

SYSTEM INTEGRATION AND REAL-TIME CONTROL ARCHITECTURE OF A LASER AIDED MANUFACTURING PROCESS

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ABSTRACT

This paper discusses a hybrid deposition–removal manufacturing system being developed at the University of Missouri–Rolla. The system consists of a laser system, five–axis CNC machining center, and powder feeder system. A description of the control software, real–time control architecture, and integration of various subsystems to build the hybrid system is given. The interaction of the real–time controller with various sensors and subsystems to monitor and regulate the process is presented. The communication between integrated process planning for the system and real–time control is also discussed in this paper.

INTRODUCTION

Rapid Prototyping (RP) technology has enabled building of parts directly from a CAD model with reduced lead–time and cost, and improved product quality. There are some 25 different RP methods available today, 70% of which are laser–based [Steen, 1998]. The laser metal forming systems involve the supply of metallic materials (powder or wire) into a laser–heated spot where the material is melted and forms a melt puddle which quickly solidifies into a bead. Examples of laser–based RP systems include stereolithography, selective laser sintering, directed light fabrication at Los Alamos National Laboratory, fused deposition modeling, laser direct casting, laser powder deposition [Keicher *et al.*, 1995], three–dimensional laser cladding [Koch and Mazumder, 1993], Laser Engineered Net Shaping (LENSTM [Griffith *et al.*, 1996]), three–dimensional printing, Laminated Object Manufacturing (LOM), etc. These technologies provide the flexibility of choosing the part material, which may be a type of metal, ceramic, composite, etc., in powder form. Many of these processes have demonstrated the feasibility of producing near–net shape metal parts with reasonably good accuracy and improved metallurgical properties. A complete review of the laser deposition process is provided in Laeng *et al.* [2000].

Most of the laser–based RP systems are one–step rapid manufacturing processes that build three–dimensional parts eliminating the intermediate step of die/mould preparation. However, these systems are only capable of producing near–net shape parts that require further processing if precision is required. This additional process necessitates another set–up that, in turn, contributes to geometrical errors and increased cycle time. A five–axis hybrid RP system consisting of deposition (laser–based) and removal (machining) is being developed at the University of Missouri – Rolla [Liou *et al.*, 2001]. Precision metallic parts are built in one set–up with increased quality and productivity. The ability of the system to build accurate parts depends, in part, upon the system’s ability to monitor and control the material deposition process. This paper describes the various monitoring and control sub–systems of the hybrid RP system, and their

integration for real-time control of the process parameters governing the laser metal deposition process.

HARDWARE SYSTEMS

The hybrid system, shown in Figure 1, consists of the hardware sub-systems listed below.

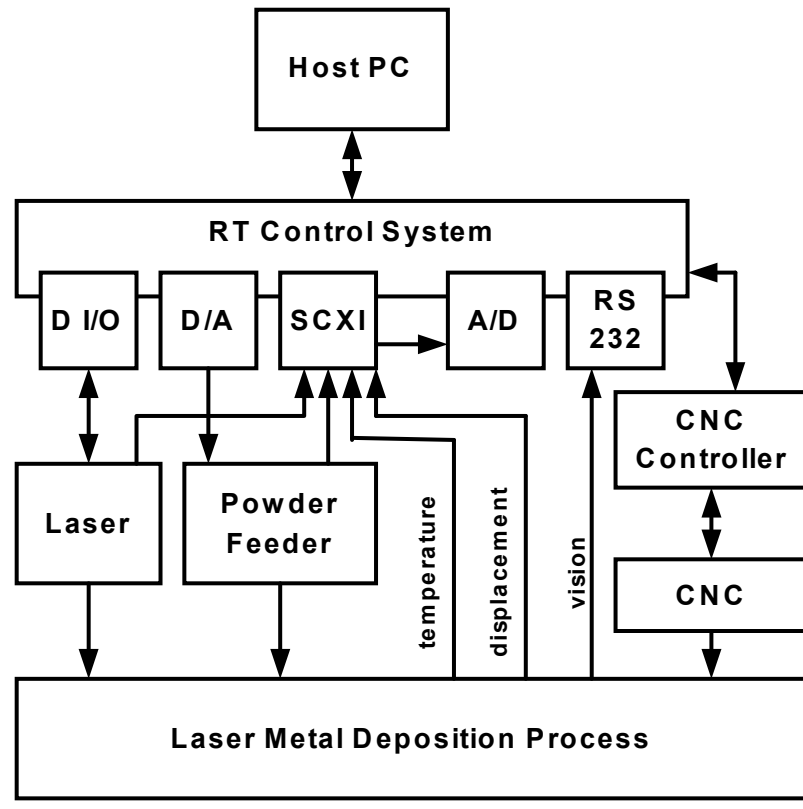


Figure 1: Laser Metal Deposition Process Hardware Schematic.

Energy Delivery System

The energy delivery system consists of a 2.5 kW Nd-YAG high-energy laser. This laser uses neodymium (Nd) as the lasing material doped in yttrium-aluminum-garnet (YAG) crystal and has a wavelength of 1.06 μm . The laser can be operated in continuous and pulsed modes. The advantage of this laser is that the energy can be efficiently delivered using optical fibers. The parameters of the energy delivery system are the laser power, beam diameter, beam mode structure, and beam focal point. The specific energy (i.e., the amount of energy delivered to the substrate) depends on the laser power, CNC traverse speed, and beam diameter and is expressed as $E = P/(Dv)$ where E is the specific energy (J/mm^2), v is the CNC traverse speed (mm/s), P is the laser power (W), and D is the spot size (mm) (i.e., the laser beam diameter at the laser material interaction). Thus, in order to regulate the amount of energy delivered to the substrate, the laser power, beam diameter, and traverse speed have to be adjusted. The melt puddle temperature and geometry (i.e., width, height, and length) can be regulated by automatically adjusting the laser power, powder flow rate, and traverse speed.

CNC Workstation

Conventional laser deposition systems employing three-axis positioning systems require support material to build overhang features of three-dimensional parts. This support material increases the part build time and may also lead to poor surface quality at the regions in contact with the part. Also, the part may need to be transferred to a machining center for further processing. Often it is difficult to machine the intricate or hidden features on the built part. To overcome these problems, the laser sub-system has been integrated with a five-axis CNC machining center. This allows the deposition and machining in a single set-up eliminating part reorientation. Also, the machining of intricate and hidden features can be conducted during the deposition process. The nozzle head is mounted on a vertical linear axis fixed to the Z-axis of the CNC machining center. The linear axis positions the nozzle head at the required stand-off distance when the deposition process begins; however, the Z-axis provides the vertical motion for the nozzle head during the deposition process. The linear slide moves the laser out of the way during machining processes. The X, Y, and Z, table positions and velocities are regulated via the CNC controller. Each linear axis is equipped with an optical encoder that provides position and velocity feedback.

Powder Delivery System

The powder delivery system consists of two hoppers that hold different materials with individual motors and feed-screws independently controlling the powder flow from each hopper. Thus, by regulating the flow of each material, a functionally gradient part can be built with the required composition. The powder coming out of the hopper is collected in a splitter, which uniformly distributes the powder into four tubes leading to the nozzle end. The specially-designed nozzle has annular openings to separate the powder from the shielding gas. Also, the nozzle end has been specifically designed to enable the powder to be delivered out at a specific angle to the vertical so that the focal point of the powder coincides with the focal point of the laser beam emerging from the nozzle. This allows maximum powder utilization during deposition. By regulating the speed of the individual motors, the powder flow rates of the individual hoppers can be regulated. Also, the powder flow angle can be regulated by varying the inner and outer shielding gas flowrates.

Control Hardware

The control hardware consists of a National Instrument (NI) PXI-8170/850 850 MHz real-time embedded controller with the following modules: multifunction board with eight 12-bit A/D and two 12-bit D/A channels, 48-bit digital I/O board, analog output board with four 12-bit D/A channels, a SCXI low pass filter board with Butterworth filters, and a two channel serial port board. The embedded controller and data acquisition and control boards are mounted on a NI PXI-1010 chassis. The real-time (RT) control system runs a set of monitoring, diagnostic, and control software programs (detailed below) on the NI Farlap real-time operating system. The applications are developed on the host PC using the NI real-time Labview programming tool and are downloaded onto the RT system for execution through Ethernet. The RT system enables the user to define the priority (low, normal, high) of the monitoring, control, and diagnostic programs being executed on the RT system. Thus, the RT system runs control algorithms, processes sensor data, and simultaneously communicates with the host PC to accept data from the user enabling deterministic, real-time performance.

MONITORING SYSTEMS

Process optimization requires the measurement and control of parameters such as the melt puddle temperature and geometry (i.e., width, height, and length). The use of vision, laser displacement, and temperature sensors integrated with the real-time embedded controller is discussed below.

Vision System

During the laser metal deposition process, the real-time measurement of the melt puddle geometry is needed to regulate the dimensional features of the bead by adjusting the control inputs (e.g., powder flowrate, CNC traverse speed). However, the bead morphology is not yet settled in the fusion zone as the melt puddle, at locally elevated temperatures, is still in a liquid form. Thus, it is necessary to measure the geometric information with a non-contact, non-invasive measurement technique.

The Complimentary Metal-Oxide Semiconductor (CMOS) camera, which satisfies the non-contact, non-invasive measurement requirement, captures the visible range of the electromagnetic spectrum. The laser metal deposition application requires scenes to be viewed and analyzed at high speeds and with very different light intensities (more than a 60 *dB* dynamic range – the ratio of largest nonsaturating input to smallest detectable input). This is a limitation of Charged Couple Device (CCD) based imaging systems. A CCD camera causes bright lights to bloom, creating unwanted streaks in the image. An embedded DSP processor-based intelligent machine vision system using CMOS technology is used to monitor the melt puddle geometry in real-time. The CMOS sensor offers a high dynamic range, up to 120 *dB*, making it possible to “see through” the bloom. This camera can achieve more than 300 frames per second for a window of 100 x 100 pixels. In computing the geometry of the melt puddle, a window of reduced size in the region of interest (ROI) was analyzed to achieve high sampling rates.

The camera is mounted on top of the nozzle with a beam bender so that it can be focused on the melt puddle during the process. The melt puddle images are processed on the DSP board to calculate the bead width and length. These parameters are sent back to the real-time controller through a serial port as input to the adaptive controller. The image processing procedure is as follows: 1) an 8-bit encoded image is captured, 2) a window of reduced size is transferred to the temporary memory of the onboard processing unit, 3) the image is converted into a binary format by the process of thresholding to eliminate the noise as much as possible, 4) encoded pixel values of the processed image are extracted and placed into a two-dimensional array, 5) an image processing algorithm uses the array to develop and extract the geometrical features of the melt puddle, and 7) the calculated parameters (i.e., width and length) are transmitted to the host PC through the serial port.

Laser Displacement Sensor

The vision system provides only two dimensions of the melt puddle. To determine the bead height, a laser displacement sensor (LDS), with a resolution of 1.5 μm and calibrated to a standoff distance of 80 *mm*, is utilized. The LDS emits a laser beam and detects the deflection in the reflected beam. The height of the deposited layer changes the standoff distance that, in turn, changes the output voltage. The change in voltage is proportional to the layer height.

Temperature Sensor

A non-contact dual-wavelength infrared temperature sensor, which operates at a $1.5 \mu\text{m}$ wavelength, is utilized to measure the surface temperature of the melt puddle. Dual-wavelength sensors tend to measure the hottest temperature viewed in the target area and provide automatic compensation for emissivity variations of some materials. The sensor is based on the principle that infrared energy emitted by an object is proportional to its temperature. The temperature sensor is focused on the melt puddle during the deposition process and outputs a voltage signal proportional to the maximum surface temperature.

Powder Supply

The powder flow rate and laser power govern the melt puddle dilution. The powder stream and laser beam have to be properly focused such that the powder is sufficiently heated and does not stick to the substrate during the process, leading to very low powder catchment efficiency. Unmelted powder particles in the melt puddle also result in an uneven temperature distribution that creates porosity and poor mechanical properties.

In order to cope with fluctuations arising in the carrier gas flow and corresponding changes in the powder spray geometry, an image analysis was performed to study the variations in the powder focal point for different inner and outer gas pressures. The principle is to realize image sequences of the powder stream at various carrier and protection gas flow rates. A sequence of images is averaged in order to remove unrepresentative features of the distribution. An adaptive thresholding algorithm is used to extract the cross section of the powder stream as shown in Figure 2. A manual procedure is used to obtain the optimal carrier and protection gas flow rates. The manual procedure involves the operator who has to measure the distance of the minimum width of the powder spray geometry from the tip of nozzle (using the PC mouse). The operator then measures the path and converts the value from pixel to mm using the constants obtained from the calibration procedure. High accuracy is not the main concern in this study, hence, no interpolation methods were used.

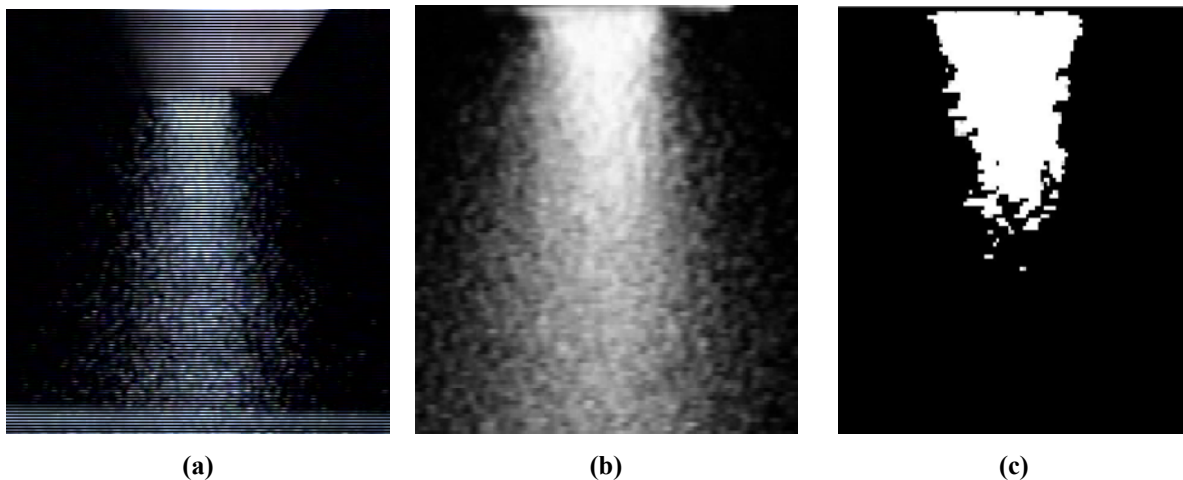


Figure 2: a) Powder Stream at the Nozzle Captured using a Strobe Light, b) Average of a Sequence, and c) Thresholded Image.

SOFTWARE ARCHITECTURE

The software architecture is shown in Figure 3. The process planning is conducted on the host PC. The process plan is sent to the interpreter. The interpreter decodes and executes the process plan one block at a time. Part of the process plan contains commands for the laser and powder feeder controllers. Other parts of the process plan contain machine tool code (i.e., G&M code) that is directly sent to the CNC controller where they are subsequently decoded and executed. The laser controller regulates the actions of the laser: turn on/off, select mode, etc. The powder feeder controller regulates the actions of the powder feeder: turn on/off and implement a control algorithm to maintain a constant powder mass flow rate. The data logging and processing software modules interface with the data acquisition and control boards to sense data and output commands to the various subsystems. The monitoring algorithms process the data and send it to the various software modules for diagnostics and control. The diagnostics and supervision system determines if there are faults in the system and what actions should be taken. This module also supervises the overall software system. Typically, constant process parameters (e.g., laser power, powder flow rate, CNC traverse speed) are utilized in the laser metal deposition process. However, the LAMP system is capable of advanced process control where these parameters are adjusted in real-time to regulate the process outputs (e.g., melt puddle geometry and temperature).

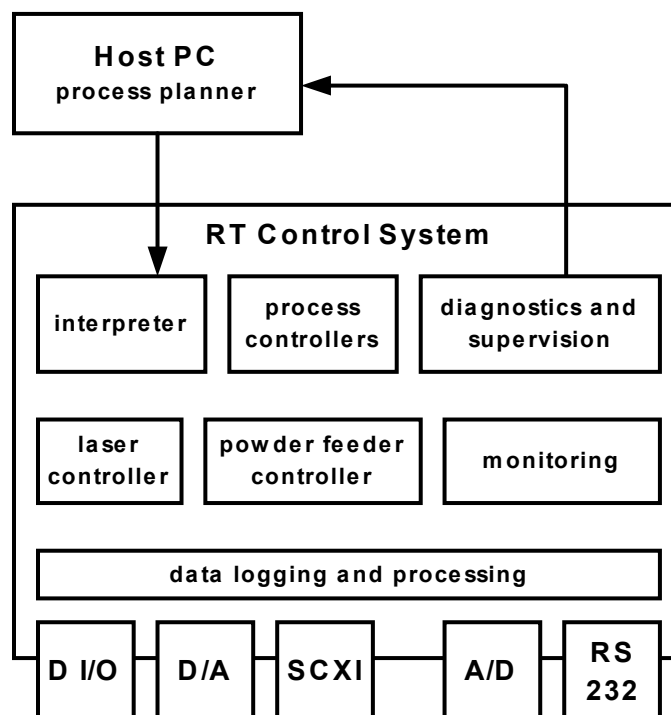


Figure 3: Laser Metal Deposition Process Software Schematic.

REAL-TIME CONTROLLER

As mentioned previously, bead height, bead width, bead length and average temperature of the melt puddle are the output parameters and are accessible for measurement in real-time. Laser power, CNC traverse speed, and powder flowrate are the inputs that can be adjusted to regulate the outputs. An analytical model was developed to relate the output parameters taking into

consideration the dynamics and nonlinearities involved in the laser metal deposition process. This model is based on mass balance, momentum balance, energy balance of the melt pool and the heat conduction in the substrate. Sensors (described above) are employed for real-time identification of the output parameters and feedback in a closed-loop geometry and temperature control system. A laser displacement sensor clamped behind the nozzle is used to measure the bead height. The temperature of the melt pool is obtained in real-time from the temperature sensor that is constantly focused on the melt pool. The CMOS camera mounted co-axially over the nozzle constantly monitors the melt pool. The images obtained from the camera are processed in real-time to obtain the melt pool length and width. The outputs from these sensors are used as feedback to a controller that regulates them to the specified/reference values by modulating the process inputs parameters. Also, the dynamics involved in the powder feeder and X, Y, and Z-axes of the CNC is taken into consideration. A Smith Predictor-Corrector algorithm is used to account for the delays due communication of the CNC and vision system with the RT system via RS 232 ports and physical transport delay in the powder feeder. Multivariable control techniques are used to account for multiple control inputs and outputs, and parameter estimation is employed to account for process variability.

Off-line process planning, simulation, and tool path generation for the hybrid RP system allow the designer to visualize and perform part fabrication from the host PC. Using STL models, the Laser Aided Manufacturing Process Planner generates a description that specifies the contents and sequences of operations. The results consist of properly sequenced tool paths for both deposition and machining processes. The RT system, discussed above, downloads the part program (in G&M code) from the process planner on the host PC before the operation begins. Special G&M codes are utilized to control the laser and powder feeder sub-systems. The RT system interprets the G&M code during the operation. As discussed above, the RT system directly regulates the laser and powder feeder sub-systems. When a block of G&M code pertaining to the CNC machining system is encountered, the RT system downloads the G&M code directly to the CNC machining system. The off-line process plan only defines the general steps necessary to build a part and modifications may be necessary. The RT system monitors various aspects of the hybrid RP process, such as accumulated deposition height, to make on-line decisions as to the process state. For one layer of deposition, if the quality is not satisfactory, the RT system will stop downloading motion commands and upload the quality information to the process planner. Then, the process planner will generate motion codes or modify process parameters to repair or remove the layer. After the current layer is completed, motion codes are again downloaded and the hybrid RP machine continues to build the unfinished part; therefore, communication between the process planner and the real-time control system is important to guarantee deposition quality.

SUMMARY

This paper has discussed a hybrid deposition-removal manufacturing system being developed at the University of Missouri-Rolla. This hybrid system is novel in that complex, precision parts can be produced in one set-up. Also, the workstation has five axes of motion minimizing the need for support structures. The system consists of a laser system, five-axis CNC machine, and powder feeder system. The control hardware and software, monitoring system, real-time control architecture, and integration of various subsystems were described. The real-time control system

is capable of effectively monitoring and regulating the laser deposition process such that productivity and quality are maximized.

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