GUAS if $\mathcal{T}$ is informative. Finally, if (15) is strict, it holds that $\Delta X(x(k)) < 0 \ \forall k$, thus $\lim_{k\to\infty} x(k) = 0$.

Theorem 1 provides a Lyapunov-based criterion for stability of the intermittently sampled RC setup given a repetitive controller R. Given a designed controller R and a state-space model of T, (15) is a linear matrix inequality which can be solved using semidefinite programming approaches to test stability of a design.

To allow for testing stability based on nonparametric models in the form of FRF measurement, Theorem 1 is converted to an equivalent frequency-domain test using the Kalman–Yakubovich–Popov (KYP) lemma, as stated next.

Lemma 1 (DT Kalman–Yakubovich–Popov Lemma [21]): Given $A \in \mathbb{R}^{n_x \times n_x}$, $B \in \mathbb{R}^{n_x \times 1}$ with A Schur and (A, B) controllable, and multiplier $M = M^\top \in \mathbb{R}^{(n_x+1)\ \times\ (n_x+1)}$. Then, the following two statements are equivalent.

1) There exists a matrix $P \in \mathbb{S}^{n_x}_{++}$ such that

$$M + \begin{bmatrix} A^\top PA - P & A^\top PB \\ B^\top PA & B^\top PB \end{bmatrix} \preceq 0. \tag{25}$$

2) The frequency response $(e^{j\omega}I - A)^{-1}B$ satisfies

$$\begin{bmatrix} \left(e^{j\omega}I - A\right)^{-1} B \\ 1 \end{bmatrix}^* M \begin{bmatrix} \left(e^{j\omega}I - A\right)^{-1} B \\ 1 \end{bmatrix} \preceq 0 \ \forall \omega \in \mathbb{R}. \tag{26}$$

The equivalence for strict inequalities holds even if (A, B) is not controllable.

Given Lemma 1, Theorem 1 can be equivalently formulated in the frequency domain, as formalized next.

Theorem 2: Consider the intermittently sampled RC setup in (11) and (12) for $v = 0$ with $U = TR(1+TR)^{-1} \in \mathcal{RH}_\infty$. If the frequency response $U(e^{j\omega})$ satisfies

$$U\left(e^{j\omega}\right) \in \mathcal{B}_\kappa \ \forall \omega \in [0, \pi] \tag{27}$$

with

$$\mathcal{B}_\kappa = \left\{ z \mid \left| z - \frac{1}{2}\left(1 - \kappa\right) \right|^2 \leq \frac{1}{4}\left(1 + \kappa\right)^2 \right\} \tag{28}$$

for some $\kappa \in \mathbb{R}$, then the intermittently sampled RC setup is GUS. If additionally $\mathcal{T}$ is informative or the inequality in (28) is strict, then, it is GUAS.

Proof: This is immediately implied by applying Lemma 1 to Theorem 1 with

$$M = \kappa \begin{bmatrix} 0 & C^\top \\ C & -2I \end{bmatrix} + \begin{bmatrix} 2\,C^\top C & -C^\top \\ -C & 0 \end{bmatrix} \tag{29}$$

and $\kappa \in \mathbb{R}$. Specifically, evaluating (26) for this M yields

$$\begin{aligned} &\left(2U\left(e^{j\omega}\right)^* U\left(e^{j\omega}\right) - U\left(e^{j\omega}\right)^* - U\left(e^{j\omega}\right)\right) \\ &\quad + \kappa\left(U\left(e^{j\omega}\right)^* + U\left(e^{j\omega}\right) - 2\right) \leq 0 \ \ \forall \omega \in \mathbb{R} \end{aligned} \tag{30}$$

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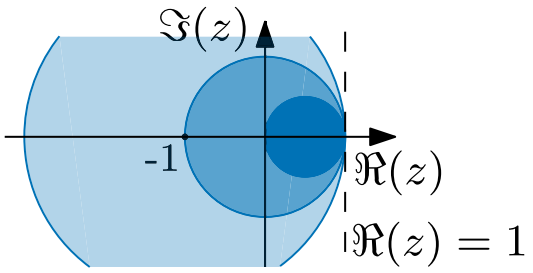

Fig. 6. Stability set $\mathcal{B}_\kappa$ of Theorem 2 for $\kappa = 0$ (●), $\kappa = 1$ (●), and $\kappa = 2$ (●). Each $\mathcal{B}_\kappa$ is a circle with center $1/2(1-\kappa)$ and radius $1/2\,|1+\kappa|$. Thus, for any $\kappa \geq -1$, each $\mathcal{B}_\kappa$ circle covers the point -1.

since by definition $U(e^{j\omega}) = C(e^{j\omega}I - A)^{-1}B$, see (11). This is equivalent to

$$\left|U\left(e^{j\omega}\right)\right|^2 - \frac{1-\kappa}{2}\left(U\left(e^{j\omega}\right)^* + U\left(e^{j\omega}\right)\right) - \frac{2\kappa}{2} \leq 0 \; \forall \omega \in \mathbb{R} \tag{31}$$

with $\left|U(e^{j\omega})\right|^2 = U(e^{j\omega})^* U(e^{j\omega})$. Completing the squares yields that (31) is equivalent to

$$\left(U\left(e^{j\omega}\right)^* - \frac{1-\kappa}{2}\right)\left(U\left(e^{j\omega}\right) - \frac{1-\kappa}{2}\right) - \left(\frac{1+\kappa}{2}\right)^2 \leq 0 \; \forall \omega \in \mathbb{R} \tag{32}$$

which is equivalent to (27) and (28) as $U(e^{j\omega})$ is formed by real-valued matrices A–C, such that $\omega \in \mathbb{R}$ can be restricted to $\omega \in [0, \pi]$.

With (27) and (28) equivalent to (26), Lemma 1 can be applied since all its preliminary conditions are met: (A, B) is controllable and $U \in \mathcal{RH}_\infty$ implies that A is Schur under minimality of (A, B, C). Consequently, (27) and (28) are equivalent to (15), which by Theorem 1 implies that the intermittently sampled RC setup is GUS. Last, if additionally $\mathcal{T}$ is informative or if the inequality in (27) is strict, the same reasoning implies that (15) is strict, such that the intermittently sampled RC setup is GUAS, completing the proof. Theorem 2 is the frequency-domain counterpart of Theorem 1. It provides a twofold stability criterion for the stability of the intermittently sampled RC setup. First, it requires that $U \in \mathcal{RH}_\infty$, which guarantees that the RC system is stable in the nominal case for which data are available at each sampling instance. This can be verified in the frequency domain based on the FRF data of $T(e^{j\omega})$ through existing RC stability tests [18, Section IV]. Second, it requires that the frequency response $U(e^{j\omega})$ is contained to a circle with center $1/2(1-\kappa)$ and radius $(1/4(1+\kappa)^2)^{1/2} = 1/2\,|1+\kappa|$. This guarantees that the RC system is also GUS, or GUAS, and thus, BIBO stable if $\mathcal{T}$ is informative.

The stability region of Theorem 2 is visualized in Fig. 6 for various κ. For $\kappa \to \infty$, this region approaches $\{z \mid \Re(z) \leq 1\}$, i.e., left of the line $\mathbb{R}(z) = 1$, corresponding to well-known nonstrict passivity-based stability tests [10], [12, Theorem 4.1].

Remark 2: Note that Theorem 2 only gives stability conditions for a specific buffer length N, such that possibly Q and L have to be redesigned for different N, in contrast to common the nominal RC stability conditions that give guarantees for any buffer length N [18]. This is a consequence of the intermittent setting.

Theorem 2 is specialized to the traditional repetitive controller (6) of Fig. 2. For other LTI repetitive controllers, similar frequency-domain checks can be derived analogously.

Corollary 1: For the typical repetitive controller of Fig. 2 with transfer function (6), it holds that

$$U(z) = TR(1+TR)^{-1} = \frac{TLQz^{-N}}{1-(1-TL)Qz^{-N}} \tag{33}$$

such that the intermittently sampled RC setup is GUS if R stabilizes T in the nominal setting and

$$\frac{T\left(e^{j\omega}\right)L\left(e^{j\omega}\right)Q\left(e^{j\omega}\right)e^{-j\omega N}}{1-\left(1-T\left(e^{j\omega}\right)L\left(e^{j\omega}\right)\right)Q\left(e^{j\omega}\right)e^{-j\omega N}} \in \mathcal{B}_\kappa \; \forall \omega \in [0, \pi]\,. \tag{34}$$

The above corollary provides conditions on L and Q for the intermittently sampled RC setup to be GUS. If this setup is additionally desired to be GUAS, either $\mathcal{T}$ should be informative, or $U(e^{j\omega})$ should be in the interior of $\mathcal{B}_\kappa$. Note, however, that the latter implicitly imposes conditions on Q. Specifically, for $Q = 1$, it holds that $U(e^{j\omega}) = 1$ for $\omega = 2\pi j k N^{-1}$ with $k = 0, \ldots, N-1$ as R has a pole at these frequencies, i.e., $U(e^{j\omega}) = 1$ is on the boundary of $\mathcal{B}_\kappa$ such that GUAS cannot be guaranteed for $Q = 1$. Instead, it should hold that $\left|Q(e^{j\omega})\right| < 1 \; \forall \omega \in [0, \pi]$ if GUAS is desired for a $\mathcal{T}$ that is not informative.

Remark 3: Intuitively, this condition on Q can be understood by noting that for $Q = 1$, the internal model in R maintains its memory if no data are provided, i.e., the repetitive controller does not diverge but also does not converge. If additionally $\mathcal{T}$ is known to be informative, the infinite amount of intermittent samples ensures that the repetitive controller converges, i.e., GUAS is obtained. Alternatively, GUAS can also be guaranteed by a Q for which $\left|Q(e^{j\omega})\right| < 1 \; \forall \omega \in [0, \pi]$, such that the internal model in R decays by itself, even in the case that no data are available at all.

The frequency-domain test of Theorem 2 and Corollary 1 can be verified based on the measured FRF data, which enables a frequency-domain design framework as detailed next.

IV. Design

In this section, an RC design methodology for the intermittently sampled setting of Fig. 1 is detailed based on frequency-domain loop shaping using the measured FRF data, constituting contribution C2. In this intermittent setting, the choice of the internal model is of high importance to achieve both high performance and desired transient behavior. Two choices of the internal model are highlighted.

A. Traditional Buffer

Consider again the traditional repetitive controller in (6) with buffer $Z = z^{-N}$. Based on the frequency-domain stability conditions of Theorem 2, a design procedure for this repetitive controller is developed that guarantees that the designed repetitive controller is stable in the intermittently sampled setting. The design procedure is presented next.

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Procedure 1 Intermittent RC design with $Z = z^{-N}$

1) Design the RC such that it is stable in the non-intermittent setting, i.e., such that $U \in \mathcal{RH}_\infty$. A sufficient condition for the traditional RC as in Fig. 2 that guarantees $U \in \mathcal{RH}_\infty$ is given by, see also [18, Section 4.1],

$$|(1 - T(e^{j\omega})L(e^{j\omega}))Q(e^{j\omega})| < 1 \quad \forall \omega \in [0, \pi]. \quad (35)$$

The following steps can be followed to guarantee (35).

a) Obtain an approximate parametric model of the system T, i.e., obtain $\hat{T} \approx T$.
b) Design L as an approximation of $\hat{T}^{-1}$, see, e.g., [28].
c) Design Q as a zero-phase finite impulse response low-pass filter such that (35) is satisfied for all ω. This can be achieved by designing $Q(e^{j\omega}) = 1$ at frequencies ω where

$$|(1 - T(e^{j\omega})L(e^{j\omega}))| \ll 1$$

for high performance, and $Q(e^{j\omega}) < 1$ at frequencies where

$$|(1 - T(e^{j\omega})L(e^{j\omega}))| \geq 1.$$

2) Design the RC such that it is also stable in the intermittent setting by ensuring that Theorem 2 is satisfied, i.e., $U(e^{j\omega}) \in \mathcal{B}_\kappa$. This can be achieved as follows.

a) Scale L as αL, $\alpha \in [0, 1]$ and decrease α until $U(e^{j\omega}) \in \mathcal{B}_\kappa$.
b) Decrease the magnitude of Q locally for the frequencies ω where $U(e^{j\omega}) \notin \mathcal{B}_\kappa$.

Procedure 1 allows for designing an repetitive controller based on the measured FRF data and intuitive frequency-domain loop-shaping techniques. Both design guidelines in step 2 are based on (locally) shrinking $U(e^{j\omega})$ toward 0 such that eventually $U(e^{j\omega}) \in \mathcal{B}_\kappa$. Whereas the first heuristic only slows down learning, the second one limits the converged learning performance around these frequencies. Thus, the former is preferred.

Remark 4: Note that $U(e^{j\omega}) \in \mathcal{B}_\kappa$ implicitly imposes conditions on Q if the intermittently sampled RC setup is required to be GUAS. Specifically, for $Q = 1$, it holds that $U(e^{j\omega}) = 1$ for $\omega = 2\pi jkN^{-1}$ with $k = 0, \ldots, N-1$ as R has a pole at these frequencies. Since $U(e^{j\omega}) = 1$ is on the boundary of $\mathcal{B}_\kappa$, only GUS can be guaranteed. For GUAS, either $\mathcal{T}$ needs to be informative, or Q has to be designed such that $\left|Q(e^{j\omega})\right| < 1 \ \forall \omega \in [0, \pi]$.

The above example illustrates that the traditional repetitive controller is at least GUS in the intermittent setting for $Q = 1$. Intuitively, for $Q = 1$, the internal model in R maintains its memory if no data are provided, i.e., the repetitive controller does not diverge but also does not converge. If additionally $\mathcal{T}$ is known to be informative, the infinite amount of intermittent samples ensures that the repetitive controller converges, i.e., GUAS is obtained. Alternatively, GUAS can also be guaranteed by a Q for which $\left|Q(e^{j\omega})\right| < 1 \ \forall \omega \in [0, \pi]$, such that the internal model in R decays by itself, even in the case that no data are available at all.

B. Alternative Repetitive Controllers

When employing a traditional buffer $Z = z^{-N}$ in the intermittently sampled setting, the sparsity of the buffer in the initial phase can cause undesired behavior, even though it satisfies the stability conditions from Theorem 2. Specifically, depending on the availability of data in the initial phase, the content of the buffer might be sparse, i.e., contain a lot of zeros. This sparsity will lead to an input signal f with high frequency content, which is likely to deteriorate the performance before convergence to a steady state.

To mitigate this undesired behavior, an internal model that can only produce signals with a limited amount of frequency components is more suitable. One option to achieve this is by directly setting the repetitive controller as follows:

$$R = L\bar{R} = LR_0 \prod_{i=1}^{M} \frac{1}{1 - \cos(\omega_i T_s) z^{-1} + z^{-2}} \quad (36)$$

in which $\{\omega_1, \ldots, \omega_M\}$, $\omega_i > 0$ are the frequencies of the internal model, L is a free filter, and $R_0 = (1 - z^{-1})^{-1}$ if it is desired that R contains an integrator, and $R_0 = 1$ otherwise. This repetitive controller has poles at $\pm e^{j\omega_i T_s}$, i.e., on the unit circle at the frequency of the disturbance, such that R contains an internal model for a disturbance with that frequency. Intuitively, it represents a feedback controller with inverse notches at the desired frequencies.

An RC structure related to (36) is the matched basis functions repetitive controller (MBFRC) given by [23]

$$R = L\bar{R} = L \sum_{i=1}^{M} \frac{(c_i z^2 - 2\, z + c_i)\, z}{(z^2 + (a_i - 2)\, c_i z\, (1 - a_i))\, (z^2 - 2c_i z + 1)} \quad (37)$$

with $c_i = \cos(\omega_i T_s)$, projection gain $a_i \in (0, 2)$ and free filter L. Intuitively, the MBFRC also includes inverse notches at the desired frequency, as the second factor in the denominator is equivalent to that of (36). The other poles and zeros result from a projection step of the error onto periodic basis functions $\cos(\omega_i T_s), \sin(\omega_i T_s)$, see [23].

For repetitive controllers (36) and (37), the freedom in L can be used to ensure that the repetitive controller is stable in the nonintermittent setting, i.e., $U = TR(I + TR)^{-1} \in \mathcal{RH}_\infty$. Specifically, $U = TR(I + TR)^{-1} \in \mathcal{RH}_\infty$ is implied by internal stability of the negative feedback loop between L and $\bar{R}T$. This can be tested and designed for in the frequency domain using the Nyquist criterion and standard loop-shaping techniques.

Remark 5: Note that the real-time implementation of an intermittent repetitive controller does not introduce additional computational complexity: while the controller is designed according to the modified stability conditions of Theorem 2, during implementation it has the same filter structure as other repetitive controllers.

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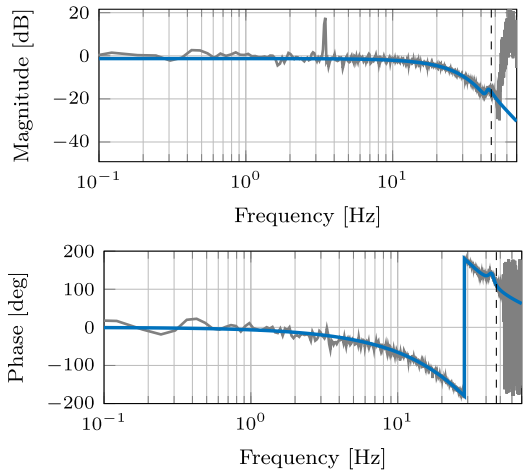

Fig. 7. Bode diagram of identified FRF (—) of the transfer function T from the repetitive controller output u to output y and approximate parametric model $\hat{T}$ (—) used for RC design. Note that no information is available above 50 Hz due to the frequency spectrum of the excitation signal. The deviation of the magnitude response around 3.5 Hz is caused by a bad signal-to-noise ratio due to the additional periodic disturbance at this frequency.

V. Experimental Results

In this section, the developed RC framework is validated on an industrial print belt system, constituting Contribution C3.

A. Experimental Setup

The framework is illustrated on the print belt system with intermittent measurements as described in Section II-B. In this print belt system, the unroundness of the rollers and the gears in the drivetrain introduces disturbance forces that limit the positioning accuracy of the print belt. Since this print belt operates with a constant velocity during the printing process, also the disturbance forces are periodic. The dominant disturbance associated with this process manifests at 3.5 Hz for the velocities used during printing. Next, a repetitive controller is designed to compensate this disturbance force.

B. RC Design

The designed repetitive controller is an MBFRC with a single harmonic $M = 1$ with $\omega_i = \omega = 2\pi \cdot 3.5$ rad/s and $a = a_i = 1$ to reject only disturbances at that single frequency. The repetitive controller is designed such that the conditions in Theorem 2 are satisfied based on the identified FRF data of T, as depicted in Fig. 7. Since $\mathcal{T}$ is informative for the print belt system, see Section III-B, GUAS and thus bounded-input–bounded-output stability of the intermittently sampled repetitive control setup are guaranteed.

C. Experimental Results

In Fig. 8 the root-mean-square of a moving window of the error, i.e., $\|e\|_{\text{RMS}} = (1/N\Sigma_{n=K-N}^{n=k} e(n)^2)^{1/2}$ is depicted. This shows that the intermittently sampled repetitive controller is able to reduce the RMS-norm of the error by a factor of 7 by using only the intermittently sampled compared to a situation with only a feedback controller. In Fig. 9, the initial and converged errors are given, which shows that the intermittently sampled repetitive controller reduces the maximum absolute error by a factor of 4 compared with a situation with only feedback. The cumulative amplitude spectrum of the error in Fig. 10 shows that the amplitude of the error at 3.5 Hz is reduced by a factor of 10. Note that there is still a small amount of error present at this frequency, which is hypothesized to be caused by a slight difference between the true disturbance frequency and the estimated frequency of 3.5 Hz.

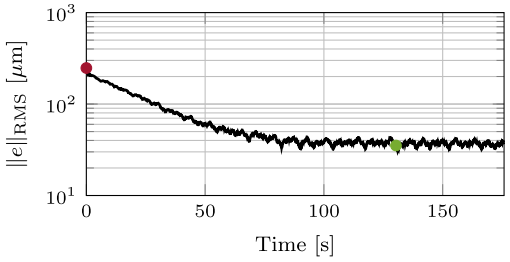

Fig. 8. Root-mean-square-norm of intermittent sampling RC error (linearly interpolated to equidistant time grid) in a moving window of length 2.9 s. The RMS-norm of the error is reduced by a factor of 7 by the repetitive controller. The time intervals to compare the performance before and after convergence in Figs. 10 and 9 are indicated by the dots (●) in red and green (●), respectively.

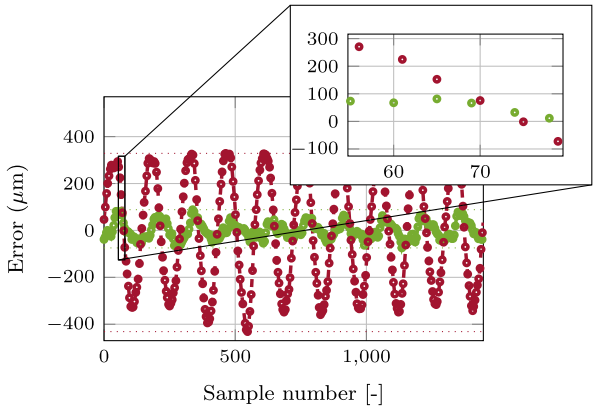

Fig. 9. Converged error (—) of the intermittent sampling repetitive controller compared with the initial error (—). The errors at the timestamps are indicated by circles (●). The maximum absolute error is reduced by a factor of 4. A zoomed-in view of a short interval of the error is depicted in the top right corner to highlight the intermittent sampling of this signal.

VI. Simulation Study

To illustrate the superior performance of the intermittently sampled repetitive controller, this controller is compared in simulation to a repetitive controller that assumes that data is available at all sampling instances.[1]

The simulation is set up to mimic the experimental print belt system as closely as possible. Specifically, it is performed using the parametric model $\hat{T}$ in Fig. 7 in the presence of a disturbance signal consisting of a single sine with a frequency of 10 Hz, with an encoder resolution of 1 cm, and a unity feedback controller that tracks a periodic reference with a frequency of 5 Hz.

[1]The code accompanying this simulation example can be found at: https://github.com/JJJK97/intermittent-sampling-RC/

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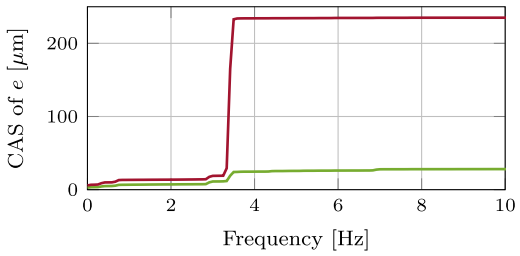

Fig. 10. Cumulative amplitude spectrum of the converged error (—) and initial error (—) of the intermittent sampling MBFRC design, constructed from the linearly interpolated equidistant error. The amplitude of the disturbance associated with the drivetrain at 3.5 Hz is reduced by a factor of 10 by the repetitive controller.

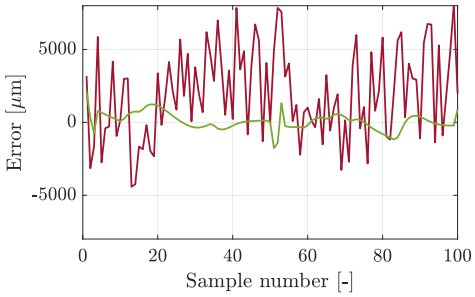

Fig. 11. True tracking error $e(k)$ in simulation when employing a repetitive controller R_1 that uses only the available intermittent error (—) is significantly lower than the error when employing a repetitive controller R_2 that assumes the error is available at every sample even though it is a quantized version of the true error (—).

Two repetitive controllers are applied to compensate this disturbance.

R_1: A traditional repetitive controller as in (6) using only exact measurements when they are available. This repetitive controller is designed according to Procedure 1 with $Q = I$ as the simulation contains no plant uncertainty.

R_2: A traditional repetitive controller as in (6) that assumes a measurement is available at every sample, even though it is a quantized version of the true position, reflecting the industry standard practice. The repetitive controller is designed according to the procedure in [17, Section 8], in which the learning filter L is designed as inverse of the plant according to [17, Section 10.1(c)], also with $Q = I$.

The resulting *true* tracking error after seven iterations is visualized in Fig. 11, from which it is observed that treating intermittent measurements as equidistant but quantized samples, as in R_2, results in a performance deterioration over incorporating those intermittent measurements as nonequidistant but exact samples as in R_1.

VII. Conclusion

To improve the control performance to the limit, all error knowledge should be used, which is precisely the approach intermittent RC takes. For example, for systems that exploit incremental encoders, intermittently sampled RC allows for a performance increase for existing systems due to the use of exact data instead of quantized data, or it could come with cost benefits since cheaper sensors with a higher quantization level could lead to similar performance levels. A new repetitive control framework is introduced, including frequency-domain-based stability guarantees without imposing any assumptions on the availability of data through a worst-case analysis. This immediately allows large-scale implementation of various relevant applications with intermittent observations, including systems with incremental encoders and systems with networked or stealth attack issues. A novel RC structure enables improved transient behavior for intermittently sampled data and can be designed based on loop shaping and identified FRF data that explicitly allows for addressing uncertainty, closely resembling traditional RC design approaches. The RC framework is experimentally validated through an implementation on an industrial print belt system.

References

[1] H. Ahn, K. L. Moore, and Y. Chen, "Discrete-time intermittent iterative learning controller with independent data dropouts," *IFAC Proc. Volumes*, vol. 41, no. 2, pp. 12442–12447, 2008. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1474667016409729

[2] L. Blanken, P. Bevers, S. Koekebakker, and T. Oomen, "Sequential multiperiod repetitive control design with application to industrial wide-format printing," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 2, pp. 770–778, Apr. 2020.

[3] L. Blanken, S. Koekebakker, and T. Oomen, "Multivariable repetitive control: Decentralized designs with application to continuous media flow printing," *IEEE/ASME Trans. Mechatronics*, vol. 25, no. 1, pp. 294–304, Feb. 2020.

[4] D. A. Bristow, M. Tharayil, and A. G. Alleyne, "A survey of iterative learning control," *IEEE Control Syst. Magagzine*, vol. 26, no. 3, pp. 96–114, Jun. 2006. [Online]. Available: https://ieeexplore.ieee.org/document/1636313

[5] G. Dan and H. Sandberg, "Stealth attacks and protection schemes for state estimators in power systems," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun.*, Oct. 2010, pp. 214–219.

[6] D. De Roover, O. H. Bosgra, and M. Steinbuch, "Internal-model-based design of repetitive and iterative learning controllers for linear multivariable systems," *Int. J. Control*, vol. 73, no. 10, pp. 914–929, Jan. 2000.

[7] D. F. Delchamps, "Stabilizing a linear system with quantized state feedback," *IEEE Trans. Autom. Control*, vol. 35, no. 8, pp. 916–924, Aug. 1990. [Online]. Available: https://ieeexplore.ieee.org/document/58500

[8] B. A. Francis and W. M. Wonham, "The internal model principle of control theory," *Automatica*, vol. 12, no. 5, pp. 457–465, Sep. 1976.

[9] H. Fujimoto, "RRO compensation of hard disk drives with multirate repetitive perfect tracking control," *IEEE Trans. Ind. Electron.*, vol. 56, no. 10, pp. 3825–3831, Oct. 2009.

[10] H. Fujioka, "Stability analysis of systems with aperiodic sample-and-hold devices," *Automatica*, vol. 45, no. 3, pp. 771–775, Mar. 2009.

[11] S. Hara, Y. Yamamoto, T. Omata, and M. Nakano, "Repetitive control system: A new type servo system for periodic exogenous signals," *IEEE Trans. Autom. Control*, vol. AC-33, no. 7, pp. 659–668, Jul. 1988.

[12] L. Hitz and B. D. O. Anderson, "Discrete positive-real functions and their application to system stability," *Proc. Inst. Electr. Engineers*, vol. 116, p. 153, Jan. 1969.

[13] C. J. Kempf, W. Messner, M. Tomizuka, and R. Horowitz, "Comparison of four discrete-time repetitive control algorithms," *IEEE Control Syst. Mag.*, vol. 13, no. 6, pp. 48–54, Dec. 1993. [Online]. Available: https://ieeexplore.ieee.org/document/248004

[14] H. Khalil, *Nonlinear Systems*. Upper Saddle River, NJ, USA: Prentice-Hall, 2002.

[15] J. Kon, N. Strijbosch, S. Koekebakker, and T. Oomen, "Intermittent sampling in repetitive control: Exploiting time-varying measurements," in *Proc. 60th IEEE Conf. Decis. Control (CDC)*, Dec. 2021, pp. 6566–6571.

[16] R. W. Longman, "Designing iterative learning and repetitive controllers," in *Iterative Learning Control*. Cham, Switzerland: Springer, 1998, pp. 107–146.

[17] R. W. Longman, "Iterative learning control and repetitive control for engineering practice," *Int. J. Control*, vol. 73, no. 10, pp. 930–954, Jan. 2000.

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[18] R. Longman, "On the theory and design of linear repetitive control systems," *Eur. J. Control*, vol. 16, no. 5, pp. 447–496, 2010.
[19] M. Steinbuch, S. Weiland, and T. Singh, "Design of noise and period-time robust high-order repetitive control, with application to optical storage," *Automatica*, vol. 43, no. 12, pp. 2086–2095, Dec. 2007. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0005109807002543
[20] R. J. E. Merry, M. J. G. van de Molengraft, and M. Steinbuch, "Optimal higher-order encoder time-stamping," *Mechatronics*, vol. 23, no. 5, pp. 481–490, Aug. 2013. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0957415813000731
[21] A. Rantzer, "On the Kalman—Yakubovich—Popov lemma," *Syst. Control Lett.*, vol. 28, no. 1, pp. 7–10, 1996.
[22] D. Shen and Y. Wang, "Iterative learning control for networked stochastic systems with random packet losses," *Int. J. Control*, vol. 88, no. 5, pp. 959–968, 2015.
[23] Y. Shi, R. W. Longman, and M. Nagashima, "Small gain stability theory for matched basis function repetitive control," *Acta Astronautica*, vol. 95, pp. 260–271, Feb./Mar. 2013. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0094576513003706?via%3Dihub
[24] M. Steinbuch, "Repetitive control for systems with uncertain period-time," *Automatica*, vol. 38, no. 12, pp. 2103–2109, Dec. 2002.
[25] N. Strijbosch and T. Oomen, "Beyond quantization in iterative learning control: Exploiting time-varying time-stamps," in *Proc. Amer. Control Conf. (ACC)*, Jul. 2019, pp. 2984–2989.
[26] N. Strijbosch and T. Oomen, "Intermittent sampling in iterative learning control: A monotonically-convergent gradient-descent approach with application to time stamping," in *Proc. IEEE 58th Conf. Decis. Control (CDC)*, Dec. 2019, pp. 6542–6547.
[27] M. Tomizuka, T.-C. Tsao, and K.-K. Chew, "Analysis and synthesis of discrete-time repetitive controllers," *J. Dyn. Syst., Meas., Control*, vol. 111, no. 3, pp. 353–358, Sep. 1989.
[28] J. van Zundert and T. Oomen, "On inversion-based approaches for feedforward and ILC," *Mechatronics*, vol. 50, pp. 282–291, Apr. 2018.
[29] M. Yamada, Z. Riadh, and Y. Funahashi, "Design of robust repetitive control system for multiple periods," in *Proc. 39th IEEE Conf. Decis. Control*, vol. 4, 2000, pp. 3739–3744.



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