Design And Integration
Of A Laser-Based Material Deposition System

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ABSTRACT

This paper aims to demonstrate the design process of an integrated five-axis Laser-Based Material Deposition (LBMD) system for rapid prototyping application. Several design evaluation methods are selected and applied to the design of the system. A three-dimensional graphical simulation software package was used as a decision making aid and as an analysis tool in the design process. Hardware integration of a five-axis computer numerical controlled (CNC) vertical milling machine, a 2.5 KW Nd:YAG laser and a linear table is discussed. A brief introduction to the system software and control architecture is also summarized. Some important design issues and considerations specific to Laser Based Material Deposition process are suggested.

Keywords: *Design methodology, System Design and Integration, System Simulation, Laser Based Material Deposition, Collision Detection, Tool Path Verification*

1. INTRODUCTION

Since the introduction of the first commercial stereolithography apparatus in 1986, many rapid prototyping (RP) systems have been developed for the ever growing industrial demands for shorter product development cycle time and at significantly reduced costs [1]. Most of the commercial RP units at that time however, were either limited to non-metal fabrication with minimal accuracy and precision or constraint to produce relatively simple parts for physical visualization of design concepts. Some of the developing systems were capable of producing direct metal prototypes. However, the commercial units still require polymer RP molds from which metal castings are formed [2].

The increasing complexity of certain parts geometry imposed by many advanced applications making the production of highly accurate functional model directly from CAD data very difficult or impossible using the available RP systems. Arising from this, many systems have been proposed. The LENS (Laser-Engineered Net Shaping) process has demonstrated the feasibility to produce near net shape metal part [3,4]. Others have tried to utilize the existing laser cladding technique, an established laser surface coating of metallic parts, to produce metal parts by layer additive approach [2,5].

This paper describes the design and integration process at the early development stage of a Laser Based Material Deposition process at the University of Missouri-Rolla, USA. A few design evaluation methods, including a graphical simulation software were employed to assist in decision making. The LBMD system consists of a 5-axis CNC machine, Nd:YAG laser and a linear table put together to work as an integrated system.

2 DESIGN AND INTEGRATION PROCESS

A survey on Laser Based Material Deposition was conducted in order to understand the process and other related issues [6]. Three design concepts were proposed as shown in figure 1, figure 2 and figure 3. The first design as shown in figure 1, integrates a 3-axis CNC milling (X,Y and Z), a 2-axis rotary table (tilting about X, rotating about Z) and a single axis linear actuator (slide up and down along Z axis) that carries the laser and powder delivery nozzle. A rigid support structure is constructed above and spans across the CNC assembly. The laser powder nozzle is attached to this support bar. This design concept provides a stable and rigid support for laser and powder assembly and thus minimizes vibration.

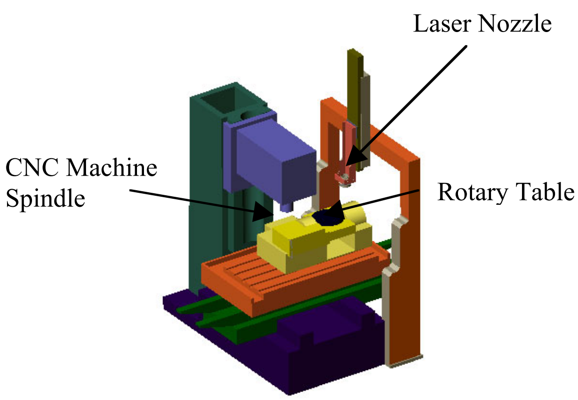


Figure 1 : Design Concept I.

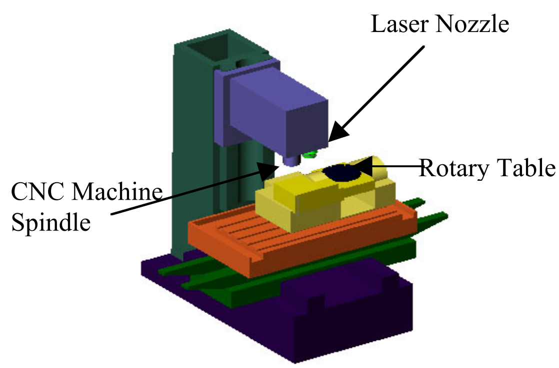


Figure 2: Design Concept II.

In design concept II as shown in Figure 2, a different design concept is proposed. The laser and powder delivery nozzle is attached to the CNC machine head assembly besides the machine spindle. This design integrates a 3-axis CNC milling machine, 2-axis rotary table and a single axis laser and powder nozzle. No support structure as in design I need to be constructed. Initially, this design is thought to be better because it eliminates the support structure for the laser and powder nozzle and does not require additional motion axis for the system. However, the cost of putting the laser nozzle to the CNC machine head assembly will be significantly large. Vibration from the machine spindle during machining process could cause misalignment of laser optic just next to it. Laser optics are also exposed to contamination from metal chips and also coolant. Chances of collision between work piece and the machine spindle and also between work piece and laser nozzle increases during rotation or tilting of work piece.

In concept Design III as shown in Figure 3, a cantilevered support with retraction and extension arm, where laser and powder nozzle is attached to, is proposed for the system. The laser and powder nozzle can be extended to the work area during metal deposition and they can be retracted to a safe location during machining process. This feature is hoped to protect the laser optics from metal chips and contaminants within the vicinity of the work area. However, accuracy could be jeopardized due to deflection in the cantilever arm and cumulative displacement error from the frequent retraction and extension of the cantilever arm. Also, to have this feature, two linear actuators are needed and considering the load and moment the beam will carry, achieving a higher displacement accuracy (0.001") becomes impossible. With the design configuration in concept design III, the total axis of control would be increased to 7. This is not desirable because it makes integration and controls of the system more complex. Synchronization and motion control of all the individual components is critical to part quality. Therefore, a simple system, but capable of good motion control is desirable.

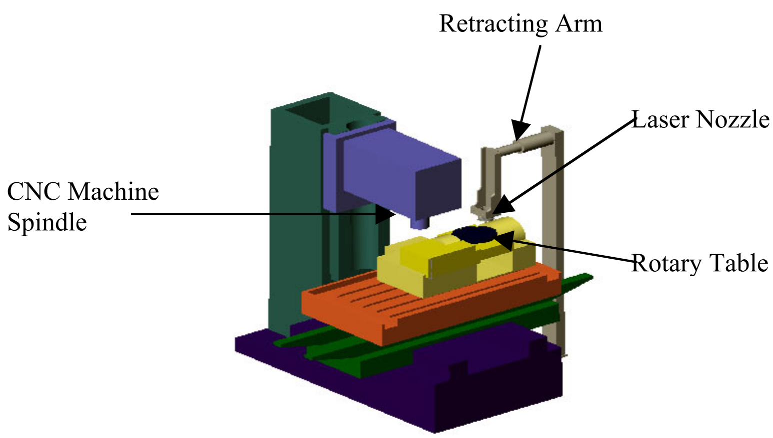


Figure 3: Design Concept III

Two methods were used in design evaluation process. The first method utilizes concept evaluation matrix to compare each design to a selected datum concept. This method provides three levels of comparison: "better than (+) ", "the same as (S) " or "less/worst than (-)" the datum. A set of evaluation criteria was established. Table 1, Table 2 and Table 3 shows the evaluation matrix for each concept. Based on this evaluation, design concept I is the most feasible option. The second method uses a scale from 1 to 5 to further evaluate the design. Table 4 shows the scores for each design. This method assigns quantitative score to each concept and we can rank the concept, as well as each criterion from the highest to the lowest score. The highest score means the best and the lowest is the least/worst. From the second evaluation method, concept I carries the highest score. Concept design I is finally selected for further analysis. The LBMD system would fabricate parts by combination of material addition (laser material deposition) and material removal (CNC milling to correct deposition errors).

Table 1: Concept Evaluation Matrix Using Conceptual Design I as DATUM

	Concept		
Criteria	**1**	**2**	**3**
Positioning accuracy of the system	D	S	_
Repeatability of the system	A	S	_
Ease of system operation	T	+	S
Ease of maintenance of laser and powder	U	_	S
Protection of laser alignment from vibration	M	_	+
Protection of nozzle and laser from		_	_
Simplicity of Integration	D	+	S
Simplicity of Synchronization	A	+	S
User safety from Laser	T	S	S
Ergonomics (user movement and interaction)	U	S	S
Minimum axis of control	M	+	S
Working volume		S	_
Rigidity and stability of nozzle support	D	+	_
Overall estimated cost for the system	A	_	S
Adaptability to multi material deposition	T	_	_
Online process control implementation	U	+	_
Score	M	6+, 5-, 5S	1+, 7-, 8S

Table 2: Concept Evaluation Matrix Using Conceptual Design II as DATUM

	Concept		
Criteria	**1**	**2**	**3**
Positioning accuracy of the system	S	D	_
Repeatability of the system	S	A	_
Ease of system operation	_	T	_
Ease of maintenance of laser and powder	+	U	+
Protection of laser alignment from vibration	+	M	+
Protection of nozzle and laser from	+		+
Simplicity of Integration	_	D	_
Simplicity of Synchronization	_	A	_
User safety from Laser	S	T	S
Ergonomics (user movement and interaction)	S	U	S
Minimum axis of control	_	M	_
Working volume	S		S
Rigidity and stability of nozzle support	_	D	_
Overall estimated cost for the system	+	A	S
Adaptability to multi material deposition	+	T	+
Online process control implementation	S	U	_
Score	5+, 6S, 5-	M	4+, 4S, 8-

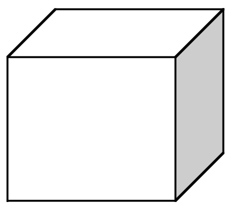
Table 3: Concept Evaluation Matrix Using Conceptual Design III as DATUM

	Concept		
Criteria	**1**	**2**	**3**
Positioning accuracy of the system	+	+	D
Repeatability of the system	+	+	A
Ease of system operation	+	+	T
Ease of maintenance of laser and powder	S	_	U
Protection of laser alignment from vibration	S	_	M
Protection of nozzle and laser from contaminants	S	_	
Simplicity of Integration	S	+	D
Simplicity of Synchronization	S	+	A
User safety from Laser	S	S	T
Ergonomics (user movement and interaction)	S	S	U
Minimum axis of control	+	+	M
Working volume	S	S	
Rigidity and stability of nozzle support structure	S	+	D
Overall estimated cost for the system	+	_	A
Adaptability to multi material deposition	+	_	T
Online process control implementation	S	+	U
Score	6+, 10S	8+, 5-, 3S	M

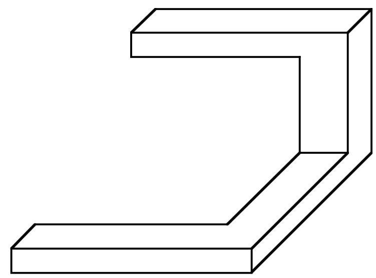
Table 4: Concept Evaluation Using Quantitative Scale (scale 1 – 5)

	Concept		
Criteria	**1**	**2**	**3**
Positioning accuracy of the system	3	5	2
Repeatability of the system	3	4	2
Ease of system operation	4	3	3
Ease of maintenance of laser and powder	4	2	3
Protection of laser alignment from vibration	5	1	4
Protection of nozzle and laser from contaminants	5	2	3
Simplicity of Integration	4	2	3
Simplicity of Synchronization	4	5	3
User safety from Laser	3	4	3
Ergonomics (user movement and interaction)	3	4	3
Minimum axis of control	4	4	2
Working volume	4	2	3
Rigidity and stability of nozzle support structure	4	3	2
Overall estimated cost for the system (least is best)	5	2	4
Adaptability to multi material deposition	4	2	3
Online process control implementation	4	3	4
Score	58	49	47

To further refine the selected design, a three-dimensional graphical simulation software was used to identify the suitable working volume for the system for two different fabrication situations; (i) simple fabrication with no part rotation and tilting and system is required to do vertical buildup only, (ii) more complex fabrication requiring part rotation and tilting and the system is depositing in the vertical direction. For both conditions, work perimeter of 12” x 12” x 12” and 8”x 8”x 8” were simulated. CNC codes were written to instruct the system to perform tool movement to cut the peripheral of the specified work perimeter, and any obstruction or collision was recorded. Simple movement is represented by a cube, while a more complex movement is represented by a part with overhang as illustrated in figure 4(a) and figure 4(b).



(a) Cube representing simple vertical buildup



(b) Part requires rotation and tilting

Figure 4: Representative objects for tool path and work volume verification

From the simulation results, the 12” x 12” x 12” work perimeter had demonstrated some collisions for rotating and tilting movement, while the 8” x 8” x 8” work perimeter had shown no collision for both simple and rotate-tilt movements. The results are presented in Table 5. Major hardware components of the system is shown in Table 6

Table 5: Simulation Results for 12” x 12” x 12” and 8” x 8” x 8” work volume

Work Envelope Representations	Deposition Process	Milling Process
Perimeter (12” X 12” X 12”)	• No collision	• No collision
With rotation and tilt (12” X 12” X 12”)	• Collision between part and rotary table base	• Collision between part and rotary table base • Collision between part and machine column.
Perimeter (8” X 8” X 8”)	• No collision	• No collision
With rotation and tilt (8” X 8” X 8”)	• No collision	• No collision

Table 6: Major Hardware Components of LBMD System

Component	Sub-Components	Primary Functions
5-axis CNC Machine	2-Axis Rotary Table	• Rotation and tilt motion • Work table for the system
	3-Axis milling machine	• X, Y and Z motion • Controls all axes motion
Powder and Laser Delivery System	Powder Storage Hopper	• Store metal powder • Releases powder to powder feeder unit
	Powder Feeder Unit	• Feeds powder into nozzle • Controls powder flow rate
	Powder and Laser Nozzle	• Deliver powder to melt pool • Deliver protection and carriage gas
	Laser Head	• Holds laser focus lenses
	Gas Supply System	• Provide Protection and Carriage gas
	Fiber Optic Cable	• Deliver laser beam to focus lenses
1-axis Linear Table	Way cover	• Protect Linear table from contaminants (dust and moisture)
	Motor and Encoder	• Provide Linear table motion • Closed loop control for linear table

4 SOFTWARE AND CONTROL SYSTEM

Typical software architecture for a Laser Based Material Deposition includes the modeling of a three-dimensional CAD model in standard Stereolithography (STL) format, generation of layer representation of the object which is equal to the deposition thickness, and creation of CNC codes for the tool path that are understandable by the machine controller [3,4,7]. The system architecture for the LBMD system is illustrated in Figure 5.

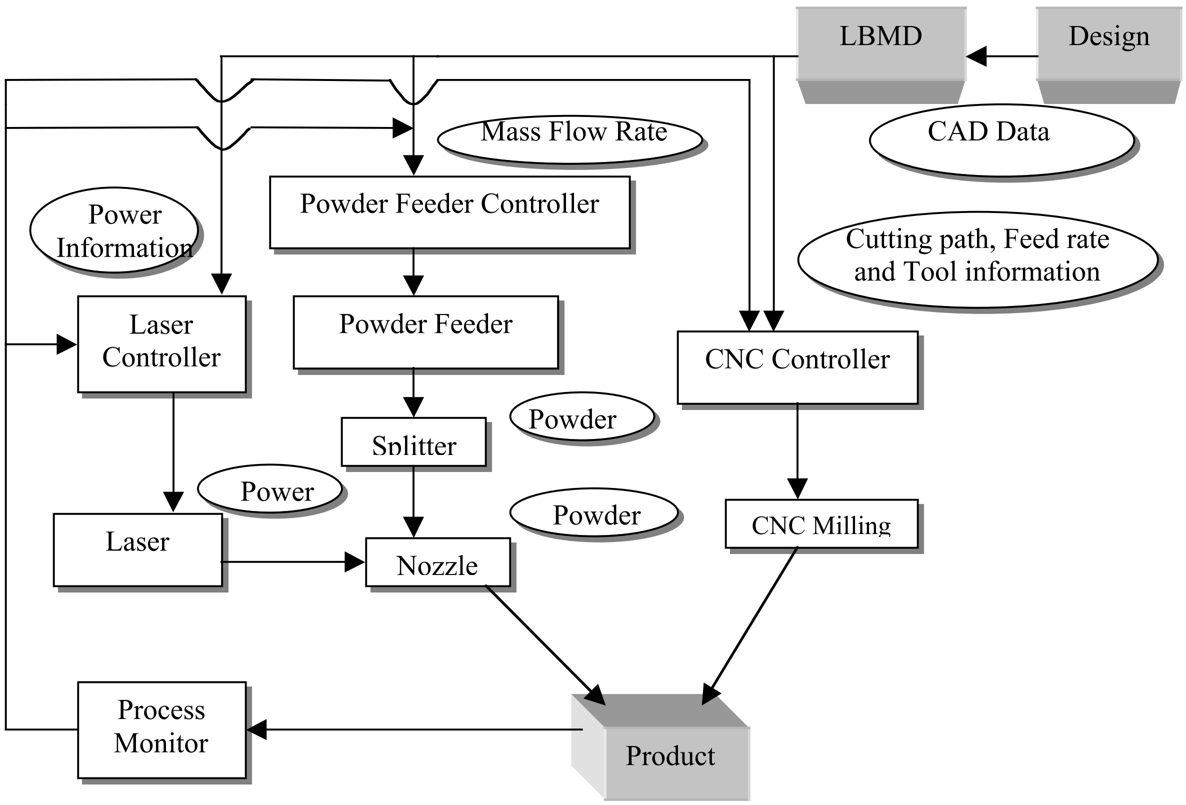


Figure 5: System Architecture [8].

5 CONCLUSIONS

Design and integration process of a Laser Based Material Deposition System have been presented and a LBMD system is proposed. A three-dimensional graphical simulation has been applied and proven to be a useful tool in the development of the LBMD system. A few important considerations in the design and integration of the system include the following: (i) system performance – high accuracy and precision, stable powder and power delivery, online control and monitoring. (ii) high temperature working environment – nozzle made of high temperature material and equipped with cooling system. (iii) protection of optical lenses or any sensitive components from moisture and dust or easily cleaned and replaceable. (iv) safety – laser radiation, metal powder, coolant mist and dust. (v) maintenance – laser alignment check should be minimize, ventilation system is needed to properly disposed contaminants (metal powder, coolant mist, dust) out of the system

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