Design of a Prototype Selective Laser Sintering System for Process Parameter Optimization

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Abstract

Selective laser sintering (SLS) is an additive manufacturing process that builds three dimensional parts layer by layer by fusing a powder. A high power laser follows a tool path to fuse the powder and produce the 3D part. This work develops a prototype SLS system which will be used to improve SLS-fabricated part quality in terms of porosity and surface roughness. First the prototype SLS system is designed for laboratory use. Design parameters include layer thickness, forward step size, side step size, laser power, and laser spot size at the powder bed. Porosity and surface roughness are estimated for sample parts representative of SLS applications.

Keywords
Selective laser sintering, additive manufacturing, rapid prototyping, porosity, surface roughness

1. Introduction
Selective laser sintering (SLS) is a rapid prototyping technique in the domain of additive manufacturing (AM). Unlike traditional manufacturing (TM) which relies on the subtraction of materials during manufacturing processes such as milling, AM processes rely on the addition of material through techniques such as fused deposition or selective laser sintering. TM methods may include cutting, machining, drilling, deep drawing, grinding, these methods are inherently wasteful because the process produces parts by removing material from a workpiece. In addition, the TM produces complex shapes by using rivets, screws and welding processes to combine subparts (Gibson, Rosen, & Stucker, 2010). AM technology can reduce total cost by reducing tools and other costly manufacturing processes. Complex shapes can be produced with simple tool paths and unused material can be reused. In the last decade, the AM technique has been used in wide fields because it can process many types of metals. As a result, AM technology has been embraced by the prototyping industry in order to rapidly produce parts in low volumes. Small to medium volumes of metal components can be produced quicker and cheaper than TM. In addition, AM technology can reduce the weight of products and produces complex pathways for cooling system. The SLS technique is a nontraditional manufacturing technique, and our world need this technique because the SLS technique can produce parts by using different raw materials, such as steel, ceramic, titanium, nylon, steel, titanium, alloy mixtures, and green sand. Some conditions should be considered before start using the SLS method to produce parts, such as production volume, mechanical properties, life cycle, geometric features, production time, production cost, and surface finish. (Kruth, Vandenbroucke, Vaerenbergh, & Mercelis, 2005).AM techniques can produce simple and complex products from digital models, for this reason it is sometimes called digital manufacturing.

The literature contains many works related to this research. Printing accuracy, and related finished part quality, is a function of many different parameters, such as layer thickness, laser power and scanning strategy (Urmoneit, Hotz, Frohlich, & Kraub, 2014; Luo & Tzou, 2004; Kruth, Vandenbroucke, Vaerenbergh, & Mercelis, 2005). Distortion, shrinkage and warping are major defects that affect the part quality. The amount of shrinkage depends greatly on the laser power, layer thickness, and scanning speed (Zaragoza-Siqueiros & Medellín-Castillo, 2014). Material selection also contributes. Some researcherss studied polymeric and metallic materials, polymer and metal powders to produce parts (Song & Koenig, 1997; Shahzad, et al., 2012; Shahzad, Deckers, Kruth, & Vleugels, 2013). Tool path generation is also strongly correlated with build time, surface quality, cost, defects, and mechanical properties of the part.(Jin, Li, Tsai, & Wang, 2011; Jin, Li, Gao, & Popplewell, 2013). Finally, laser and powder interactions are

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significant and may limit laser selection based on desired materials (Kruth, Levy, Klocke, & Childs, 2007; Simchi, 2006; Murali, et al., 2003).

The paper investigates the design and construction of a protoytype of SLS system for future use in parameter optimization. Based on the literature, it is known that design parameters of the SLS system, such as step size and laser selection, contribute to porosity and surface roughness. In addition, process parameters, such as material selection, laser spot intensity, powder bed temperature, shielding gas, and process speed will have large impacts. This work is a first step towards systematically evaluating the effects of these design and process parameters on part quality, as measured by porosity and surface roughness.

This paper is organized as follows. Section 2 discusses SLS variables that effect on the part quality. Section 3 is the design of SLS system. Section 4 describes the plan for system validation. Section 5 concludes the work.

2. Selective Laser Sintering

SLS is a method used to fuse the particles by scanning a laser across powdered material in the shape of the desired part. After melting the first layer, the powder bed moves down and a new layer of powder is distributed on top of the first layer. The powder bed may be heated to reduce part defects and reduce the required laser power (Medellín-Castillo & Torres, 2009; Gusarov, Yadroitsev, Bertrand, & Smurov, 2009; Rochus, et al., 2007). Fig. 1 shows the a schematic representation of an SLS system. A powder feeder mechanism moves horizontally to distribute new powder, a piston carries the powder bed up and down to maintain a fixed distance between the laser and the top power layer, and the laser moves on the XY plane. The SLS system has a controller to coordinate sensors and actuators as well as to prepare the system for operation by zeroing axes, warming the powder bed, etc. (Evans, 2012).

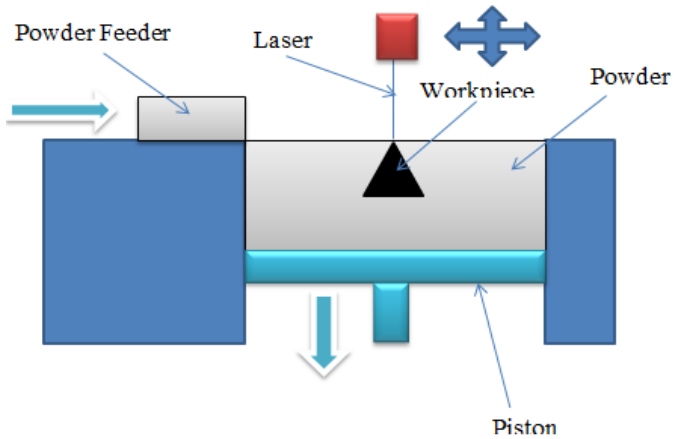


Figure 1. SLS process and equipment (side view)

The steps use to produce 3D parts by using the SLS technique are shown in Figure First a 3D part is designed using commercial CAD software. The model is oriented for optimal printing and then sliced into layers consistent with the resolution of the SLS system, finally the model will be a series of 2D layers that use to produce a part by AM systems (Zhou, 2014). An interface program can read a 3D object codes and system actuators. The interface program will control the actuators and sensors that will build the 3D objects according to the codes received from a 3D simulation program, and the code SLS has all dimensions of 3D part, positioning, and other manufacturing information (Evans, 2012).

2.1 Tool path planning

The tool path is considered the laser trajectory that will be used to produce the 3D part. The tool path selected has a large impact on part quality, including porosity and surface roughess. Tool paths fall into two classifications: internal and external. Internal tool paths fill the part interior while external tool paths create the part surface and contribute directly to surface roughness. The additive processes focus on internal path to define better forward step and side step of the tool to complete all the internal volume of the 3D part. The tool path variables are considered because these variables will effect on mechanical properties and a quality (Zaragoza-Siqueiros & Medellín-Castillo,

2014). Figure 3 shows common types of the tool paths, including zig zag, zig, isoparametric, isoscalop, and smooth zig zag.

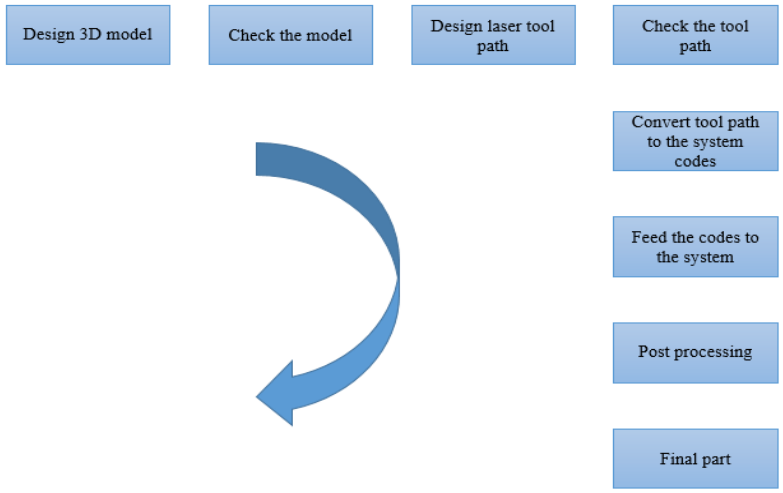


Figure 2. Process for production of a part using the SLS technique

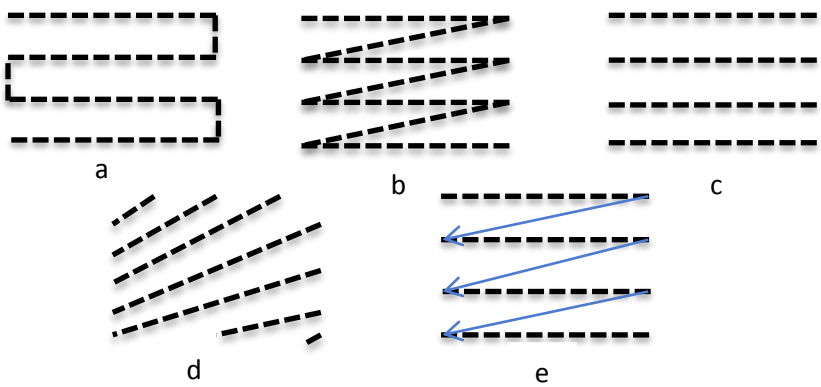
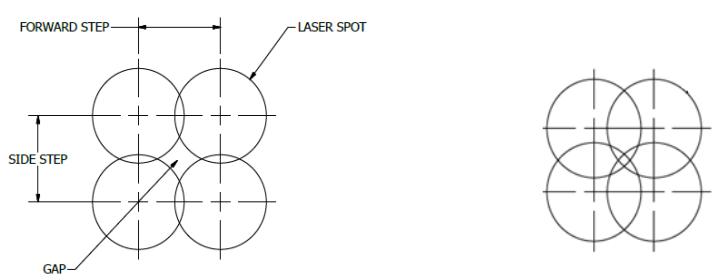


Figure 3. Tool path types: (a) Zig Zag. (b) Zig. (c) Isoparametric. (d) Isoscalop. (e) Isoparametric-Zig

Figure 4 is for forward step and side step, and called approximation forward step and side step, that means when increasing forward step and side step that will produce a gap between laser points, and this gap will increase or decrease depending on the forward step and side step. So, tool path approximation cannot produce part has good quality.



(a) (b)

Figure 4. Forward step, side step and gap of laser spot (a) Approximation spot (b) Interpolation spot

2.2 Surface finish

Surface roughness value (Ra) is a measure of part surface finish. For the SLS process, Ra depends on the building orientation, layer thickness, and post-processing. The theoretical calculation of the roughness depends on the method is called "staircase", this method calculates roughness of repaying prototyping depending on surface angle and the layer thickness. The average surface roughness (Ra) can be estrimated by estimate; by (Zaragoza-Siqueiros & Medellín-Castillo, 2014):

$$\mathrm{Ra} = \frac{L}{2}\left|\frac{\cos(\theta-\phi)}{\cos\phi}\right| \quad (1)$$

Where L is the layer thickness, θ is the surface angle, and ϕ is the profile surface angle as seen in Figure 5. The proposed guidelines of surface finish are calculate surface roughness theoretically, and determine layer thicknesses, and use surface angles close to 90° should be used to get surface roughness. (Zaragoza-Siqueiros & Medellín-Castillo, 2014)

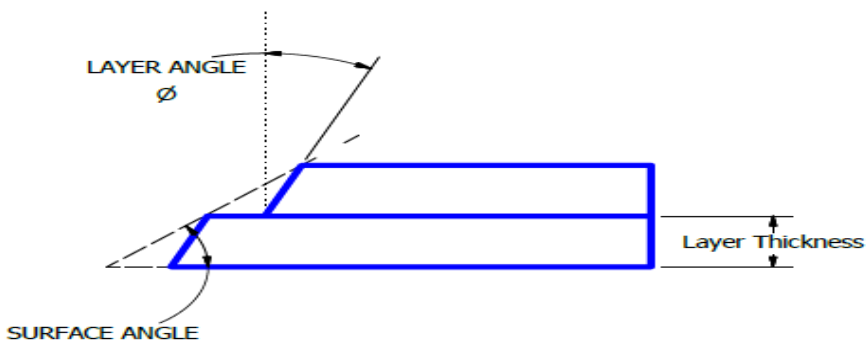


Figure 5. Surface roughness parameters in RP systems (Zaragoza-Siqueiros & Medellín-Castillo, 2014)

Sometimes during sintering process produces expansion marks between layers, this expansions marks lead to high roughness and porosity because the powder sintering happens close to powder melting point and gaps between particles will produce porosity, this happens because of unsintered powder.

2.3 Porosity

A porosity is a lot of spaces in a part that has produced because the unstable manufacturing process, and the reason of creating porosity because interactions between metals and manufacturing surrounding or a powder not full melt during manufacturing. One of the rapid manufacturing that produces a high porosity inside structure of the party is SLS technique, the researchers studied the SLS processing parameters that affect the part properties, such as hardness, surface roughness, strength, etc. The porosity makes the final part be weak, so for this reason in the manufacturing process by using the SLS method trying to reduce porosity in the partition structure to increase a part quality. There are a lot of parameters that can increase or decrease the part porosity, such as step size (forward step and side step), laser beam diameter, laser power, scanning speed, and layer thickness. In addition, during sintering processes should consider heat generated to melt the powder because this will be effective on the surface roughness One of very common defects during the SLS process is a porosity, so this defect make the 3D part will be weak and not tough. To avoid the porosity during the SLS process should consider a particular height and width of one step of laser that has met a powder after applied a high power, the ratio between width must be bigger than height 5 times. (Zaragoza-Siqueiros & Medellín-Castillo, 2014; Davim, 2012).

3. Prototype Design

Before starting design any system should determine what is the purpose of this system, which problems this system can solve it, what are the specifications required to get the target of this design. Figure 4 explains the research steps. This research focuses on increase an accuracy of the SLS system, so the problem of this research is a resolution. The second step is specifications, such as forward step, side step and layer depth. The system components will pick them up depending on the previous steps, and after picking up the components and assembly process of the SLS system, the validation process will check the system specifications and the system will change to reach the required resolution.

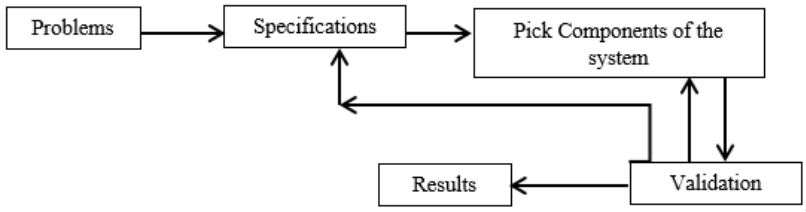


Figure 4. Research flowchart

Some systems work on number of axis, these axis will increase or decrease depending on the system's work and purpose that designed for it. In this research, the system is designed for working with 4 axes, first axis is X direction, second axis is Y direction, third axis is Z direction and fourth axis is for powder distributor. Table 1 shows the theoretical specifications of the SLS system.

Table 1. Specifications of the prototype SLS system

Structural Material	Steel
Motor Type	Stepper motor
Communications	USB
File Formats	G-Code
Table Dimensions (mm)	152x152
Travel Dimensions	240x240x70
Operating speed (RPM)	56.667
Max. Speed (mm/s)	0.566
Max. Acceleration (mm/s^2)	0.7487
XY-Direction (Forward Step & Side Step)	
Required resolution for forward step and side step (mm/step), mm	0.003
Operating pulses (pulse)	200
Z-Direction (Layer Depth)	
Required resolution (mm/step)	0.003
Operating pulses (pulse)	200
Part Production	
Max. Roughness (Ra) mm	0.51
Total time (s) for one layer 30mm*30mm	752

In this section the elements of the prototype SLS system will be described. These include the frame, laser, gantry system for moving the laser, powder distribution system, and electronic control system.

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3.1 Laser

Many commercial SLS machines use CO_2 lasers (10.6 pm wavelength) ranging from 20 to 50 W. Diode lasers have been applied by UMIST to sinter CulSn powder (60 W CW laser operating at 810 nm) and by ILT in Germany (Kruth, Leu, & Nakagawa, Progress in Additive Manufacturing and Rapid Prototyping, 1998). For this prototype SLS system, a 10 W laser at 450 nm is used. Operating at lower power than commercial systems reduces available materials but is less expensive to purchase and operate and is safer for student use in a laboratory. A lens with a custom fabricated lens holder is used to focus the laser beam to achieve the required melting depth. The laser is mounted to the gantry system.

A high power laser applied to the powder material surface produces two zones. The upper zone will be liquid and lower zone will be solid, as shown in Figure 5. The laser beam should be wider than the molten zone and depth of the laser also should be deeper than the thermal penetration depth to get appropriate melting of the powder and make interference btween a new layer and previous layer. Surface temperature increase due to laser irradiation on thermo-physical parameters of solid and liquid phases during melting process (Davim, 2012). The laser power needed to fuse the powder is calculated using

$$T_w\,(t) = \frac{A_s I}{K_s}\,\delta\,(t) \tag{12}$$

where $T_w\,(t)$ is surface temperature, A_s is Absorptivity, I is power density of laser beam, $K_s$is thermal conductivity and $\delta\,(t)$ is a temporal function representing the temperature penetration depth in the solid. Based on the necessary surface temperature for the selected material, necessary laser intensity is derived.

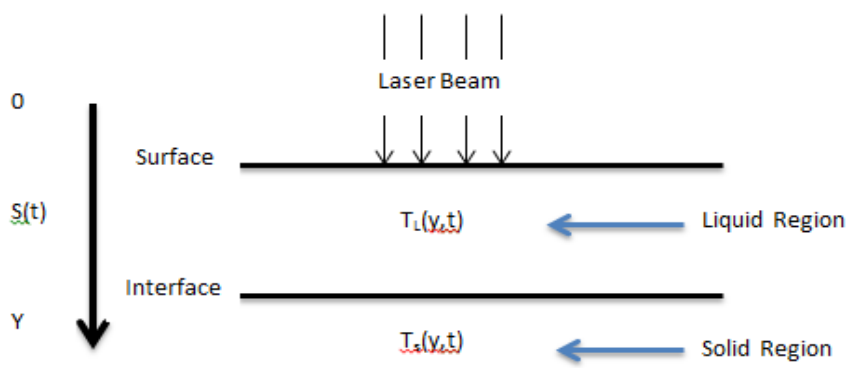

Figure 5. The geometry of laser irradiation (Davim, 2012).

The reasons of using a laser in the AM are providing high power energy and can move quickly, the laser uses in AM to melt a powder, but there is a relationship between laser and powder, so before pick up a laser should study and calculate laser power depending on a powder type that will melt. Therefore, the required laser to melt the powder will change depending on the thermal properties of powders. The power laser W/ mm^2 has been calculated depending on powder specific heat capacity KJ/kg K; powder melting temperature c^o; powder density g/mm^3; power thermal conductivity w/mk; powder thermal diffusivity, m^2/s; absorptivity; temperature of the powder surface k; processing times; and temperature penetration depth m.Laser lens use to focus the laser beam and change a laser spot size, that means make it smaller or bigger, this because sometimes very hard to find a laser beam diameter exactly depending on what the researchers calculate. A lens can reduce time and total cost to get a proper laser beam diameter. In this project has been used a lens to focus laser beam diameter from 4mm to 0.3 mm. The specifications of the lens that has used in this research are: The lens diameter (9 mm), effective focal length EFL (90 mm), back focal length BFL (88.68mm), radius R1 (46.51 mm), edge thickness ET (1.78 mm) and center thickness CT (2 mm), as shown in Figure 6.

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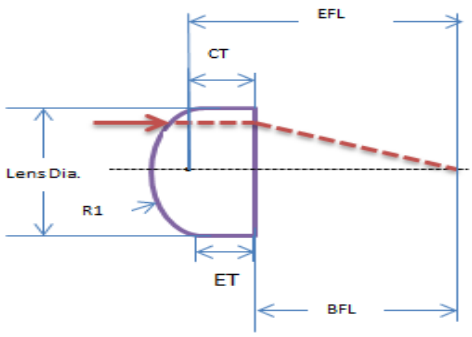

Figure 6. 9.0mm Dia. X 90.0mm FL lser lens

3.2 Frame and gantry

The prototype SLS system uses a 20” x 20” x 20” single frame built from a combination of steel structural components and plastic components printed using a fused deposition process. Four axes are defined: X, Y, Z and A. The XY plane is the horinzontal plane in which the laser moves. The Z axis corresponds to the layer depth of the powder. The A axis refers to the linear motion of the powder distribution. Rendered views of the prototype SLS design are shown in **Error! Reference source not found.**. **Error! Reference source not found.** is the bill of materials for the prototype SLS system.

Table 2. Bill of material for prototype SLS system

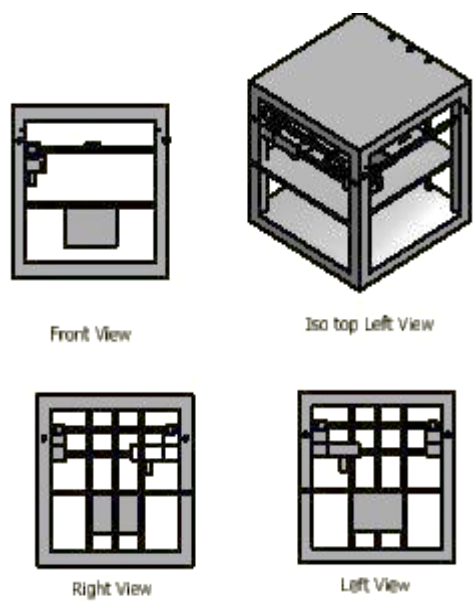

Figure9. SLS system views

The gantry system can be driven with either a flexible belt drive or a ball screw drive, as shown in the following sections. In either case, it is assumed that for each movement of the gantry, only a single axis is actuated at a time and that each movement will require both an acceleration and a deceleration period. The entire time to move from one position to another is called the positioning period and the operating patter for speed versus time is shown in Figure

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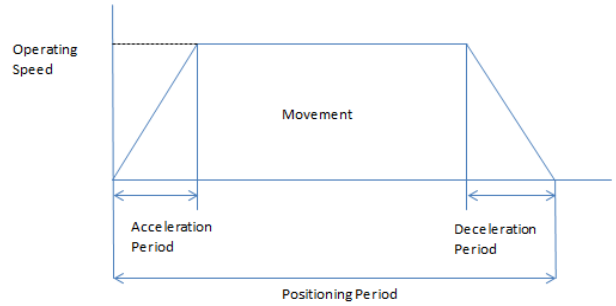

Figure 10. Gantry crane operating pattern for speed versus time

3.3 Flexible Belt Drive and Ball Screw Drive

The accuracy in the automation system is an important point for the system specifications. The accuracy in of SLS system means forward step and side step in X and Y direction respectively. In this project, the resolution and minimum accuracy will calculate by using eq. 5. Furthermore, eq. 8 is operating speed value is one of the steps that is required to feed to the SLS system, and it will calculate from eq. 8, but before calculate the operating speed should calculate required resolution and an operating pulses be calculate form eq. 6 and 7 respectively.

The accuracy means in this research is the minimum movement can the SLS system produce in X, Y and Z directions, and the required accuracy is the variable values needed to get specific properties of a 3D part after feed them to the SLS system, and the minimum accuracy determines depending on the specifications of the subsystem.

$$\text{Forward step/side step resolution per pulse } (\Delta l) = \frac{\pi.\ D}{360^{\circ}} \cdot \frac{\theta_s}{i}\ \text{mm/step} \tag{5}$$

$$\text{Required resolution} = \frac{360^{\circ} * \Delta l}{DP * \pi}\ {}^{\circ}/\text{step} \tag{6}$$

$$\text{Operating pulses } (A) = \frac{l}{DP} \cdot \frac{360^{\circ}}{\text{Required resolution}}\ \text{Pulses} \tag{7}$$

$$\text{Operating speed (RPM)} = \text{Operating pulse speed} . \frac{\text{Required resolution}}{360^{\circ}} \cdot 60 \tag{8}$$

For use of a ball screw in place of a flexible belt, equations 9 and 10 are for ball and screwdriver, fist equation shows the minimum resolution in X and Y direction and second equations is for better pulses for the stepper motors.

$$\text{Plate resolution } (\Delta l) = \frac{PB}{360} \cdot \frac{\theta_s}{i}\ \text{mm/step} \tag{9}$$

$$\text{Operating pulses } (A) = \frac{\text{Feed per unit}}{\text{Ball screw pitch}} \cdot \frac{360^{\circ}}{\text{Step angle}}\ \text{pulses} \tag{10}$$

Step response is the time behavior of system output, the input changes from 0 to 1, the idea can extend to get the mathematical parameters of the system that use to analyze and understand an operation system. The overshoot is the maximum value of the oscillation of the step response signal. The settling time is "the time for departures from final value to sink below some specified level, say 10% of final value". (Ogata, 2010). Figure 11 shows the step response of the gantry system that has been calculated from eq. 11 after converting the gantry system to a transfer function, where b is viscous friction coefficient, k is the spring constant and m is mass. In this research has been used two types of the gantries are belt drive and threaded bar-nut, the oscillation increases with the belt drive. In addition, table 2 is a comparison between two types of the gantries throughput. The results of threaded bar-nut are better than belt drive.

$$G(s) = \frac{bs+k}{ms^2+bs+k} \tag{11}$$

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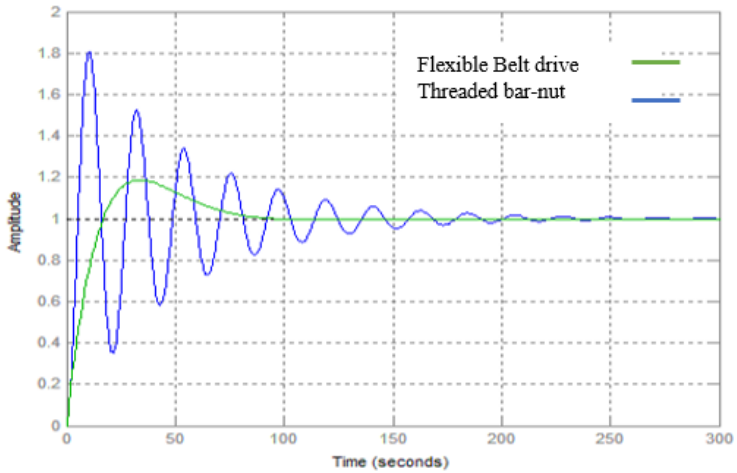

Figure 7. Step response of simulated gantry system with flexble belt drive and ball screw drive

Table 3. Step response paramerers for flexible belt drive and ball screw drive

Response Parameter	Flexible Belt Drive	Ball Screw Drive
Peak Amplitude	1.81	1.19
Overshoot (%)	80.5	18.5
Time (S)	10.8	34.1
Settling Time	195	78.4
Rise Time (S)	3.67	12.7

3.4 Powder Distribution Mechanism

The powder distribution mechanism consists of powder feeder and one piston. The powder feeder has a container that is filled manually. The powder feeder moves horizontally to distribute fresh powder onto the SLS working surface. The second part of a powder distribution mechanism is the piston driven vertically by a lead screw. The piston carries the working surface. When the first layer of powder on the working surface is fused by the laser, the piston moves the working surface down and the power feeder spreads a new layer of powder on top of the completed layer.

4. Prototype Validation

The validation process is responsible to check the mechanical or electrical systems that designed to produce a part. It checks, update, study and calibrate all parts a system to prove the system specifications. The checking operation of the SLS system during running includes: frame and gantry system, stepper motor and end stop, distribution powder system and table feeder system., laser power and safety system.

The system frame does not have any load applying for it, so just will build the system and test it manually if it is not stable or not rigid. To increase rigidity there are some things can do to any mechanical system, a common method is by using a stronger 4-bolt variety.

Second validation is an electrical circuit that includes wiring, stepper motor, end stop and connection points with microprocessor by using voltmeter device. To avoid any problems will happen during running the system, so should read a user manual for each sensor, stepper motor, etc. this because each part has different specifications.

Gantry system movement validates in the XY field by running the system and observes the movement along the X axis and Y axis. Second thing will validate in the gantry system is a gantry stop at specific points. The position will validate by feeding that position to the system, after run the system the gantry will move and should be stopped at specific points.

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The dial indicator is tool that has used to measure runout/deviation on shafts of the system during running. The runout value change depending on the shaft components, so when increasing components of the shafts the runout will increase. Table 3 shows the results of the runout of the system shafts during running the system.

Table 3. System runout

N	Axis	Runout
1	X	0.015”
2	Y	0.030”
3	Z	0.020”

The validation in X, Y and Z directions has measured by using stepper motor and a microcontroller. The interface program that used to make the connection between stepper motor and a microcontroller a small C program. After fed a specific distance to the validation system the system moved exactly same distance that has fed to the system (the distance was 10 mm).

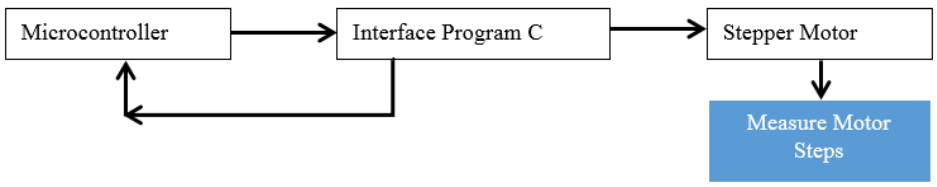

Figure 8. Forward and side step validation flowchart

The powder bed will move on Z axis, and validate powder bed will be by measuring layer depth. Laser spot will calculate using methods from. (Urmoneit, Hotz, Frohlich, & Kraub, 2014) The The laser fused point size will be measured by using microscope STM. The checking laser fused will happen by running the system to fuse some points of powder with change laser parameters, and we will take better parameters to use them in this research. Alignment and level are very important in the design of a mechanical system, so will use the level device to keep all the SLS parts straight.

In addition, after design tool path of 3D shape we are going to check tool path if it has defects. After checking, the tool path is ready to use in the SLS system. The validation of tool path will happen with open the tool path after design with a tool path simulation program to check a part tool path from first point to the last point. At this step, we can fix the tool path if it has any defects to avoid errors that will happen during the manufacturing process

One of the specifications of this research that is an accurate, pitch of the shaft and step angle of the stepper motor have an effect on the accuracy. Minimum forward step, side step and layer depth have designed equal to 0.003 mm/step. In addition, the maximum speed of the system is designed equal to 0.566 mm/s. Figure 9 (A) shows the estimated surface roughness of the part. The maximum theoretical roughness is 0.51 mm has been calculated from eq.1. The fused spots size change depending on the laser power and processing time, and that has been calculated depend ing on the conductivity, thermal diffusivity,temperature of the surface processing time, abserptivity and temperature penetration depth, such as shown in Figure 9 (B).

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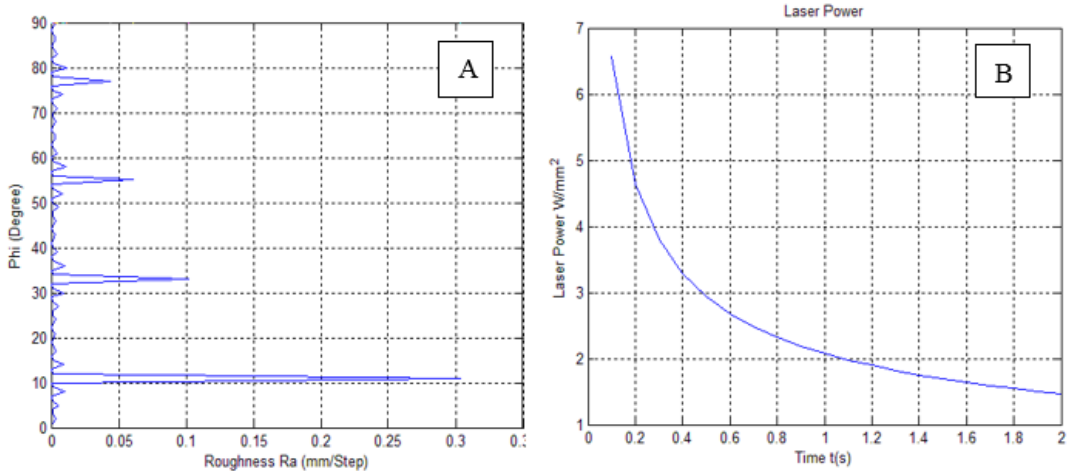

Figure 9. (A) Estimated surface roughness results and (B) relationship between laser power and melted size with different processing time

5. Conclusions

Design, build, and optimize manufacturing parameters of selective laser sintering system (SLS) were proposed, and validation was discussed in this project. The SLS system can produce different powders like ceramic, metal, rubber, etc. But that depends on the laser power because each material needs a different laser power, so for this reason this technique is used in a wide range of fields, such as mechanical engineering, civil engineering, architectural engineering, the medical field, etc. Simulation program is used to build 3D models and used to build and test tool path before feeding it to the SLS system, this because to reduce errors that will happen during the printing process. Optimizing the manufacturing process will control deviation that happen between designed part and manufactured parts, also optimized parameters will increase part accuracy and reduce the total cost. In this paper increased the system accuracy by redesign the mechanical system instead of a change stepper motor. In addition, lens has been used to focus the laser from 5 mm to 0.3mm, the laser with 0.5 mm spot size is very expensive, so for this reason the lens used. The gantry system designed by using a belt and a threaded bar, the threaded bar better than the belt during the movement because the step response results proved that. The laser power was reduced by using a heater to increase a powder temperature before start running the system.

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