Automation of A Hybrid Manufacturing System Through Tight Integration of Software and Sensor Feedback

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Abstract

This paper presents a framework for the automation of the Laser Aided Manufacturing Process (LAMP) lab at the University of Missouri-Rolla. The groundwork for the proposed system involves the integration of the LabVIEW software package and a PXI-8195 real time controller with several sensors and actuators. The incorporation of all key control parameters into one virtual instrument will help achieve the goal of an automated hybrid system. To achieve this goal, a five-phase plan, which will be further discussed in the paper, has been developed. The first phase of this plan, which includes the deposition of a thin walled structure without DNC communication between LabVIEW and the CNC has been achieved, and will be the focus of this paper.

Introduction

The Laser Aided Manufacturing Process (LAMP) at the University of Missouri-Rolla (UMR) is a hybrid laser metal deposition (LMD) manufacturing system consisting of a laser, powder feeder, and motion system. The laser is used as a heat source while the powder feeder delivers metal powder at a specified rate into the path of the laser beam, thereby creating a melt pool. The laser beam and powder stream are directed vertically, while the substrate moves in three dimensions using the x, y, z, A, and B axes, molten tracks are deposited in layers, which cool rapidly to fabricate a part. Sensors monitor the temperature, layer height, and melt pool geometry in real time via a real time (RT) control system.

The overall goal of the UMR LAMP lab is the complete automation of the hybrid laser aided manufacturing process. To achieve this goal, a five-phase plan to automation has been developed. The five-phase plan involves utilizing sensor feedback to gain overall control of the diode laser, powder feeder, and motion system through a RT control system implemented on a single host computer. Virtual instruments (VI) created within the LabVIEW software package will be used to monitor, drive, and control the hybrid LMD process in real time. The LabVIEW VI will include simulated controllers to compensate for undesired dynamics and noise, thus insuring accurate builds with a stable automated LMD process.

The major focus of this paper will be to discuss the work performed to complete the first phase of the plan, which includes the deposition of a thin walled structure without DNC communication between LabVIEW and the CNC. To demonstrate the implementation of this phase, the paper will look at the equipment, software, and hardware required for control; the results from phase one's implementation; and conclusions drawn from the first phase.

Prior Work

Hybrid manufacturing systems are a conglomeration of many off-the-shelf components that are combined in a modular fashion to achieve a new process. Research was conducted on hybrid systems, individual components, and control applications. While the following research of hybrid systems contains many of the pieces required for an LMD process, there is a general lacking in the areas of total system integration and control.

Two pertinent real-time control applications dealing with laser and vision control are quality control inspection and position control. Real-time vision control for a fabric inspection system was shown to be very successful with dedicated hardware for the vision system being controlled via a Pentium 4 PC [1]. Morgan [2] developed a very reliable way of monitoring high power CO_2 lasers based on the feedback of a light sensor and how to control the focal position of the laser. Both applications mentioned are not associated with LMD, but contain aspects useful in the development of the hybrid system with relation to real-time control.

Under the solid freeform fabrication (SFF) category, two articles by Malone [3,4] demonstrate successful types of positioning systems, deposition tools, and software. However, Malone has shown that small-scale systems are capable of deposition when being controlled by one computer system. Upton [5] has completed research on flexible manufacturing systems (FMS) where the key idea is that co-ordination of workflow is performed by a central control computer. Both authors have laid groundwork in the area of hardware and software integration.

Others at UMR have done research within the LAMP lab or dealing with lasers that is the most relevant to the automation of the LAMP lab. Specifically, Hua [6] has done extensive research in adaptive layer process control with lasers. Additionally, before the LAMP lab went through a major equipment upgrade in the summer of 2005, work went into system integration, experimental analysis, and modeling of the LAMP lab [7,8]. Although many of the components of the LAMP lab were changed, the fundamentals of the aforementioned research remains pertinent to the continued automation of the LAMP lab.

Framework

A five-phase framework has been proposed for the automation of a hybrid LMD system, which will be utilized in the UMR LAMP lab. The framework lays out the major steps to achieving automation using real-time control hardware and integration of software with sensor feedback. Detailed steps for implementation of the five-phase framework are elucidated in the Methodology section. The parameters needed for successful framework completion are further discussed in the Parameters and Equipment for System Integration and Automation section.

Phase 1: The first phase of automating the hybrid LMD process is to deposit a thin wall structure without DNC communications between LabVIEW and the CNC. Phase one demonstrates the ability to command the diode laser and powder feeder by the RT system and to simultaneously fabricate a part when a tool path is loaded on the CNC from another source.

Phase 2: Phase 2 of the framework is similar to the first. A thin wall structure is deposited with DNC communication of the toolpath to the CNC from the VI running the laser and powder feeder. Depending on the type of CNC used and amount of on-board memory, drip-feeding of the tool path to the CNC may be required to fabricate the thin wall structure.

Phase 3: Building upon the second phase, the third phase incorporates feedback from an intelligent vision system which monitors melt pool geometry. During deposition, the melt pool is monitored for elliptical geometry because as the substrate traverses, the round pool elongates. A feedback controller should be implemented that can interpret geometric feedback and compare it to the desired output. Once the melt pool leaves the allowed dimensions for the chosen laser power and powder mass flow rate, the deposition process reaches a warning mode. If the vision system continues to report poor melt pool geometry for more than the allotted time, the LMD process faults and is shut down immediately

Phase 4: The fourth phase includes more sensor feedback by monitoring the temperature of the melt pool by a non-contact optical sensor. Due to the high priority of creating quality depositions, regulating the temperature of the melt pool is critical to achieving the desired microstructure. Modify the phase 3 controller to process additional data and simultaiously determine if the feedback is desirable. Once the measured temperature leaves the allowed range for the chosen laser power and powder mass flow rate, the deposition process reaches a warning mode. If the temperature sensor continues to report an out of range temperature for more than the allotted time, the LMD process faults and is shut down immediately.

Phase 5: The fifth phase incorporates the final sensor feedback, height of deposited layers, needed to complete the hybrid LMD system framework for automation. Incorporation of the laser displacement sensor feedback is an offline process that requires the deposition to pause so the sensor can scan the deposited structure, attain data, and display the data in real time. Modify the phase 4 controller to automatically process the offline feedback, and provide the option for an operator to decide if the data is acceptable. If the data is acceptable, the LMD process will continue, otherwise it will be shut down.

Methodology

Development of the automation program to command and monitor a hybrid LMD system is comprised of several smaller tasks that build upon each other. The details needed to follow the proposed framework are contained within this section and describe the underlying work necessary for success. Completing the steps in sequence is critical when using this methodology.

Step 1: Test all LMD system devices for compatibility with the RT system hardware. Make necessary modifications to the devices as needed; such as building a special cable.

Step 2: Use the software package online diagnostic program to test if the software can accurately communicate with the devices. If using LabVIEW, the program Measurement and Automation Explorer (MAX) is used for online diagnostic tests [9].

Step 3: Create a basic VI to monitor the input and output of each device individually. The VI should contain at least a graph or chart that displays the output; fields for input parameters such as voltage, sampling rate, input channel, encoding type, ect., and a field to specify or monitor the save file path where the collected data will be stored.

Step 4: Perform open-loop step tests using the VI's created in Step 3 and record data to be analyzed. With a suitable mathematical software package, analyze collected data, and compare it to the predicted outcome. Look for system dynamics that will require additional modeling for compensation. Look for delays in the output that will inevitably affect the overall system performance.

Step 5: If emulation is necessary, create mathematical models for the devices that exhibit significant dynamics to understand how to remove their disturbance from the overall system. Add code to the VIs created in Step 4 mimicking the mathematical models. Repeat Step 4. If emulation is not needed, then skip Step 5.

Step 6: For devices that only need to be monitored, new VIs will not be required in this step. Again, execute Step 4 using the VIs from Step 5 if emulation was used, until desired results are achieved. Develop an adequate controller that will regulate the output signals sent by the RT system to the controlled devices of the LMD process. A new VI should be created for each device and include the controller code. Execute Step 4 until the open-loop tests provide desirable results. Next, update the new VIs to incorporate the feedback from monitored devices and perform closed-loop tests until desirable results are achieved.

Step 7: Modify the VI's in Step 6 to incorporate fault conditions to stop the LMD process if poor deposition is detected and display a warning to the user. Choose a length of time that allows the system to recover on its own from undesired feedback via the feedback controller. The warning time should be selected to compliment the controller design and be slightly longer than the anticipated settling time for disturbances. The chosen time allows for the system to compensate for the disturbance, or halt the system promptly if compensation is not possible so that the part can be salvaged.

Step 8: Once all devices are operating properly, merge all the control and monitor VI's into a composite VI to command and monitor the entire process. Furthermore, be sure that all devices have the correct sampling times set.

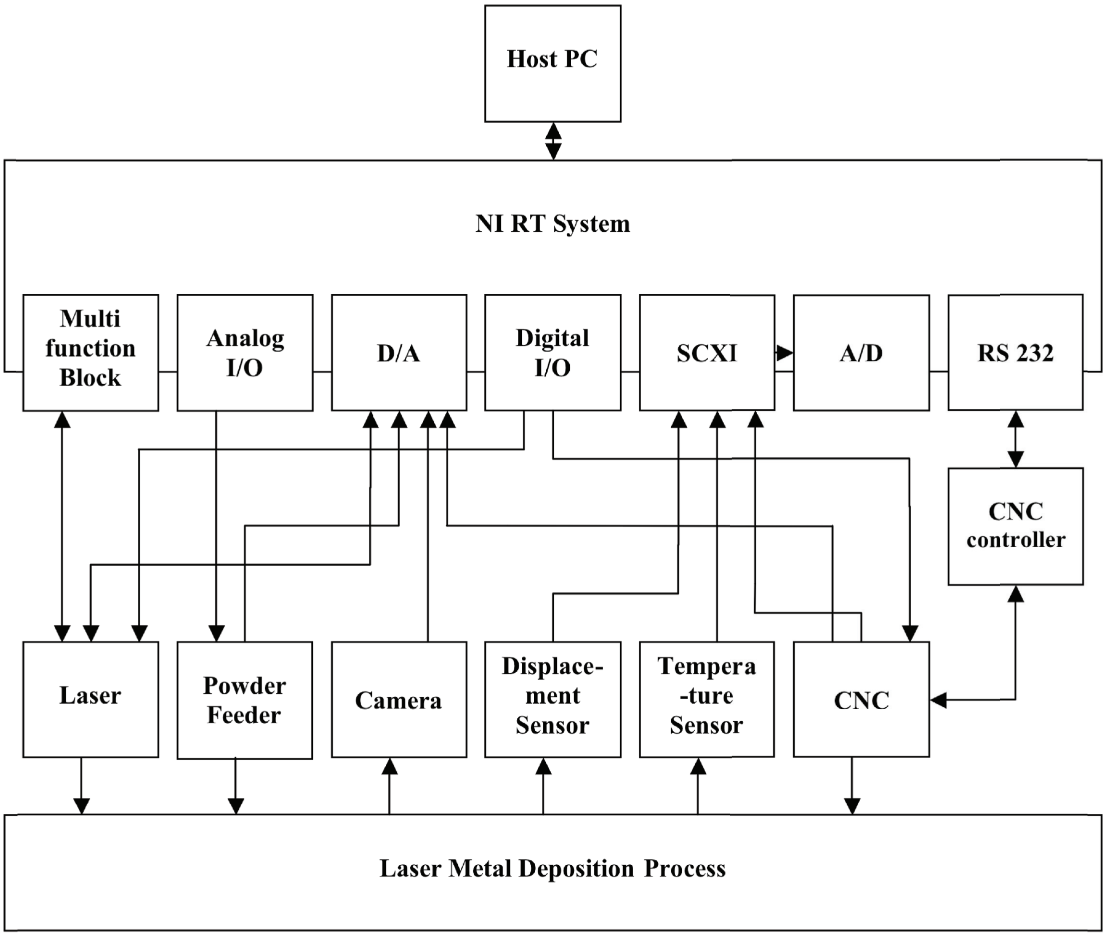

Figure 1: Block Diagram of LAMP Lab Automation System

Parameters and Equipment for System Integration and Automation

System integration of software and sensor feedback for an automated system is typically accomplished through a real-time control system [10]. Communication and automation play a major role in the automation scheme of the RT control system for the hybrid LMD process. Therefore, a fast sampling controller, network card, analog and digital I/O ports, serial ports, hardware timers and counters, D/A converters, A/D converters, and hardware filters are some of the key aspects of a reliable RT control system. Conversely, a robust software package is required for overall tight system integration. LabVIEW, the software chosen for the LAMP lab, is a powerful software package developed by National Instruments. The LabVIEW software package is a robust and expandable software package for design, control, and testing [9]. Development of VI's, component control, and monitoring for the LAMP lab are completed as described in the methodology section. Figure 1 shows all the device inputs and outputs of the LAMP lab hybrid LMD process.

The advantages to implementing an integrated system are three-fold. First, the hybrid LMD process can be made safer by becoming an automated process and removing people from directly interacting with the components and laser. Second, the options for control and feedback are endless and versatile. There are no limits on the number of VIs that can be created with the LabVIEW software package, so numerous programs can be developed and executed on the RT system or stored for later use. Thus, the hybrid LMD system is only limited by the hardware, which includes the I/O and CPU of the RT system. Third is repeatability leading to better quality control. With full automation, the hybrid LMD process will fabricate parts that have predictable and desirable characteristics more frequently.

Some process parameters are not appropriate for real time control and should be held constant during the process of fabrication. The spot diameter provides the clad width and is determined by the focal length of the laser lens and the standoff distance. Thus, repositioning the z-axis can only change the spot diameter. This would require G codes to be sent to the CNC. Changes to the G and M codes sent to the CNC cannot be completed in real time because there is a delay when waiting for the last line of code in a program to be executed. Another factor is that the setup of the powder feeder nozzle must ensure that the metal powder converges at the melt pool in a diameter roughly the size of the spot diameter. Altering the spot diameter would thus require an adjustment to the powder feeder nozzle, which cannot be done in-process. The table velocity is also not a candidate for real-time control. Only after a tool path program has been completed can the table velocity be changed because the whole program is sent to the CNC at once. Similarly, the tool path must also be set before the process begins. The two process variables that can be used for real time control are laser power and powder mass flow rate since they can be controlled independently of the other process parameters and the CNC.

Key parameters for system integration are the ones that can be manipulated in real-time to induce a change in the final product or monitored for use with a feedback control scheme. By controlling and monitoring the key parameters, the quality of fabrication will increase and be repeatable. An overview of the parameters is given next along with how the device was affected by the steps presented in the methodology section.

The main difficulty involved with controlling the powder mass flow rate in process is the natural delay that occurs between the control signal and the actual output. Powder mass flow rate is controlled by a command voltage, which regulates the rotational speed of the powder delivery shaft. The powder must then traverse the delivery system before entering the melt pool thereby creating a delay between the effective mass flow rate and the desired mass flow rate. Argon is used as the carrier gas for transporting the powder from the powder feeder to the laser collimator at a pressure of 40 psi. Also, a special cable was made to make the powder feeder mass flow rate (gpm) controllable by the RT system. Other considerations include the location f where the powder stream converges to the location of the melt pool and preheating the powder to remove moisture. Preheating improves flow and helps minimize porosity in the finished part.

Controlling the diode laser power by a command voltage was achieved by way of a special cable that connected the laser to the RT control system. The only delay is the 0.5 ms response time of the laser [11]. The difficulty with controlling the laser power is determining what the desired laser power should be based upon the desired clad dimensions. Increasing the laser power increases the size of the melt pool and could increase the size of the deposition height if enough powder is present. The laser power must also be within a certain effective range for a given material since the final mechanical properties of the part, such as porosity, density, and microstructure, are closely related to laser power through melt pool temperature and solidification time. Laser power must also be large enough to induce melting in the substrate, but must also be below the point where dilution causes poor solidification.

Real time monitoring of the melt pool length and width are important to maintain the dimensional accuracy during laser deposition [8]. Melt pool geometry is directly affected by the laser power and powder mass flow rate. Dilution of the melt pool will result in poor cladding and produce unacceptable part quality. In order to monitor the melt pool geometry, a side bracket attached to the collimator emulating an axial mount with the use of two dichromic mirrors allows for a CMOS camera to acquire melt pool images during deposition in real-time. The length and width of the melt pool are extracted using an image-processing algorithm in real-time and used for feedback control during the last three phases of the framework.

Layer height must be determined to calculate the number of layers that need to be run to minimize the use of raw material [8]. A non-contact laser displacement sensor is used to measure the layer height after an individual layer or a given number of layers have been deposited. Height is affected equally by the powder mass flow rate and the laser power. A higher laser power combined with more powder, leads to a bigger clad. In order to measure the height with the RT system reliably, a hardware filter was installed into the RT control system to alleviate most of the noise in the signal. The same is true for the temperature sensor, but with the addition of resistors to reduce the voltage output.

Melt pool temperature is monitored continuously, in real time, using a dual-wavelength non-contact temperature sensor. If the temperature is too low, then the powder injected into the molten pool will not melt. Moreover, if the temperature is too high, it risks the danger of melting the previous layers too much or causing damage to the work piece [8]. The sensor measures the peak temperature of the melt pool formed during laser deposition and is used for feedback control during the last three phases of the framework.

Direct Numerical Control (DNC) is a feature of the CNC machine that allows for a host PC with an RS-232 port to communicate with the CNC remotely. The 64Kb of memory local to the CNC is used when downloading a program at 9600 baud into the CNC memory for execution [12]. Since the CNC memory size is very small compared to a complete tool path program, the 64Kb of memory can then be used as a buffer for the program and frequently replenished by the remote PC until the full program has been loaded into memory and executed. This is also known as "drip feeding." The buffer fills after a few lines of code have been executed and continues to stay full at 256 lines of code until the last line of the program has been sent. However, the most important advantage to DNC is the way it handles large program files by drip feeding them to the CNC smoothly until the program is finished. This allows for large tool path programs to be automatically executed. Using the diagnostic software, it was discovered the CNC needed a special command to initiate DNC capabilities thus allowing for the phase two progress to begin.

Results

Phase one of the LAMP lab framework has been completed and is demonstrated by the preliminary results shown in Figure 2. The thin wall structure was deposited semi-automatically, which means that the host PC communicating to the RT system commanding the laser power and powder mass flow rate did not drip feed the tool path to the CNC. Another computer currently dedicated to performing DNC was used to send the tool path program to the CNC. Additionally, the main VI did not incorporate feedback control when the preliminary results were attained. The user of the main VI could control the powder feeder and laser voltage commands, and monitor and record their respective feedback signals. The integration of the software with the hardware was evident when the laser and powder feeder responded to the command signals without any complications, noticeable delay, or the loss of data samples. Given the robust nature of LabVIEW, the preliminary deposition task was simple to implement and was performed effortlessly by the RT system.

Figure 2: Semi-Automatic Deposition of a 20 Layer Thin Wall Structure

As one can see from Figure 2, the deposition was very clean and had nice quality on the outside. The first deposition (bottom) warmed the substrate, subsequently allowing the second deposition (top) to have better dimensional accuracy. Microstructure and porosity are still yet to be determined for the samples in Figure 2. To achieve such results, a powder mass flow rate of 8.25 gpm and a laser power of 700 W were used, which corresponds to a command voltage of 1.3 V and 6 V, respectfully.

The correct command voltage for the laser and powder feeder were determined experimentally through open-loop step tests. Table 1 provides the steady state results of gpm and rpm for command voltages between 1–2 V, in 0.1 V increments. The rpm was recorded by the RT system at a sampling rate of 1000 Hz, and the caught grams of powder were measured on a scale. A VI was created to automatically send a command voltage to the powder feeder for one minute, shut off the powder flow by sending 0 V, and then stop the program. During that minute, powder was captured in a glass jar at the end of the nozzle and weighed on a scale for 30 seconds to allow enough time for an approximate reading of total grams of powder, as recorded in Table 1.

Consequently, the four tests were averaged and checked for acceptable standard deviation. The results were suitable and can be found in Table 2. The data in Table 2 provides a reliable guide for the user when programming a VI for control, because the gpm has been correlated to command voltage. Figure 3 shows the relationship between command voltage and the powder mass flow rate with a calculated slope of 10.4 when analyzed using the least squares method. Pleasingly, the correlation coefficient was found to be 0.999. Deviation within the rpm test data is negligible in most cases, but the gpm deviation was large for voltages of 1.00, 1.60, 1.70, and 2.00. It is hypothesized that fluctuations between gpm test results are mainly caused by the powder wheel mechanism consisting of a cam and flexible follower within the powder feeder. The position where the powder wheel starts and stops during each test has a great impact on the amount of powder released by the mechanism, because each cycle of the powder wheel is not identical. Large deviations were also partially due to measuring the grams by hand with a scale and recording the value that was displayed most frequently within the 30 seconds the jar rested on the scale. Moreover, the type of distribution system installed before the collimator splits the main powder stream into four, and can become clogged, statically charged, or leak carrier gas, which can deteriorate powder delivery performance significantly.

Table 1: Results of Powder Mass Flow Rate Open Loop Tests

Command Voltage (V)	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM
	test 1		test 2		test 3		test 4	
1.00	4.90	0.5047	4.60	0.499	4.80	0.5024	4.73	0.5013
1.10	6.02	0.6548	5.80	0.6497	5.90	0.6575	5.92	0.6572
1.20	7.15	0.811	7.13	0.8067	7.14	0.8089	7.19	0.8071
1.30	8.42	0.9564	8.33	0.9562	8.23	0.9557	8.25	0.9572
1.40	9.50	1.115	9.37	1.11	9.40	1.11	9.36	1.11
1.50	10.40	1.263	10.38	1.264	10.40	1.263	10.35	1.262
1.60	11.48	1.422	11.52	1.422	11.39	1.425	11.30	1.427
1.70	12.52	1.578	12.22	1.58	12.30	1.581	12.23	1.58
1.80	13.00	1.737	13.13	1.739	13.00	1.742	13.13	1.727
1.90	14.35	1.88	14.46	1.881	14.29	1.884	14.25	1.882
2.00	15.14	2.044	15.03	2.047	15.41	2.047	15.84	2.047

Table 2: Averages and Standard Deviations for Data in Table 1

Command Voltage (V)	GPM Avg.	RPM Avg.	GPM Std. Dev.	RPM Std. Dev.
1.00	4.76	0.5019	0.13	0.0024
1.10	5.91	0.6548	0.09	0.0036
1.20	7.15	0.8084	0.03	0.0020
1.30	8.31	0.9564	0.09	0.0006
1.40	9.41	1.1113	0.06	0.0025
1.50	10.38	1.2630	0.02	0.0008
1.60	11.42	1.4240	0.10	0.0024
1.70	12.32	1.5798	0.14	0.0013
1.80	13.07	1.7363	0.08	0.0065
1.90	14.34	1.8818	0.09	0.0017
2.00	15.36	2.0463	0.36	0.0024

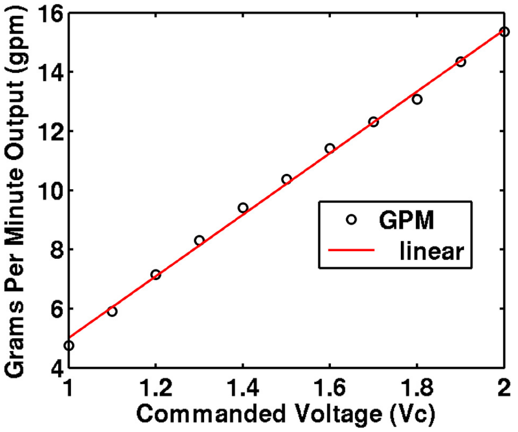

Figure 3: GPM Test Results of the Remotely Commanded Powder Feeder

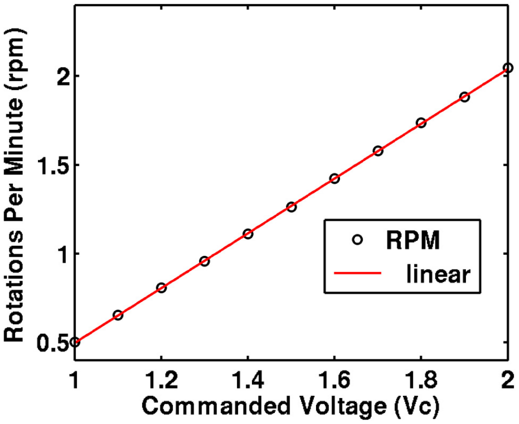

Figure 4: RPM Test Results of the Remotely Commanded Powder Feeder

Figure 4 relates the average command voltage to the rpm. When the rpm data was analyzed using the least squares method, the slope was found to be 1.5. The correlation coefficient was found to be exactly 1.000 indicating a nice linear relationship as shown in Figure 4. Finally, the gpm and rpm test results were correlated in Figure 5 and the slope was found to be 6.7 by the least squares method. The results in Figure 5 were greatly affected due to the powder feeder mechanism and powder distribution system as previously mentioned. However, the relationship between the rpm and gpm is approximately linear with a calculated correlation coefficient of 0.998. Deposition test results have proven the collected data in the voltage range of 1-2 V to be reliable for use with the LMD process.

Correlation between the commanded voltage and output wattage to the substrate was conducted using a Coherent Power Meter with the water-cooled LM5000 sensor head, rated for 5 kW. The sensor head was placed below the collimator at a standoff distance of 14.478 mm (0.57 in), and a voltage was commanded in 1 V increments to the laser by the laser VI. The bolded columns of Table 3 list the given documentation of the diode laser. The recorded measurements from the power meter tests at the substrate are labeled Pm Test, and the data standard deviation are in Table 3. Correlation between the provided documentation and the power measured at the substrate is in Figure 6. By the least squares method, the slope for the given information was found to be 167.00, and the slope for the measured information was found to be 128.00. It was calculated that the laser output correlation coefficient of the Pm Test average was 0.990, which is demonstrated by the large deviations at 1 and 10 V, where as, the given information correlation coefficient was 0.995. Due to losses in heat and the fiber optic medium, the power meter displayed a lower output wattage than what was to be expected as per the diode laser documentation. Furthermore, at the lower range of the voltage input, the output wattage is very close to the provided documentation. It is only at higher command voltages that the laser does not perform as expected.

Table 3 : Laser Power Meter Test Results

Vc (V)	Pm Test 1 (W)	Pm Test 2 (W)	Amps Displayed (A)	Pm Test 3 (W)	Pm Test 4 (W)	Amps Displayed (A)	Pm Std. Dev.	**Nuvonyx Displayed Amps (A)**	**Nuvonyx Output Power (W)**
1	0	0	5	0	0	5	0	**10**	**57**
2	17	17	11	17	17	11	0	**15**	**225**
3	220	220	16	220	220	16	0	**20**	**399**
4	380	380	21.5	370	370	21.5	5.7735	**25**	**574**
5	560	550	27	520	510	27	23.8048	**30**	**737**
6	700	700	32.5	660	650	32.5	26.2996	**35**	**884**
7	820	840	38.5	800	770	38.5	29.8608	**40**	**1014**
8	940	930	43.5	900	890	43.5	23.8048	**45**	**1124**
9	1030	1020	49	1010	990	49.5	17.0783		
10	1050	1020	49.5	1050	1020	49.5	17.3205		

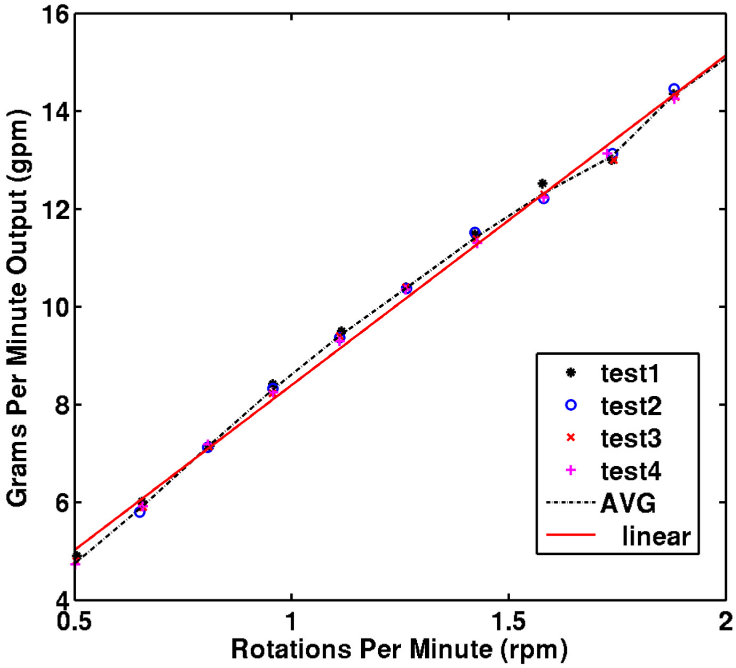

Figure 5: GPM Results Compared to RPM Results of the Remotely Commanded Powder Feeder

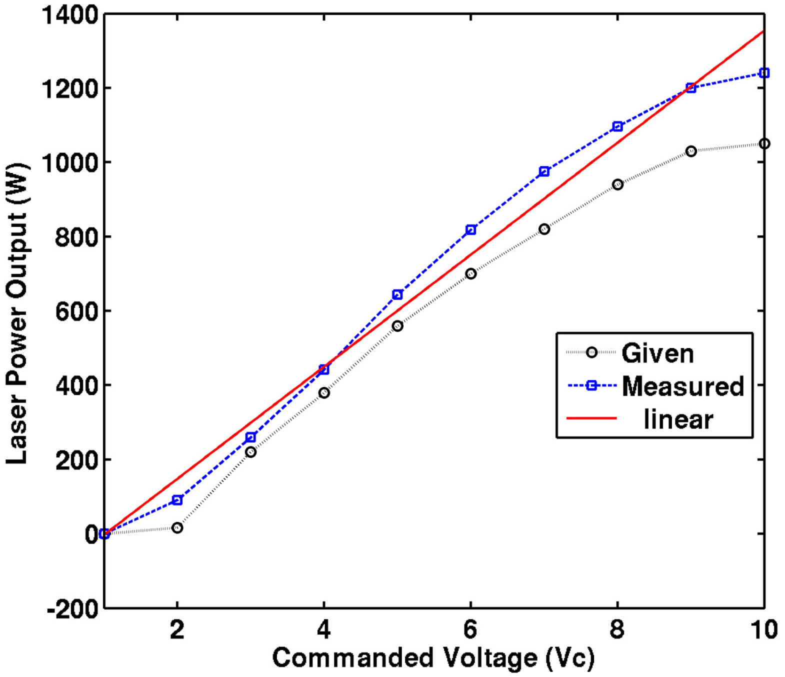

Figure 6: Comparison of Actual Laser Output to Given Laser Documentation

Conclusions and Future Work

The framework for accomplishing the goal of automating the UMR hybrid LMD system has been presented. By following the presented methodology for integrating hardware and software, individual manipulation and monitoring of laboratory components has been achieved successfully. Methodology steps one and two proved to be very helpful in alleviating many unseen problems that did not seem evident in the beginning. Mainly, the temperature sensor needed to be modified for use with the RT system. Preliminary results were demonstrated through deposition samples as shown in Figure 2. The collected data presented in the results section demonstrates that phase one of the framework was successfully completed, because the main VI was only given control parameters and did not rely on feedback. Integration of the software package, RT system, and LMD components was confirmed to be imperative and achievable for the success of full automation.

The future work needed for completing the framework is to actively send information from the RT system directly to the CNC by way of RS232 communication to complete the DNC requirement of phase two. Once the DNC is completed, the last three phases will incorporate the feedback of the monitoring devices and how they interact with the overall system. A robust controller will need to be developed that can handle the feedback from three devices adequately. Real-time processing of feedback from devices simultaneously and driving the computed error signal to a minimum will be the capabilities of the controller. After feedback control is in working order, fault conditions will be added to increase the quality of deposited parts created in the LAMP lab.

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