Norm Optimal Iterative Learning Control for a Roll to Roll Nano/Micro-Manufacturing System

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Abstract — Recent advances in micro/nano-scale manufacturing have transitioned from batch modes of fabrication on rigid substrates to continuous modes of fabrication on flexible substrates. The majority of these continuous systems utilize a Roll to Roll (R2R) system approach. To maximize the effectiveness of the R2R system it is important to maintain high precision motion and tension control. For micro/nano-manufacturing the continuous substrate is often processed using both stepping motions and continuous scanning motions. In this work, a Norm Optimal Iterative Learning Controller (NOILC) is utilized to simultaneously improve the position tracking precision, as well as the web tension regulation. The approach is demonstrated on an experimental testbed for both continuous and stepping trajectories with greatly improved performance compared to $H_2$ optimal feedback.

I. INTRODUCTION

Iterative Learning Control (ILC) is a method by which specific signals are learned through repeated iterations. First described in [1], ILC examines the error from previous trials and maps it to input signals in the current trial. This signal-based identification scheme has proven to be tremendously effective for systems that perform the same task repeatedly. Good overviews of the breadth and impact of ILC can be found in [2]. ILC is particularly useful for manufacturing systems that, by definition, perform repeated actions. In the past several years, significant work has been performed on the theory [3, 4] as well as practice [5]-[7] of ILC. The interested reader is referred to [8] for detailed background on the various approaches available. In this paper, we utilize the feedforward nature of the ILC approach to improve the longitudinal web handling capabilities, i.e. coordinated positioning and web tension maintaining, of a Roll to Roll (R2R) fabrication system. A lifted domain Norm Optimal ILC (NOILC) [9, 10] framework is used.

A typical R2R system consists of actuated and idler rollers interconnected by a web. A web is described as any flexible material processed in a continuous manner; for example: paper, plastics, textiles and metal strips. The focus on this work is utilizing flexible substrates for flexible electronics in systems such as solar cells, micro-batteries, biosensors, etc. [11]. These devices are typically fabricated in multistep batch to batch processes. In a R2R environment, the multistep processes are localized into multiple zones in the system; each of which performs a particular process such as printing/imprinting, coating, annealing, curing, etc. [12]-[14]. The multi-zone system studied here is illustrated in Fig. 1. Due to process rate variations, there are often mismatches in the various transfer rates of different zones. This necessitates a hybrid fabrication approach where continuous motion is interspersed with stepping, or start/stop motion. Whether continuous or stepping, it is imperative that the web positioning and tension is strictly controlled for process yield purposes. In this work, the focus is on the longitudinal control realizing full well that lateral web steering is also a critical issue [15].

There has been significant work on controlling the tension and position coordination for R2R systems [16]-[19]. However, most of these target high throughput systems operating at hundreds of feet per minute (fpm). For micro/nano-manufacturing, many R2R systems have lower velocity but tighter requirements on positional tracking accuracy. An additional challenge is that due to the presence of hybrid stepping/scanning motions, both continuous and start/stop motions should be performed with similar levels of precision. In this paper, we demonstrate that lifted NOILC provides a suitable framework for achieving the desired precision levels for the MIMO R2R system under study.

The remainder of the paper is organized as follows. Section II describes the experimental system setup as well as a state space model representation of the system. A Linear

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Quadratic Regulator (LQR) feedback controller design is discussed in Section III along with a model-based feedforward augmentation. Section IV presents the NOILC formulation and simulation results for both the LQR and NOILC controllers. Experimental implementation on the R2R system is presented in Section V and Section VI provides concluding remarks and future directions.

II. EXPERIMENTAL SETUP AND SYSTEM MODELING

A. Free Body Diagram and Equation of Motion

The picture of the physical R2R system at the University of Illinois at Urbana-Champaign, which is the subject of investigation in this paper, is presented in Fig. 2. The R2R system consists of 5 rollers, interconnected with a web-like material (Kapton, DuPont™). For the purpose of this paper, we focus on the web handling ability in the longitudinal direction and leave coordination with fabrication stations (e.g. material deposition) as the focus of the future work.

Forces acting on each roller are indicated by the red arrows on the Free Body Diagram (FBD) presented in Fig. 3. Henceforth, let \( i \) denote the roller number. The unwinder (\( M_1 \)) and the rewinder (\( M_4 \)) are actuated by two servo motors (BM130, Aerotech), while the rest are idler rollers. \( M_3 \) is mounted on a load cell (CL5-15, MAGPOWR) for web tension measurement and \( M_4 \) is equipped with a high resolution encoder (RESM20USA075, Renishaw) for accurate measurement of the web position.

According to the FBD presented in Fig. 3, the equation of motion of each roller can be generalized into (1), where \( \theta_i \), \( \dot{\theta}_i \), and \( \ddot{\theta}_i \) indicates the roller position and its time derivatives. The motor torque, \( \tau_i \), is proportional to the control input (2). Friction on each roller, \( f_i \), is assumed proportional to the roller angular velocity as in (3). The web tension \( T'_i \) and \( T_i^- \) rotate \( M_i \) in the prescribed positive and negative direction, respectively, indicated by the green arrows in Fig. 3. Additionally, the web is assumed to be a linear spring described by (4), where \( k \) denotes the spring constant equivalence of the web.

![Figure 2. Picture of the physical Roll to Roll System. Rollers are mounted on a 3ft by 2ft breadboard for reconfigurable setup. Fabrication stations are not shown.](image)

![Figure 3. Free Body Diagram of the R2R system presented in Fig. 2. Forces acting on the rollers are indicated by the red arrows. The green arrows indicate the direction of positive displacement and the blue arrows indicate the positive direction of motor torque.](image)

\[
\begin{align*}
J_i \ddot{\theta}_i &= \tau_i + R_i (T'_i - T_i^-) - f_i \\
\tau_i &= K_i u_i, \ i \in \{1, 5\} \\
f_i &= h \dot{\theta}_i \\
T'_i &= k (R_i \theta_{zi} - R_i \theta_i), \ i \in \{1, 2, 3, 4\} \\
T_i^- &= T_i^+ \quad i \in \{2, 3, 4, 5\}
\end{align*}
\]
III. FEEDBACK CONTROLLER DESIGN

The goal for the web controller is to ensure a given position and tension profile. Particular to our system, we want the system output $\tilde{y} = \theta_1$ to track $\tilde{r} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix}$. To achieve zero steady state tracking error, $\tilde{r}$ is augmented with integrators as shown in (9) and (10). The augmented state space representation, $\tilde{P}_{CL}$, is given by (11).

$$z_1(t) = \int_0^t r_1(s) - \theta_1(s) \, ds$$

(9)

$$z_2(t) = \int_0^t r_2(s) - T_m(s) \, ds$$

(10)

$$\tilde{P}_{CL} = \begin{bmatrix} \frac{\tilde{x}}{\tilde{v}} \\ \frac{\tilde{v}}{\tilde{v}} \end{bmatrix} = \begin{bmatrix} A_{10} & 0 \\ -C_{20} & 0 \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{v} \end{bmatrix} + \begin{bmatrix} B_{10} \\ 0 \end{bmatrix} \tilde{u} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tilde{r}$$

(11)

$$\tilde{y} = \begin{bmatrix} 0 \\ C_{20} \end{bmatrix} \tilde{v}$$

An LQR feedback controller is designed to minimize the cost function described in (12). The weighting matrices $Q_{FB} \in \mathbb{R}^{12 \times 12}$ and $R_{FB} \in \mathbb{R}^{2 \times 2}$ are defined in (13). Applying the LQR controller to (11), we obtain the closed loop system, $\tilde{P}_{CL}$, described in (14), where $K$ denotes the LQR feedback gain matrix. The tracking performance of $\tilde{P}_{CL}$ is presented in Fig. 4 and numerical values for the LQR controller can be found in Appendix B. As can be seen in Fig. 4, the feedback control exhibits some overshoot in position as it regulates the web tension.

$$J_{FB} = \tilde{w}^T Q_{FB} \tilde{w} + \tilde{u}^T R_{FB} \tilde{u}$$

(12)

$$Q_{FB} = \begin{bmatrix} 0 & 0 & \cdots & \cdots & 0 \\ 0 & \ddots & \cdots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \cdots & \vdots \\ \vdots & \cdots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

$$R_{FB} = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix}$$

(13)

IV. NORM OPTIMAL ILC DESIGN AND SIMULATION

To improve the tracking performance of the system, an ILC feedforward controller is added to the closed loop system $\tilde{P}_{CL}$. Since ILC operates in the sampled data domain, $\tilde{P}_{CL}$ should be converted to its discrete system counterpart $\tilde{P}_D$ as described in (15). Conversion from a continuous to discrete system is performed on the numerical system model of $\tilde{P}_{CL}$ using zero order hold method and a sampling time that matches the experiment, which is 4 ms in this work.

$$\tilde{P}_D = \begin{bmatrix} \tilde{v}(k+1) = A_d \tilde{v}(k) + B_d \tilde{r}(k) \\ \tilde{w}(k) = C_d \tilde{v}(k) \end{bmatrix}$$

(15)

The serial form of the ILC architecture [5, 20] as presented in Fig. 5 is chosen, along with the lifted domain Norm Optimal ILC (NOILC) framework, to generate ILC input signals $[9, 10]$. NOILC is a $H^2$ optimization framework which minimizes a quadratic cost function described in (16), where $j$ indicates the iteration index. Here, $e$ and $u$ denote the lifted error and input vectors, defined in (17).

$$J = e_j^T Q e_j + u_j^T S u_j$$

(16)

$$e = [\tilde{e}(0)^T \ \tilde{e}(1)^T \ \cdots \ \tilde{e}(N-1)^T]$$

(17)

$$u = [\tilde{u}(0)^T \ \tilde{u}(1)^T \ \cdots \ \tilde{u}(N-1)^T]$$

In (17), $Q, R$ and $S$ are symmetric positive definite matrices, commonly expressed as $(qI, rI, sI)$ where $q, r, s, \gamma \in \mathbb{R}^+$ and $I$ is an Identity Matrix with appropriate size. The resulting ILC control input from this quadratic optimization process, $u_{j+1}$, is presented in (18).
\[ u_{j+1} = L_u u_j + L_e e_j \]

\[ L_u = \left( P'QP + S + R \right)^{-1} (P'QP + R) \]

\[ L_e = \left( P'QP + S + R \right)^{-1} (P'Q) \]

(18)

Here, \( P \in \mathbb{R}_ {m_m \times m_m} \) is a lower triangular Toeplitz matrix that maps all system inputs of \( \bar{P}_D \) to the system outputs in the lifted domain; \( m_m \) and \( m_P \) denote the number of inputs and outputs of \( \bar{P}_D \) respectively. Note that we require \( P'QP + S + R \) to be positive definite to ensure convergence.

The matrix \( P \) can be constructed using (19). Readers are referred to [9] for detailed derivation of the learning gain \( L_u \) and \( L_e \).

\[
P = \begin{bmatrix}
C_D B_D & 0 & 0 & 0 \\
C_D A_D B_D & C_D B_D & 0 & 0 \\
\vdots & \vdots & \ddots & \ddots & 0 \\
C_D A_D^{m-1} B_D & \ldots & C_D A_D B_D & C_D B_D
\end{bmatrix}
\]

(19)

The main constraint for the lifted NOILC framework lies on the trial length, \( N \). As \( N \) becomes large, computation of the learning gains \( L_u \) and \( L_e \) becomes expensive as it involves inversion of \( P'QP + S + R \), [21, 22]. In this work, we operate with trajectories short enough to stay within the computational constraints.

A 4-second continuous motion is utilized to examine the NOILC performance. Simultaneously, web must follow a specified tension profile. Note that the signal from the load cell is an amplified analog signal polluted with some noise. To reflect this phenomenon, a noise signal is added to \( T_m \) in the simulation. The matrices \( (Q, R, S) \) are designed according to (20) and the numerical values of \( \bar{Q}, \bar{R} \) and \( \bar{S} \) can be found in Appendix B. The tracking performance of the NOILC is presented in Fig. 6.

\[
Q = \text{diag}(\bar{Q}, \ldots, \bar{Q}) \quad \bar{Q} = \begin{bmatrix}
\bar{q}_1 & 0 \\
0 & \bar{q}_2
\end{bmatrix}
\]

\[
R = \text{diag}(\bar{R}, \ldots, \bar{R}) \quad \bar{R} = \begin{bmatrix}
\bar{r}_1 & 0 \\
0 & \bar{r}_2
\end{bmatrix}
\]

\[
S = \text{diag}(\bar{S}, \ldots, \bar{S}) \quad \bar{S} = \begin{bmatrix}
\bar{s}_1 & 0 \\
0 & \bar{s}_2
\end{bmatrix}
\]

(20)

In Fig. 6, we observe a significant phase lag on the tracking performance of the LQR. A feedforward controller (FF), based on model inversion compensates for some of the phase lag. However, the NOILC offers significant improvement over both the LQR and LQR+FF. As presented in Fig. 5, the input signal in (17) is the reference signal to the closed loop system. As such, it is the reference modification that provides the desired system output response. In Fig. 7, we can compare the modified reference signal generated by the NOILC and the feedforward controller. The non-causal nature of the NOILC generates a reference input that starts commanding motion prior to nominal and feedforward reference signal. This non-causal aspect affords tracking improvement and justifies our focus on the LQR+NOILC approach in experimental implementation.

![Figure 6. Tracking performance of the R2R system when NOILC is applied in the simulation environment.](image)

![Figure 7. Modified reference trajectory generated by NOILC.](image)

![Figure 8. Normalized RMS error convergence of the simulated R2R system.](image)
The convergence of the normalized RMS error is presented in Fig. 8. Since there is anticipated signal noise on the web tension measurement, based on experimental experience, a relatively high value is used for $r_2$ in (20), resulting in more conservative tension tracking than position tracking.

V. EXPERIMENTAL RESULTS

A. Experiment Tracking Results

To validate the simulation results, the same reference trajectory used for the simulation is run on the experimental system. The controller is designed using the Control and Simulation Module in LabVIEW 2012 and compiled to a real time target (cRIO-9022, NI) using a 4 ms sampling time. The cRIO controller generates the command signal for the motor and further amplified using an Aerotech BA30-320 power amplifier. The feedback controller and learning gains of ILC used in the experiment are the same as in simulation. The tracking performance of the experimental system is presented in Fig. 9 and the corresponding ILC inputs in Fig. 10. In both figures, we observe trends similar to the simulation results presented in Section III. The RMS error convergence is presented in Fig. 11.

Figure 9. Tracking performance of NOILC on the experimental system.

Figure 10. Modified reference trajectory generated by NOILC.

Figure 11. Normalized RMS error convergence of the experimental R2R system.

B. Case Study: Stepping Motion

The previous subsection experimentally verified the ILC’s performance enhancement for smooth trajectories. We now examine ILC’s effectiveness for stepping types of position trajectories while regulating tension. The weighting matrices for this case study can be found in Appendix B. Fig. 12 demonstrates the tracking performance improvement similar to those observed in Sections IV and V-A. The output error presented in Fig. 13 provides readers with a closer look on the improvement that NOILC contributes to the tracking performance of the R2R system.

In Fig. 14, we can observe a very distinctive reference pattern occurring for each step. This suggests that the NOILC could be used to generate appropriate reference trajectories that can be utilized in a stand-alone fashion for web stepping. Similar approaches examined the creation of these types of basis functions for recurring motion primitives [23]. Fig. 15 presents that the convergence characteristics are similar to the case with smooth trajectories presented in section V – A.
VI. CONCLUSIONS AND FUTURE WORK

This paper presents coordinated position and tension control of a Roll to Roll web system using Lifted Norm Optimal Iterative Learning Control. A serial formulation of ILC was used in conjunction with a LQR feedback controller. As illustrated by the simulation and experimental results, the NOILC is capable of greatly increasing the positioning precision and, at the same time, maintain the web tension.

Future work will include coordination of the web’s lateral position control with its longitudinal position and tension control shown in this paper. Additionally, and more critically, the integration of nano/micro-scale manufacturing components [24] will serve as the test of the controller’s web handling ability.

APPENDIX A: SYSTEM MODEL

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{K_s}{J_s} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}^T
\]

\[
C = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & kR_s & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & kR_s & 0 & 0
\end{bmatrix}
\]

TABLE I: NUMERICAL VALUE OF SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Definition</th>
<th>Unit</th>
<th>(i)</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>(R)</td>
<td>m</td>
<td>1–5</td>
<td>3.81E-2</td>
</tr>
<tr>
<td>(J)</td>
<td>kg.m²</td>
<td>1.5</td>
<td>4.0E-4</td>
</tr>
<tr>
<td>(b)</td>
<td>N.m.s</td>
<td>1–5</td>
<td>1.9E-3</td>
</tr>
<tr>
<td>(k)</td>
<td>N/m</td>
<td>1–5</td>
<td>1E-2</td>
</tr>
<tr>
<td>(K_T)</td>
<td>Nm/V</td>
<td>1.5</td>
<td>7.725E3</td>
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</tbody>
</table>

APPENDIX B: CONTROLLER PARAMETERS

**Table 2: LQR PARAMETERS**

<table>
<thead>
<tr>
<th>(q_1)</th>
<th>(q_2)</th>
<th>(r_1)</th>
<th>(r_2)</th>
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<tr>
<td>100</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TABLE 3: ILC PARAMETERS FOR CONTINUOUS SCAN MOTION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>M2</td>
<td>N1</td>
<td>N2</td>
</tr>
<tr>
<td>-----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

<p>| TABLE 4: ILC PARAMETERS FOR STEPPING MOTION (SECTION V-B) |
|----------------|----------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th>T1</th>
<th>T2</th>
<th>R1</th>
<th>R2</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>50</td>
<td>10</td>
<td>300</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
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REFERENCES


