Development of software and hardware components to the Internet of an additive manufacturing system based on vat photopolymerization technology

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Abstract. The global competition and shifts in consumer’s demand are forcing companies to enhance their productivity by reducing the manufacturing time, cost and increasing the value of final merchandise. Recent engineering researchers find that the additive manufacturing (AM) process could be an innovative solution due to its advantages in building complex shapes using different materials. However, the lack of developing tools to automate AM equipment has limited applying this technique to fabricate products within a production system. Thus, an internet of additive manufacturing (IoAM) system for the Vat photopolymerization process is proposed. The IoAM system is composed of three components which are described. The first one is the machine hardware integrated by all the various mechanical parts of a conventional Bottom-Up DLP 3D printer managed by a control board based on IoT technology. The second element is a web interface that controls and monitors a single or an array of machines from one or multiple operators and devices. The last module is firmware, which is the intermediary between the software and hardware. Besides, it is responsible for executing the adaptive control for the printing parameters, which has allowed to speed up the manufacturing process. The geometric calibration method to overcome distortion of photomask produced by DLP and the energy calibration algorithm to solve the non-uniform energy distribution have permitted to fabricate objects with high resolution around 30µm in the XY axis and 50 µm as a layer thickness.

1. Introduction

Conventionally, subtractive manufacturing (SM) methods and injection moulding has been employed to produce physical objects. The SM procedures fabricate 3D objects by successively removing material from a solid block performing diverse machining operations, such as turning, drilling, and milling. Thus, a machine equipped with a manifold of tools is required for the planning process to establish the sequence of the operations to execute, and the estimation process of the value of the cutting parameters are involved. Therefore, high-skilled operators are demanded. Additionally, if the object's geometry constrains its construction in one workpiece, it should be subdivided into a part that will be assembled later. According to the facts described earlier, SM technologies have limited the creation of custom objects and decreased fabrication time.

However, the companies and researchers have examined that the advantages of additive manufacturing (AM) technologies could be an innovative solution to produce objects due to capability to construct
complex geometries with less-time process planning, lightweight, diverse type of materials, less assembly time, and effortless fabrication of customized objects. Applicable in the production of aeronautic, biomedical, automotive, and dental care products. Application of 3D printing in the industrial field done by Sculpteo [1].

The production of goods, such as food, drinks, electronic devices, clothes, means of transport, and medicine, is currently being produced by automation systems that transform raw material into products. Even though, to achieve the elevated level of production, humanity has been passed through varieties of steps which have been called "Industrial Revolutions" [2], [3].

In 1750, the stages of the industrial revolution started with the mechanization of the textile industry to additive manufacturing technology[4]. In the further steps of creating the CAD, CAM, CAE software, the Internet, computers characterized this period [5] for advanced applications by AM. Additive manufacturing technologies have unique capabilities but still limited to high production speed, accuracy and selection of materials for a particular application. Researches are going to achieve better accuracy and high-speed printing[6],[7],[8] for all the processes of AM and their technology. One of the main targets in this project relies on the speed-up production process without comprising the quality of the surface and accuracy of the objects.

The fourth industrial revolution is underway in industries globally due to the emerging of favourable technology, such as robotics, the Internet of things and services and additive manufacturing procedures. For a degree of automation, the Internet of things devices and technologies should be utilized [9].

AM invention had registered for a patent in the US by “Apparatus for producing a 3D object by stereolithography”[10]. AM is a legal term to describe the manufacturing process that constructs 3D objects from a CAD model by adding layer-by-layer material, such as metal, photopolymer resin, plastic, concrete, human tissue[11]. The American Society for Testing and Materials (ASTM) has categorized all the AM techniques into seven families [12], [13].

2. System design

The Vat photopolymerization (VP) additive manufacturing technology is widely accepted for prototyping, aeronautic, dental care, jewellery, and biomedical fields. Its ability to fabricate 3D objects with great details and accuracy faster than the most popular AM method, the Fusing Deposition Modeling (FDM). The research relies on developing a new Internet of Additive manufacturing (IoAM) system to automatize the fabrication process using the Bottom-UP DLP type VP technology. This system has three main components: machine hardware, software, and firmware, as illustrated in Figure 1 and described as follows.

![Figure 1. Diagram of IoAM.](image1.png)

![Figure 2. Bottom-Up DLP-VP.](image2.png)

Two elements integrate the machine hardware of this IoAM. The first is related to all mechanical components utilized in a conventional Bottom-UP DLP 3D printer, such as a digital light processing projector, building platform, Z-Axis mechanism, and a vat. While, the second corresponds to the active and passive electronic devices chosen to build a new printed circuit board (PCB), for instance, a limit switch, a power supply, a stepper motor and its driver. Besides, a microcontroller is already in this group
responsible for establishing the wireless communication to the operator and saving the printing files. Further, it is in charge of reading the data provided for the sensors implemented on the PCB and transmitting electric signals to the actuators to control the machine hardware for executing diverse operations in the fabrication process.

The software in this system is involved in a manifold of programs utilized in the pre-processing and printing process. Regarding the first stage, three software must be employed. The first one is the Creation Workshop to obtain the sliced photomasks of the 3D model. The second was labelled as a packaging program. It produces a zip file when a script.txt file and the set of masks has been loaded. The script file contains the magnitude of the printing parameters. The last software in this phase is a web interface that should provide the necessary tools to set up the machine and send the zip file to the microcontroller. However, it is also adopted for the printing process phase even though it implements new services. For instance, monitor and manage multiple machines interconnected in a local network from different stations or employers. In addition, it must be equipped with a tool to customize and visualize the printing parameters online.

The firmware should be the intermediary between the software and the hardware. It is responsible for defining the parameters for the wireless communication as well as reading the instructions expedite by the user, and transform them into signals to the PCB.

3. Results and discussions

The development of a control board of IoAM for the printing process employing the vat photopolymerization method relies on performing sequential steps to solidify each mask to produce the whole printed model. Therefore, a set of electronic devices to control each component of the DLP 3D printer is required. The function of each element has a specific job that has to do for the printing process are explained below in figure 4. The actuator used to achieve those movements of the building platform, and a bipolar stepper motor Nema 23 was linked with the screw of the Z-axis mechanism. An optical limit switch is responsible for restricting the maximum and minimum position to move through the Z-axis mechanism. RS232 module board can transform the data sent by serial communication protocol (input) to RS232 (output). An emergence bottom to authorize the operator to stop the manufacturing process. The RGB- Led was chosen to confer to the user visual information. The fan is responsible for energy expelled from the inside of the machines’ frame. Power supply device should provide different levels of voltage, for instance, 5VDC and 12VDC. Webcam tool can capture digital frames and sent them to a server or a monitor.

Figure 3 represents a control diagram of how the electronic components are connected with the mainboard, Raspberry Pi B. The brick colour defines the quantity of voltage is supplied by the power source. The blue colour is for 12VDC, which is the voltage that a stepper motor Nema17 works. The purple is the devices requires 3.3V, and it is provided by one of the pines of the microcontroller. While the green is for those whose voltage operation is 5VDC delivered by an external power source, and the red is for 110VAC. The single computer chip is equipped with 40 pins labelled as General Port Input Ports–GPIO. Those ports could be configured as analogue and digital input or analogue or digital output as well as to communicate with another external device.
The printing webpage window that provides to control the manufacturing process of each 3D printer. The interface designed for this webpage demonstrates in Figure 5. The first service implemented is the monitoring through the webcam and the streaming web server. A video of the manufacturing process or a picture can be visualized on the screen. The *video button* takes a record of the process during 10 seconds, and the image button takes a picture. On the right side, there are three main buttons *start*, *pause* and *stop* the production process. The *start button* becomes green, *pauses* to yellow, and stops red when one of them is pushed. The *reset button* is only available for the administrator account to reset the equipment.

**Figure 3.** Control diagram of the hardware element connected with the Raspberry Pi.  
**Figure 4.** 3D View of the control box.  
**Figure 5.** Printing webpage.
On the right middle side (red rectangle), diverse information getting from the server, such as the current status of the machine, name of the model that is being printed, the number of layers, and the progress of the production process, are exhibited. However, the tools that are in the yellow square corresponds to the overwritten operation. It relies on modifying online the default value of exposure time, pulling-up distance, and pulling-up speed. Three input boxes and three buttons (OVERWRITE) to define and transmit the new value for each printing were attached to this interface.

3.1. Geometric calibration process

The geometric calibration process aims to adjust the photomask within the printable area. The left side, known as the reference points board, is equipped with an array of sixteen yellow squares to represent each of the references points (Rp) shown on the tank. A toolbar equipped with three buttons to control the calibration process and control of the reference point provides the tools to move each reference point to the left, right, up, and down pushing their button, respectively shown in figure 6.

The first one, the Show button, is responsible for sending the command to the firmware to display all the reference points in the positions that had been set up in the firmware or saved in the last calibration process. To disable all the Rp, the hide button should be pushed. The last one in this section is the Saved Button who transmits a message to the Raspberry Pi to communicate that the calibration process has been finished.

The third subdivision, which is at the bottom-right, provides the tools to move each reference point to the left, right, up, and down pushing their button, respectively. Additionally, a drop-down menu centre of the four buttons to settle the resolution of the movement of the Rp was added. This resolution has three levels, 1px, 5px, and 10 px, which means if the last one was selected, the Rp would move 10px each time that one of the buttons is forced.

Setting up the machine relies on drawing the grid pattern in CAD software and printed it out, and placed onto the tank where the region enclosed by the red rectangle, which is a printable area of this machine. Another is adjusting the reference points for the mask is projected onto the printable region and correct the distortion image; the initial position of the sixteen reference points must be shown on to the tank. Figure 8 indicates that all reference points are misaligned for each corner of the rectangle, which is the desire position. The webpage has sixteen yellow squares labelled with a number from 1 to 16 (Figure 10 ) to indicate the position of each point on the vat, as exhibited in Figure 7.

Figure 6. Geometric calibration interface. Figure 7. The grid pattern on the tank interface.

Figure 8. Initial position of RP. Figure 9. Grid pattern. Figure 10. No.of each RP.
The adjustment process of a reference point starts when a yellow square is shaved. As a result, the colour changes to cyan colour as exposed in Figure 11 (a). Additionally, an information window on the screen appears to display the current position (X, Y) of the Rp selected as reflected in Figure 11 (b). For instance, the actual position of the Rp number five is (46,362) px. Conversely, the point chosen is still brightened on the tank, and the others were hidden, as illustrated the Figure 11 (c). Then, the position of this point could be shifted by pushing the UP, RIGHT, LEFT, and DOWN buttons from the interface. The result is detailed in Figure 11 (d), where their final position is to (41,373).

![Figure 11](image)

**Figure 11.** Adjusting the position of the reference points (a) Selecting the reference points on the interface (b) Displaying the initial position (X, Y) of the reference point (c) Initial Position of the reference point (d) Final position of the reference point (e) The final result of adjusting all reference points.

Alternatively, the adjusting process should be repeated several times until the position of all the reference point has been situated in their correct place, as exhibited in Figure 11 (e). Finally, to begin the computation process related to the calibration process, the *Save button* should be paused. The results of the calculation are described below. After the reference point is adjusted to the desired location in each iteration, the sample is printed and measured to get the desired location.

The position of the XY coordinate of the circle has measured in the 3D measurement system for all the iteration.

![Figure 12](image)

**Figure 12.** Testing a geometric calibration process. (a) Dimensions of the energy calibration sample. (b) Result of the fabrication of the energy calibration sample.
Figure 13 shows the result of this process where all the circles have been drawn in green colour. The estimation of the position for the centre of the circle requires a reference point whose coordinates are setting up as (0,0). In this case, the circle placed at the top right was chosen. The set of yellow lines is a tool that the 3D microscope software provides to find the XY position at any point. Therefore, one of the intersections must be positioned in the reference point and the other in the desired point that will be measured.

![Reference (0,0)](image)

**Figure 13.** XY coordinates of a circle given by the Keyence VR-3000 3D microscope software.

Figure 14 (a) demonstrates that several reference points, such as 3rd, 8th, and 11th, have not been positioned in the correct place because the human eye’s perception is not able to see in the micrometre range. For example, Figure 14 (b) manifests that the 11th reference point drawn in red and its centre in rendering has an offset of 0.08 mm in the X-axis and 0.45mm in the Y from the request position marked as a black point. This error should be 30um (0.03) because it is the resolution of the DLP projector installed in the BVP57HD Bottom-Up DLP 3D printer. Hence, that reference point should be shifted 2px to the left and 15px down using the geometric calibration web page’s control buttons.

![Grid pattern](image)

**Figure 14.** Geometric calibration process (a). Drawing about the real position of the centre of each circle of the energy calibration photomask. (b) Zoom in the 11th reference point.

Finally, after moving all the misaligned reference points, the reference points’ final position to achieve a tolerance of ± 0.03mm (30um) in the printed 3D model is described in Table1. Then, using a 3D measurement system to acquire the position XY of the centre of each circle should be executed several times. In this case, the XY coordinates written in Table 1 were obtained after four iterations where the maximum and the minimum absolute value are 141 and 5 um, respectively.
Table 1. The final result of the geometric calibration process.

| Rp | X(µm)  | Y(µm)  | Rp | X(µm)  | Y(µm)  |
|----|--------|--------|----|--------|--------|
| 1  | 0      | 0      | 9  | -30.937| -20009.776|
| 2  | 17684.196| -65.704| 10 | 17726.918| -19980.080|
| 3  | 36931.938| 50.398 | 11 | 36816.539| -19989.270|
| 4  | 54574.880| 69.358 | 12 | 54708.454| -19995.520|
| 5  | -45.670 | -9302.716| 13 | 81.320 | -29440.266|
| 6  | 17771.140| -9199.900| 14 | 17753.436| -29470.260|
| 7  | 36894.617| -9159.148| 15 | 36825.378| -29298.660|
| 8  | 54518.413| -9208.568| 16 | 54647.168| -29286.700|

3.2. Energy calibration process

The production of a uniform distribution of energy in the whole printable area. In Figure 15, two buttons to manage the energy calibration were placed. The first, the Print button, sends a command to the firmware to display for ten seconds. The Execute button transfers the data of the grey values entered in each reference point to the server to start the computation process of the dilation, smoothing, and re-scale algorithm, which usually takes about one minute. After every iteration of grey value adjusted to achieve similar thickness or height at every references points for the sample shown in Figure 16 shows.

Figure 15. Energy calibration interface.

Figure 16. The 3D view by 3D microscope.

The grey value indicates the brightness of a pixel, and the minimum grey level is 0. The maximum grey level depends on the digitization depth of the image. For an 8-bit-deep image, it is 255. In a binary image, a pixel can only take on either the value 0 or the value 255. It was finding the suitable grey value for each reference point to produce a depth curing in the whole printable area around similar values of thickness of printed sample at every RP shown in Figure 16 because it creates with the highest
magnitude light of intensity. The approach proposed in this project is to determine a specific grey value lower than 255 to the maximum depth. Table 2 details the outcome for the eight cycle iteration where the highest depth is 0.91mm, and the lowest 0.81mm, so that, the $\Delta h = 0.1\text{mm}$. For the different intensity of light adjusted by grey values to achieve the same height at every RP for the printed whole area as shown in Table 2. Finally, it is evident from the data of the previous iteration, and the energy calibration has been successful executing by modifying the intensity light value for each reference point to balance the depth curing in the whole working area. A weak zone of the tank has been recognized, which is constituted by the 4th, 8th, 12th, and 16th because the height in this region was the smallest in the eight iterations, whereas the strong area is formed by the 5th, 6th, 9th, and 10th reference point.

Table 2. Curing depth for the eighth iteration in the energy calibration process.

| Rp | Gray Value | Height (mm) | Rp | Gray Value | Height (mm) | Rp | Gray Value | Height (mm) |
|----|------------|-------------|----|------------|-------------|----|------------|-------------|
| 1  | 72         | 0.81        | 2  | 80         | 0.88        | 3  | 110        | 0.88        |
| 5  | 80         | 0.9         | 6  | 85         | 0.91        | 7  | 100        | 0.87        |
| 9  | 68         | 0.83        | 10 | 83         | 0.86        | 11 | 95         | 0.85        |
| 13 | 82         | 0.88        | 14 | 83         | 0.8         | 15 | 108        | 0.86        |
| 13 | 82         | 0.88        | 14 | 83         | 0.8         | 15 | 108        | 0.86        |
| 16 | 210        | 0.81        |

3.3. Printing process

The printing process stage relies on building the physical object layer-by-layer using the mechanical components of the equipment hardware, software, and firmware. This phase starts pushing the Start button of the printing process web page, which becomes green as illustrated in Figure 19, where the machine's current status, name of the model “Demo ETower” are displayed as well. However, the data presented in this picture is associated with the 1185th layer, which represents 84.3% of the progress of the fabrication process. Therefore, the value of the exposure time 500ms, pulling-up distance equal 1250um, and the pulling-up speed 6500 are the magnitudes of the printing parameters.

![Printing Process](image)

Figure 18. Bottom-up DLP 3D printer.

Figure 19. Monitoring the manufacturing process of the Eiffel Tower.
The mechanical hardware is related to the elements of an actual Bottom-up DLP 3D printer, in which the IoAM will be implemented. A 3D view of the equipment chosen for this application is exhibited in Figure 18 was designed and built by the Additive Manufacturing Center for Mass Production (AMC). The highlight feature of the vat photopolymerization additive manufacturing technology is related to the ability to fabricate physical objects with great detail and accuracy. Thus, the achievement of this characteristic employing the software, printed circuit board (PCB), and firmware designed for the research is reflected in Figure 20 (a), where all the details of the tower have been successfully built. For instance, the last layers of the 3D model (Figure (b)) where the area is less than 4mm², the shell structure, and the set of thin pillars as presented in Figure (c).

![Eiffel Tower printed with the Internet of Additive manufacturing System](image)

**Figure 20.** Eiffel Tower printed with the Internet of Additive manufacturing System (a) Final result of the building process (b) Zoom-in of the top part of the printed Eiffel Tower (c) Zoom in the middle of the printed Eiffel Tower.

The main contribution of this research is explained in detail. In order to compare the advantages among the IoAM system and the conventional Bottom-Up 3D printer where the customization of the printing parameters are not enabled, the Eiffel Tower with identical size, layer thickness, DLP projector, and machine was manufactured. As a result, the printing time employing fix values of the process parameters for the whole manufacturing process, which is the standard procedure by a current 3D, was about 55 mins. Thus, one of the main targets in this project which relies on speed-up the production process without compromising the quality of the surface and the accuracy of the objects, has been accomplished because the production time has been reduced from 55 mins to 48 mins. Further, another attribute of this system is that the machine can work in a standalone manner so that the permanent connection to a PC is not required as the standard 3D printers works.

4. **Conclusion**

The new technology of IoAM has allowed conventional Bottom Up-DLP 3D printers to produce 3D objects, namely, utilizing external devices such as PC to execute some calculations during the manufacturing process is not required in this system as the current technology works. The software and hardware created for the IoAM permitted implementing two tools labelled as one-user-multiple machines and multiple-users-single machine, which are remarkably important to improve the productivity in a chain production using AM machinery. The first one provides the ability that a single operator can control, configure and monitor the production process of a rack of 3D printers from a single workstation or PC. Thus, the number of operators could be reduced as well as the cost of production. While the multiple-users single feature permits that the representatives for different divisions involved
in the manufacturing process such as the designing, engineering, delivering, production can manage a 3D printer simultaneously to obtain feedback about the performance of the procedure. This tool is favourable in decision-making about the printing parameters, geometric features of the model, and material that play an essential role in generating successfully printed objects.

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