Real-Time Process Measurement and Feedback Control for Exposure Controlled Projection Lithography

Xiayun Zhao, David W. Rosen*

George W. Woodruff School of Mechanical Engineering

Georgia Institute of Technology

Atlanta, Georgia, 30332

*Corresponding author. Tel.: +1 404 894 9668 Email: david.rosen@me.gatech.edu

Abstract

The Exposure Controlled Projection Lithography (ECPL) is an additive manufacturing process that can cure microscale photopolymer parts on a stationary substrate with patterned ultraviolet beams underneath. An in-situ interferometric curing monitoring and measuring (ICM&M) system is developed to measure the ECPL process output of cured height profile. This study develops a real-time feedback control system that utilizes the online ICM&M feedback for automatically and accurately cure a part of targeted height. The experimental results directly validate the ICM&M system's real-time capability in capturing the process dynamics and in sensing the process output, and evidently demonstrate the feedback control system's satisfactory performance in achieving the desired height despite the presence of ECPL process uncertainties, ICM&M noises, and computing interruptions. A comprehensive error analysis is reported, implying a promising submicron control with enhanced hardware. Generally, the study establishes a paradigm of improving additive manufacturing with a real-time closed-loop measurement and control system.

1. Introduction

Additive manufacturing (AM) refers to a wide range of manufacturing technologies, which are agile and high-valued for fabricating parts directly from a three-dimensional digital model [1]. It is poised to affect major industries such as aerospace, biomedical devices, and polymeric electronics in the world. However, the inspirational vision is not fully a reality yet due to several technical challenges, including challenges associated with the measurement of AM parts' dimensions and with the relationship between process parameters and parts' properties [2, 3]. A portfolio of research being undertaken will help overcome these challenges and fulfill the vision, leading to greater proliferation of AM technologies [4, 5].

Currently, a gap exists between high-fidelity modeling research and real-time process measurement and online control efforts. Given the research progress in metal AM [6-9], the modeling, metrology, and controls of polymer and soft materials AM are emerging as new research priorities for the monitored dimensional accuracy and materials and mechanics properties significantly affect the quality and performance of the final product [10]. The physics of polymers such as photopolymerization in additive lithography process and melting and recrystallization in plastic filament extrusion process are not adequately understood to develop robust mathematical models. Supercomputing can greatly impact such modeling efforts. Multi-physics complex process models need to be reduced to lower-order models for real-time parameter identification and control of AM processes [3]. For thermoplastic extrusion based AM, an in-situ infrared thermography method is developed to measure the temperature profiles of printed layers [11], which is a first step in the development of strategies to control and model the printing processes while the ultimate real-time control of part strength is not yet achieved. For photopolymer based AM processes, there is a scarcity of literature in real-time measurement and control; and this study could address such a research gap with the lab-built exposure controlled projection lithography (ECPL) system and the in-house interferometric monitoring and measurement (ICM&M) system as introduced below.

1.1 The plant - ECPL system

The ECPL system aims to deliver a series of timed and patterned UV light beams into the resin chamber where photopolymerization occurs to form 3D object [12]. The UV light routes successively from the UV light source thru the beam conditioning system, the dynamic mask generator – digital micromirror device (DMD), and the projection system, to the resin chamber. The UV lamp is Omnicure S2000 UV curing system produced by Lumen Dynamics, and produces UV radiation at wavelength of 365nm which initiates crosslinking for the selected material of photo initiators and monomers. The beam conditioning system consists of several different diffusers and collimating lenses arranged as to best produce a collimated and homogeneous incident radiation on the dynamic mask generator. The dynamic mask generator consisted of a Texas Instruments' Digital Micromirror Device (DMD) where the "ON" micromirrors direct light vertically upwards into the resin chamber and the "OFF" micromirrors reflect light off the working path. The either "ON" or "OFF" state for a single micromirror corresponds to an individual pixel in the binary bitmap (size 1024×768) displayed on the DMD, which is connected to the computer as a secondary monitor. The purpose of the projection system is to focus the incident radiation from the DMD into the resin chamber. The resin chamber consisted of two glass slides separated by spacers of known thickness - 200 µm. The photopolymer resin is loaded between the two glass slides, which allows the inner resin to get cured with minimal oxygen inhibition. Inside this resin chamber, when exposed to UV radiation, photopolymer resin would crosslink to form a solid part that could grow as continuing radiation passes from beneath the solid polymer into the upper uncured monomer. The dynamic mask and exposure time determine both the shape and height of the part. After exposure is complete the build chamber is removed and washed as to remove all uncured monomer. The cured part is then post-cured in a bath of UV light as to further cross-link the part and strengthen it.

1.2 The sensor - ICM&M system

The ICM&M system has been developed to detect the height of photopolymer part produced by the ECPL process [13-15]. It is based on a Mach-Zehnder interferometer [16]. A coherent laser shines through a beam expander, moveable iris, and beam splitter, onto the resin chamber. Light reflecting off the resin chamber penetrates through the beam splitter and into the camera. Due to the optical path differences between the light beams reflected from different interface surfaces, an interference pattern is observed by the camera which records the intensity dynamics across the illuminated chamber area.

Detailed discussions of the sensor model and algorithms can be found in the authors' previous publications [13, 14]. The experimental results from an offline implementation of the ICM&M method on a series of online acquired interferogram data show that the system has evident potentiality to track in real time the changes in height profile with different exposure durations and exposure intensities [15].

1.3 Implementation software

For ECPL process operation, measurement and control, a software is needed to interface the hardware equipment including the UV lamp, DMD and CCD camera. Particularly, implementing the ICM&M method in real time requires a high-performance software that handles data acquisition and analysis for measurement as well as performs decision making and actuation for control purpose. Therefore, a parallel computing software was developed in MATLAB with real-time acquisition in the foreground and online measurement running in the background [17].

1.4 Motivation

As the ICM&M system can capture the real-time curing dynamics, online monitoring and control of a part's growth from the onset of solidification to the end of dark reaction is enabled. This study is aimed to implement and validate further the previously developed ICM&M system in a real-time fashion, as well as to develop a real-time system for controlling the ECPL process output of cured part's height (i.e., thickness). An overview of the system under investigation is shown in Fig. 1. The study could provide a paradigm for improving photopolymerization based additive manufacturing processes (e.g., mask-projection stereolithography) with closed-loop control strategies.

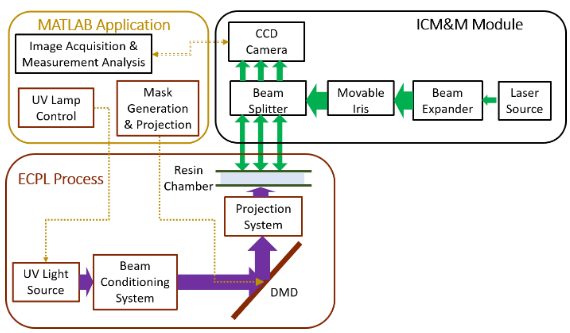

Fig. 1. The integrated ECPL system: ECPL process, ICM&M module, and MATLAB software for ECPL M&C

2. Design of a closed-loop controller

This section designs a negative feedback On-Off scheme for controlling the part growth in real-time during the ECPL process.

2.1 The control scope

The ECPL process is a complex nonlinear system and there could be multiple control actions including manipulating the resin composition, temperature, UV exposure time, exposure intensity and exposure pattern for curing a target 3D object. In this preliminary study of real-time measurement feedback control, to simplify the multi-input control problem, a basic exposure time controller is designed to understand the real-time controllability of the vertical dimension, i.e., cured height in the ECPL process. Manipulating other process factors, especially the chemical components (e.g. initiators, and oxygen inhibitors), exposure intensity and pattern, could be conceived in future work to complement the outcomes of these exposure time control for multiple output of desired properties such as lateral dimensions and mechanical properties.

2.2 The control mode

As a preliminary controller with ICM&M feedback, the ECPL exposure time controller under investigation involves some discrete switching concept which is a fundamental control method of On-Off control [18]. In control theory, an On–Off controller is a discontinuous feedback controller that switches abruptly between two states [19]. Such a control mode is easier to implement but expects some process tolerance or deviation. A typical example of On-Off controller is a thermostat which senses the temperature and maintains it near a desired set point by switching the heater on and off.

Similarly, with the ICM&M system available online, an On-Off control mode is designed to determine when to shut down the UV lamp for controlling the height of ECPL cured part. The On-Off controller employs a negative feedback to correct errors between the measured height and target height; thereby, when the cured height approaches the reference value, the UV lamp is switched off to terminate the curing.

2.3 The actuator

For controlling the ECPL process, the exposure source UV lamp that allows for control of overall exposure intensity across the chamber, and the pattern generator DMD that comprises an array of micromirrors to deliver spatial control of exposure intensity, could both be adopted as actuators. In this basic controller design, only the UV lamp is used to control the exposure for curing blocks in the upcoming validation experiments. The UV lamp could be either completely on or completely off. Please note that the UV lamp is equipped with an iris which could provide discrete percentage levels from 0% to 100% in an increment of 1% that fine tunes the exposure intensity. In this study of On-Off controller, only the two extreme limits of UV lamp shutter – fully on and fully off- are employed; and in the future design for more advanced control methods, the full range of UV source intensities along with the DMD could be utilized for more control flexibility and capability. In the On-Off control for ECPL process, given a constant UV iris level and a fixed DMD bitmap, the input of UV light is a step function as shown in Fig. 2.

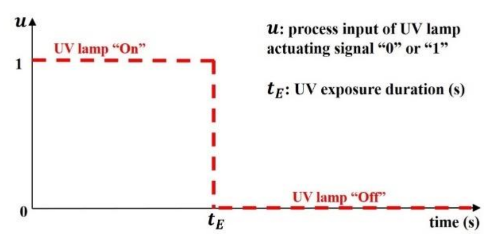

Fig. 2. On-Off control input in the ECPL process

2.4 The control scheme

2.4.1 Compensator

A real-time monitoring of UV curing reaction rates of some stereolithography resin using a reflectance infrared spectrometry technique, revealed a significant additional conversion of reactive groups as the so-called dark curing, a post-irradiation polymerization process after termination of exposure [20]. Similarly, dark curing is expected in the ECPL process and cannot be neglected with the experimental materials in this study.

In the ECPL On-Off control strategy, the inherent dark curing could introduce near the set point of the target total height a significant deadband, where no control actions are available to regulate the cured height after switching off the UV lamp. Consequently, the part of dark curing is uncontrollable by the simple On-Off feedback controller, and should be accounted for upfront by a compensator which is aimed to reduce the cured height error attributed to dark curing. It is difficult to provide a kinetic model of the effects of dark curing. For simplification, in this study, to quantify the contribution of dark cured height (z_{Dark}), it is assumed that dark cured height is linearly dependent on the exposed cured height and thus on the total cured height (z_{Total}), with a constant ratio $r_{D/T}$ as shown in Equation (1). The ratio value $r_{D/T}$ could be identified experimentally with the specific material used in the process.

$$r_{D/T} = \frac{z_{Dark}}{z_{Total}} \quad (1)$$

In a previous study for ICM&M validation, experiments were conducted to cure multiple samples [15], and the ICM&M method was applied off line to measure the dark cured height and total cured height of the 24 samples. Histograms of the resultant ratios show that the average ratio of dark cured height to total height is around 9.75%, similar to some literature [21] which reports that the dark reaction contributes to about 10% conversion of monomer at the locus where irradiation is received. Therefore, the lumped percentage of dark curing in the entire ECPL curing ($r_{D/T}$) was estimated to be 10% which is to be used in the compensation for the part of dark curing in the real-time On-Off control experiments.

Provided a set point (z_s) of desired total cured height of a target 3D part, the compensator estimates by Equation (2) a reference value, which will be input to the succeeding feedback controller serving as a trigger point (z_t) for switching the UV lamp.

$$z_t = z_s \times (1 - r_{D/T}) \quad (2)$$

2.4.2 Feedback controller

The closed-loop feedback controller is a key component in the On-Off control system. It compares the measured height z_m (feedback from the ICM&M system) with the reference value z_t (derived from the compensator), and calculates the difference as shown in Equation (3) for an error signal z_e.

$$z_e = z_m - z_t \quad (3)$$

The delays in measurement and control are especially subject to stochastic computing environment factors and more difficult to predict compared with the actuation delay that is easier to characterize. Experiments can be conducted to quantify the actuation delay, and a statistical mean value of repeated experiments is used to estimate the actuation delay τ_{act} in the controller. To unveil the system's full potentiality, with a forward-looking assumption that the delays in measurement and control would become insignificant in a future enhanced system, only the relatively predictable and physically inevitable delay in the actuation is addressed in the feedback controller design. Consequently, the measurement latency and control delay is not specifically accounted for in this initial controller design but considered in the error analysis (Sections 4.2 and 4.4).

The actuation delay can lead to a deadband in the controller, referred in the ECPL process as a tolerance of controlled height. The controller is supposed to shut down the UV lamp when the feedback error hits the non-zero tolerance rather than exactly zero so that the extended light curing due to the delay would bring the feedback error down to around zero. Therefore, the height control tolerance z_{tol} is estimated as one half of the over-cured height caused by the delayed termination of the UV exposure using the method of linear interpolation as shown in Equation (4). The symbol z_{cycle} denotes the cured height per oscillating cycle in the ICM&M detected time sequence of interferogram grayscales at the measured pixel, and its value has been characterized to be approximately12 µm [15]. $T_{Process}$ is the period of the interferogram intensity signal at the end of illuminated curing process, and is dependent on both the exposure time and intensity. In this study, a rough average value of $T_{Process} \approx 5s$ could be used for estimating the controller tolerance. With an empirical value of $\tau_{act} \approx 0.4s$, z_{tol} is estimated to be 0.5 µm which is used in the real-time measurement and control experiments reported in this study.

$$z_{tol} \approx \frac{1}{2} \times \left(z_{cycle} \times \frac{\tau_{act}}{T_{Process}} \right) \quad (4)$$

With a proper setting of the tolerance z_{tol}, the controller algorithm for updating online the ECPL process input (u) of UV lamp actuating signal is developed in Equation (5). Via switching off the UV lamp at an optimal time point decided by the algorithm, the controller is aimed to bring the final process output as close to the set point as possible.

$$u = \begin{cases} 1 \ (\text{"}On\text{"}), & -z_e > z_{tol} \\ 0 \ (\text{"}Off\text{"}), & -z_e \leq z_{tol} \end{cases} \quad (5)$$

2.4.3 Overall control system

As summarized in Fig. 3, a real-time monitoring and control system for the ECPL process output of cured height is developed based on the classical feedback control theory [22]. The block diagram illustrates the control scheme with signals (shown as red symbols), control logic (shown as blue equations) and interpretations. The set point z_s means the desired total cured height, while the trigger point z_t means the reference value of cured height at which a control signal of cutting off the UV exposure is sent. It is noted that the trigger point flags the impending end (not immediate end due to the actuation delay τ_{act}) of exposed curing stage, only which the feedback controller can intervene. As explained previously, the feedback control loop cannot manipulate the dark curing stage, which is therefore compensated for in the pre-compensation instead. The developed in-situ ICM&M system is used to sense the cured height in real time. With the measured information of cured height z_m under UV exposure, an On-Off feedback controller with a deadband of height tolerance z_{tol} is used to determine the optimal time when to terminate illuminating the workpiece on the building platform.

Please note that $r_{D/T}$ is tunable in the controller setting for better control accuracy if an empirical ratio obtained from the model in Equation (1) turns out to be inadequate. Another adjustable parameter in the controller is z_{tol}, whose value is anticipated to vary with process as estimated by Equation (4).

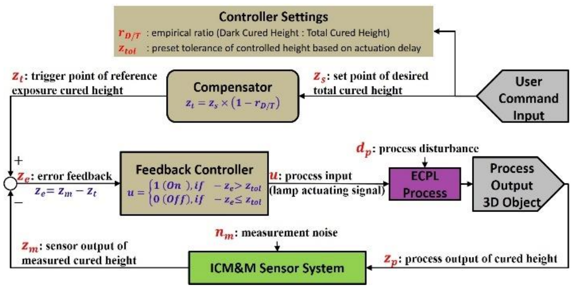

Fig. 3. Scheme diagram of feedback control for real-time cured height in ECPL process

3. Experiment design for real-time ECPL process measurement and control

Theoretically, one could deploy the software onto the physical system, conduct an in-process measurement of the height profile for an entire region of interest, and simultaneously apply online a control method with the accessible measurement result to cure a part with desired height. The ideal approach of real-time implementation of ECPL process feedback control demands prohibitively large computing memory and fast computing speed, to synchronize the ICM&M analysis with the real-time interferogram data acquisition, as well as to realize timely hardware (i.e., the UV lamp in the ECPL system) responses to the feedback control algorithm with minimal delay. In general, a reliably fast measurement and actuation for real-time process control would be computationally expensive.

Given the restricted computing resource, only a limited number of pixels can be measured online as a demonstration of the ICM&M method's qualification as a real-time process metrology. A fast curing process can sustain an online measuring for one pixel, which does not demand much computation time. In a slow curing process, a relatively long measurement interval would not affect the measurement accuracy significantly, and could support a multi-pixel measurement without hindering the software thread for acquisition. Ideally, a multi-pixel measurement is preferable, since it is more robust and more representative in the estimation of cured height than one single pixel is. With the current system and software, in a slow curing process, three pixels could be measured online simultaneously between two consecutive measurements without causing severe latency between the ICM&M acquisition and analysis. In the designed experiments, in addition to measuring and controlling a normal ECPL process under a moderate exposure intensity, another set of experiments with a relatively slow process is planned, altogether, to demonstrate the ICM&M method's potentiality in real-time measurement both locally and globally, as well as to validate the On-Off control method's capability of controlling the process with different set points and different dynamics (e.g., curing speed).

Another consideration in the experiment design is to relax the constraint of measurement latency which could be well unleashed in a high-performance computing system, to provide a fairer and truer evaluation of the developed real-time system's performance. Because of the observation that severe measurement latency occurs at the onset of ICM&M and lasts for a while before settling down to an acceptable level, in this study, a target height is selected to be sufficiently large so that its required exposure time could overcome the troublesome window of high measurement latency. The chosen target height is expected to take the process to where the thread of measurement and control analysis could catch up with that of data acquisition, thereby the assumption of negligible ICM&M latency in the controller design (Section 2.4.2) can be justified.

Specifically, in this study, two groups of experiments, with different exposure intensities corresponding to different UV iris levels at 22% and 5%, respectively, are designed to demonstrate the capability of the developed methodology of real-time measurement and control for the ECPL process. It has been found that the curing process under lower-intensity exposure is slower [15], therefore, an ECPL process at 22% UV iris level is adopted for the first group of experiments (denoted as "normal process"), and the 5% UV iris level is used in the second group of experiments (referred to as "slow process"). In each single run of experiment, under a constant UV exposure intensity (i.e., fixed UV iris level), a square bitmap of 250×250 pixels is displayed on the DMD to cure a flat-top block of desired height. The target height is set to be 80 µm in the "normal process" experiment and 40 µm in the "slow process" experiment. The ICM&M method and the On-Off feedback controller are applied in unison to measure and control the cured height in real time. An ex-situ confocal laser microscope is used to measure the cured part for obtaining the actual process output of cured height. The designed experiments are as shown in Table 1 with the varying factors accentuated.

Table 1. Experimental design for real-time ECPL process measurement and control

		Experiment Groups		
		Group #1: Normal Process	**Group #2: Slow Process**	
			Subset #1	**Subset #2**
ECPL Process Conditions	**Exposure Intensity (UV Iris level)**	**22%**	**5%**	**5%**
	Exposure Pattern Bitmap Size (Pixels × Pixels)	250×250	250×250	250×250
ICM&M Settings	**Measurement Interval (Frames/Run)**	10	10	**30**
	Number of Pixels Measured Real Time	1	1	**3**
Controller Settings	**Set Point of Target Height z_s**	**80 µm**	**40 µm**	**40 µm**
	Ratio of Dark and Total Cured Heights $\gamma_{D/T}$	0.1	0.1	0.1
	Tolerance of Controlled Height z_{tol}	0.5 µm	0.5 µm	0.5 µm

4. Experiment results and discussion

The study reports result for six samples in Group #1, six samples in Group #2 Subset #1 and four samples in Group #2 Subset #2.

Offline measurements for these samples, including a commercial confocal microscope measurement of the real cured parts and an offline ICM&M analysis of the real-time acquired interferogram videos, are presented in the reference [17].

4.1 Real-time in-process measurement

To test the performance of the ICM&M method in real time measurement for the ECPL process, one representative pixel is measured online in Experiment Group #1 and in the first subset of Experiment Group #2. To further demonstrate the measurement capability and to investigate the effect of online sampling bias, more than one pixels (i.e., three pixels due to the limited computation power) are measured and a robust average of the multiple measurements is used as the final measurement online in the second subset of Experiment Group #2.

A summary of the real-time measurement results, particularly for the exposure height and total height measured online, are displayed in the reference [17].

In this study, the real-time ICM&M error, defined as the deviation between the real-time ICM&M and microscope results, is broken down into two independent parts as below.

(1) The first part is real-time measurement bias, which is estimated as the deviation between the real-time sampled and the offline ICM&M measured population results. Comparing with the offline ICM&M implementation which can measure a significantly more pixels (i.e., 729 pixels in Group #1 and 441 pixels in Group #2) and to deploy more robust algorithms that require data from more pixels, the real-time ICM&M results obtained from a limited spatial sampling of only one or three pixels due to computation constraints, is prone to misrepresent the overall population height thereby causing a measurement bias.

(2) The second part is the ICM&M system error, which is estimated as the deviation between the offline ICM&M and microscope results. The offline ICM&M results is more comparable with the microscope in terms of average and standard deviation across the entire cured part and could reveal better the inherent error of the ICM&M method (including the error due to the calibration error and the refractive index modeling inaccuracy) as discussed in the authors' previous paper [15]. Please note that, since the microscope cannot measure out the exposure height, for estimating the ICM&M system error in measuring the exposure height, a value of 90% (approximated ratio of exposure height to total height) of the deviation in measured total heights is used for process control error analysis in Section 4.4 (Table 2).

In addition to online sampling bias, low signal-to-noise ratio (SNR) of the online measured pixel's time sequence of grayscales is another significant error source in real-time measurement. Notably, the noise is especially evident in the slow process (Group #2) that employs a low exposure intensity [17]. For example, as shown in reference [17], Sample 5 in Group #2 Subset#1 displays a quite flat data curve of low SNR and results in the worst estimation of exposure height among all the samples in both Group #1 and Group #2. Also, as shown in the reference [17], Sample 4 in Subset#2 presents obvious misleading cycles in the supposed-to-be resting period, and results in the largest error in Group #2 between real-time and offline measured total heights.

To conclude from the real-time measurements of both the normal and slow ECPL processes, it is anticipated based on the worst-case scenario that with the current real-time ICM&M system at least 50% ECPL parts could be measured accurately for exposure height and for total height. The real-time measurement errors stem primarily from the measurement bias due to the limited spatial sampling, from the real-time data's low SNR (especially in the case of slow processes), and from the inability to perform the robust ICM&M method [17] due to real-time computation limits. In the future, the real-time measurement error due to the limited and unknowingly biased ROI could be solved by selecting a more representative and complete set of ROI provided that more computation power is available. Also, the real-time measurement accuracy could be further improved with better quality data from a better camera.

4.2 Real-time feedback control for exposure height

As the real-time ECPL process measurement by the ICM&M method being examined above, another key issue is to evaluate the feedback control accuracy in the closed loop as shown in Fig. 3.

4.2.1 System delays

As is common for real-time measurement and control systems [23], there exist in the ECPL On-Off feedback control system considerable delays in measurement, in feedback control and in actuation, primarily due to the racing of multithreads in the parallel computing and in a real-time-unguaranteed operating system. The measurement latency resides between real-time acquisition and online analysis in the ICM&M system. The feedback control delay refers to various delays in the controller, including (1) the missed sensing of the target trigger point due to discrete measurement, especially a significantly long measurement interval; (2) the sensor-to-controller time lapse for transmitting measurement result; and (3) the controller time for implementing control algorithms. The actuation delay τ_{act} includes (1) the controller-to-actuator time delay for transferring the control signal; and (2) the actuator delay in mechanically operating the UV lamp.

With the real-time measurement of one pixel for curing at 22% UV iris level or of three pixels for curing at 5% UV iris level, the average image acquisition speed shows a similar rate about 18 frames per second, in other words, the average acquisition interval is 55ms per frame consistently in the experiments. Therefore, Group 2.2 (Group #2 Subset #2) which conduct measurement every 30 frames has a longer measurement interval of approximately 1.68s, compared with other experiments which conduct measurement every 10 frames corresponding to an interval of 0.55s. Delays in the real-time process measurement and control experiments are displayed in Fig. 4 (detailed values are listed in the reference [17]). The measurement latency tends to be smaller for the slower process in Group #2 compared with that in Group #1. In the experiments which have a measurement interval of 0.55 s for measuring only one pixel online (Group #1 and Group #2 Subset #1), the control delay due to the transmission and controller computation dominates. In the experiments with a triple interval to enable measuring multiple pixels (Group #2 Subset #2), the control delay due to missed detection by the discrete measurement or the measurement interval effect is more significant, while the other part of control delay is negilibly small because the long measurement interval allows abundant time for transmitting the feedback signal as well as for performing the control algorithm.

Real-time measurement with longer measurement interval is prone to postpone detecting the measurement and delaying the control. Regardless of the process speed, sufficiently fast measurement and fast computation is demanded to detect process deviation so that exposure time and intensity adjustment can be done to rectify the problem in a timely manner [24]. Computing power limitation is the root cause for the delays and should be addressed to unleash the potentiality of the real-time control system.

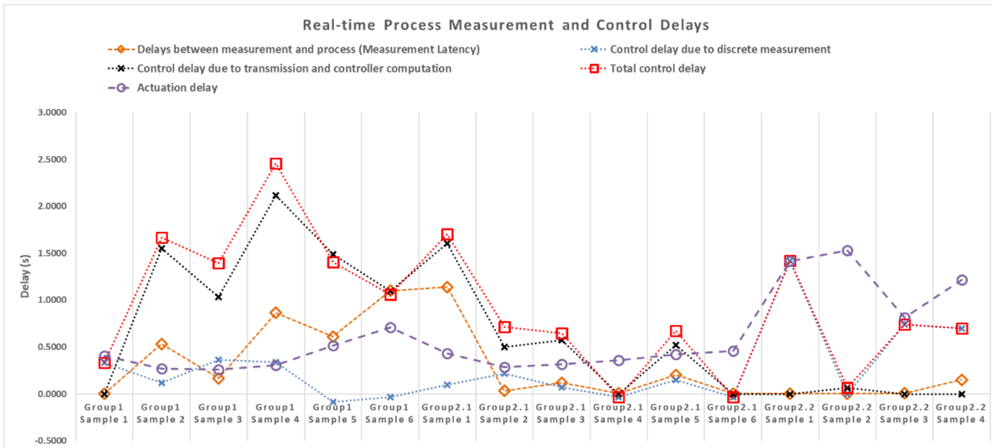

Fig. 4. Delays in the real-time process measurement and control experiments

4.2.2 Results of exposure height control

Frequently, it makes more sense to describe the performance objective in terms of measurement rather than the process output, since often the only knowledge of process output is obtained from the online measurement [22]. The On-Off feedback control loop's performance should be fairly evaluated by assuming that the target exposure height is accurately provided by the leading compensator and that the real-time measurement is accurate. Please note that the errors in the compensator and online measurement will be incorporated into a comprehensive analysis later in Section 4.4. Therefore, to evaluate purely the feedback control ability in presence of measurement noise and process disturbance within the time interval of UV exposure, the online measurement at triggering time point is compared against the provided reference point. Results are plotted in Fig. 5 and Fig. 6 for Group #1 and Group #2, respectively. Generally speaking, the normal process shows larger errors in exposure height control than the slow process does, which is understandable as the slow process is less sensitive to process delays. The observed deviation reflects the error in the feedback control for exposure height, which is accounted by the feedback control delay as shown in Fig. 4. For each sample in the two groups of experiments, the estimation result of the over-cured height due to the feedback control delay matches well with and accounts for the deviation observed in Fig. 5 and Fig. 6.

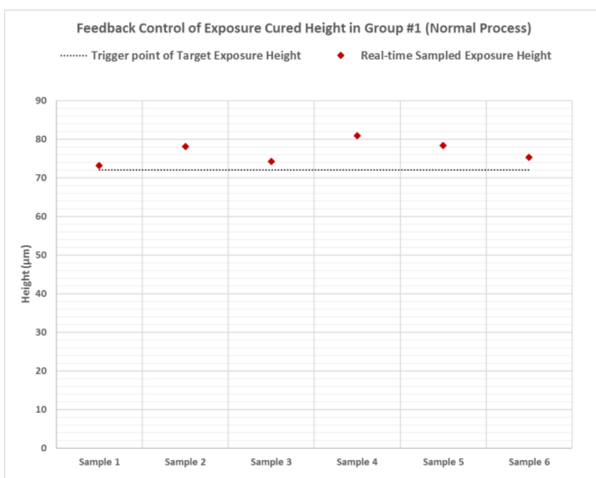

Fig. 5. Real-time feedback control results for exposure height in the real-time measurement and control experiments Group #1

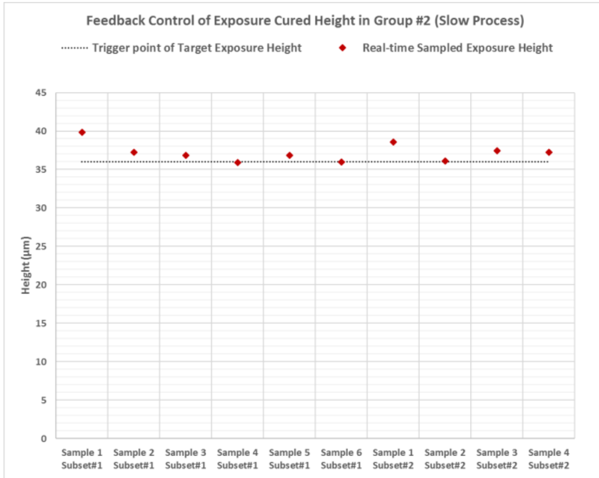

Fig. 6. Real-time feedback control results for exposure height in the real-time measurement and control experiments Group #2

4.3 Real-time overall control for total height

As presented in Fig. 3, the overall process control system consists of two parts – the pre-compensation for dark height and the On-Off feedback control for exposure height. The most direct and desired metric for the entire control system's performance is to check whether the process output approximates the set point of target total height in the presence of measurement errors and uncertainty due to process distrubance and measurement noise.

Therefore, to evaluate the overall control ability (including both the compensator and feedback controller) with the uncertainties and noises in both the ECPL process and the ICM&M sensor, the ultimate error for total height control is estimated by comparing the process output that is measured by an ex-situ microscope against the setpoint of desired total height. Results are plotted in Fig. 7 and Fig. 8 for Group #1 and Group #2, respectively. In the normal process measurement and control (Group #1), the setpoint of total height falls in the range of the actual height profile measured by the microscope for each of the 6 samples, and the errors are all below 4 µm (i.e., the relatively errors are all under 5%). In the second group of slow process control, 7 out of 10 samples have a deviation from the measured average height less than 4 µm. Main reasons for less control accuracy in the slow process measurement and control include larger measurement interval and notably lower SNR in the grayscale data. Especially, the worst sample - Sample 5 in Group #2 Subset #1, is completely off the spread of the measured height and has the biggest error of (-6.71) µm, which is caused by the real-time measurement error due to poor data quality and measurement bias (as explained in Section 4.1). Moreover, Sample 1 in Group #2.1 has the second largest error of 5.05 µm which is attributed to the feedback control delay induced by the measurement interval effect. A comprehensive analysis for the final process output of cured height is performed in Section 4.4 and presented in Table 2.

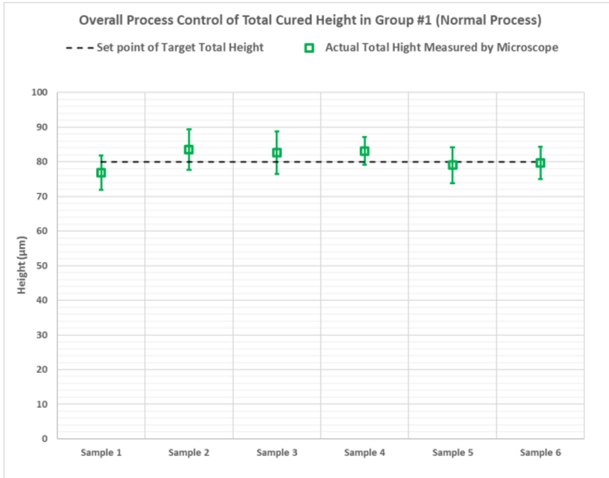

Fig. 7. Overall process control results for the parts cured in the real-time measurement and control experiments Group #1

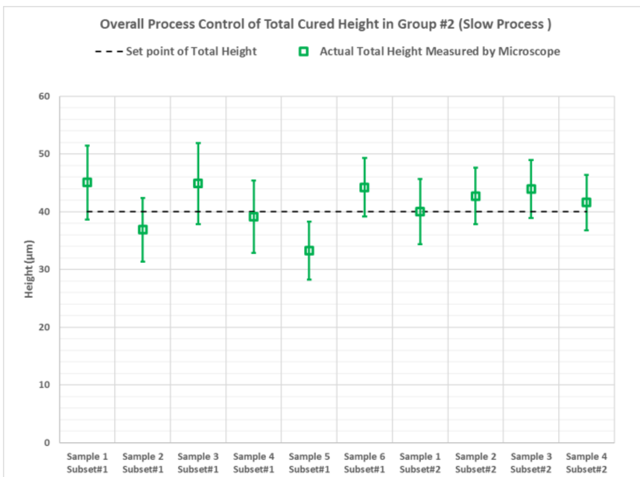

Fig. 8. Overall process control results for the parts cured in the real-time measurement and control experiments Group #2

It is noted that the integrated system of measurement and control achieves good repeatibility at maintaining the process output around the target setpoint, despite process variations in each individual experiment. As is shown in reference [17], the process dynamics reflected by the time sequence of grayscales of the online measured pixels exhibit vivid differences among the repeated experiments in the same group. Moreover, the latency and system delays also vary from run to run of experiment as shown in Fig. 4. Therefore, obvious part-to-part and batch-to-batch variations are observed in the real process, due to possible exposure non-uniformity and fluctuation, materials variation, process uncertainties (especially dark curing), ICM&M system error and data noise, and computation instability. Nevertheless, the measurement and control system is proven to perform well in the presense of disturbances and uncertainties, being capable of tracking the process dynamics, and manipulating the input accordingly to obtain a desired output.

4.4 Error analysis

In the developed real-time measurement and control system for the ECPL process, the ultimate error in total height is broken down into two parts: error in exposure height and error in dark height. The former is attributed to two main categories of causes: real-time measurement error and system delays, while the latter is caused by inaccurate compensation. A comprehensive set of error sources includes totally six factors as mentioned above, and the estimations of the corresponding errors are summarized in Table 2.

Given the independent error sources of bias in online sampling, system error in ICM&M method, latency in real-time measurement, delays in real-time control and actuation, and uncertainty in the dark curing, the method of multiple linear regression is employed for error analysis about the system. In the multiple linear regression, predictors are the six types of errors identifed and estimated above (as shown in Column 2 – Column 7 in Table 2), and the response is the actual error in total height; thus the regression coefficients are computed by a function of "regress" in MATLAB [25].

Results of the multiple regression analysis of the error sources in the entire process measurement and control system are shown in Table 2. Table 2 shows the breakdown analysis for the overall error with all the six error sources in the process measurement and control system, presents their contributions in the form of "weight" which is the coefficient of corresponding type of error in the multiple regression error model, and illustrates how these factors interplay to output the ultimate error.

The coefficients of the multiple regression indicate how influential the corresponding error source is in the resultant error; hence the larger the absolute value of the weight, the more deviation the source could cause in the final output of total height. It is found that the most significant error sources are real-time measurement bias due to limited spatial sampling and data noises, ICM&M error, feedback control delay, and compensation for dark curing. It is noted that all the measurement related sources (measurement bias, ICM&M error, measurement latency) have negative weights, which is anticipated in a negative feedback control system. The actuation delay has the least weight, which makes sense as the control system is designed with a "height tolerance" (Fig. 3) to at least partially (if not fully) account for its potential effect of introducing a deadband (Section 2.4.3). The measurement latency turns out to have a small weight of -0.13, which is justified by the intentional target height that is chosen to be big enough to achieve a better synchronization between the acquisiton and the analysis loops as introduced in the design of experiments. It is reasonble to think that with sufficient computation power, the developed system can output arbitrary target height that falls in the measurement range (experimentally verified range is 0 to at least 200 μm) of the current ICM&M system with accuracy and precision.

To verify the error model for the cured height with the weighted error sources, the fitted error and residual are calculated as shown in the two rightmost columns in Table 2. It indicates that various possible error sources have been well identified and understood. With this understanding and appropriate improvements in hardware, it is conceivable that the real-time control method with the aid of the developed ICM&M system could achieve a sub-micron control accuracy. Furthermore, the close to zero residuals for all the samples demonstrate vividly that the error analysis is accuracte and adequate with all possible sources incorporated; hence, implications for the significant error sources can bolster the upcoming discussion and recommendation for future improvement.

5. Future work

The experiment results and ultimate error analysis provide a thorough and detailed investigation about the capabilities and limitations in the current real-time measurement and control system for the ECPL process, shedding light onto research directions for improving the system. Future research effort is aimed to solve the real-time measurement bias and system delays by boosting the computing software and hardware, to improve the ICM&M system by better calibration, and to address the compensation by modeling the process (especially the dark curing part) more accurately, so that the current process control error of 5% is anticipated to be reduced further. This section elaborates on some methods for improving the control accuracy.

5.1 A predictive On-Off feedback control to address discrete measurement issue

Due to the possible ICM&M sensing failure or communication problem or long measurement interval, the discrete measurement effect is pronounced in the feedback control delay. There is a need to introduce the concept of "timeout" from a control perspective [23]. As it is not always beneficial to wait for a new measurement before doing control, a controller that uses a timeout can be designed to stop the exposure upfront when the predicted height would reach the target before the arrival of next measurement. Furthermore, a process equipped with the On-Off control will constantly overshoot its setpoint [19]. It is recommended to combine a predictive control with the feedback control to manipulate the input around the reference point.

Specifically, in the EPCL process control, the "timeout" is defined as an automatic upfront cessation of exposure before a new measurement is available, when the remaining exposure time for reaching the target height predicted at the current measurement time point is smaller than one measurement period. The key problem is to determine how long the residual exposure is before a timeout should be executed in-between the two measurements.

Therefore, one can augment the existing design of the On-Off feedback controller with a predictive model which can determine online when a timeout is needed. An evolutionary cycle-to-cycle (EC2C) controller was designed, and a linear predictive model with online adaptively estimated parameters was developed to predict the remaining exposure time [26]. The timeout is decided to be activated at the end of a predicted under-one-measurement-period residual exposure time, which is calculated by the predictive model using exponentially weighted historic measurement data. The simulation study of the designed EC2C demonstrated that performance in the ECPL process closed-loop measurement, and control can be increased by use of timeout [26]. The described methodology can be extended to other layer-by-layer additive manufacturing process feedback control.

5.2 Control dark curing in the ECPL process

In this study, as introduced in Section 2.4.1, the compensator adopts an empirical process model that assumes a constant ratio of dark height to total height (0.1 in the experiments) to determine the reference point for the feedback controller. An inadequate or excessive compensation would be a significant error source in the ECPL process control for the final cured part accuracy, as demonstrated in the error analysis in Section 4.4. As dark curing is shown to present disturbing uncertainties and errors in the ECPL process control, in order to improve the process model thus the compensation accuracy, alternative effective control strategy for dark curing could be considered in future development of more advanced control system for the ECPL process.

The speed of the dark reaction depends on the sensitivity of the photopolymer, which can be controlled by factors such as the materials of monomer and matrix [27, 28]. The dark curing in photopolymerization process could be reduced by rapid oxygen-scavenging of radicals [29]. The current ECPL process neither adds polymerization inhibitor in the resin purposefully, nor prevents atmospheric oxygen which plays a role of inhibitor from diffusing into the chamber. There is not sufficient inhibitor to stop the crosslinking immediately for effective control of the dark curing.

Therefore, for the ECPL process, to improve the On-Off control accuracy, oxygen could be introduced into the resin chamber at the time when the UV lamp shuts down so that dark curing could be suppressed. Notably, as one disruptive photopolymerization based AM technology, the continuous liquid interface production successfully achieves high-speed and high-resolution 3D printing of complex microstructures, fundamentally by establishing and controlling an oxygen-inhibited dead zone [30]. Similarly, herein, the proposed "rapid quenching" method of manipulating the inhibitive oxygen via adjusting online the chemical composition in the reaction chamber, is expected to increase the process controllability by reducing the error and uncertainty in the controller's reference value thereby to improve the control accuracy at the total cured height.

Additionally, another approach to mitigate dark curing effect is to gradually decrease the intensity (i.e., iris level) toward the end of the process so that as the process approaches the target height, there should be little to no dark reaction. Such a strategy could be used with a trade-off of manufacturing speed, hence it might not be suitable in applications where a fast process is desired.

Table 2. Error analysis for the real-time measurement and control of the ECPL process

Exp. Index	**Error in Exposure Height (μm)**					**Error in Dark Height (μm)**	**Overall Error in Total Height (μm)**		
	Real-time measurement error		**Over-cured height (μm) under extended exposure due to *****			**Compensation Error ******	**Actual Observation *******	**Multiple Regression Estimation (μm)**	
	Real-time Measurement Bias *	**ICM&M System Error ****	**Measurement Latency**	**Feedback Control Delay**	**Actuation Delay**			**Fitted Error**	**Residual (Actual vs. Fitted)**
Group1 Sample 1	-0.48	3.11	0.02	1.17	1.52	-1.38	-3.15	-3.21	0.06
Group1 Sample 2	-6.27	4.77	2.00	6.08	1.02	-3.63	3.51	3.37	0.14
Group1 Sample 3	-7.31	3.34	0.62	2.22	0.96	-3.04	2.61	2.71	-0.10
Group1 Sample 4	-1.97	4.72	3.24	8.90	1.14	-2.64	3.12	3.01	0.11
Group1 Sample 5	3.97	2.60	2.29	6.41	1.93	-0.40	-1.01	-0.70	-0.31
Group1 Sample 6	-0.87	2.77	4.12	3.31	2.66	-1.18	-0.37	-0.34	-0.03
Group2.1 Sample 1	-0.62	-0.81	2.10	3.85	0.80	-0.50	5.05	4.99	0.06
Group2.1 Sample 2	4.83	-0.70	0.06	1.24	0.53	-0.49	-3.10	-3.22	0.12
Group2.1 Sample 3	-0.76	-3.16	0.22	0.80	0.59	-0.32	4.87	4.99	-0.12
Group2.1 Sample 4	0.60	0.08	0.01	-0.07	0.66	-0.32	-0.88	-1.07	0.19
Group2.1 Sample 5	11.38	-4.23	0.37	0.86	0.78	-1.05	-6.71	-6.76	0.05
Group2.1 Sample 6	-0.58	-4.77	0.01	-0.06	0.85	-1.91	4.20	4.13	0.07
Group2.2 Sample 1	2.95	-1.13	0.01	2.57	2.61	-1.00	0.02	0.25	-0.23
Group2.2 Sample 2	-2.19	-0.60	0.01	0.10	2.82	-0.36	2.71	2.85	-0.14
Group2.2 Sample 3	1.46	-4.34	0.01	1.46	1.50	-1.37	3.93	3.82	0.11
Group2.2 Sample 4	1.07	0.51	0.28	1.25	2.24	1.29	1.60	1.16	0.44
Weights of Error Source	**-1.013**	**-1.165**	**-0.130**	**1.081**	**0.074**	**1.050**	**Coefficients result from Multiple Regression**		

Notes: explanation about how the corresponding error item is estimated	
*	Data (Real-time vs. Offline ICM&M) in Table S2
**	Data (Offline ICM&M vs. Microscope) in Table S1 multiplied by 0.9 (estimated ratio: exposure height /total height)
***	Data (the red columns) in Table S3
****	Data (Offline ICM&M Estimated Dark Height) in Table S1 subtracted by Desired Dark Height
*****	Data (Microscope) in Table S1 subtracted by Target Total Height

6. Conclusion

As the ICM&M method has proven capability of measuring the ECPL process cured part off line, this study demonstrates directly and vividly another merit of the ICM&M system. It has real-time measurement capability. With the in-situ measurement being made available, as a result of this research effort, an economical and effective cyber-physical system of real-time measurement and control is realized in the ECPL process to replace the previous problematic open-loop process planning methods [12, 31, 32]. The developed real-time system features online parameter estimation, which is essential for controlling the grey-box ECPL process with unmeasurable variations and disturbances. Specifically, in this study, a basic feedback controller, aided by a simple photopolymerization process model and a well-developed in-situ optical dimensional measurement system, is designed and implemented to control the ECPL process cured height in real time. The goal is to cure a part with desired height by the real-time measurement and control system. The system's performance is evaluated with two groups of experiments that cure square blocks with different desired cured heights under different exposure intensities. The experimental results have exemplified both the measurement system's and the control system's capabilities at: (1) adapting to different process dynamics; (2) adapting to different setpoints; (3) global measurement and control with multiple pixels measurement online; (4) performing well (error $\leqslant$ 5 μm) with the presence of system delays and process uncertainties (e.g. dark curing); and (5) submicron control with the well-understood error sources and a conceivably enhanced system in the future.

Substantive recommendations have been provided to further augment the fundamental control system. Furthermore, given the limitations of the facile On-Off control method, to achieve more comprehensive and capable control, manipulating the exposure intensity at intermediate levels, that is, an exposure intensity control system such as PID control and advanced adaptive control methods could be explored to control the geometrical dimensions and optical properties which are desired for applying the ECPL in fabricating micro-optics and micro-fluidics components.

This proof-of-concept study demonstrates that one can implement the real-time ECPL process control with the developed ICM&M method on the currently resource-constrained prototyping ECPL system, which can be enhanced with more advanced devices and more computation power to a full-fledged photopolymer 3D printing machine. The real-time measurement feedback control reported in this paper might be the first of its kind for photopolymerization based AM systems, as commercial stereolithography apparatus do not adopt such an in-situ metrology and closed-loop control system yet. To conclude, this study opens up an avenue for real-time closed-loop advanced control of photopolymerization based additive manufacturing processes to facilitate their applications for precision manufacturing in a wide spectrum of industries.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1234561. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Reference

[1] Gibson, I., D.W. Rosen, and B. Stucker, *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2nd ed. 2014: Springer-Verlag New York. XXI, 498.

[2] Plant, A., *Additive Manufacturing for Health: a National Institute of Standards and Technology (NIST) Perspective*, in *National Science Foundation (NSF) Workshop on Additive Manufacturing for Health*, Y. Huang and S.R. Schmid, Editors. 2016: National Science Foundation (NSF) Workshop on Additive Manufacturing for Health.

[3] Huang, Y. and M.C. Leu, *Frontiers of Additive Manufacturing Research and Education*, in *An NSF Additive Manufacturing Workshop Report*. 2014: An National Science Foundation (NSF) Additive Manufacturing Workshop Report.

[4] *Measurement Science Roadmap for Polymer-Based Additive Manufacturing*, in *NIST Advanced Manufacturing Series*. 2016, National Institute of Standards and Technology: Gaithersburg MD, USA.

[5] *Measurement Science Roadmap for Metal-Based Additive Manufacturing*. 2013, National Institute of Standards and Technology (NIST)

[6] Bikas, H., P. Stavropoulos, and G. Chryssolouris, *Additive manufacturing methods and modelling approaches: a critical review.* The International Journal of Advanced Manufacturing Technology, 2016. 83(1-4): p. 389-405.

[7] Frazier, W.E., *Metal Additive Manufacturing: A Review.* Journal of Materials Engineering and Performance, 2014. 23(6): p. 1917–1928.

[8] Hu, D. and R. Kovacevic, *Sensing, modeling and control for laser-based additive manufacturing.* International Journal of Machine Tools & Manufacture, 2003. 43: p. 51–60.

[9] Hagqvist, P., et al., *Resistance based iterative learning control of additive manufacturing with wire.* Mechatronics, 2015. 31: p. 116-123.

[10] *Measurement Science Roadmap for Polymer-Based Additive Manufacturing*. 2016, National Institute of Standards and Technology (NIST)

[11] Seppala, J.E. and K.D. Migler, *Infrared thermography of welding zones produced by polymer extrusion additive manufacturing.* Additive Manufacturing, 2016. 12: p. 71-76.

[12] Jariwala, A.S., *Modeling And Process Planning For Exposure Controlled Projection Lithography*. Ph.D. thesis, Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA, 2013.

[13] Zhao, X. and D.W. Rosen, *Real-time interferometric monitoring and measuring of photopolymerization based stereolithographic additive manufacturing process: sensor model and algorithm.* Measurement Science and Technology, 2017. 28(1).

[14] Zhao, X. and D.W. Rosen, *A data mining approach in real-time measurement for polymer additive manufacturing process with exposure controlled projection lithography.* Journal of Manufacturing Systems, 2017. Special Issue: Cybermanufacturing.

[15] Zhao, X. and D.W. Rosen, *Experimental validation and characterization of a real-time metrology system for photopolymerization based stereolithographic additive manufacturing process.* International Journal of Advanced Manufacturing Technology, 2016.

[16] Jariwala, A.S., R.E. Schwerzel, and D.W. Rosen, *Real-Time Interferometric Monitoring System For Exposure Controlled Projection Lithography.* Proceedings of the 22nd Solid Freeform Fabrication Symposium, 2011: p. 99-108.

[17] Zhao, X., *Process Measurement and Control for Exposure Controlled Projection Lithography*. Ph.D., Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA, 2017.
[18] Lambert, J.R., *Control Modes - On/Off Control*, in *Contemporary Measurement Concepts*. 2014, Lulu.com.
[19] Haber, R., R. Bars, and U. Schmitz, *Predictive On–Off Control*, in *Predictive Control in Process Engineering : From the Basics to the Applications (1)*. 2012, Wiley-VCH. p. 103-134.
[20] Chartoff, R.P. and J. Du. *Photopolymerization reaction rates by reflectance real time infrared spectroscopy: application to stereolithography resins*. in *Solid Freeform Fabrication Symposium*. 1999. Austin, TX.
[21] Tang, Y., *Stereolithography Cure Process Modeling*. PhD, School of Chemcial & Biomolecular Engineering, Georgia Institute of Technology, Atlanta, 2005.
[22] Doyle, J.C., B.A. Francis, and A.R. Tannenbaum, *Feedback control theory*. 2013: Courier Corporation.
[23] Nilsson, J., *Real-Time Control Systems with Delays*. Department of Automatic Control, Lund Institute of Technology, 1998.
[24] Ngo, Y.S., K.T. Ang, and A. Tay, *Method for real-time critical dimensions signature monitoring and control: Sensor, actuator, and experimental results.* Review of Scientific Instruments, 2013. 84(1): p. 015116.
[25] MathWorks. *Multiple linear regression*. 2016; Available from: https://www.mathworks.com/help/stats/regress.html.
[26] Zhao, X. and D.W. Rosen, *Simulation Study on Evolutionary Cycle to Cycle Time Control of Exposure Controlled Projection Lithography.* Rapid Prototyping Journal, 2016. 22(3): p. 456-464.
[27] Arimoto, H., et al., *Measurement of refractive index change induced by dark reaction of photopolymer with digital holographic quantitative phase microscopy.* Optics Communications, 2012. 285(24): p. 4911-4917.
[28] Stansbury, J.W. and D. Kim, *Methods For Extensive Dark Curing Based on Visible-Light Initiated, Controlled Radical Polymerization*. 2011, Stansbury Jeffrey W

Dongkwan Kim: USA.
[29] Lee, J.H., R.K. Prud'homme, and I.A. Aksay, *Cure depth in photopolymerization: Experiments and theory.* Journal of Materials Research, 2001. 16(21): p. 3536-3544.
[30] Tumbleston, J.R., et al., *Continuous liquid interface production of 3D objects.* Science, 2015. 347(6228): p. 1349-1352.
[31] Zhang, Y., *Empirical process planning for exposre controlled projection lithography*. M.S., Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA, 2016.
[32] Zhao, X., *Process Planning For Thick Film Mask Projection Micro Stereolithography*. M.S. thesis, Mechanical Engineering, Georgia Institute of Technology, Atlanta, USA, 2009.