Design and construction of a test bench for the manufacture and on-machine non-contact inspection of parts obtained by Fused Filament Fabrication

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Abstract: Industrial application of additive manufacturing (AM) technologies is subjected to limitations related to the lack of dimensional and geometrical accuracy of manufactured parts. Many works were dedicated to improve quality of parts manufactured by AM, but integrated solutions in commercial-type AM machines have not been achieved yet. With this aim, the present work describes the design, manufacture and starting-up of a mechatronic test bench first prototype, with the double capability of 3D printing by Fused Filament Fabrication (FFF) and non-contact inspection of deposited layers. Both systems operate coordinately as the part is constructed. Final tests describe the effectiveness of both integrated systems and state the basis for further research.

Keywords: Fused Filament Fabrication, Additive Manufacturing, Non-contact inspection, On-machine inspection.

1. Introduction

Despite the great potential of AM processes in the production of complex geometry parts and non-uniform properties, industrial application of these technologies is subjected to some limitations related to economic constraints, technological limitations and, specially, the lack of dimensional and geometrical accuracy of manufactured parts. The latter is a common concern to all AM processes and, in particular, to those based on FFF, which are greatly affected by the material behaviour, the adjustment of process parameters and the construction of the AM machines.

Investigated solutions to this problem have evolved from finding of manufacturing errors and their possible causes, to works oriented to minimize them. In this way, whereas some research focused on improving parts quality by acting on the process parameters [1], others made corrections to the initial parts geometry [2] or compensations for the machine geometrical errors [3]. Despite these works, it was not possible to develop a unified model covering all error causes and their influence on the resulting geometrical inaccuracies due to the differences between AM processes. Although standardized test parts could be manufactured by different AM technologies to compare the geometrical errors obtained under each one of them (e.g., patterns for Robin rounds [4]), no conclusions could be stated drawing how to improve parts quality in each case due to the difficulty of extrapolating the results to other geometries. Another concern is that measurements are taken out of the machine, so that the reference system is missed [5]. Moreover, the experimentation required to analyse manufacturing errors is costly.

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for the best combination of working conditions includes a high number of experiments that result prohibitive in an industrial environment.

Difficulties encountered in these works have given rise to theoretical results, with limited possibility of becoming practical solutions at an industrial level and integrated into commercial-type AM machines. The usual way of working is based on different levels of trial and error process and, to a large extent, this situation is due to deficiencies in real-time monitoring [6]. Application of real-time compensation of manufacturing trajectories is in harmony with what is proposed by the AM world main actors as the National Institute of Standards and Technology [7]. Therefore, it is justified the search for a real-time error compensation method applicable to any type of geometry which does not significantly increase production time, in order to favour its industrial application and to increase the quality and added value of the manufactured components.

The work presented here describes the design, manufacture and starting-up of a 1st prototype of a mechatronic test bench with the double capability of 3D printing by FFF and non-contact inspection of deposited layers, operating coordinately as the part is constructed. The work is part of a research project aimed at the geometrical optimization of parts manufactured by FFF, performing on-machine inspection of each deposited layer in order to compensate for the predictable errors of the next layers.

2. Design specifications

The test bench shall have the following capabilities and characteristics:

- Manufacturing of parts by FFF with a precision similar to that of a mid-range commercial-type 3D printer. For this purpose, usual technology of conventional FFF machines shall be adopted.
- Digitizing of layers’ contours deposited by the printing head with the possibility of testing different non-contact inspection sensors.
- Both the printing and inspection subsystems shall be operated free of collisions.
- General dimensions not larger than 1000 × 600 × 1200 mm (Length × Width × Height).
- Workspace for the construction of prismatic parts with dimensions about 280 × 280 × 280 mm.
- Good accessibility to the workspace for the user, the printing and the inspection subsystems.
- Cartesian configuration with a robust and stable structure.
- The printing head and the inspection one shall be capable of describing 2D paths.
- Height position of the construction table (printing bed) shall be adaptable perpendicularly to the printing head working plane for each layer.

3. Test bench detailed design

3.1. Structural frame

The final design of the test bench structure consists on a prismatic frame standing on the floor, composed by aluminium extruded profiles of 45 × 45 mm (profile 45 × 45 F) by MiniTec, including T-grooves on each side to easy assemble auxiliary components (figure 1(a)). All the frame corners are reinforced by right angle brackets to increase structural stiffness. The printing bed structure is also composed by aluminium extruded profiles of 30 × 30 mm. Both the extrusion and the inspection bridges are constituted by 60 × 60 × 6 mm (Length × Width × Height) aluminium 6060 bracket profiles with equal sides. Static FEM analysis was performed under predictable vertical loads of 50 N (3D printing subsystem weight) and horizontal of 17 N along X direction (movement load of the extrusion bridge at maximum acceleration) using a safety factor of 1.5 to cover the lack of a dynamic test. The maximum structural displacement was about 0.007 mm (figure 1(b)).

3.2. Guiding systems

The selected guiding systems consisted of linear guides with ball rail systems IKO ML-15, assuring good positioning precision and repeatability of the following movable subsystems:
• The extrusion and inspection bridges, that can be moved along the $X$ and $U$ directions, respectively. Both bridges share the same two guides to ensure collinearity.
• The printing head, that can be translated along $Y$ direction on the extrusion bridge, perpendicularly to $X$ axis. It is attached to a linear guide on this bridge.
• The inspection head, that can be moved on the inspection bridge along $V$ direction, perpendicularly to $U$ direction. The scanning head is attached to a linear guide on this bridge.
• The construction table, assembled on two pairs of slide units on two linear guides, that enable vertical movement along $Z$ direction, perpendicularly to the rest of axes.

![Figure 1.](image)

**Figure 1.** (a) Structural configuration of the test bench. (b) Structural deformation.

### 3.3. Power transmission systems

Transmissions were based on timing belts (Optibelt Omega profile 3M) and pulley systems for the movements of both the printing head ($X$ and $Y$ axes) and the inspection one ($U$ and $V$ axes). Ball-screw-based transmission systems were discarded since they provided higher speed movement and positioning resolution than required in the case of the printing head. Although this type of transmission could be appropriate for the inspection head, it was also discarded considering that it was an expensive solution for this experimental test bench. It was decided that a simpler transmission could be sufficient to carry out the planned inspection tests. In any case, the transmission lowest resolution that can be achieved is 4.6 µm, which is enough for the expected precision of an FFF process.

A double parallel transmission was adopted for $X$ and $U$ displacements in order to avoid a yaw effect of the bridges, since the driving motors were located on a side of the structure. A simpler direct transmission was used for $Y$ and $V$ movements. Figure 2(a) and figure 2(b) show the components of the transmission systems ($X$ and $Y$ axes) for the printing head. Analogous transmission systems were applied for the inspection head. All shafts, made of DIN 42CrMo4 steel, are supported on pairs of deep groove ball bearings (SKF 625-2Z) and were calculated to resist the transmission efforts (maximum 11 N) with a reasonable bending deflection (maximum of 10.3 µm) with a safety factor greater than 35 in all cases.

Regarding the vertical movement of the construction table, a transmission based on a square-threaded power screw IGUS PTGSG-10X2-01-R and a nut IGUS JFRM-AB-2525-TR10X2 was adopted, providing an efficiency of $\epsilon = 0.128$. A short pitch screw ($p = 2$ mm) was chosen, which provides a very small positioning resolution of the construction table (0.3 to 10 µm, depending on the micro stepping rate of the driving motor) as well as a self-locking effect that avoids the use of a motor braking...
system. Figure 2(c) shows the transmission components of the Z axis. The power screw is connected to
the driving motor by means of an elastic coupling GMT FAMM-S 25, supported by a pair of angular
contact ball bearings SKF 7200 BEP near the motor and simply supported on a deep groove ball bearing
SKF 619/8-2RS1 on the top end of the screw, free of axial constraint. A resistance study based on Euler’s
critical buckling load [8] provided a maximum value of 917.1 N whereas the maximum load to move
vertically is about 124 N so that a safety factor of 7.4 is assured.

Figure 2. Transmission components: (a) X axis. (b) Y axis. (c) Z axis.

3.4. Driving motors
Stepper motors are generally used in FFF machines due to their controlling simplicity providing
adequate positioning resolution for 3D printing. Stepper motors were adopted in the test bench for
driving not only the printing system but also the inspection one, since a positioning resolution of 4.6 µm
is feasible and enough to detect printing deviations, which are in a superior order of more than 50 µm.

The main selection criteria of the stepper motors took into account the axial and radial loads, the
motor resolution including micro stepping, the pull-out torques and the holding torques.

NEMA 17 stepper motors Pololu SY42STH47-1206A were selected for both the printing head and
the inspection head movements and a NEMA 23 Pololu SY57STH76-2006A for the construction table
displacement. Table 1 shows the requirements for the motors to fulfil as well as their specifications. It
can be observed that all requirements are widely satisfied. In the case of the axial load in Z direction
(123.8 N), it is transmitted through the power screw to the bottom bearings, so that no axial load is
supported by the motor axis. Micro stepping of the printing head motors was adjusted to 1/16, so that a
resolution of 9.2 µm is achieved. In the case of the inspection head, micro stepping was 1/32 and
resolution is 4.6 µm. Finally, a resolution of 0.625 µm is met for positioning the construction table,
corresponding to a micro stepping of 1/16.
Table 1. Requirements to fulfil and specifications of the selected motors.

|                      | Bridges (X, U) | Heads (Y, V) | Table (Z) | NEMA 17 | NEMA 23 |
|----------------------|---------------|--------------|-----------|---------|---------|
| Axial load (N)       | 0             | 0            | 123.8     | 10      | 10      |
| Radial load (N)      | 11            | 6.1          | 0         | 28      | 28      |
| Pull-out torque (N m)| 0.053         | 0.029        | 0.308     | 0.43    | 1.30    |
| Operation speed n (rpm)| 200          | 200          | 300       | 0-1500  | 0-900   |
| Holding torque (N m) | -             | -            | 0.039     | 0.32    | 1.35    |

3.5. Printing head
A Bowden-type extrusion system E3D Titan (E3D V6 hotend) was selected for the test bench so that, since the wire pulling system is located out of the printing head, the weight of the printing bridge may be reduced and it can be moved more easily. The extrusion system is intended for 3 mm wire diameter and 0.2/0.4/0.8 mm of nozzle diameters. Other components included are: a 12 V-30 W heater cartridge (PT100, 30 W), two axial 12 V fans (for the hotend and the deposited layer) and a thermistor to measure temperatures up to 285 °C. Figure 3(a) shows the detailed design of the printing head.

3.6. Construction table
As aforementioned in subsection 3.1, the construction table is assembled on an aluminium profile structure and can be moved vertically by means of four slide units along two linear guides. A 4 mm thickness aluminium plate rests on three springs supported on the frame and guided by 3 adjustable bolts for levelling purpose. A 300 × 300 mm silicon bed is adhered at the bottom of the plate to supply the necessary heat to the construction table. A removable borosilicate glass, where the parts are printed, lays on the top of the aluminium plate. The main components of the table can be seen in figure 3(b).

3.7. Control system
Controlling the test bench operation implies to manage the printing head, the inspection head and the inspection sensor installed on this head. For this purpose, independent controllers were provided for the printing subsystem and the inspection one and a PC was used as the top level controller to handle each of these subsystems as well as to synchronize data gathered by the inspection sensor with the inspection head position.

An MKS RUMBA motherboard with an ATmega16U2 processor was chosen as printer’s controller due to its capacity to handle all the necessary components (up to 6 motor drivers with micro stepping, 5 thermistors, 5 PWM signals, 6 limit switches, output of 12-35 V for power supply to motors, hot bed, fans, leds and other sensors) and its compatibility with the most common firmware used in 3D printing.
such as Marlin, Repetier or Sprinter. Marlin firmware (version 1.1.9) was finally selected due to its widespread use and its capability to configure all the test bench components.

The control system chosen for the inspection head was Arduino Mega 2560, including an ATmega2560 processor and other characteristics that make it possible to control both motors on the inspection bridge (U and V axes), limit switches, encoders for a more precise positioning control of axes and synchronization with the rest of the test bench subsystems. To connect Arduino Mega 2560 with the motors, drivers and limit switches, a specific PCB was developed. The control software of the inspection head was developed in Arduino and, as any other program of this type, it consists of a definition of variables, constants and functions, Setup function (automatically run as Arduino is started) and Loop cyclic function. The operation is based on G-Code commands similar to those of the printing system.

The top level control software running on an external PC was developed in Qt and is connected via serial ports to both control boards of the printing and the inspection systems. The application allows the user to perform a manual operation (e.g., calibration, edition of parameters, motors movement, printing head heating) or even to upload G-Code files and send the code lines to the printing system to construct the part. On the other hand, it is also possible to manage the inspection head independently but always free of collision between both systems. Thus, it is possible to modify an imported G-Code that had been generated by any slicing software (e.g., Slic3r or Cura) in order to insert stop instructions between the desired layers, move the printing head to a safe position, operate the inspection head to digitize the deposited layer, move the head to a safe area, and continue printing next layer.

Table 2. Dimensional parameters and deviations of measured values with respect to nominal ones, for a test part of two different sizes manufactured in the test bench and in a BCN 3D printer.

| Dimension | Nominal value | BCN 3D deviation | T-Bench deviation | Nominal value | BCN 3D deviation | T-Bench deviation |
|-----------|---------------|------------------|------------------|---------------|------------------|------------------|
| h (mm)    | 45            | 0.020            | -0.262           | 135           | 0.053            | -0.356           |
| d_{A-C} (mm) | 50      | -0.034           | -0.051           | 140           | -0.128           | -0.306           |
| d_{B-D} (mm) | 50      | 0.106            | 0.086            | 140           | -0.007           | -0.123           |
| d_{A-C} (mm) | 40      | -0.166           | -0.203           | 130           | -0.199           | -0.477           |
| d_{B-D} (mm) | 40      | -0.031           | -0.436           | 130           | -0.184           | -0.794           |
| d_{A-A'} (mm) | 5       | 0.053            | 0.111            | 5             | 0.028            | 0.085            |
| d_{B-B'} (mm) | 5       | 0.013            | 0.290            | 5             | -0.001           | 0.449            |
| d_{C-C'} (mm) | 5       | 0.078            | 0.040            | 5             | 0.045            | 0.091            |
| d_{D-D'} (mm) | 5       | 0.123            | 0.232            | 5             | 0.179            | 0.228            |
| α_{A-B} (°) | 90       | 0.293            | -0.077           | 90            | 0.248            | -0.033           |
| α_{B-C} (°) | 90       | -0.368           | 0.094            | 90            | -0.365           | 0.054            |
| α_{C-D} (°) | 90       | 0.317            | -0.07            | 90            | 0.331            | -0.002           |
| α_{A-D} (°) | 90       | -0.241           | 0.054            | 90            | -0.214           | -0.018           |

4. Performance tests

4.1. Printing tests

Geometrical adjustments of parallelism and perpendicularity of the guides were carried out initially on the test bench with the help of dial gauges and bevelled-edge squares. Next, several test parts were printed to adjust the machine working parameters until good results were observed based on dimensions and surface appearance.

Then, a new test was performed in order to analyse quadrature of the printing axes. For that, 9 cylinders of 10 mm diameter and 10 mm height were constructed, regularly distributed in a 3 × 3 matrix on the printing table. Then, the construction glass with the adhered cylinders was moved to a CMM, where geometrical measurements were analysed. A general quadrature deviation of 0.31° between X
and $Y$ axes was detected. The test was repeated twice more to ensure that the errors were systematic. Thus, a pre-processor was developed to make compensations for the detected systematic deviation onto the STL file, previously exported from the CAD model, and then the G-code file for the printer was generated by using a slicing software.

After this stage, other tests were conducted on different parts to check if compensations were effective and also to compare results obtained in the test bench against the same geometries produced in a commercial 3D printer, model BCN 3D, available in the lab. This way, two different sizes of a part were produced both in the test bench and in the BCN 3D. Table 2 shows the main dimensional parameters analysed and the deviations of the measured values with respect to nominal ones. It can be observed that:

- The BCN 3D printer presents a lack of quadrature of about 0.3° whereas it seems that this problem has been solved in the test bench.
- The total height of test bench parts is about 0.3 mm shorter than the nominal value whereas it is quite accurate in the case of BCN 3D parts.
- Notorious deviations appear in both external and internal dimensions specially in the biggest part manufactured with the test bench, whereas low deviations are achieved in the BCN 3D.

4.2. Digitizing tests
After testing the proper working of the inspection head controller, a practical application of digitizing was performed by means of a Contact Image Sensor (CIS), extracted from a commercial flatbed paper scanner, attached to the inspection head by a tailor-made adjustable fixture, as it is shown in figure 4.

![Figure 4. Test bench and CIS sensor assembled to the inspection head.](image)

A specific control board and software were developed for the CIS sensor to work synchronized with the inspection head movement, so that acquired images had a proportional resolution in both $X$ and $Y$ directions. An intrinsic calibration procedure was applied to the integrated CIS sensor following the steps developed by Blanco et al [9], based on scanning a linear-array certified dot artefact and compensating the acquired images for the detected geometrical distortions. Although the CIS sensor image native resolution is 600 × 600 dpi, high-resolution up to 2400 × 2400 dpi images can be obtained by interlacing some low-resolution captures. Figure 5 shows the high-resolution images obtained from layers digitized on three different example parts. These parts were printed in the test bench and the images taken by the integrated CIS sensor using the top level control software described in subsection 3.7 together with the specific digitizing application developed for the CIS sensor.
5. Conclusions
Design, construction and starting-up of a mechatronic test bench with the double capability of 3D printing by FFF and non-contact digitizing is described in this work. This machine was developed in the framework of a research project aimed at improving printed part geometry by detecting and compensating for layer shape deviations in real time, as the part is being constructed.

The test bench is provided with independent controllers for both the 3D printing and the inspection subsystems, but also with a top level control software that enables a coordinated working of both subsystems to make it possible to digitize a layer after being deposited and to continue then producing the part. Robustness and accessibility were some constructive criteria but also the use of technology similar to that of a commercial FFF 3D printer.

Several tests were performed in the test bench to adjust the printing subsystem which improved quadrature of the part, but it still seems necessary to perform some adjustments in the transmission relationship parameters to improve dimensional accuracy of parts in order to meet similar results than those achieved with a BCN 3D printer. On the other hand, the inspection subsystem was tested by attaching a CIS sensor to the inspection head and digitizing several parts as they were constructed within the printing subsystem, what demonstrates fulfillment of this essential requirement and shows the main novelty of this work.

Results obtained allow us to continue with next steps in the research, which will involve a fine printing adjustment of the test bench, integration of other non-contact inspection sensors (conoscopic holography, laser triangulation and a high-resolution camera), with all the implicit requirements, in order to select the most effective technology for the project purposes, and development of contour procedures for each of these digitizing technologies.

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