Contact Image Sensor integration in Fused Filament Fabrication machines for layer inspection

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Abstract: One of the limiting factors for industrial application of additive manufacturing (AM) is the lack of geometrical accuracy of manufactured parts. To improve precision, non-contact sensors should be integrated into AM machines, capable of performing in-situ inspection of the part and being able to detect and compensate for the actual geometrical errors. A non-contact digitizing system is proposed in this work for the inspection of the deposited material layers, based on a Contact Image Sensor (CIS) extracted from a commercial flatbed paper scanner. In order to integrate this sensor in an AM machine, a methodology was developed that includes the sensor operation analysis, the design of the necessary hardware and software to be externally controlled and the subsequent processing of the captured images. Results prove that the CIS sensor can be integrated in any device external to the original scanner.

Keywords: Integration, Contact Image Sensor, In-situ inspection, Digitizing, Fused Filament Fabrication.

1. Introduction

One of the main limitations of additive manufacturing (AM) is the lack of dimensional and geometrical accuracy of manufactured parts. As a solution, some authors propose the development of in-situ geometrical inspection systems and, simultaneously, the application of error compensation techniques with respect to the original CAD model [1]. Most of these works were not only scarce, but also were mainly focused on controlling and compensating for thickness deviations of the deposited layers, but not for their contour [2,3].

In any case, and as the National Institute of Standards and Technology (NIST) mentioned in a recent report, in-situ process monitoring and control represents a significant opportunity to reduce variations and ensure quality in the parts manufactured by AM [4]. In particular, to reduce the geometrical errors, it will be necessary both to develop in-situ geometrical inspection systems for the deposited layers and, at the same time, to apply techniques to compensate for errors detected with respect to the CAD model of the part. For this, it will be essential to find a suitable technology for measuring the deposited layer geometry and integrating it into the AM machine itself.

With this aim, the present work studies the feasibility of integrating a Contact Image Sensor (CIS), extracted from a commercial-type paper scanner, into an AM machine. A previous work developed by Phuc and Seitta [5], already demonstrated the capacity of this technology to digitize the material layers deposited in an AM process. In this case, the sensor was installed in the machine head and movement
was synchronized with the digitizing speed of the scanner. However, this was a partial integration of the sensor since the hardware and software used was the one within the commercial scanner. In other studies, such as those carried out by Blanco et al. [6] and Majarena et al. [7], the sensor was not integrated into the AM machine, but they showed the ability of these sensors for capturing images on parts manufactured by Fused Filament Fabrication (FFF).

Prior to the CIS sensor integration in the AM machine, it was necessary to carry out in this work a reverse engineering process to analyse the sensor’s operating principle and its interaction with the rest of components of the original scanner. In this way, a procedure was developed to perform the integration of the sensor in any device external to the scanner. The necessary hardware and software were designed to integrate the CIS sensor into an AM machine and controlling it from a computer. Finally, further routines were developed for the captured grayscale images to match the desired resolution.

Given the difficulty of integrating any of these sensors into a commercial AM machine, a specifically designed test bench was used. This bench represents a prototype of AM machine capable of manufacturing parts based on FFF technology and performing non-contact digitizing tasks. For this purpose, the test bench was provided with two mobile carriages, one for 3D printing and the other one for non-contact digitization with the CIS sensor during the manufacturing process. The integration of the CIS sensor will allow for capturing images of deposited layers, which will be analysed in future works for recognition, geometrical error detection and subsequent compensation.

2. Equipment

A CIS sensor from a low-cost commercial office scanner (Epson Perfection model V39) was used in this work. Apart from the CIS sensor and all its mechanical components, the scanner consists of a control board, which coordinates all the elements of the scanner, and a control panel for user operation.

2.1. Scanner operation

Prior to the CIS sensor integration in the test bench, it was necessary to analyse the scanner operating principle in order to know how the electrical signals are transmitted between the sensor and the control board during a digitizing process.

First, each of the 13 pins associated with the connection between the sensor and the control board was identified. For this purpose, a digital oscilloscope, model TDS 1001B by Tektronix (40 MHz, 500 MS/s) was used. During the signal identification process, both power and control signals were distinguished. Two different power supplies were found (5V and 3.3V DC supplies) together with several reference GND pins. On the other hand, there were identified several control signals: three of them, related to the RGB LED light control, a 3MHz sinusoidal clock signal (figure 1(a)), a square pulse trigger signal (figure 1(b)), and two analogue signals representing a line of pixels captured by the sensor (figure 1(c)). Table 1 lists all the signals involved in the control and operation of the sensor.

![Figure 1. (a) Clock signal (pin 7). (b) Trigger signal (pin 5). (c) Analogue signal (pins 10 and 12).](image-url)

During the scanning operation, the control board emits a trigger pulse each time a line is to be captured. This is done by keeping the clock signal (CLK) active. Then, the sensor responds with two analogue signals synchronized with the clock frequency (AN_1 and AN_2) until all the pixels of the
scanned line have been provided.

**Table 1.** Identified scanner control board pins.

| Pin | Description       | Voltage range (V) | Category |
|-----|-------------------|-------------------|----------|
| 1   | VCC / Common anode| 5                 | Power    |
| 2   | LED B             | 0 – 5             | Control  |
| 3   | LED G             | 0 – 5             | Control  |
| 4   | LED R             | 0 – 5             | Control  |
| 5   | Trigger           | 0 – 3.3           | Control  |
| 6   | GND               | 0                 | Power    |
| 7   | CLK               | 0 – 3.3           | Control  |
| 8   | GND               | 0                 | Power    |
| 9   | 3.3 V VCC         | 0 – 3.3           | Power    |
| 10  | Analogue 1        | 0 – 3.3           | Output   |
| 11  | GND               | 0                 | Power    |
| 12  | Analogue 2        | 0 – 3.3           | Output   |
| 13  | GND               | 0                 | Power    |

In addition, it could be observed that each line was captured three times, between each sensor’s displacement. This is because each line is captured by projecting red (R), green (G), and blue (B) light sequentially. Therefore, the conversion to a greyscale image is given by the weighted combination of each of the R, G, and B components at each pixel. It was also found that the maximum resolution of the scanner used is 600 DPI and that the construction of higher resolution images is done by combining and further processing several of these images.

2.2. **CIS sensor installation in the test bench**

The test bench where the CIS sensor is to be installed on, was designed and constructed including two mobile carriages. One of the carriages is intended for 3D printing and the other one to perform layers inspection by digitizing them with the CIS sensor as they are deposited. The sensor is fastened to the inspection carriage through a tailor-made fixture that also enables its height adjustment and orientation with respect to the test bench manufacturing bed (figure 2).

![Figure 2. Test bench and CIS sensor fixture assembled to the inspection carriage.](image-url)
Apart from the CIS sensor, and using the appropriate adapters, the inspection carriage head allows for installing other types of devices for non-contact digitizing.

The CIS sensor calibration method is explained in detail in [6]. For this purpose, a linear-array certified dot artefact was used, whose distances between points in the X and Y directions are known. The artefact is previously scanned to calculate the relative position between real and scanned points. Once this relation is known, an interpolation method (a linear interpolation triangle-based model) was designed to correct the position of the points associated with to the contour of the scanned parts and thus, compensate for the geometrical distortions of the CIS sensor.

3. Hardware and software developed to control the CIS sensor

To be able to carry out the integration of the CIS sensor in a different equipment than the original scanner, it will be necessary to develop a specific control board including a microcontroller that will process the I/O signals while also will manage and control the sensor’s operation.

3.1. Selection of electronic components

Sampling rate becomes one of the main parameters to select the most suitable microcontroller since it defines the limits of the microcontroller’s application. This speed will influence the similarity that will exist between the signal sampled by the sensor and the signal that is finally recovered.

Using a function generator (model PROMAX GF-232), the minimum sampling rate of the sensor was found to be around 1.1 MHz. Taking this information into account, a Teensy 4.0 microcontroller was chosen, which runs at 600 MHz and is able to emit clock signals at compatible frequencies to the scanner's sensor. This microcontroller includes an integrated 1 MS/s sampling rate A/D conversion module, which is insufficient for the application. For this reason, the final decision was to use an external A/D converter with parallel interface, model AD7822, capable of providing a sampling rate of 2 MS/s and 8-bit resolution. The sensor simultaneously distributes the captured image through two channels, so it was necessary to use two A/D converters and, consequently, to take up 16 digital pins of those available in the microcontroller.

The remaining electronic components that integrate the control board are mainly resistors for the control of the sensor RGB LED and connectors for the wiring to the sensor.

| Pin | Bit MSB | Bit LSB |
|-----|---------|---------|
| GPIO-6 | 21 | 27 | - |
| | 20 | 26 | - |
| | 23 | 25 | - |
| | 22 | 24 | - |
| | 16 | 23 | - |
| | 17 | 22 | - |
| | 15 | 19 | - |
| | 14 | 18 | - |
| | 18 | - | 17 |
| | 19 | - | 16 |
| GPIO-9 | 4 | - | 6 |
| | 3 | - | 5 |
| | 2 | - | 4 |
| GPIO-7 | 11 | - | 2 |
| | 12 | - | 1 |
| | 10 | - | 0 |

3.2. Design of the control board

The most important step in the design of the control board has to do with selecting the microcontroller.
pins to be connected to the A/D converters. The microcontroller has got 40 pins assigned in a non-sequential order to the bits of the 4 registers (6, 7, 8 and 9) available in the General Purpose Input/Output (GPIO) memory.

Each of the A/D converters has got 8 pins, which allow 8-bit information to be sent. To maximize reading speed, it was important to select the 8 microcontroller pins to be connected to each A/D converter, so that the bits assigned to the GPIO memory registers were arranged as sequentially as possible. In this way, as various bits can be read simultaneously, the number of binary operations to be performed are reduced.

To this end, among the 40 pins available, combinations were chosen that allowed 16-bit values (8 bits for each A/D converter) to be configured as sequentially as possible. Table 2 shows the two combinations of bits chosen (MSB and LSB) that enable parallel reading of the 16 bits of the converters at a reading speed of 50 ns per conversion. The A/D conversion and reading speed is fast enough to not interfere with the main digitizing program, whose period is 500 ns.

Figure 3 shows the Printed Control Board (PCB) that was finally designed and built.

![Figure 3. Designed and built PCB.](image)

Figure 4 shows the Flowchart for a line capture routine from the microcontroller.

![Figure 4. Flowchart for a line capture routine from the microcontroller.](image)
3.3. Design of control routines
The microcontroller routines were programmed in C++ using the Arduino’s IDE. Three routines were considered in this case. The main routine was configured as a client and its purpose is to wait for different commands via serial communication (requests the program to digitize a line, to switch on a LED, to end the digitizing process, etc.). A second routine takes care of digitizing images and a third routine captures a complete line of images. This will be further explained later.

When the line capture routine is called, the process of capturing a whole line of pixels starts. This routine requires a synchronous operation between the sensor and the A/D converters (figure 4). In this case, the program initializes an array of the same size than the line to be captured, where each one of its pixels will be collected. The necessary flags are then activated to handle the reading functions and the clock signal is enabled for the sensor and the A/D converters to operate at a same frequency. Once the clock is activated, a trigger signal is emitted to the sensor, whose pulse width will match the selected image resolution.

When the falling edge of the trigger signal is reached, the microcontroller starts to collect the information pixel-wise. One pixel is collected for each of the two analogue signals associated to each digitized line. Each pair of pixels is collected at a value of 16 bits, where each pixel is encoded either in the upper or lower 8 bits of that value.

Once the pixel array is completed, the clock signal and the use of interrupts are deactivated, and the pixel vector is sent through the serial port.

4. Procedure for capture images from a computer
In order to facilitate user’s access to the sensor’s control parameters, a desktop GUI (Graphical User Interface) was developed. This interface also allows for managing the emission of commands and coordinating the capture of images from the sensor with its position as it is moved on the test bench in which is integrated.

Complete image digitization by means of the designed GUI is managed as follows:

- 1st: Serial communication with the CIS sensor microcontroller and with the test bench control board is enabled and setup.
- 2nd: The user selects the process parameters: resolution, initial and final positions for digitizing, image colour, etc.
- 3th: The digitizing routine starts. According to the chosen resolution, the number of lines to be captured and the separation between them are calculated. Then, a command is sent to the displacement system so that the sensor is positioned at the starting point.
- 4th: An iterative process is carried out. A command is sequentially emitted requesting the capture of the line, waiting until the complete line is collected and then shifting the sensor to the next position. This process is repeated for all the lines to be digitized until the line corresponding to the final position is captured.
- 5th: All the information received is stored in a CSV (Comma-Separated Values) file and the program orders to reset the sensor position to prepare for the next digitizing.
- 6th: The captured data is decoded and processed to obtain the final image. This stage is explained in more detail in the next section.

This process will be repeated each time the user requests a new sensor digitizing operation.

5. Processing of the information captured by the CIS sensor
As aforementioned, each image captured by the CIS sensor is stored line-by-line in a CSV file. Each file’s line contains the captured pixels array each time the sensor control system activates the trigger signal. However, these pixels are derived from two analogue signals that are collected overlapping one each other in 16-bit coded values. For this reason, the first step to interpret each line of the text file is to decode each pixel in order to identify the 8 bits coming from each of the two analogue signals. The
resulting two text files will be associated to each of the analogue signals, where each line will contain 8-bit coded values. Each of these 8-bit values represents the grey level of each pixel in the captured image.

This way, data from the generated text files can be interpreted and translated into a grayscale image. Two images will be obtained since there are two data files, each one coming from one analogue sensor signal. The resulting image captured by the sensor will be the merging of these two images.

(a)  

(b)  

(c)  

Figure 5. (a) Images with 600 dpi × 600 dpi resolution. (b) Images with mixed 600 dpi × 2400 dpi resolution. (c) Interlaced images with 2400 dpi × 2400 dpi resolution.

On the other hand, and according to the selected resolution at the beginning of the digitizing process, the sensor captures one or more low-resolution images that must be then composed to obtain the desired final resolution image. In this case, a column-based image interlacing algorithm has been used. In this way, the new image maintains its resolution along the digitizing direction, fixed by the resolution corresponding to the test bench inspection carriage movement, but its resolution increases along the sensor’s reading direction.

To evaluate the performance of the integrated CIS sensor, a part manufactured by FFF was digitized. As an example, figure 5(a) shows an image obtained at low resolution (600 dpi). In this case, the sensor makes a single capture. If 2400 dpi resolution is desired, the sensor will take four captures at 600 dpi in the sensor reading direction and at 2400 dpi in the digitizing direction (figure 5(b)). As it can be seen, the images are apparently distorted. The interlacing of these four images allows the final image to be obtained with a resolution of 2400 dpi, as it can be seen in figure 5(c).
6. Conclusions
The use of a CIS technology sensor is proposed in this work to perform digitization of deposited layers of plastic material deposited in AM based on FFF. The sensor used was extracted from a low-cost commercial flatbed paper scanner.

Given the difficulty of integrating the CIS sensor into a commercial AM machine, a tailor-made test bench was designed and built with the double capability of manufacturing parts by FFF and performing non-contact digitizing tasks. For this purpose, the test bench was provided with two mobile carriages, one for deposition of extruded material and the other one for handling the CIS sensor used to digitize and inspect the layers deposited by the printing head.

A reverse engineering process was carried out initially to analyse the operation and interaction of the sensor with the original scanner components and next, a procedure to integrate the CIS sensor into an external device was developed. Then, hardware and software routines were designed to control the CIS sensor installed on the test bench from a computer. Finally, given that the information captured by the sensor corresponds to two overlapping halves of the digitized image, a decoding process was developed to deal with identification of the pixels associated to each of the images halves and consequently, to merge them into a unique final image. Moreover, interlacing techniques were used to obtain images with resolutions up to 4800 dpi.

All these work stages provide a general procedure for the integration of a low-cost CIS sensor in a different equipment than the original scanner. Apart from the feasibility of integration, it has been demonstrated that the system is able to provide images with sufficient quality and resolution which will be adequate for a later analysis of the layers contour geometrical errors. The study of these errors will involve the application of different digital image processing strategies for the contour detection and measurement, and the development of an error compensation model. However, this analysis will be the focus of future works.

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