VISION BASED ITERATIVE LEARNING CONTROL FOR A ROLL TO ROLL MICRO/NANO-MANUFACTURING SYSTEM

BY

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DISSERTATION

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Abstract

Nano and micro-manufacturing has emerged to be an essential component to progress in many areas of science and has huge potential to foster innovation and economic growth. Recent advances in micro/nano-manufacturing have transitioned from batch modes of fabrication on the traditionally rigid substrates to continuous modes of fabrication on flexible substrates. The majority of these continuous systems utilize a Roll to Roll (R2R) system approach. Regardless of the manufacturing technique being employed, the transition from a multistep batch processes to a R2R environment will naturally pose many multidisciplinary challenges.

The broad objective of the thesis is to enable a customizable and high resolution device fabrication through printing on a R2R system. A reconfigurable R2R system which serves as a continuous manufacturing platform for various micro/nano-manufacturing processes is built. Here, a particular focus is placed on integrating the Electrohydrodynamic-Jet (E-Jet) printing system to the R2R system environment. Regardless of the micro/nano-manufacturing processes that are employed, the presence of hybrid stepping/scanning motions, both continuous and start/stop motions, should be performed with similar levels of precision. Since the web undergoes a repetitive trajectory, Iterative Learning Control (ILC) can thereby be used to improve the position tracking precision, as well as the web tension regulation. We seek to further improve the position tracking performance by combining ILC with direct visual observation on the pre-existing features on the web. The pre-existing features may serve as fiduciary markers for the vision sensing and, thus, one can accurately place the E-Jet nozzle relative to the feature location on the web. Additionally, the thesis also explores the potential application of E-jet printing on a non-conductive substrate.
To my wife
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Chapter 1
Introduction

1.1 Motivation

Nano and micro-manufacturing has emerged to be an essential component to progress in many areas of science and has huge potential to foster innovation and economic growth. Recent advances in micro/nano-manufacturing have transitioned from batch modes of fabrication on the traditionally rigid substrates to continuous modes of fabrication on flexible substrates. The majority of these continuous systems utilize a Roll to Roll (R2R) system approach. [1]–[4]. A R2R system incorporates a range of processes where the flexible substrate or the web is transferred between two moving rollers during which the processes are sequentially applied to the web. Figure 1.1 illustrates a continuous manufacturing process.

Figure 1.1 Illustration of a Roll to Roll System [5]
Both subtractive and additive processes are possible within a R2R manufacturing system. However, more recently, the additive processes has received significant attention from the industry for the many benefits it offers. Figure 1.2 presents a range of commercial product targeted by the printed electronics industry. It is projected that by the year 2019, the printed electronics industry may reach a market value of around US$ 59 billion [2]. Some of the advantages which additive processes bring to the table include the scalability to cover a large area, the flexibility to manufacture highly customizable patterns, and generating less environmental waste. Many experts believe that the adaptation of additive processes to the R2R system is the solution for achieving low cost products in the future [2], [6].

**Figure 1.2 The Growth Projection of the Printed Electronics Industry** [7]

Despite of the advantages mentioned previously, the industrialization of printed electronics from a multistep batch processes to a R2R environment will naturally pose many multidisciplinary challenges. At present, there are only a limited selection of functional printable materials and these usually require sintering process at a relatively high temperature (>150°C). Consequently, the web must also have a good thermal stability to withstand treatment at such high temperature. From the machine design point of view, one of the major barriers to obtain reliable functional devices through the R2R process is the feature registration, which can be described as the ability to overlay two or more materials at one specific location. For micro/nano-manufacturing, in particular, the requirements for the feature registration is even higher considering the size of the feature.
Gravure printing, flexographic printing, inkjet printing, and nano-imprint lithography (NIL) are a few examples of readily available additive manufacturing processes that are compatible with the R2R system. Among these processes, inkjet printing is thus far the only non-contact additive process adopted in the R2R platform. Inkjet printing is a flexible manufacturing process because it is digitally driven. It is suitable for applications which require a high degree of pattern customization, such as RFID and smart labels. One of the limiting factors of inkjet printing is the maximum achievable feature resolution, which is on the order of tens of microns [8].

In the recent years, Electrohydrodynamic-jet (E-jet) printing has emerged as a high resolution alternative to the previously mentioned direct solution-based fabrication approaches [9]. It is an alternate printing technique for solution-based deposition applications requiring resolutions between 100nm to 10μm. A comparison of the droplets produced by the E-jet and Inkjet printing processes is depicted in Figure 1.3. Recent advancements in E-jet printing speed and reliability have transformed this technology from a laboratory research tool to a viable manufacturing process [9]–[11]. However, the need to obtain high resolution features on a R2R manufacturing system motivates us to investigate the feasibility of E-Jet printing in the R2R system environment.

Figure 1.3 Comparison Between E-jet and Ink Jet Printed Droplets.
1.2 Electrohydrodynamic Jet Printing

E-jet printing uses an electric field to induce fluid flows from micro capillary nozzles to create devices in the micro/nano-scale range [9]. The E-jet printer as well as the printing process is detailed in [12] and various colored ink droplets were dispensed into uniform patterns on a thick paper or transparency that is placed beneath a conductive plate. This method easily surpassed the conventional state of the art ink-jet technology at the time. Nevertheless, further manufacturing issues such as speed/throughput, droplet resolution/repeatability, ink variations and potential applications of the process were not clearly addressed until [9]. In 2007, Park et al. introduced the E-jet printing process and reported various applications primarily in the area of printed electronics [9]. Further work [10] made process improvements including the resolution, reliability, and throughput. Since E-jet is very flexible with respect to printing materials, including heterogeneous integration [13], there is a wide array of promising opportunities for printed electronics, biological sensing applications, and micro-optics [14]–[17].

Figure 1.4 Schematic of a Standard E-jet Printer
Figure 1.4(a) illustrates the basic components of an E-jet system, which include an ink chamber, conducting nozzle, substrate, and translational stage. The inset shows the conductive nozzle for a sense of scale. In addition to the unit hardware, a computer interface varies the tunable system parameters including: applied voltage, back pressure, and standoff distance between the nozzle tip and the substrate. These process parameters are dependent on the ink material, nozzle diameter, and substrate material.

To achieve printing, the back pressure pushes the ink through the nozzle towards the tip. The applied voltage generates an electric field between the nozzle and the substrate causing concentration of charge on the pendant drop emanating from the tip. This concentrated charge generates shear stress, deforming the meniscus to a conical shape termed a Taylor cone, as highlighted by the red box in Figure 1.4. The shear stress generated by the charge overcomes the ink surface tension, thereby releasing a droplet. As the applied voltage increases, the printing process will transition through various printing modes [9]. Figure 1.5 presents various printing applications of E-Jet printing systems, primarily for printed electronics and biosensors application.

![Figure 1.5 Various Applications of E-Jet Printing Systems. [11], [14]–[16], [18]](image-url)
1.3 Overview of Iterative Learning Control (ILC)

Iterative Learning Control (ILC) is a method by which specific signals are learned through repeated iterations. First described in [19], ILC examines the error from previous trials and maps it to the 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. ILC exploits the trajectory repetition to compensate for any unmodeled dynamics, nonlinearities and repeated disturbances. At a glance the repeatability requirement may appear restrictive. However, for manufacturing systems, which by definition performs repeated action, ILC is particularly appealing. In recent years, significant works have been performed on the theory [20], [21] as well as practice [22]–[24] of ILC. A detailed background on the various ILC approaches are summarized in [22], [25].

ILC can be independently implemented on a stable open loop plant or appending the input signal from the feedback controllers. The latter may adopt either a serial or a parallel architecture as illustrated in Figure 1.6. In a parallel ILC architecture, the ILC input, \( u_{j+1} \), is injected directly to the plant, \( P \), along with the command signal from the feedback controller, \( u_c \). On the other hand, in a serial ILC architecture, \( u_{j+1} \) appends the reference signal of the feedback loop, \( x_d \).

![Figure 1.6](image1.png)  
Figure 1.6 (a) Parallel ILC architecture, (b) Serial ILC architecture
ILC stores the error signal, $e_j$ and the input signal, $u_j$ from the current iteration in system memory and then uses it later to modify the control input for the next iteration, $u_{j+1}$. According to the block diagram in Figure 1.6, the ILC input signal for a standard single input single output (SISO) system can be formulated as (1.1). $j$ is the iteration index and $k$ denotes the discrete time step index. As described in (1.2), $q$ is the forward time-shift operator, which parameterizes the Q-Filter, $Q(q)$ and the learning filter, $L_e(q)$.

$$ u_{j+1}(k) = Q(q)[u_j(k) + L_e(q)e_j(k)] $$  
(1.1)

$$ q(x(k)) = x(k+1) $$  
(1.2)

In general, ILC uses the root mean square (RMS) value of the error signal as a measure to quantify the tracking performance for each iteration. An appropriately designed learning and Q-filter subsequently refines the ILC input and reduces the error signal as illustrated in Figure 1.7. As such, the RMS value of the error signal asymptotically converges at some iteration index and the error and input signals stop updating. It should be noted that the learning law presented in (1.1) is only one of many ILC update laws available in the literature. In this work, we specifically use the lifted Norm Optimal Iterative Learning Control (NOILC), which will be briefly described in the next subsection.

![Figure 1.7 Illustration of the Iterative Learning Control Process](26)
1.4 Thesis Scope

Fabrication of functional devices such as solar cells, micro-batteries, biosensors, etc. are typically performed in multistep 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. [13], [27], [28]. 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. There has been significant work on controlling the tension and position coordination for R2R systems [29]–[31]. However, most of the previous work targets 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 position tracking accuracy.

The broad objective of the thesis is to enable a flexible and high resolution device fabrication through printing on a R2R system. A reconfigurable R2R system which serves as a continuous manufacturing platform for various micro/nano-manufacturing processes is built. Here, a particular focus is placed on integrating the E-jet printing system to the R2R system environment. Regardless of the micro/nano-manufacturing processes that are employed, the presence of hybrid stepping/scanning motions, both continuous and start/stop motions, should be performed with similar levels of precision. Since the web undergoes a repetitive trajectory, Iterative Learning Control (ILC) can thereby be used to improve the position tracking precision, as well as the web tension regulation. We seek to further improve the position tracking performance by combining ILC with direct visual observation on the pre-existing features on the web. The pre-existing features may serve as fiduciary markers for the vision sensing and, thus, one can accurately place the E-Jet nozzle relative to the feature location on the web. Additionally, the thesis also explores the potential application of E-jet printing on a non-conductive substrate.
Chapter 2
Design and Fabrication of a Reconfigurable Roll to Roll (R2R) Manufacturing System: Mechanical Design and Electronics Instrumentation

This chapter discusses the design work of the reconfigurable Roll to Roll (R2R) system. The first section of this chapter covers the mechanical design of the R2R system which is subsequently followed by the electronics instrumentation. The instrumentation allow the system to be monitored and controlled by a single computerized Data Acquisition and Control (DAQ) unit.
2.1 Mechanical Design

A typical R2R system consists of a set of actuated and idler rollers interconnected by a web. By and large, a web is described as any flexible material processed in a continuous manner, e.g., paper, plastics, textiles and metal foil. Although R2R systems are a relatively mature technology, many batch processes are not readily compatible with the R2R approach. We designed a reconfigurable R2R system to study the feasibility and potential of various novel micro/nano-manufacturing processes. In this thesis, the focus is primarily placed on integrating the E-Jet printing system to the R2R environment. The physical picture of the R2R system being developed is presented in Figure 2.1. It has two main subsystems including a web handling module and an E-Jet printing module. As presented in Figure 2.2, all modules are assembled on a 2 ft by 3 ft optical breadboard (TD-13, Newport), which is secured on two pieces of heavy duty steel posts on both end. The following subsections will discuss in details about the web handling modules and the E-Jet printing modules on the R2R system.

![Figure 2.2 Perspective and Exploded View of the R2R System](image)
2.1.1 Subsystem 1: Web Handling Module

Within the web handling module, there are two actuated rollers, commonly termed the unwinder and the rewinder rollers. Several idler rollers (UL-300-050 X7"MOD, Webex) complement the actuated rollers and define the trajectory which the web undergoes. Two fixed holes with 2” OD are opened up at the top corners of the breadboard to mount the bearing housings for both winder rollers. Following the configuration presented in Figure 2.3, each idler roller, excluding idler #2, #5, and #6 is mounted on an aluminum hub and can be arbitrarily placed on the breadboard, where the holes on the board are uniformly spaced by 1 inch. Instead of being mounted to a passive aluminum hub, idler #2 is mounted on a load cell (CL-15, Power Torque) to estimate the tension of the web. Idler #5 and #6 are integrated components of the offset guide (Symat-25B, FIFE) and have slightly smaller OD in comparison to the other rollers. This configuration allows for a basic web handling process and E-Jet printing on the R2R system.

Figure 2.3 Roller Placement on the Breadboard
An air chuck (800 GH, Tidland) and a stainless steel shaft constitute the winder roller as presented in Figure 2.4. It is where the web core is inserted and secured. When air pressure (>60 psi) is applied to the chuck, the three rubber grippers expand and lock the position of the web core. The air pressure is applied using a special inflation tool (Part # 128054, Tidland) into the pressure inlet. Two ball bearings, which are spaced apart by about 1 inch and support the winder shafts, define the location of the central axis of the winder rollers. These bearings must be press fitted on a pillow block with very good concentricity. Any misalignment on the bearings may exert unwanted normal force on the bearings and consequently restraining smooth angular motion of the winder roller.

**Figure 2.4 Winder Roller Configuration**

A rigid shaft coupler (61005K422, McMaster) connects the winder roller shaft to the actuation system. The actuation system as presented in Figure 2.5a) is comprised of a brushless motor (BM 130, Aerotech) and a harmonic drive with 50:1 gear ratio. Both the motor and the harmonic drive are integrated on an aluminum housing. With 4 threaded stainless steel spacers (91075A033, McMaster), this aluminum housing is attached to a 0.5” thick adjustment plate. As illustrated in Figure 2.5b, larger clearance holes are drilled on the adjustment plate, allowing some wiggle room for the actuator assembly to compensate for any parallel misalignment with respect to the winder shaft. The adjustment plate, prior to being fixed on the breadboard, must be tuned in both the vertical and the horizontal direction until the central axis of the motor and the winder roller shafts are aligned. The final assembly of the winder roller and the actuator is presented in Figure 2.5c.
A load cell measures the web tension and this measurement, in conjunction with the position measurement from the encoders, are used for handling the web in the longitudinal direction. The shaft of idler #2 is slightly smaller than the borehole diameter of the load cell, and therefore an aluminum sleeve is designed to compensate for this difference. An exploded view of the load cell assembly is presented in Figure 2.6a. The load cell is oriented sideways because it can measure forces exerted only in the direction indicated by the +/- signs in Figure 2.6b. Two idler rollers are placed nearby the load cell such that the web enters and exits idler #2 at an angle relatively parallel to the sensor orientation in the load cell. This configuration also helps to improve the measurement sensitivity of the web tension.
Behind idler #8, a high resolution ring encoder is attached to provide a more accurate measurement on how far the web has translated. As presented in Figure 2.7, the ring encoder is attached to the idler roller using an adapter plate to minimize direct machining work on the idler roller. It is necessary for the ring encoder to spin concentrically with respect to the rotating axis to maintain a constant offset distance between the read head and encoder markers. Otherwise, the encoder may generate an inconsistent position reading. The offset distance of the encoder read head can be adjusted by manually shifting the slotted adapter mount up and down until the green LED on the read head lights up.

Figure 2.6 a) Exploded View of Load Cell Assembly b) Load Cell Configuration

Figure 2.7 High Resolution Ring Encoder Configuration on the R2R System
As the web traverses in the longitudinal direction, the web may also shift its position in the lateral direction due to inaccurate placement of the web. A laser scanner is placed right after the web exits the offset guide. The laser scanner detects the location of the web edges and assists the offset guide to compensate for any variation in the web lateral position. For an optimal web guiding solution, it is recommended for the web to have a “twist-displace-twist” configuration. In this work, the web enters and exits the web in a “Z” pattern as indicated by the orange spline in Figure 2.8.

![Figure 2.8 Offset Guide Configuration on the Breadboard](image)

**2.1.2 Subsystem 2: E-Jet Printing Module**

On a conventional E-Jet printer, the nozzle tip is held stationary approximately 30 μm above the conductive substrate. Additionally, patterns are printed by translating the substrate relative to the stationary nozzle. E-Jet printing on a R2R configuration is performed differently. The web or the substrate on which the E-Jet droplets are printed does not move during printing, but instead the nozzle tip is translated to produce the intended pattern. Moreover, the web is not electrically conductive and thus cannot dissipate charge as efficient as printing on a silicon wafer. A stainless steel plate is connected to the ground of the E-Jet voltage amplifier and is placed underneath the web to connect the electric field generated between the nozzle and the ground plate.
As shown in Figure 2.9, the E-Jet printing station is placed slightly higher with respect to the neighboring idler rollers. Consequently, when tension is applied, the web will always pull the web downward against the printing ground plate and thereby minimize any insulating air gap. The ground plate is also polished to ease the sliding of the web and improve the reflectivity of the light that is used for process monitoring. The E-Jet printhead is mounted on a motorized precision XY stage (MX80L, Parker) and a manual tip tilt stage is placed underneath to align the nozzle tip with respect to the substrate. The nozzle holder is fabricated using SLA and screwed on a manual linear Z stage. The Z stage is fixed beneath the XY stage and is used to set the standoff distance between the nozzle and substrate.

![Figure 2.9 E-Jet Printing Station (Back View)](image)

As seen in Figure 2.3, there is a camera placed adjacent to the E-Jet printing station and directed towards the nozzle tip. On the R2R system, the E-Jet printhead moves around in the XY direction and may leave the field of view of the camera for our current system. For this reason, the camera cannot monitor the entire printing process. Nevertheless, the camera is still necessary to perform initial calibration of the E-Jet printer including setting the nozzle standoff distance and obtaining the optimal E-Jet printing voltage. Additionally,
the camera is also useful to visually servo the fiduciary markers on the web for feature registration purpose. Details on the visual servoing control algorithm will be discussed in Chapter 5. Figure 2.10 shows the field of view the camera when directed towards the nozzle tip.

![Image Obtained by the CCD Directed Towards the E-Jet Nozzle Tip](image)

**Figure 2.10 Image Obtained by the CCD Directed Towards the E-Jet Nozzle Tip**

### 2.2 Electronics Instrumentation

All control and measurement signals are transmitted from and to a host PC via two NI Real Time (RT) targets. The first one is a PC (Optiplex 990, Dell) which is converted to an RT target. Within this RT target, a data acquisition card (PCIe 6363, NI) and a frame grabber (PCIe 8235, NI) are connected to perform the vision based control algorithm for handling the web. Another RT target connected to the host PC is a Compact RIO (cRIO-9022) system from NI. This device is primarily used to coordinate the motion control of the XY stage and the E-Jet voltage amplifier. It should be noted that both RT devices must be connected to the same subnet on the networked system. Figure 2.11 describes the complete electrical connection diagram of the R2R system. The diagram is split into two branches, where the red branch describes all of the electronics connected to the RT target and the blue branch describes the electronics connected to the cRIO target. Details of every connections found on Figure 2.11 can be found in Appendix A.
Figure 2.11 Electrical Connection Diagram of the R2R System
2.2.1 RT Target 1: Real Time PC Target

LabVIEW 2013 is used to program the R2R system and design the user interface. There are additional software addons other than the core LabVIEW software that must be installed on the Host-PC, including: 1) LabVIEW FPGA Module, 2) LabVIEW RT Module, 3) NI-RIO 2013, 4) NI-DAQmx, 5) NI-Device Drivers, 6) LabVIEW Control Design and Simulation Module, 7) LabVIEW Vision Development Module, 8) LabVIEW Vision Acquisition Module, 9) LabVIEW Soft Motion Module, and 10) LabVIEW Mathscript RT Module. In the NI Measurement and Automation Explorer (NI-MAX), all RT targets connected under the same subnet as the Host PC should be available under the Remote Systems as shown in Figure 2.12. Moreover, if we expand the tree diagram of the Real Time PC, both the data acquisition card (PCIe-6363) and the camera should (GE 680, Allied Vision Technologies) should be listed as well. It is recommended to install all software available on the RT target rather than installing the software selectively.

![Figure 2.12 RT Target Device Setup (Measurement and Automation Explorer)]
Electrical connections from and to the data acquisition card (PCle-6363, NI) are routed using two screw terminal blocks (SCB-68A, NI). For the web handling controller, the Real Time PC reads the position signal using the counters on the data acquisition card and sends control inputs to the motor amplifiers using the analog output channel. The encoder on the servo motor is rated for 4000 counts per revolution (quadrature). Additionally, a harmonic drive with 50:1 gear ratio is attached in front of the motor. Therefore, one full rotation of the winder roller is equivalent to 200000 encoder counts. Similarly, the ring encoder that is attached on idler #8 has 200000 counts per revolution. However, it should be noted that when the idler roller is rotated faster than 12 rad/s, the encoder signal may output a zero change in the position measurement due to aliasing. This phenomenon is captured by the velocity profile of the idler shown in Figure 2.13.

![Velocity profile of the idler](image)

**Figure 2.13 Aliasing on the High Resolution Ring Encoder**

As mentioned in the previous section, the instantaneous tension value of the web is measured using the load cell. In order to get an accurate force reading, the load cell must first be calibrated by some known weights. There are two potentiometers on the load cell amplifier which controls the zero offset and the gain of the output signal. The gain must be adjusted properly to provide the best signal sensitivity without saturating the output signal to the upper limit of the analog input channel on the DAQ card. Figure 2.14 presents the calibration schematic used and the mapping from the voltage signal to the actual web tension. The wire is fixed at the upper end, while various masses are hung at the lower end of the wire to map the output signal to the force applied.
A high speed Gigabit Ethernet (GiGE) Camera is connected to the Real Time PC using a GiGE frame grabber (PCIe-8235). Any potential system user is encouraged to ensure that the Vision Acquisition and the NI Device Drivers have been installed on the Real Time PC. When both software have been installed properly, the Real Time PC should recognize the camera and list it under NI-IMAQdx Devices as shown in Figure 2.12. Since this camera is technically transferring data via an Ethernet connection, the user has to make sure that no firewall blocks the IP address. The transfer rate of the camera is highly dependent on the image size and also the exposure time settings. The camera settings can be set through “NI-Max” or initialization routine on the LabView program.

2.2.2 RT Target 2: Compact RIO

Similar to the Real Time PC, the Compact RIO (cRIO 9022, NI) must be connected to a LAN connection having the same subnet as the Host PC. If all the software mentioned in the previous subsection are installed properly, the cRIO should be discoverable in NI-Max. On the R2R system, this RT system is primarily used to perform motion control of the E-Jet printhead. Two motion controller modules (cRIO 9516, NI) are used to coordinate the motion of the XY stage (MX80L, Parker). The cRIO-9516 has a built in PID controller with 20 kHz sampling rate. This motion controller communicates with the motor drives (VIX250-AH, Parker) to obtain feedback signals and send the control inputs.
The XY stages are driven by two separate motor amplifiers and the axis coordination is performed by the NI Softmotion module. Each VIX250-AH motor drive require two 24 Volts DC power supplies; one is for driving the motor and the other is to power the input/output pins on the drive. Although the position control loop is performed by the NI motion controller, the feedback signal from the XY stage should not be connected directly to the NI motion controller. Instead, the feedback cable from the XY stage should be connected to the X2 connector of the VIX drive. Encoder signals for the position control loop should be obtained from the X4 connector of the VIX drive. Connecting the X2 cable directly to the NI controller may damage the encoder read head of the stage. In contrast, the limit switches of the stage (X5 cable) should be directly connected to the NI motion controller.

Two motion axes should be visible under the cRIO target within the LabVIEW project explorer. Each axis corresponds to one NI-9516 controller connected to the cRIO target. The control loop in the NI motion controller samples at a rate of 20 kHz and adopts a PID + Feedforward control structure (see Figure 2.15). All electrical related to the XY stage as defined in Figure 2.11 must be connected, prior to running the motion controller. There are several axis settings that must be configured, such as the PID gains, signal direction of the limit switches, encoder scaling, and etc. The parameter values of the axis settings can be found in Appendix B. For the NI Softmotion module to work, the cRIO chassis must be set to "Scan Engine Mode".

Figure 2.15 NI Motion Controller Block Diagram
There are three other cRIO modules attached to the chassis. They are an analog output module (cRIO 9264, NI), an analog input module (cRIO 9205, NI) and a digital I/O module (cRIO 9403, NI). The digital I/O module is used to trigger the digital enable switch on the E-Jet Voltage amplifier (677B-L-CE, Trek), while the analog output module is used to generate the output voltage of the E-Jet amplifier and to control the output pressure from the air regulator (200SNNF01DF030100, Marsh Bellofram). The analog input module can be used to measure any additional analog signals from sensors used in the system. All I/O pins that are used must be mapped in the FPGA chipset. Figure 2.16 presents the block diagram of the FPGA program. The last loop in this figure is used to output a PWM signal for the E-Jet voltage amplifier.

Figure 2.16 Block Diagram of LabVIEW FPGA for Mapping the I/O Pin
2.3 Bills of Material

Table 2.1. Major Electronic Components used in the R2R System

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Note:

* Items are salvaged and obsolete, it is replaceable by similar items
Table 2.2. Major Mechanical Components used in the R2R System

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<td>McMaster Carr</td>
<td>7578K731</td>
<td>4</td>
<td>$19.64</td>
<td>$78.56</td>
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<td>8</td>
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<td>7578K831</td>
<td>4</td>
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<td>8364T14</td>
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<td>R12</td>
<td>4</td>
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<td>TD-13</td>
<td>1</td>
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<td>RK3884</td>
<td>1</td>
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<td>Thorlabs</td>
<td>RK4101</td>
<td>8</td>
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<td>RK5000</td>
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<td>Webex</td>
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Note:
- Stock materials and machining hours are not included (Approximately US$5000.00)
Chapter 3
Dynamic Model and Feedback Control Synthesis

The R2R system presented in Figure 2.1 consists of 9 idler and 2 actuated rollers which are interconnected with a thin polymeric material. For the purpose of this thesis, Kapton Tape\(^1\) was the material being transported. A simplified illustration of the roller configuration is presented in Figure 3.1 to analyze the dynamic model of the system. The green arrows in Figure 3.1 indicate the direction of positive motion on each roller and the red arrows are the system inputs. In this system, there are three position sensors, which directly measure the angular position of roller 1, 9, and 11. Additionally, a load cell is attached to roller 3 to measure the tension of the web.

The Free Body Diagram (FBD) of each of the rollers can be generalized into Figure 3.2, where the subscript \( i \) indicates the roller number. According to this FBD, the corresponding equation of motion is defined in (3.1). Here, \( \dot{\theta}_i \) and \( \ddot{\theta}_i \) indicate the roller angular position and its time derivatives. The motor torque, \( \tau_i \), is proportional to the control input (3.2). The friction on each roller, \( f_i \), is assumed proportional to the roller angular velocity as in (3.3). The web tension \( T_i^+ \) and \( T_i^- \) rotate \( M_i \) in the positive and negative direction, respectively, as indicated by the green arrows in Fig. 3.2. Additionally, the web is assumed to be a linear spring described by (3.4), where \( k_i^{\text{spring}} \) is the spring constant equivalence of the web in between the adjacent rollers. Most R2R systems in the existing literature [29]–[31] operate at several hundreds of fpm. At this speed, the radius, \( R_i \), and inertia, \( J_i \), of the rewinder and unwinder change rapidly due to web material transfer. However, since the R2R system in Figure 2.1 will operate at less than 1 fpm, a Linear Time Invariant (LTI) model becomes a valid assumption.

\[
J_i \ddot{\theta}_i = \tau_i + R_i \left( T_i^+ - T_i^- \right) - f_i \\
\tau_i = K_r u_i, \ i \in \{1,11\} \\
f_i = b_i \dot{\theta}_i \\
T_i^+ = k_i^{\text{spring}} \left( R_{i+1} \dot{\theta}_{i+1} - R_i \dot{\theta}_i \right), \ i \in \{1,...,10\} \\
T_i^- = T_i^{+*}, \ i \in \{2,...,11\}
\]
Some of the parameters in (3.1) – (3.5), such as \( R_i \) and \( J_i \), can be directly measured or computed based on the geometry and mass properties. However, some other parameter, such as the torque constant, \( K_T \), and the damping coefficient, \( b_i \), must be obtained empirically from experiments. When the winder roller (\( M_1 \) or \( M_{11} \)) is disconnected from the rest of the R2R system, the equation of motion can be written as (3.6). The motor (BM130, Aerotech) is driven using a motor drive (BA 30, Aerotech) and the electrical current provided by the amplifier is proportional to the motor torque as described in (3.2). The motor current can be controlled using the analog output signal, \( u_m \), from the DAQ card. Given a voltage step input, the motor accelerates the winder roller until it reaches the steady state velocity as presented by the velocity response plot in Figure 3.3. Note that the winder roller is connected to the motor shaft via a harmonic drive with 50 to 1 gear ratio. Therefore, one full rotation of the winder roller corresponds 50 full rotations of the motor shaft (3.7) and, at the same time, the load torque is amplified by 50 times at the end effector. The velocity response of the winder roller resembles the behavior of a first order system with a time constant, \( \alpha \), of 0.03 second.

\[
J_i \ddot{\theta}_i + b_i \dot{\theta}_i = K_T u_{M_i} \tag{3.6}
\]

\[
50\theta_{M_i} = \theta_i \tag{3.7}
\]
As presented in (3.8), the transfer function from $u_{M_1}$ to $\dot{\theta}_1$ is constructed by taking the Laplace transform of (3.6). The transfer function in (3.8) is rearranged to match the generic transfer function formulation of a first order system, $\frac{K_G}{s+\alpha}$, where $\alpha$ and $K_G$ denote the time constant and the gain of the system respectively. From Figure 3.3, $\alpha$ and $K_G$ can be obtained and, consequently, the numerical parameters of the roller can be deduced by invoking (3.9) and (3.10). The velocity response of the unwinder, $M_1$, and the rewinder, $M_{11}$, are very similar because both are driven by two almost identical motors. Therefore, the motor torque constant, $K_T$, and damping coefficient, $b$, of both winder rollers have similar value.

$$\begin{align*}
\frac{\dot{\theta}_1(s)}{U_{M_1}(s)} &= \frac{K_T}{J_1s+b_1} = \frac{\frac{K_T}{b_1}}{\frac{J_1}{b_1}s+1} \\
\alpha &= \frac{J_1}{b_1} \\
K &= \frac{K_T}{b_1}
\end{align*}$$

(3.8)  
(3.9)  
(3.10)

According to Figure 3.4, the angular velocity of the winder roller (red color) shows a non-linear relationship with respect to $u_M$ (black color). In this figure, the gain, $\frac{K_T}{b_1}$, corresponds to the slope of the velocity response, which in (3.8) is assumed to be constant. This non-linear behavior shows up because $b_1$ may be velocity dependent. In order to hold the input-output relationship in (3.8) valid, $u_M$ must be mapped such that the velocity of the winder roller increases linearly as $u_M$ increases. The mapping function can be constructed by curve-fitting the velocity response in Figure 3.4 against the input signal. The curve-fitting should only be applied outside the deadzone of the motor and a DC offset is used inside the deadzone. The value of the DC offset can be obtained by looking at the intersection of the red and black plots in Figure 3.4. The DC offset helps in minimizing a delayed response on the motor. This compensation should be done on the two winder rollers, both in the positive and negative direction. The linearized velocity response after the mapping of $u_M$ is presented in Figure 3.5.
The damping coefficients of the idler rollers, $b_i, i \in \{2, \ldots, 10\}$, are rather difficult to obtain. Since the idler rollers spin much more freely than the winder rollers, $b_i, i \in \{2, \ldots, 10\}$ is therefore assumed to be approximately 20 percent of $b_1$ or $b_11$. As defined in (3.11), the web spring constant equivalence, $k_i^{i+1}$, is approximated using the Hooke’s law, where $E$ is the Young’s Modulus of the web material, $A$ is cross sectional area of the web, and $l_i^{i+1}$ is the length of the web between the adjacent rollers. All numerical values of the system parameters are tabulated in Appendix C.

$$k_i^{i+1} = \frac{EA}{l_i^{i+1}}$$ (3.11)
3.1 State Space Representation

Substituting (3.2) – (3.5) in (3.1), we obtain a MIMO LTI state-space representation describing the open loop system dynamics, $P_{ol}$, where the system states are defined in (3.13). The inputs of $P_{ol}$ are the analog signals sent to the motor drives, $u_{M_1}$ and $u_{M_2}$, which actuate $M_1$ and $M_{11}$ respectively. The measureable system outputs are the angular position of $M_1$, $M_g$, and $M_{11}$, as well as the web tension, $T_M$. Here, $T_M$ is defined as the average value of $T_{3}^{-}$ and $T_{3}^{+}$, and can thereby be related to system states by (3.14). The formal state-space representation of the R2R system defined in (3.12) has 22 system states, 2 system inputs, and 4 measurable outputs. This configuration is neither controllable nor observable when computed numerically.

\[ \dot{x} = A_{22x22}x + B_{22x2}u \]
\[ y = C_{4x2}x \]

(3.12)

\[ x_{2i-1} = \theta_i \]
\[ x_{2i} = \dot{\theta}_i \] \( i \in \{1,\ldots,11\} \)

(3.13)

\[ T_M = \frac{T_{3}^{-}+T_{3}^{+}}{2} = \frac{k_3^3}{2} \left( R_3x_5 - R_2x_3 \right) + k_3^4 \left( R_4x_7 - R_3x_5 \right) \]

(3.14)

As previously mentioned, there is a harmonic drive attached to the motor shaft on each winder roller. The harmonic drive does not only reduce the output speed of the motor, but also reduces the effect of any external torque applied at the end effector. This implies the dynamics of the winder rollers are insensitive to the torque induced by the web tension. Assuming zero torque induced by the web tension on both winder rollers, the R2R system model can be greatly simplified into a 2 roller systems, i.e., the unwinder roller (\( M_1 \)) and the the rewinder roller (\( M_{11} \)) only. Since there are only two rollers being considered in the model, the indexing scheme will be slightly altered for notational convenience. Hereafter, the index \( i = 1 \) is assigned for the unwinder roller, while \( i = 2 \) is assigned for the rewinder roller. The reduced state-space model of the R2R system is presented in (3.15).
The states of the reduced system are defined in (3.16) and additionally, the system matrix, $A$, $B$, and $C$, are defined in (3.17). In $P_{OL}$, the instantaneous position of the web is assumed equal to $\theta_2$ and the tension of the web is redefined in (3.18). The lumped spring constant equivalence of the web, $k$, can be obtained empirically from the experimental testbed by monitoring the change of web tension, $\Delta T_m$, as a function of $\Delta (\theta_2 - \theta_1)$. Based on the experiment, the approximate value of $k$ is $7725.8$ N/m.

\[
\bar{x} = \begin{bmatrix} \dot{\theta}_1 & \dot{\theta}_1 & \theta_2 & \dot{\theta}_2 \end{bmatrix} 
\]  

\[
A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{b_L}{J_x} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{b_L}{J_x} \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ \frac{k_F}{J_x} & 0 \\ 0 & 0 \\ 0 & \frac{k_F}{J_x} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} 
\]  

\[
T_m = k \left( R_2 \theta_2 - R_1 \theta_1 \right) = k \left( R_2 x_3 - R_1 x_1 \right) 
\]  

### 3.2 State Space Model Validation

Reduction on the state space model from a 22 states system to a 4 states system may compromise the fidelity of the model. It is therefore necessary to empirically validate the reduced model with the experimental R2R system. The R2R system is a quasi-stable MIMO system and thereby making open loop system identification (System ID) impractical. Assuming the state space model closely represents the experimental system, a feedback controller can be designed to close the loop of the R2R system. Details on designing the feedback controller can be found in section 3.3. This feedback controller allows the R2R system to track user defined position and tension reference profile. Both reference signals are perturbed with chirp signals with a maximum frequency of content ranging from $0.01$ Hz to $2$ Hz. A window of the resulting input signal generated by the feedback controller is presented in Figure 3.6.
Figure 3.6 Input Signal Generated by the Controller to Track the Chirp Reference

The validation of the state-space model can be done by comparing the output response of the simulated model with the empirical data subject to the input signals presented in Figure 3.6. It should be noted that the input signal presented in Figure 3.6 has been filtered by a zero phase low-pass filter with a 10 Hz cutoff frequency for better visual presentation. In reference to (3.17), there are free integrators on the state-space model which correlate the angular position and velocity of the roller. Consequently, any disturbance and/or measurement noise will get integrated and drift the simulated output signals. The signal drift issue is also apparent for the web tension, because it is modeled as a linear function of the angular position. For this reason, the output signals are filtered with a zero phase high-pass filter with a cutoff frequency of 1 Hz. Figure 3.7 compares the filtered web position signal from the simulation and experiment. By the same token, the comparison of the tension measurement from the simulation and experiment is presented in Figure 3.8. According to Figure 3.8, there is a slight phase lag observed on the empirical web tension measurement, which is a most likely caused by the friction on the actuator. These validation results shows that the model is accurate enough to be used for designing feedback and/or feedforward controllers.
Figure 3.7 Comparison of Web Velocity Response

Figure 3.8 Comparison of the Time Derivative of the Web Tension
3.3 Feedback Control Synthesis

The goal of the feedback controller is to ensure the web tracks a given position profile and simultaneously regulates the tension. Particular to the R2R system discussed in this chapter, we want \( \hat{y}_R = [\theta_2, T_M]^T \) to track \( \hat{r} = [r_1, r_2]^T \), where \( r_1 \) and \( r_2 \) are the reference web position and tension, respectively. To achieve zero steady state tracking error, \( P_{OL} \) is augmented with integral of the error signals, \( \bar{z}(t) \) as shown in (3.19) and (3.20). The augmented state space representation, \( \tilde{P}_{OL} \), is given by (3.21).

\[
z_1(t) = \int_0^t e_1(s) ds = \int_0^t r_1(s) - \theta_4(s) ds \tag{3.19}
\]
\[
z_2(t) = \int_0^t e_2(s) ds = \int_0^t r_2(s) - T_M(s) ds \tag{3.20}
\]
\[
\begin{pmatrix}
\dot{\bar{x}} \\
\dot{\bar{z}}
\end{pmatrix} =
\begin{pmatrix}
A_{4 \times 4} & 0_{4 \times 2} \\
-C_{2 \times 4} & 0_{2 \times 2}
\end{pmatrix}
\begin{pmatrix}
\bar{x} \\
\bar{z}
\end{pmatrix}
+ \begin{pmatrix}
B_{4 \times 2} \\
0_{2 \times 2}
\end{pmatrix} \bar{u} + \begin{pmatrix}
0_{4 \times 2} \\
I_{2 \times 2}
\end{pmatrix} \bar{f}
\]
\[
\begin{pmatrix}
\bar{y} \\
\bar{\xi}
\end{pmatrix} =
\begin{pmatrix}
C_{2 \times 4} & 0_{2 \times 2}
\end{pmatrix}\begin{pmatrix}
\bar{v}
\end{pmatrix}
\tag{3.21}
\]

An LQR feedback controller is designed to minimize the cost function described in (3.22). The weighting matrices \( Q_{FB} \in \mathbb{R}^{6 \times 6} \) and \( R_{FB} \in \mathbb{R}^{2 \times 2} \) are defined in (3.23). The focus of the feedback controller is to stabilize the R2R system and more importantly bring the error signal to zero. Therefore, high values are assigned on \( q_5 \) as well as \( q_6 \). The numerical value of the LQR weighting matrices are tabulated in Table 3.1. Applying the LQR to (3.21), we obtain the closed loop system, \( \tilde{P}_{GL} \), described in (3.24), where \( K \) denotes the LQR feedback gain matrix. The matrix \( K \) can be computed by invoking the ‘lqr’ command in Matlab. The numerical value of \( K \) is presented in (3.25) and the resulting simulated tracking performance is presented in Figure 3.9.

\[
J_{FB} = \bar{v}^T Q_{FB} \bar{v} + \bar{u}^T R_{FB} \bar{u} \tag{3.22}
\]
\[ Q_{FB} = \begin{bmatrix} q_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & q_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & q_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & q_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & q_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & q_6 \end{bmatrix}, \quad R_{FB} = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix} \] (3.23)

\[ \vec{p}_{CL} = \begin{cases} \dot{\vec{v}} = (\vec{A} - \vec{B} \vec{K}) \vec{v} + \vec{F} \vec{r} \\ \vec{y} = \vec{C} \vec{v} \end{cases} \] (3.24)

\[ K = \begin{bmatrix} 514.41 & 9.204 & -476.378 & -0.7810 & -70.591 & 70.831 \\ -476.378 & -0.781 & 514.415 & 9.2049 & -70.831 & -70.591 \end{bmatrix} \] (3.25)

**Table 3.1 Numerical Value of the LQR Weighting Matrices**

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<td>0</td>
<td>100</td>
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<td>10000</td>
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**Figure 3.9 Simulated Tracking Performance of the Feedback Controller**


3.4 Feedback Control Implementation

The performance of the feedback controller designed in the previous section is evaluated on the experimental R2R system as well. The feedback controller is implemented using a LabVIEW Real Time (RT) target. The RT target used in the system is essentially a CPU (Optiplex 980, Dell) which runs LabVIEW RT operating system. It is equipped with a high performance data acquisition card (PCIe-6363,NI) to read measurement signal from the sensors and send command signals to the R2R system. The data acquisition system reads 4 measurement signals as described in the first paragraph of Chapter 3. As shown in Figure 3.10, the feedback controller on the RT target is designed using the Control Design and Simulation Module from NI and it operates at 5 kHz sampling frequency. In the experimental system, the position of the web is defined by the high resolution ring encoder mounted on $M_g$ and the web tension is defined by the load cell measurement. The error signals are defined by comparing both these output measurements to the reference signals.

![Figure 3.10 Feedback Controller Implementation in LabVIEW – RT](image)

The experimental tracking performance of the R2R system is presented in Figure 3.11. In reference to Figure 3.4, the motors must operate within the deadzone for translating the web at 0.1 rad/s. The resulting control signals, $u_{M_1}$ and $u_{M_2}$, change signs frequently, forcing both motors to closely track the reference signals as presented in Figure 3.12. Relatively high values of $q_2$ and $q_4$ (=100) in the LQR formulation is used to reduce the effect of the stick-slip friction. When $q_2$ and $q_4$ are set to 0, the effect of motor stick-slip friction becomes apparent as presented in Figure 3.13.
Figure 3.11 Tracking Performance of the Experimental System

Figure 3.12 Input Signals Generated by the Feedback Controller, $\bar{u} = -K\tilde{w}$
Figure 3.13 Tracking Performance of the Experimental System ($q_2=q_4=0$)
Chapter 4
Design and Implementation of Norm Optimal ILC on the R2R System

In this chapter, Iterative Learning Controller is designed to improve the tracking performance of the feedback system described in Chapter 3. 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.

4.1 Norm-Optimal ILC Design

To improve the tracking performance of the system, an ILC 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 (4.1). Conversion from continuous to discrete system is performed on the numerical system model of $\tilde{P}_{cl}$ using the ‘c2d’ command in Matlab with the zero order hold method with the appropriate sampling time. In (4.1), $A_D, B_D$ and $C_D$ (see Appendix D for numerical values) in sequence define the state transition, input and output matrix in the discrete space and, additionally, $k$ defines the discrete time step index.

\[
\tilde{P}_d \begin{cases}
\bar{y}(k+1) = A_D \bar{v}(k) + B_D \bar{r}(k) \\
\bar{y}(k) = C_D \bar{v}(k)
\end{cases}
\]  

(4.1)
The serial form of the ILC architecture [26], [32] as presented in Figure 4.1 is employed along with the lifted domain Norm Optimal ILC (NOILC) framework [33], [34] to generate the ILC input signals. At each iteration, the error and ILC input signals are stored in the system’s memory and are used to modify the ILC input signal at the next iteration. NOILC is a $\|\|_2$ optimization framework which minimizes a quadratic cost function described in (4.2), where $j$ indicates the iteration index. Here, $e$ and $u$ are the lifted error and input vectors, defined in (4.3). In (4.3), $Q, R$ and $S$ are symmetric positive definite matrices, commonly expressed as $(ql, rl, sl)$ where $q, s, r \in \mathbb{R}^+$ and $I$ is an Identity Matrix of appropriate dimension.

![Figure 4.1 Serial ILC configuration for the R2R system](image)

$$J = e_j^T Q e_j + u_j^T S u_j + (u_{j+1} - u_j)^T R (u_{j+1} - u_j)$$ (4.2)

$$e = \begin{bmatrix} \bar{e}(0)^T & \bar{e}(1)^T & \cdots & \bar{e}(N-1)^T \end{bmatrix}$$

$$u = \begin{bmatrix} \bar{u}(0)^T & \bar{u}(1)^T & \cdots & \bar{u}(N-1)^T \end{bmatrix}$$ (4.3)
The resulting ILC control input from the quadratic optimization process, $u_{j+1}$, is presented in (4.4). $P \in \mathbb{R}^{m_u N \times m_N}$ is a lower triangular Toeplitz matrix that maps all system inputs of $\hat{P}_D$ to the system outputs in lifted domain, where $m_i$ and $m_o$ denote the number of inputs and outputs of respectively. The matrix can be constructed using (4.5), where each element on this matrix is a block matrix of size. The interested reader is referred to [33] for detailed derivation of the learning gain and . For the solution of the NOILC algorithm to monotonically converge, (4.6) must be satisfied. By substituting (4.4) into (4.6), we obtain (4.7) which requires to be positive definite.

$$u_{j+1} = L_u u_j + L_e e_j$$
$$L_u = \left( P^T Q P + S + R \right)^{-1} \left( P^T Q P \right)$$
$$L_e = \left( P^T Q P + S + R \right)^{-1} \left( P^T Q \right)$$

(4.4)

$$P = \begin{bmatrix}
C_D B_D & 0 & 0 & 0 \\
C_D A_D B_D & C_D B_D & 0 & 0 \\
\vdots & \ddots & \ddots & \ddots \\
C_D A_D^{N-1} B_D & \cdots & C_D A_D B_D & C_D B_D \\
\end{bmatrix}$$

(4.5)

$$\|L_u - L_e P\|_2 < 1$$

(4.6)

$$\left\| \left( P^T Q P + S + R \right)^{-1} R \right\|_2 < 1$$

(4.7)

The practical limitation for the lifted NOILC lies in the trial length, $N$. As $N$ grows large, computation of the learning gains $L_u$ and $L_e$ becomes intractable [35], [36]. In this work, we operate with trajectories short enough to stay within the computational constraints. As mentioned in Chapter 3, the feedback controller of the R2R system operates at a 5 kHz sampling frequency. At this frequency, the number of data sampled from running a 10 second experiment will be 50000 data points on each measurement channel. In reference to (4.4), this implies an inversion of a square matrix with a size of 100000. In order to lower the computational expense, the measurement signals are down-sampled to 5 milliseconds, thereby reducing the size of $P$ down to 4000 by 4000.
4.2 Simulation Results

The NOILC algorithm is evaluated on the R2R model which is subjected to a continuous position and trapezoidal tension reference profile. The NOILC weighting matrices \((Q, R, S)\) are designed according to (4.8) to provide an additional degree of freedom in optimizing the generated ILC input signals. The numerical values of the NOILC weighting matrices are tabulated in 4.1 and the resulting simulated tracking performance of the R2R system is presented in Figure 4.2. At the 0th iteration, while the ILC input signals are not applied, a phase lag on the position tracking performance (blue plot) is apparent. In contrast, the position tracking performance of the R2R system is significantly improved after 20 iterations with the ILC.

\[
Q = \text{diag} \left( \bar{Q}, ..., \bar{Q} \right) \quad \bar{Q} = \begin{bmatrix} \bar{q}_1 & 0 \\ 0 & \bar{q}_2 \end{bmatrix} \\
R = \text{diag} \left( \bar{R}, ..., \bar{R} \right) \quad \bar{R} = \begin{bmatrix} \bar{r}_1 & 0 \\ 0 & \bar{r}_2 \end{bmatrix} \\
S = \text{diag} \left( \bar{S}, ..., \bar{S} \right) \quad \bar{S} = \begin{bmatrix} \bar{s}_1 & 0 \\ 0 & \bar{s}_2 \end{bmatrix}
\] (4.8)

<table>
<thead>
<tr>
<th>\bar{q}_1</th>
<th>\bar{q}_2</th>
<th>\bar{r}_1</th>
<th>\bar{r}_2</th>
<th>\bar{s}_1</th>
<th>\bar{s}_2</th>
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</table>

Table 4.1 Numerical Value of the NOILC Weighting Matrices (Continuous)

As presented in Figure 4.1, the input signal in (4.4) is the reference signal to the closed loop system. As such, it is the reference modification that provides the desired system output response. In Figure 4.3, we can contrast the modified reference signal generated by the NOILC \((j = 20)\) to the nominal reference signal \((j = 0)\). The non-causal nature of the NOILC generates a reference input that starts initiating motion prior to the nominal reference signal. Consequently, the R2R system can preemptively compensate for the phase lag on the web position tracking. The performance improvement introduced by adding the ILC input signals at each iteration is well captured by the normalized RMS error plot presented in Figure 4.4.
Figure 4.2 Simulated ILC Tracking performance of the R2R system (Continuous)

Figure 4.3 Modified reference trajectory generated by NOILC (Continuous)
The previous simulation results demonstrate the performance enhancement for tracking a smooth continuous positioning trajectory and non-constant tension. Several micro/nano-manufacturing processes such as photolithography, screen-printing, and E-Jet printing are performed semi-continuously on the R2R system. Currently, with one single nozzle, E-Jet printing takes more than 30 minutes to completely fabricate a 1 square inch area. However, as the number of nozzles on the E-Jet print head increases, it is likely that the manufacturing process can be completed in the order of seconds [37]. Assuming each stepping motion corresponds to the period between each fabrication process, it is therefore necessary for the web to completely settle down at the intended position before the stepping motion resumes. The measurement signal from the load cell is polluted by signal noise, and thus \( r_2 \) is set to 300. A high value of \( r_2 \) is used to preserve the ILC input signal profile from the previous iteration, preventing the system from learning the non-repetitive noise signals present. The tracking performance, ILC input signals and the RMS convergence of the stepping motion case are presented in Figure 4.5 and 4.6 respectively.
Figure 4.5 Simulated ILC Tracking performance of the R2R system (Stepping)

Figure 4.6 Modified reference trajectory generated by NOILC (Stepping)
For the stepping motion case, ILC is proven to also be effective in improving the position tracking performance of the R2R system. With only the feedback controller, the web barely settles at the targetted steady-state location before another stepping motion is initiated. In contrast, the additional ILC input signal allows the web to settle completely in time, prior to the upcoming stepping command. In Figure 4.6, we can observe that the ILC signal actively damps the residual oscillation from the stepping action. Since the tension profile is relatively simple compared to the one presented in Figure 4.2, and a higher value of $\bar{r}_2$ is used, there is not much modification made to the reference profile of the web tension. Basically, the reduction on the normalized RMS error of the web tension is lower than with position as there is not much room to improve. The resulting RMS error at each iteration is presented in Figure 4.7.

![Normalized RMS Error of the Simulated R2R System (Stepping)](image)

**Figure 4.7 Normalized RMS Error of the Simulated R2R System (Stepping)**
4.3 Experimental Results

To validate the simulation results, the same reference trajectory used from the simulation study is employed on the experimental system. Both experimental results for the continuous and stepping motion case are presented in this section. At the 0\textsuperscript{th} iteration, the ILC input signal sent to the system is the nominal reference signal. The error and ILC input signals are acquired, down-sampled and stored in the hard drive in the form of a LabVIEW measurement file (.lvm). The stored measurement data are used by Matlab to compute the ILC input signal for the upcoming iteration using (4.4).

The tracking performance of the experimental system for the continuous motion case is presented in Figure 4.8. The general trends of the experimental results are very similar to the simulation results. A small difference occurs in the web tension tracking performance. Immediately after \( t = 5\)s, the web changes direction of motion and a small spike occurs on the tension. This may be a result of either the friction or the backlash in the gearbox. However, this behavior can be effectively compensated by ILC input signals presented in Figure 4.9. The normalized RMS error is presented in Figure 4.10.

![Figure 4.8 NOILC Tracking Performance on the Experimental System (Continuous)](image-url)
Figure 4.9 Modified Reference Trajectory Generated by NOILC (Continuous)

Figure 4.10 Normalized RMS Error of the Experimental R2R System (Continuous)
The previous results experimentally verify the performance enhancement introduced by ILC for smooth trajectories. Next we examine the ILC’s effectiveness for stepping types of position trajectories while regulating constant tension. Results presented in Figure 4.11 show that the ILC signal allows the web to settle at the intended target position at each step before the next stepping motion resumes. The output error presented in Figure 4.12 reveals a closer look on the improvement that NOILC contributes to the tracking performance of the R2R system. In Figure 4.13, 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 [38]. The corresponding normalized RMS error plot is presented in Figure 4.14. There is almost no improvement on the web tension tracking since the constant tension profile reference is relatively simple.

![Figure 4.11 NOILC Tracking Performance on the Experimental System (Stepping)](image_url)
Figure 4.12 Output Error of the R2R system (Stepping)

Figure 4.13 Modified Reference Trajectory Generated by NOILC (Stepping)
To summarize, this chapter presented simultaneous 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.

Figure 4.14 Normalized RMS Error of the Experimental R2R System (Stepping)
Chapter 5
Vision Based Iterative Learning Control on R2R System

Fabrication of nano/micro-scale functional devices often times involves multiple steps. In the context of a continuous or semi-continuous manufacturing process, each fabrication step is performed successively in multiple localized zones. As the substrate or the web traverses downstream in the process flow, proper registration of the pre-existing features is necessary prior to entering the next fabrication zone in order to accurately complement previous manufacturing steps. Non-collocated sensors, loss of traction between the web and the roller, structural rigidity, and web deformation are several of many factors that contribute to inaccurate feature registration. A direct visual observation helps to circumvent the uncertainty of the feature location on the web.

5.1 System Setup

Here, \( G(s) \) is the frequency domain representation of the inner loop, \( \tilde{P}_{ci} \), which was previously described in (3.24). \( G(s) \) maps the reference signals \( \mathbf{r} = [r_1 \ r_2]^T \) to the system outputs \( \mathbf{y} = [y_1 \ y_2]^T \) as defined in (5.1), where the subscript 1 and 2 are associated with the web position and tension respectively. As described in chapter 3, the web position, \( y_1 \), is measured by a high resolution ring encoder and a load cell measures the tension of the web, \( y_2 \).
As presented in Figure 5.1, a camera is directed normal to the surface of the web and is assumed to be mounted on an infinitely stiff inertial reference frame. The camera used in this setup is a Gigabit Ethernet monochrome camera (GE680, AVT), which can acquire 200 images every second at a VGA resolution. The top half of the inset in Figure 5.1 shows the actual image of the pre-existing features on the web as observed by the camera, while the lower half of the inset shows the processed binary image. On a large scale R2R system, these markers can be either made specifically for positioning purpose or it might also be pre-existing devices manufactured in the prior manufacturing station.

\[
\begin{bmatrix}
Y_1(s) \\
Y_2(s)
\end{bmatrix} = 
\begin{bmatrix}
G_{11}(s) & G_{12}(s) \\
G_{21}(s) & G_{22}(s)
\end{bmatrix}
\begin{bmatrix}
R_1(s) \\
R_2(s)
\end{bmatrix} = C(s)D(s)A(s)B(s)
\]

(5.1)

Figure 5.1 Configuration of the Vision System on the R2R system
Most high precision electromechanical systems, including $G(s)$, in general operate at 1 kHz or faster. However, the information extracted from a vision sensor may require a longer time to process and thereby cannot be used as a direct feedback signal for $G(s)$. As presented in the block diagram in Figure 5.2, the machine vision is introduced to the R2R system as the position sensor at the outer loop of $G(s)$. Based on the experimental setup, the image acquisition along with the image processing requires at least 5 millisecond to consistently provide position measurement to the outer loop, while $G(s)$ samples data every 0.2 millisecond. Additionally, we also assume zero dynamics on the vision sensor.

![Figure 5.2 A Dual State Feedback Control Architecture](image)

In Figure 5.2, the position outer loop feedback control, $C(s)$, assumes the form of a PI controller to ensure a zero steady state error. The accuracy of the web tension is not as critical as the web positioning. Therefore, the tension regulation relies solely on the LQR designed for the inner loop, described in Chapter 3. A simple PI controller can be used in the outer loop because $G(s)$ has been decoupled by the LQR described in Chapter 3. The PI gains cannot be set too high due to the limited stability margins of $G(s)$. The PI gains are heuristically tuned such that the outer loop achieves a stable tracking performance. With $K_p = 1$ and $K_i = 1$, the resulting tracking performance of the outer loop is presented in Figure 5.3. Here, the web undergoes a stepping motion and simultaneously maintains a constant tension. It is assumed that each step corresponds to the period during which the fabrication process is taking place. It is therefore necessary for the web to completely settle down at the intended position before the stepping motion resumes. In Figure 5.3, we can observe a slow transient response on the web position tracking, similar to the results in Figure 4.8. We seek to improve the vision based position tracking performance using ILC.
To improve the transient response of the visual servoing system of the R2R system, the outer loop architecture presented in Figure 5.2 is augmented with ILC. As presented in Figure 5.4, both the error signals $\epsilon_1^j$ and $\epsilon_2^j$, as well as the ILC input signals at the current iteration, $u_{ILC1}^j$ and $u_{ILC2}^j$, are recorded in the system memory and used to update the ILC signals at the next iteration, $u_{ILC1}^{j+1}$ and $u_{ILC2}^{j+1}$.

![Figure 5.3 Tracking Performance of the Dual State Feedback Architecture](image)

**5.2 Vision Based NOILC Design**

Figure 5.4 Dual State Feedback Control Architecture with Coupled NOILC
Other than error and ILC input signals from the current iteration, the lifted NOILC formulation also requires the mapping from the ILC input signals, $u_{ILC}^j$, to the system outputs, $\mu^j$, denoted by $P$ in chapter 4. For a state space system model, $P$ can be conveniently expressed using (4.5). However, in the frequency domain, $P$ can be constructed using the finite impulse response from $u_{ILC}$ to $\mu$. In order to obtain the impulse response, the transfer function which map the $u_{ILC}$ to $\mu$ must first be defined. According to the block diagram presented in Figure 5.4 and assuming no dynamics on the machine vision, the system output $\mu$ can be defined

$$
\begin{bmatrix}
\mu_1(s) \\
\mu_2(s)
\end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\
G_{21}(s) & G_{22}(s)\end{bmatrix} \begin{bmatrix} R_1(s) \\
R_2(s)\end{bmatrix}
$$

(5.2)

where

$$
R_1(s) = U_{FB1}(s) + U_{ILC1}(s) \\
R_2(s) = U_{ILC2}(s)
$$

(5.3)

For convenience, the Laplace operator, $s$, will be dropped in the following equations. By setting $\mu^*_1$ to zero, the feedback input signals, $U_{FB1}$, can be written in terms of the system outputs as presented in (5.4).

$$
U_{FB1} = -C_1 \mu_1
$$

(5.4)

Substituting (5.3) and (5.4) to (5.2), the system outputs can be rewritten as a function of the ILC inputs (5.5).

$$
\begin{align*}
\mu_1 &= G_{11}(-C_1 \mu_1 + U_{ILC1}) + G_{12} U_{ILC2} \\
\mu_2 &= G_{21}(-C_1 \mu_1 + U_{ILC1}) + G_{22} U_{ILC2}
\end{align*}
$$

(5.5)

A slight algebraic rearrangement of (5.5) allows the system outputs, $\mu_1$ and $\mu_2$ to be explicitly expressed in terms of the ILC inputs, $U_{ILC}$. In (5.6), the matrix $\overline{G}(s)$ maps $U_{ILC}$ to $\mu$ and the matrix indices are further described in (5.7).
\[
\begin{bmatrix}
\mu_1 \\
\mu_2
\end{bmatrix} = 
\begin{bmatrix}
\bar{G}_{11} & \bar{G}_{12} \\
\bar{G}_{21} & \bar{G}_{22}
\end{bmatrix}
\begin{bmatrix}
U_{ILC1} \\
U_{ILC2}
\end{bmatrix}
\]

\begin{align}
\bar{G}_{11} &= \frac{G_{11}}{1 + G_{11}C_1} \\
\bar{G}_{12} &= \frac{G_{12}}{1 + G_{11}C_1} \\
\bar{G}_{21} &= \frac{G_{21}}{1 + G_{11}C_1} \\
\bar{G}_{22} &= \frac{G_{22} + G_{22}G_{11}C_1 - G_{21}G_{12}C_1}{1 + G_{11}C_1}
\end{align}

The transfer matrix \( \bar{G} \) must be converted to its discrete system counterpart, \( \bar{G}_D \).

The conversion from the continuous to the discrete system is performed using the ‘c2d’ command in Matlab with a 5 millisecond sampling time to match the sampling time of the machine vision. By invoking the ‘impulse’ command on \( \bar{G}_D \) in Matlab, the time series impulse responses of \( \bar{G}_D \) are obtained and the corresponding plots are presented in Figure 5.5. The impulse response data are essentially the system’s Markov parameters, which are used to establish the input–output matrix, \( P \). The interested reader is referred to [39] for details in constructing \( P \).

**Figure 5.5 The Finite Impulse Responses of \( \bar{G}(s) \)**
The super-vectors $e$ and $u$ for the system in Figure 5.4 are defined in (5.8). These are used to compute the ILC input signals for the next iteration. The learning gains and the update laws have been previously defined in are similar to those defined in (4.4). The numerical values of $\bar{q}_i, \bar{r}_i$ and $\bar{s}_i$ used are tabulated in Table 5.1.

$$e = \begin{bmatrix} e_1(0) \\ e_2(0) \\ \vdots \\ e_1(N-1) \\ e_2(N-1) \end{bmatrix}^T,$$

$$u = \begin{bmatrix} u_{ILC1}(0) \\ u_{ILC1}(1) \\ \vdots \\ u_{ILC1}(N-1) \\ u_{ILC2}(0) \end{bmatrix}^T.$$  

(5.8)

Table 5.1 Numerical Value of the NOILC Weighting Matrices

<table>
<thead>
<tr>
<th>$\bar{q}_1$</th>
<th>$\bar{q}_2$</th>
<th>$\bar{r}_1$</th>
<th>$\bar{r}_2$</th>
<th>$\bar{s}_1$</th>
<th>$\bar{s}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1000</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 5.6 contrasts the output signal of the feedback controller (FB) to the ILC output signals at the 20th iteration. The corresponding normalized RMS error at each iteration is presented in Figure 5.7.
5.3 Image Acquisition and Machine Vision Algorithm

A Gigabit Ethernet frame grabber (PCle-8235, NI) is mounted on the Real Time PC Target (RT-PC) and connected to the high speed GiGE camera. As previously mentioned, this vision system can 200 monochrome images every second at a VGA resolution (640 pixels by 480 pixels). On the experimental setup, the image resolution is set down to 640 pixels by 50 pixels and the exposure time is set to 200 μs. With this settings, the image acquisition, image processing, and the feedback controller altogether can consistently complete the computation within 5 milliseconds. The top half of the image presented in in Figure 5.8 shows the actual image acquired by the camera, while the lower half of the image is processed binary image which will be used to define the web position. The center to center distance of each fiduciary marker is 1/64".

Figure 5.8 Acquired Image of the Fiduciary Markers
Several image processing steps are performed in order to obtain a usable binary image, including image thresholding, hole filling, and the removal of small particles. These image processing routines and the object analysis are programmed using the Vision Assistant software module from NI. There are 5 to 6 detected objects within the image and object index increases starting from the leftmost detected object. Note that the object index may change as the web translates forward or backward. The relative distance of the object from the current and the previous image data, $dP(k)$, is defined in (5.9), where $k$ denotes the time step index and $m$ denotes the object index defined in (5.10). The position of the web, $\mu_t(k)$, according to the vision sensor is be defined in (5.11).

$$dP(k) = P_m(k) - P_3(k-1)$$ (5.9)

$$m = \arg \min_{m \in [2,3,4]} |P_m(k+1) - P_3(k)|$$ (5.10)

$$\mu_t(n) = \mu_t(0) + \sum_{k=0}^{n} dP(k)$$ (5.11)

Figure 5.9 benchmarks the velocity measurement of the vision sensor to the velocity measurement of the high resolution ring encoder. Both velocity profile look very similar and thus validates the proposed machine vision algorithm in (5.9) - (5.11). The vision based position measurement is assumed to be the true position of the web.

![Figure 5.9 Comparison of Web Velocity Profile Measured by Encoder and Camera](image-url)
5.4 Experimental Results

Experiments are conducted to validate the performance improvement introduced by NOILC. In the experiments, the ILC input signals are generated using the decoupled NOILC algorithm. Additionally, the same reference signals used in the simulation are employed in the experiments for a more direct comparison. Fig. 5.10 presents the output tracking performance of the experimental system. Similar to the simulation results, the feedback controller as indicated by the blue line, produces a sluggish motion, and the tracking performance is significantly improved by the ILC signals at the 20th iteration. The corresponding ILC input signals are presented in Fig. 5.11. Here, we can observe that the non-causal nature of the NOILC generated input signals that initiates motion prior to the starts and stops events in the reference signals. The normalized RMS error of the experimental system is presented in Fig. 5.12. At the 20th iteration, the RMS error of the web position tracking is reduced down to around 5 percent of the RMS error at the 0th iteration. The experimental results validate the simulation results in Section 5.3.

![Output Tracking Performance of the Vision Based ILC](image)

**Figure 5.10 Output Tracking Performance of the Vision Based ILC**
Figure 5.11 Input Signals of the Vision Based ILC

Figure 5.12 Normalized RMS Error of the Vision Based ILC (Experiment)
This chapter presents the coordinated position and tension control of a Roll to Roll web system using a dual state feedback architecture, where machine vision is used to visually servo the web position. Norm Optimal Iterative Learning Control is augmented in the outer loops and significantly improves the position tracking of the web. Simulation results of the NOILC formulations are presented in this chapter. Additionally, experimental results validate the performance improvement of the proposed algorithm. The visual servoing approach discussed in this chapter is helpful to align preexisting features on the web to E-Jet printing station.
Chapter 6
E-Jet Printing on the R2R System

E-Jet printing is generally performed on a conductive non-flexible substrate. However, in the R2R environment, the substrate is neither conductive nor flexible, thereby considerably altering the printing behavior. This chapter discusses the E-Jet printing setup on the R2R system along with the user interface which coordinates the web handling controls and printing axis. Additionally, some printing results are presented to demonstrate the feasibility of E-Jet printing on a R2R system.

6.1 System Setup

As mentioned in Chapter 2, there are two real time (RT) targets which are used to control the E-Jet printing system, i.e. the Real Time PC (RT-PC) and the Compact RIO (cRIO). The RT-PC is primarily used for web handling control, whereas the cRIO controls the motion and voltage of the E-Jet print head. Coordination of both RT targets is performed by a LabVIEW program, named “Host.vi”, which resides on the Host PC. As presented in Figure 6.1, a Graphical User Interface is developed within this LabVIEW program. This GUI allows users to send command signals to all connected hardware presented in Figure 2.11 and displays relevant sensor measurements to monitor the status of the system. The camera feed is also included for the initial setup and calibration of the E-Jet print head. The background program of this GUI constantly communicates with the LabVIEW programs which run locally on each RT target through the Local Area Network (LAN). The numbering in Figure 6.1 represents the different modules in this GUI. Each module will be individually described in the following subsection.
6.1.1 Module 1: XY Axis Motion Control (Parker Stage)

The XY axis motion control module includes some basic functionalities of a generic Cartesian gantry robot such as: jog axis, home axis, move to origin, and execute program. The current position of the axes are displayed on the table and the LED indicators show whether the axes are armed. Each time the “Host.vi” is started, the axes assume the stage position during initialization to be the (0,0) coordinate. When the home button is pressed, the stage will seek the end-of-limit switch, reset the encoder value and brings the axis to the absolute origin (0,0). The axis status will display “Homed” when the axis has been homed at least once.

Each axis can be manually jogged by pressing the cursor buttons, labelled “x-”, “x+”, “y-”, and “y+” on the GUI. The jog size and velocity parameters for each axis are specified by the numerical text boxes at the right hand side of the cursors. These parameters have a working unit of millimeters (mm). Additionally, the axis can also be programmed to execute a sequence of motion commands (G-Code), which is loaded from a text file. The
G-Code must be written in accordance to the formatting guideline presented in Figure 6.2. Each column in Figure 6.2 consecutively represents the x-axis jog size, y-axis jog size, velocity, and digital enabled. A value of 1 for the digital enabled implies printing and a value of 0 implies no printing. A Matlab based program is written to automatically generate G-Code from any bitmap images. The GUI for the G-Code generator is presented in Figure 6.3 and the details of the G-Code background algorithm can be found in [40].

![Figure 6.2 G-Code Formatting Guideline for the E-Jet Motion Axis](image)

![Figure 6.3 Image to G-Code Converter Program for the R2R System](image)
A tilt calibration feature is programmed into the motion axis to assist users in the alignment process to make sure the XY stage moves parallel with respect to the ground plate. Recall that in E-Jet printing, the nozzle must be placed fairly close (< 100 um) to the ground plate to generate a sufficient electric field. Any slight tilt can possibly cause the nozzle to hit the ground while moving over the ground plate or become far enough that the field is insufficient to drive emission. In a conventional E-Jet printing system, the nozzle remains in place and the substrate is moved by the linear stage. This setup allows the tilt calibration to be done visually using the camera feed. In the R2R system, the nozzle moves via the stage motion and may leave the field of view of the camera. Consequently, tilt calibration using the visual aid becomes impractical. To calibrate the tilt of the nozzle, a laser interferometer (D20, Philtec Inc.) is used to measure the standoff distance with respect to the ground plate at various XY locations.

As presented in Figure 6.4, the measurement data from the laser interferometer can be used to generate a surface map of the ground plate, which may be used to assist the tip-tilt adjustment of the XY stage. The surface map at the left hand side of Figure 6.4 represents the condition during which the XY stage does not move parallel to the ground plate. By iteratively adjusting the knob on the tip-tilt stage and running the calibration routine after each successful adjustment, the XY stage will be levelled and the final surface map should resemble the right image in Figure 6.4. The left knob on the tip tilt stage as depicted in Figure 6.5 adjusts the misalignment in the U direction, whereas the right knob aligns the XY stage in the A direction. Once aligned, the XY stage will remain parallel with respect to the ground plate unless the knob of the tip-tilt stage is accidentally altered.

Figure 6.4 Surface Map of the Ground Plate Generated by the Interferometer
6.1.2 Module 2: E-Jet Voltage and Pressure Control

The E-Jet voltage and pressure control module allows user to control the printing voltage and back pressure of the E-Jet printhead. There are two signal types that can be generated by the voltage amplifier: a DC signal and a PWM signal [10]. The description of the PWM parameters are summarized in Figure 6.6. A user can specify the printing voltage parameters and pressure using this module by assigning numerical values to the voltage and pressure cluster presented in Figure 6.7. The “CNC Enable” button must be set to ‘active’ while the G-Code is being executed, otherwise no voltage signal will be generated.
6.1.3 Module 3: Camera Feed Display

The frame grabber resides on the RT-PC and, therefore, the acquired image must be streamed to the Host-PC. On the RT-PC, the image is encoded into a string of data and sent to the Host-PC through the TCP-IP protocol. A TCP-IP receiver is programmed on the Host-PC to collect the data string package. Once the data package is received, the string is decoded back into a visual image. An example image from the camera feed is presented in Figure 6.8. This figure shows the camera view during the E-Jet process. The nozzle comes in and out of the field of view of the camera during printing and therefore it is not possible to do real time visual monitoring of the entire printing process. The camera is only used to seek the voltage level at which a droplet is ejected from the nozzle. If the nozzle maintains the same standoff distance relative to the ground within the span of the XY stage, printing can be guaranteed.

![Figure 6.7 Voltage and Pressure Cluster to Control the E-Jet Printhead]

![Figure 6.8 Example Image from the Camera During E-Jet Printing]
6.1.4 Module 4: Web Handling Control

The LQR designed in Chapter 3 is used to perform the web handling control. Users can change the web position and tension directly from the GUI. However, for an online user interface application, where users can send command signals and monitor the sensor measurement in real time, the control design simulation module cannot be used. The feedback controller must be converted into a discrete time-step program running in a ‘while’ loop. Since the feedback controller is only a matrix multiplication of the feedback gain matrix, $K$, with the system states, $\mathbf{v}(k)$, it is relatively simple to implement this feedback controller. In the ‘while’ loop, the integral and the time derivative of the error can be computed using the trapezoidal rule (6.1) and backward difference (6.2) respectively, where $\Delta t = 0.0002s$ denotes the period of the ‘while’ loop. Figure 6.9 shows the input panel to adjust the web position and tension. The R2R system will control the web to track the reference commands R1 and R2 whenever the values are changed. The rate limiter of the reference signal is specified by the variable $dR1/dt$ and $dR2/dt$. The instantaneous position and tension of the web are displayed by the charts presented in Figure 6.10.

\[
\int_0^t f(ds)ds \rightarrow \sum_0^k \frac{f(k-1)+f(k)}{2} \Delta t \tag{6.1}
\]

\[
\frac{d}{dt} f(t) = \frac{f(k)-f(k-1)}{\Delta t} \tag{6.2}
\]
6.2 Printing Results on the R2R System

Prior to printing, alignment of the XY stage with respect to the ground plate must be ensured. The alignment is necessary to ensure consistent printing conditions and reduce any possibilities of the nozzle hitting the substrate. Figure 6.11 demonstrates the feasibility of the E-Jet printing process on the R2R system. The printed lines are equally spaced by 500 μm and intentionally made thick (500 μm width) such that the pattern can be macroscopically captured by a digital camera. The inset at the top left corner shows the lines as being viewed by the E-Jet camera. The pattern is printed using organic silver material (IJ-010, Inktec). In this figure, the Kapton web is 1 inch in width and 2 mil (~50 μm) in thickness.

Figure 6.11 E-Jet Printing on the R2R System

Printing with a 50 μm non-conductive material implies that the nozzle must be placed slightly higher than 50 μm above the ground plate. With a 30 μm standoff distance, the nominal E-Jet printing voltage is around 300 Volts. In the current setup, the tip of the nozzle is placed approximate 80-100 um above the ground plate and we require 600 Volts to generate a sufficient electric field for ejecting the droplet. The printing behavior is considerably altered compared to printing on a conductive substrate as the charge carried by the printed droplet does not decay immediately after hitting the ground. The
accumulation of charge induces undesirable printing behavior such as spraying, which may results in reduction of printing resolution. One way to minimize spraying on the substrate is by switching the polarity of the jetting voltage. The pattern in Figure 6.11 is E-Jet printed using the PWM mode with a base voltage of -600 V, a maximum voltage of +600 V, a period of 2 ms, a pulse width of 1 ms, and a back pressure is set to 1.5 psi. The XY stage uses a raster printing pattern at a rate of 2 mm/s and completed the pattern within 40 minutes. Using the same printing condition, a series of an arbitrarily shaped pattern can also be printed as shown in Figure 6.12. The result is generated using the aid of the G-Code generator presented in Figure 6.3.

![Figure 6.12 A Series of E-Jet Printed NanoCEMMS Logos on the R2R System](image)

Figure 6.12 A Series of E-Jet Printed NanoCEMMS Logos on the R2R System

Figure 6.13 shows a 2D array of E-Jet printed silver interconnects on the same Kapton substrate as Figure 6.11 and 6.12. The silver-interconnects are printed multiple times to ensure connectivity of the final sintered product. According to the microscope image presented in Figure 6.13, the width of the silver interconnects are approximately 18 µm. After 20 minutes sintering at 150°C most of the ink solvent evaporates, leaving traces of conductive silver interconnects behind. Out of the three measurements presented in 6.14, the results consistently suggest the resistance of the printed interconnects are approximately 45Ω. The conductivity of the silver interconnect is around $5 \times 10^4$ S/m (~0.25% of bulk silver) assuming a triangular cross section with a height of 100 nm. Although the conductivity is low, the printing condition and post processing of the printed pattern can be tuned to obtain a higher conductivity. The results presented in this chapter demonstrate both the flexibilities and functionalities of E-Jet printing on the R2R system.
Figure 6.13 2D Array of E-Jet Printed Silver Interconnects

![Image of 2D Array of E-Jet Printed Silver Interconnects]

Figure 6.14 Conductivity of the Silver Interconnects Presented in Figure 6.13

![Conductivity Measurement Graph]

- Measurement 1
- Measurement 2
- Measurement 3
Chapter 7
Conclusion

7.1 Summary of Research Contributions

This dissertation presents the development of a reconfigurable R2R system to study the potential of various micro/nano-manufacturing processes in a continuous or semi-continuous environment. In particular, this dissertation discusses the integration of an E-Jet Printer to the R2R system. Detailed descriptions of the mechanical and electronic design of the R2R system are presented in this thesis, along with the development of controls algorithm for handling the web in the longitudinal direction. The key contributions of this dissertation fall into two areas. First, the development of a vision based ILC algorithm to improve the position tracking and tension regulation of the web on the R2R system. Second, the adaptation of the E-Jet printing process from a batch to a semi-continuous process.

7.1.1 Vision Based ILC for a R2R System

A vision based ILC algorithm is implemented on the R2R system using a dual state feedback architecture to improve the positioning tracking performance of the web. In the context of a semi-continuous manufacturing process, each fabrication step is performed successively in multiple localized zones. As the substrate, or the web, traverses downstream in the process flow, proper registration of the pre-existing features is necessary prior to entering the next fabrication zone in order to accurately complement previous manufacturing steps. Non-collocated sensors, loss of traction between the web and the
roller, structural rigidity, and web deformation are several of many factors that may contribute to inaccurate feature registration. ILC with direct visual observation helps to circumvent the uncertainty of the feature location on the web by using direct measurement of the substrate registration as a feedback output. The effectiveness of the proposed algorithm is validated by the experimental results.

7.1.2 E-Jet Printing on the R2R System

The E-Jet printing process has shown a wide array of promising opportunities for various industrial applications including: printed electronics and biological sensing applications. However, E-Jet printing has only been performed to date on a rigid and conductive substrate. The results of thesis demonstrate that E-Jet printing can also be performed on a continuous, non-conductive, and flexible substrate material. As the throughput of E-Jet printing improves, the need for integrating this technology into a more continuous platform becomes apparent. Several patterns printed with organic silver material are presented to demonstrate flexibility and scalability of this high resolution additive manufacturing technology.

7.2 Future Work

This research work has many aspects yet to be explored with the underlying objective to manufacture functional devices involving two or more fabrication techniques, includes E-Jet printing. An incomplete list of future works are summarized in the following subsection.

7.2.1 Extension of the Vision Based ILC on the R2R System

In this thesis, the experimental validation of the proposed vision based ILC algorithm is performed by directing the camera normal to the web surface. However, the camera setup for higher throughput runs of E-Jet printing is typically oriented approximately 45 degrees relative to the substrate. Some challenges associated with the angled camera setup includes limited focused region and interpreting the actual position of the web using a projected image. The focusing issue requires a more sophisticated machine
vision algorithm to identify the features on the web. Additionally, the image acquired by
the CCD sensor is a projected image and thereby must be mapped accordingly to infer the
actual position of the web.

Additionally, the web handling control in this dissertation focuses on the
longitudinal direction only. In the current experimental setup, the web is carefully aligned
and, as a result, the features on the substrate’s fiduciary markers do not drift too much in
the lateral direction. It also helps that the experimental runs have been over relatively short
durations, preventing lateral error from accumulating. However, this idealized setup may
not reflect the actual setting in a realistic manufacturing environment. Therefore, it is
necessary to address the lateral web handling problem in conjunction with the proposed
vision based ILC algorithm discussed in this dissertation. A sketch of the problem
described above is presented in Figure 7.1.

![Figure 7.1 Schematic of Visual Control for Longitudinal and Lateral Direction](image)

**7.2.2 Development of New Classes of E-Jet Applications**

This dissertation demonstrates that E-Jet can be performed on transparent flexible
materials in addition to the previously demonstrated conductive silicon based substrates.
Applications of E-Jet printing on rigid conductive substrates revolve around printed
electronics and biological sensors. A transparent substrate, such as Kapton film, may be
used to transmit the light. It is therefore suitable for fabricating optical devices which can
manipulate the light photons. Some example optical devices which have been explored are
presented in Figure 7.2, including the E-Jet printed microlenses, diffraction grating, as
well as E-Jet printed quantum dots or dye for color altering application for blue LEDs.

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Figure 7.2 Various Novel E-Jet Printing Applications [41]

Overall, the results of this dissertation have opened up a large opportunity space for E-jet fabrication. It is hoped that the readers of this will be encouraged to leverage the work already performed and open up new opportunities for future fabrication on flexible substrates.
List of References


“High-resolution electrohydrodynamic jet printing.,” *Nat. Mater.*, vol. 6, no. 10, pp. 782–9, Oct. 2007.


block-copolymer films formed by electrohydrodynamic jet printing and self-


Appendix A : Electrical Wiring

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<td>Enc 0 Phase A+</td>
<td>14</td>
<td>A+</td>
</tr>
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<td>9</td>
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<td>Enc 0 Phase B+</td>
<td>15</td>
<td>B+</td>
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### B.7

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<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>COM</td>
<td>1</td>
<td>Ground</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Forward Limit</td>
<td>6</td>
<td>+End of Travel</td>
</tr>
<tr>
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<td>20</td>
<td>Reverse Limit</td>
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<td>-End of Travel</td>
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<tr>
<td>4</td>
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### B.8

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<th>Signal</th>
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<td>Drive Command</td>
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<td>ANA1+</td>
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<tr>
<td>2</td>
<td>31</td>
<td>Drive Command COM</td>
<td>2</td>
<td>ANA1-</td>
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<tr>
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<td>17</td>
<td>COM</td>
<td>3</td>
<td>0V</td>
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<tr>
<td>4</td>
<td>15</td>
<td>Digital Input 1</td>
<td>6</td>
<td>Fault</td>
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<tr>
<td>5</td>
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<td>Enc 0 Phase A-</td>
<td>9</td>
<td>A-</td>
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<td>6</td>
<td>29</td>
<td>Enc 0 Phase B-</td>
<td>10</td>
<td>B-</td>
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<td>7</td>
<td>33</td>
<td>Drive Enable</td>
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<td>Energize</td>
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<td>25</td>
<td>Enc 0 Phase A+</td>
<td>14</td>
<td>A+</td>
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<td>9</td>
<td>27</td>
<td>Enc 0 Phase B+</td>
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<td>B+</td>
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### B.9
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<th>Signal</th>
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<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>COM</td>
<td>1</td>
<td>Ground</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Forward Limit</td>
<td>6</td>
<td>+End of Travel</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>Reverse Limit</td>
<td>7</td>
<td>-End of Travel</td>
</tr>
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**B.10**

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<th>Signal</th>
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<td>1</td>
<td>P0</td>
<td>Digital Output</td>
<td>Digital Enable</td>
<td>Amp Input</td>
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**B.11**

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<th>Signal</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>AO0</td>
<td>Analog Output</td>
<td>Amp Input</td>
<td>Voltage Command</td>
</tr>
<tr>
<td>2</td>
<td>AO GND</td>
<td>Ground</td>
<td>Ground</td>
<td>Ground</td>
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**B.12**

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<th>Device 2 Pin #</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>AO1</td>
<td>Analog Output</td>
<td>S+</td>
<td>Voltage Command</td>
</tr>
<tr>
<td>2</td>
<td>AO GND</td>
<td>Ground</td>
<td>Ground</td>
<td>Ground</td>
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</table>

**B.13**

<table>
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<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X1</td>
<td>Power</td>
<td>X1</td>
<td>Power</td>
</tr>
<tr>
<td>2</td>
<td>X2</td>
<td>Feedback (Bundled)</td>
<td>X2</td>
<td>Feedback (Bundled)</td>
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**B.14**

90
<table>
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<tr>
<th>No.</th>
<th>Parker Motor Drive 1 (VIX 250AH)</th>
<th>Direction</th>
<th>E-Jet Voltage Amplifier</th>
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<td></td>
<td>D Sub 15 HD</td>
<td></td>
<td>D Sub 15 HD</td>
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<tr>
<td></td>
<td>Device 1 Pin #</td>
<td>Signal</td>
<td>Device 2 Pin</td>
</tr>
<tr>
<td>1</td>
<td>X1</td>
<td>Power</td>
<td>→</td>
</tr>
<tr>
<td>2</td>
<td>X2</td>
<td>Feedback (Bundled)</td>
<td>←</td>
</tr>
</tbody>
</table>
Appendix B: Axis Configuration

1. Drive Enable:
   - Output Type → Sinking, Active State → On, Safe State → Off
2. General Settings:
   - Type → Servo Drive Interface, Feedback Source → Encoder 0, Axis Enabled
3. Trajectory:
4. Move Complete Criteria → In Position
5. Spline → Cubic B Spline
6. Position Loop
   - Gains: Kp → 220, Kd → 4000, Ki → 1.2, ILim → 1000.000
   - Rates: Loop Rate → 0.05 ms, Update Period → 1, Derivative Sample Period → 2
   - Limits: 1000 Unit
   - Location: Run position loop on hardware
7. Limit Switches:
   - Forward Limit: Enable, Stop Mode → Don’t Stop, Input Type → Sourcing, Active State → Off
   - Reverse Limit: Enable, Stop Mode → Don’t Stop, Input Type → Sourcing, Active State → Off
   - Forward Limit: Disable, Stop Mode → Don’t Stop, Input Type → Sourcing, Active State → Off
8. Encoder:
   - Enc. 0: Units → Unit, Counts/Unit → 1, Encoder Velocity → 1000000 c/s, Active → All High
   - Enc. 1: Units → Unit, Counts/Unit → 1, Encoder Velocity → 10000000 c/s, Active → All High
9. Digital I/O
   - DI0 (DSUB Pin 4): Input Type → Sinking, Active State → Off
   - DI1 (DSUB Pin 8): Input Type → Sinking, Active State → Off
### Appendix C: Numerical Parameters

*Appendix C contains the numerical parameters of the R2R systems*

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Roller Index (i)</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$R_i$</td>
<td>${1,\ldots,5}, {8,\ldots,11}$</td>
<td>38.1E-3</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>${6,7}$</td>
<td>25.4E-3</td>
<td></td>
</tr>
<tr>
<td>$b_i$</td>
<td>${1,11}$</td>
<td>0.061</td>
<td>N.m.s</td>
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<tr>
<td></td>
<td>${2,\ldots,10}$</td>
<td>0.031</td>
<td></td>
</tr>
<tr>
<td>$J_i$</td>
<td>${1,11}$</td>
<td>0.0019</td>
<td>kg.m$^2$</td>
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<tr>
<td></td>
<td>${2,\ldots,10}$</td>
<td>0.0004</td>
<td>kg.m$^2$</td>
</tr>
<tr>
<td>$\kappa_r$</td>
<td>${1,11}$</td>
<td>0.327</td>
<td>N.m/V</td>
</tr>
</tbody>
</table>
Appendix D : Block Diagram

Figure D.1 Host PC Front Panel Interface
Figure D.2 Host PC Block Diagram
Figure D.3 Host PC Loop 1

Figure D.4 Host PC Loop 1, Event: Timeout

Figure D.5 Host PC Loop 1, Event: Motion Com Value Change
Figure D.6 Host PC Loop 1, Event: EJet Voltage Value Change

Figure D.7 Host PC Loop 1, Event: Reference Value Change

Figure D.8 Host PC Loop 1, Event: Stop Value Change
Figure D.9 Host PC Loop 1, Guard Clause

Figure D.10 Host PC Loop 2
Figure D.11 Host PC Loop 2, Case : Initialize

Figure D.12 Host PC Loop 2, Case : Update Motion

Figure D.13 Host PC Loop 2, Case : UpdateR2R
Figure D.14 Host PC Loop 2, Case: Update Voltage

Figure D.15 Host PC Loop 2, Case: Idle

Figure D.16 Host PC Loop 2, Case: Shutdown
Figure D.17 Host PC Loop 2, Guard Clause

Figure D.18 Host PC Loop 3

Figure D.19 Host PC Loop 3, Case: Initialize
Figure D.20 Host PC Loop 3, Case: Stream

Figure D.21 Host PC Loop 3, Case: Shutdown

Figure D.22 Host PC Loop 4
Figure D.23 Host PC Loop 4, Case : Initialize

Figure D.24 Host PC Loop 4, Case : Stream

Figure D.25 Host PC Loop 4, Case : Shutdown
Figure D.26 RT-PC Block Diagram
Figure D.27 RT-PC Loop 1 (Web Handling)

Figure D.28 RT-PC Loop 1 (Web Handling), Case: Initialize
Figure D.29 RT-PC Loop 1 (Web Handling), Case: Monitor

Figure D.30 RT-PC Loop 1 (Web Handling), Case: Shutdown

Figure D.31 RT-PC Loop 2 (Network Stream)
Figure D.32 RT-PC Loop 2 (Network Stream), Case: Initialize

Figure D.33 RT-PC Loop 2 (Network Stream), Case: Monitor

Figure D.34 RT-PC Loop 2 (Network Stream), Case: Shutdown
Figure D.35 RT-PC Loop 3 (Command Receive)

Figure D.36 RT-PC Loop 3 (Command Receive), Case : Initialize

Figure D.37 RT-PC Loop 3 (Command Receive), Case : Monitor
Figure D.38 RT-PC Loop 3 (Command Receive), Case : Shutdown

Figure D.39 RT-PC Loop 4 (Camera)

Figure D.40 RT-PC Loop 4 (Camera), Case : Initialize
Figure D.41 RT-PC Loop 4 (Camera), Case: Monitor

Figure D.42 RT-PC Loop 4 (Camera), Case: Shutdown
Figure D.43 cRIO Loop 1 (Command Drive)

Figure D.44 cRIO Loop 1 (Command Drive), Case: Initialize
Figure D.45 cRIO Loop 1 (Command Drive), Case: Enable Axis

Figure D.46 cRIO Loop 1 (Command Drive), Case: Monitor
Figure D.47 cRIO Loop 1 (Command Drive), Case : Jog X-

Figure D.48 cRIO Loop 1 (Command Drive), Case : Jog X+
Figure D.49 cRIO Loop 1 (Command Drive), Case: Home X

Figure D.50 cRIO Loop 1 (Command Drive), Case: Jog Y-
Figure D.51 cRIO Loop 1 (Command Drive), Case : Jog Y+

Figure D.52 cRIO Loop 1 (Command Drive), Case : Home Y
Figure D.53 cRIO Loop 1 (Command Drive), Case: Home All

Figure D.54 cRIO Loop 1 (Command Drive), Case: Origin
Figure D.55 cRIO Loop 1 (Command Drive), Case : Execute Program

Figure D.56 cRIO Loop 1 (Command Drive), Case : Calibrate
Figure D.57 cRIO Loop 1 (Command Drive), Case: Shutdown

Figure D.58 cRIO Loop 1 (Command Drive), Case: Reinitialize
Figure D.59 cRIO Loop 2 (Voltage Control)

Figure D.60 cRIO Loop 2 (Voltage Control), Case: Initialize

Figure D.61 cRIO Loop 2 (Voltage Control), Case: Monitor
Figure D.62 cRIO Loop 2 (Voltage Control), Case: Shutdown

Figure D.63 cRIO Loop 3 (Command Receive)
Figure D.64 cRIO Loop 3 (Command Receive), Case: Initialize

Figure D.65 cRIO Loop 3 (Command Receive), Case: Monitor
Figure D.66 cRIO Loop 3 (Command Receive), Case: Shutdown

Figure D.67 cRIO Loop 4 (Network Stream)
Figure D.68 cRIO Loop 4 (Network Stream), Case : Initialize

Figure D.69 cRIO Loop 4 (Network Stream), Case : Monitor

Figure D.70 cRIO Loop 4 (Network Stream), Case : Shutdown
Appendix E: LabVIEW SubVIs

Figure E.1 Calculate Speed.vi

Figure E.2 Deadband 1.vi
Figure E.3 Deadband 2.vi

Figure E.4 derivative.vi
Figure E.5 FC1.vi
Figure E.9 MIMO_Feedback.vi

Figure E.10 MIMO_LQR_TimeLoop.vi
Figure E.11 rateLimiter.vi

Figure E.12 SignalGenerator.vi

Figure E.13 imDecodeRT.vi
Figure E.14 Configure Camera.vi

Figure E.15 imageDecodeRT.vi
Figure E.16 openReadDAQArray.vi
Figure E.17 closeReadDaqArray.vi
This VI reads the sensor measurements from the Load Cell, Encoder 1, Encoder 2, Encoder 3.

Figure E.18 ReadDaqArray.vi
Figure E.19 WriteDaqArray.vi

Figure E.20 commandSelector.vi
Figure E.21 initializeProgram.vi

Figure E.22 mm2cts.vi

Figure E.23 motionHomeX.vi
Figure E.24 motionHomeY.vi

Figure E.25 motionCalibrate.vi
Figure E.26 motionCalibrate.vi, Case: Read Command

Figure E.27 motionCalibrate.vi, Case: Move Stage
Figure E.28 motionCalibrate.vi, Case: Measure Distance

Figure E.29 motionData.vi
Figure E.30 motionReadData.vi
Figure E.31 motionRunProgram.vi
Figure E.32 motionRunProgram.vi, Case : Read Command
Figure E.33 motionRunProgram.vi, Case : Enable Digital
Figure E.34 motionRunProgram.vi, Case : Dwell On
Figure E.35 motionRunProgram.vi, Case : Move Stage
Figure E.36 motionRunProgram.vi, Case: Disable Digital
Figure E.37 motionRunProgram.vi, Case : Dwell Off
Figure E.38 voltageGenerator.vi

Figure E.39 Shutdown.vi
The Encoder Resolution is 500 nm per count. The encoder tick is converted into mm.

Figure E.40 motionReadDataSimple.vi