Conception and project of an AM machine with multiple printing heads

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Abstract

Additive manufacturing technologies consist in mechanisms that allow a part to be fabricated by adding material layer by layer in which the adjacent layers must form bond between them, resulting in a final part whose quality can be compared to one of a similar part produced using a subtractive process. The downside of AM technologies resides mostly on the production time, usually too high to be competitive for high volume fabrication. This paper aims to provide a solution for this problem through the design of an innovative machine in which multiple printing heads collaborate in the production of a single part, reducing the total production time. In addition, the common single printing bed was replaced by multiple fully independent ones in order to obtain a more efficient process.

Keywords: Additive manufacturing, modular, FDM, multiple printing heads, multiple build platforms

1. Introduction

Additive manufacturing (AM) is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM International, 2012) and it can be divided into four groups depending on the state of the base material, as suggested by Kruth *et al* (1998).

One of the groups is the liquid state material processes where the material can be liquid at room temperature and then cured to solidify or can be solid at room temperature, molten to allow it to be shaped and then solidified again, usually by simple cooldown.

Fused deposition modelling (FDM) is a process included in this group and is one of the most commonly used AM technology, for both home and industrial purposes, due to its low machine and materials costs. The low investment required to fabricate parts by FDM is a result of the patent expiry in 2012, which led to many companies creating FDM machine and selling them at much lower prices (Stansbury & Idacavage, 2016). In addition, this situation has led to many researches and investigations in order to improve the efficiency (especially time) and the part quality. Nevertheless, it still isn't economically competitive against polymer injection, for example, when fabricating components for mass production, due to its diseconomies of scale.

The idealized concept enables the use of any AM technology in which material is deposited through a nozzle to create a part. However, to validate the concept, a machine had to be designed and FDM was the technology chosen to make this first approach.

2. FDM

The FDM process, as represented in Figure 1, consists in having the base material processed in the form of filament, typically thermoplastic polymers, and then stored in a cartridge or a spool. The filament is inserted into an extruder responsible for pulling the material from the spool and pushing it through the heating element. The extruder can be connected directly to the last component, meaning that these are solidary, or can be independent and be connected by a tube, called Bowden cable, which guides the filament to the heating element. The material is progressively heated until the glass-transition temperature is reached, being the amorphous polymers, like acrylonitrile butadiene styrene (ABS), the more suitable to be used in this process (Gibson *et al*, 2009) and some semi-crystalline polymers too, like polylactic acid (PLA), as suggested by Hopkinson *et al* (2006).

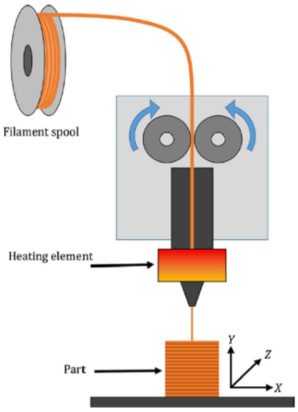

Figure 1 – FDM process. Retrieved form Stansbury & Idacavage (2016).

Both the heating element temperature and the material feed rate must be well configured so the point where the material reaches the glass-transition temperature is coincident with where the nozzle's inside diameter starts decreasing. At the end of the nozzle the diameter of the filament will be the minimum of the whole process at it will depend on the nozzle used for that application. As soon as the material exits this component it starts cooling until it's fully solidified.

However, as explained by Sun *et al* (2008), the material deposited has to bond to material previously deposited so the part is created and it has good mechanical properties. This happens through sintering, which is the blend of polymers between to roads in contact and with enough heat to make this happen, the roads being each line deposited of each layer of the process.

The physical properties of the filament and of the heating element limit the speed of the process since the sintering of the material must happen in certain conditions which means the feed rate is limited by the heat exchange.

On the other hand, as the total production time of a part is the sum of the time of deposition of every road in every layer of the part, the roads wider and taller the roads are, the shorter will be the total time. And this can be achieved by widening the nozzle's exit. Although this may appear as an advantage, the void spaces created in this case are bigger than the void spaces created with a smaller nozzle which diminished the mechanical properties of the final part. In addition, as explained by Panda *et al* (2016) the dimensional accuracy of the final part is directly dependent of the layer height because each layer is considered to have a rectangular section and for parts whose exteriors aren't normal to the base there will volumetric errors correspondent to the difference between the projected part dimensions and the fabricated part. This can be observed in Figure 2 and it's called staircase effects.

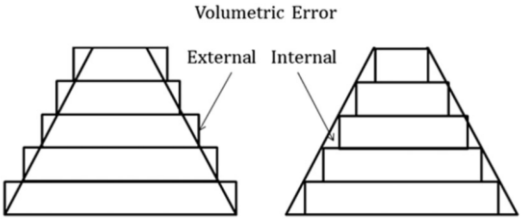

Figure 2 – Staircase effects. Retrieved form Panda *et al* (2016).

These two factors, speed and quality, and the part size are always correlated with each other and in most system it's impossible to achieve the three at same time, this means it is impossible, using current technologies, to fabricate a part with large dimensions with the best quality possible and in a short period of time (Figure 3).

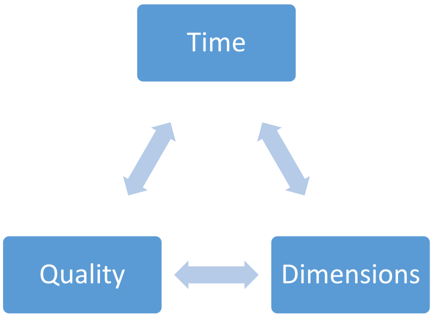

Figure 3 – Current problem in AM.

In industries like automobile it's important to be able to manufacture various prototypes for various parts to be tested. They can be fabricated in a smaller scale, which allows more tests in a short period of time, or they can be fabricated in the real size taking more time to produce, since the quality is a factor that can't be overlooked in this kind of applications.

Two approaches were made in order to allow the three factors to be maximized simultaneously.

One of the concept is called adaptive slicing (Sabourin *et al*, 1997) and it consists of depositing the exterior roads (the part contours) with a small diameter nozzle, improving the surface quality, a depositing the interior with a larger nozzle, improving the total time. But this only works if the part hasn't a functional purpose, because the mechanical properties of it are not the best.

The other concept still isn't commercialized but it is protected by some patents. The system with most versatility belongs to Uzan & Yakubov (2015) and it relies on the fabrication of a single part using multiple printing heads simultaneously. In this system it is only possible to have one linear actuator in each side of the machine, oriented with its length, in where many perpendicular linear actuators move. The second only move one printing head in its direction and it's obvious that the wider the machine the most this component has to be rigid, which can lead to very high costs on equipment. Wachsmuth (2008) also proposes a system with multiple printing heads but it is limited to a maximum of 9 in a 3 by 3 configuration.

Both of the approaches in the second concept aren't as efficient as they could be and also don't have all the capabilities that could make it an indispensable technology.

3. Considerations and specifications

The development of the system described on this paper is set on the work done by Frutuoso (2016) which consisted in a computer program to control the printing heads by creating paths who minimize the fabrication time by testing multiple orientations and positions for it and dividing each layer in regions to be deposited by different printing heads. This division is made so that there is a common region between areas deposited by adjacent printing heads in any direction and this region in each layer is deposited by alternate printing heads. This is represented in Figure 4 and the purpose of it is to improve the mechanical properties of the part in the joining regions.

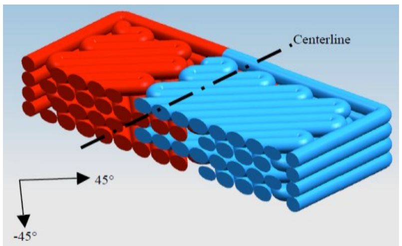

Figure 4 – Alternate deposition region. Retrieved from Wachsmuth (2008).

In order to obtain great advantages from the control program designed, multiple printing heads must be placed in two directions (*x* and *y*), depending on the size of the parts to be fabricated. One of the features of the software is the ability to define the number of printing heads in both directions and this led to the invention of a system where the printing heads are included in movable modules.

It was considered that the printing area of each head was similar to most commercialized FDM systems, which means the dimensions are 200 mm both in *x* and *y* directions, and the height available to fabrication is 250 mm. In the case where multiple printing heads are fabricating a single part it's necessary that the areas of adjacent heads intersect. It was defined that for a test phase the intersection would be 25 mm in each direction, resulting in an area of 250 mm x 250 mm.

Since there are only 25 mm shared in each direction of the printing area of each head, the area that is only reach by one printing head has the initial 200 mm x 200 mm meaning that each of them has to "invade" the space of the adjacent ones.

The movement along the *y* axis of each printing head is independent from one another and is provided by a linear actuator. This called deposition modules are supported by a pair of linear rails aligned with that direction. Since it isn't needed that two modules switch position in this direction, the rail can be common to all the modules placed in the same position along *y*.

The movement of the printing head along the *x* axis is made along another rail, aligned with this direction, but in this case de rail is only attached to the respective module.

To avoid collisions between modules placed in adjacent pair of rails, these have to have different rails heights, as shown in Figure 5. In this Figure it is shown that there is a vertical element with different heights, marked with the number 1 and a component responsible for maintaining the exit of the nozzles coplanar, with the number 4. The number 2 refers to the linear rails and the number 3 to the printing heads.

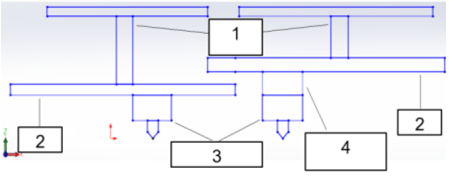

Figure 5 – Different elements of the modules.

Although there is no patent that protects an AM system with this configuration, this might not be enough to be considered an inventive idea, so another feature was created for this machine in where the build platform (printing bed) is divided in smaller build platforms, with dimensions corresponding to the dimensions of the printing area. Each of this smaller bases have a linear actuator aligned with the *z* axis to grant them independence. Each group of build platform and linear actuator forms another module that can be removed from its place and placed in another space.

To prove this concept, the system projected consisted in a structure capable of supporting four platform modules. In this structure were introduced 3 base modules and 3 deposition modules.

Based on some commercialized FDM systems, the linear speed of the printing head in both directions specified for this machine is 100 $mm.s^{-1}$ and the acceleration is 4000 $mm.s^{-2}$. Using a Bowden cable type extrusion and a nozzle with an exit diameter of 0,4 mm, the maximum deflection difference in any point of the machine is equal to 0,1 mm and the maximum deflection of any component of it is equal to 0,2 % of his length.

4. Developed concept

The concept created to fill this gap in the AM industry is shown in the Figure 6 and it can be divided in four major group of components: the structure (1); the platform modules (2); and the two different kinds of deposition modules (3 and 4).

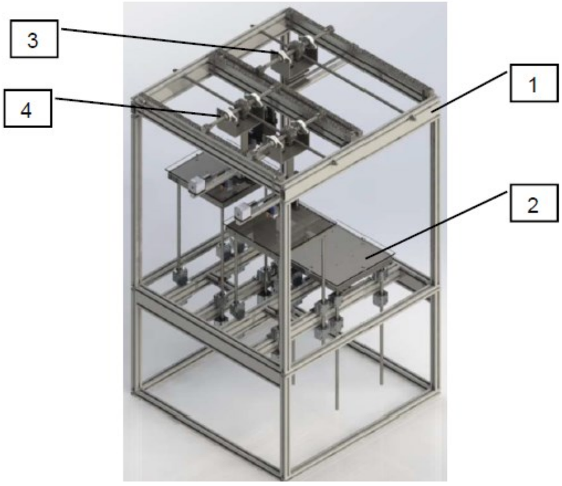

Figure 6 – Modular AM system proposed.

The structure of this system, represented in Figure 7, can also be divided in three zones: the superior zone, consisting in the top horizontal structural members and the top vertical ones; the inferior zone, which includes the middle horizontal structural members and the bottom vertical ones; and the base zone, formed by the four horizontal structural members whose only purpose is to give stability to the system.

The inferior zone of the structure is designed so that there are four positions to place any platform module, since they're all identical, as long as that intended position isn't already occupied. As this system is intended to be scalable, this zone can be defined has having *m* x *n* platform module positions, in which *m* refers to the maximum number of these that can be mounted simultaneously in the *x* axis direction and *n* refers to the same but in the *y* axis direction.

The superior zone of the structure has *m* pairs of rails mounted in the *y* axis direction, *m* being the same as in the previous paragraph. In the current concept the inferior zone has a 2 x 2 platform module positions, so there are 2 pairs of rails to fulfill the fabrication needs. This part of the structure includes a linear guide to prevent that the deposition modules have a pendulum like effect, since all of this modules have the shape of a "T" and the constraints of it in the structure are only translational ones.

Figure 7 – Model of the structure.

The platform module consists in a build platform, with a printing area of 200 mm x 200 mm, and all the components that are attached to it. It's the number and placement of these simultaneously in the structure that define the maximum *x* and *y* dimensions of the part that can be fabricated and also it's geometry in these directions.

The build platform (Figure 8) includes a glass, over which the material of the part will be deposited, and a polyimide film that can heat the glass in order to ensure a better connection between this component and the deposited material and to prevent cracks and deformation of the final part by creating a more uniform temperature gradient. The glass is fixed to a quadrangular steel plate by four screws with springs in between, like many commercialized systems, to allow an easy, although inefficient, calibration. There is also an electric motor attached to a lead screw in the center of the plate to allow movement of the module along the *z* axis and four linear guides, one in each end, to ensure the best positional precision possible.

Figure 8 – Model of the platform module.

In the Figure 9 are represented the two different deposition modules created to allow a alternated layer deposition of adjacent modules along the *x* axis direction without the *y* axis position limitation, as shown in Figure 5.

If the production only requires the utilization of build platforms adjacent in the *y* axis direction, both modules can be placed in the same pair of rails aligned with this direction, since it is the only rail used. However, if it is required the utilization of more than one pair of rails the placement of the deposition modules in these must be alternated, i.e., two adjacent pairs of rails mustn't support the same kind of deposition modules.

Both the superior and inferior module include an actuator to allow movement of the entire module along the *y* axis direction over the rails and a linear bearing housing to slide over the linear guide that prevents the pendulum effects. These components are fixed to a "T" shaped gantry that has different heights depending on which module it is attached, being smaller in the superior deposition module than in the inferior. Fixed to the bottom of each gantry is a linear rail aligned with the *x* axis in which slides a carriage with the printing head actuated by an electric motor with a lead screw, also supported by this rail. In the superior deposition module, the printing head has an extra part, as explained in the previous section, identified with the number 4 in Figure 9, to maintain the nozzles' exit coplanar.

(a) (b)

Figure 9 – Model of the deposition modules.
(a) Superior. (b) Inferior.

Referring to the Figure 10, in order to reconfigure the disposition of the deposition modules inside the system, the nut (9) of the linear guide (8) that prevents the pendulum effect of the deposition modules is unscrewed and the linear guide is removed from the structure. With a 90º rotation of the modules, these are removed from the system in an upwards motion. In the other hand, to reconfigure the disposition of the platform modules, it's needed that there aren't any deposition modules directly above the platform module that is intended to remove. Firstly, the shaft coupling that fixes the lead screw of this module to the electric motor is separated from the screw. Next, all the platform module's components, except the lead screw, are removed in an upwards motion and the last is unscrewed manually from the respective nut (15). To place it back again, the reverse process is made.

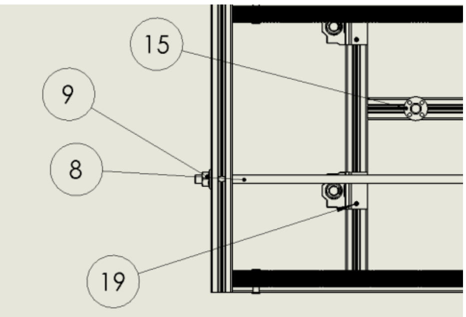

Figure 10 – Representation of some elements of the structure.

5. Detail Design

The three main factors that originated the creation of this document where explained in the section 2 and are: dimensions; time; and quality.

The first is solved by having a scalable structure in which multiple deposition modules can collaborate in the production of a single part, being its dimensions limited to the amount and disposition of the platform modules.

The time is dependent of the capability of the software developed in Frutuoso (2016) to find the part position and orientation and to create the printing heads' trajectories that minimize the production time. It is also related to the number of printing heads used to the production of a single part and to the speed and acceleration of each of them. In the design of the deposition modules, it was defined that the movement along the *y* axis was provided by a pair of rack and pinion systems in where the pinions are attached to both ends of a motor shaft that is actuated by an electric motor and a combination of gears. In this level, it was evaluated the transmission relation between all the gears in order to transform the angular velocity and acceleration of the motor in linear velocity and acceleration of the deposition module, making sure that enough force is transmitted too. On the other hand, the movement along the *x* axis is granted by an electric motor connected to a lead screw. Yet again, a balance between the transformation of the angular velocity and acceleration into linear velocity and acceleration and the transformation of torque into linear force must be made. The lead of the screw is multiplied by the angular velocity and acceleration to find the values of the linear velocity and acceleration, respectively. On the other hand, as shown in Budynas & Nisbett (2011), the equation to calculate the tangential force, P_r, is as follows:

$$P_R = F \times \frac{\mu_e \cos\lambda + \sin\lambda}{cos\,\lambda - \mu_e\, sin\,\lambda}$$

In this equation, F refers to the axial force required, μ_e refers to the friction coefficient and λ to the lead angle. As μ_e is always less than 1, the greater the lead angle the greater the tangential force required. As this force is related to the torque by multiplying it by the screw radius, the torque required also raises with λ. The power of the motor is almost constant regardless of the working point and the power is the multiplication of the torque by the speed, so when one raises the other must decrease, which means that there has to be a precise adjustment of the lead angle in order to guarantee this actuation fulfills the requirements.

Finally, the quality is greatly dependent of the exit diameter of the nozzle, i.e., the smaller the diameter the greater the quality. However, the height of deposition also affects the part quality, narrowing or flattening the road width and even by the solidification of the deposited material before the contact with the previous one. Since there aren't many forces involved in this AM process, the project made in a first approach was a deflection one instead of a project for the stresses. For the vertical members of the structure a buckling analysis was also made to guarantee that the low deflection of the horizontal members isn't neglected by the instability of the system.

In order to design the system with a safety factor, all the constraints that would otherwise be considered as fixed were considered as simply supported, using the set of equations suggested by Budynas & Nisbett (2011). The only exception was the rail aligned with the *x* axis direction as it is fixed in the middle and the most important point to study is where the printing head is the closest to the electric motor that moves it along this direction. As demonstrated in Figure 11, it was considered a fixed constraint in the center of the rail, which was transformed in a fixed constraint in one end of a similar member with half the length. P_{ci} represents the weight of the printing head, P_{ci} represents the weight of the linear actuator and w_{gl} represents the distributed force due to the rail's weight. The calculations were done as it follows:

$$\delta_{cc}^{ca} = \frac{Fx^2}{6EI}(x - 3a) = \frac{1{,}9\times123^2}{6\times193000\times2270{,}81}(123 - 3\times180) \cong$$

$$\cong -0{,}00456\ mm$$

$$\delta_{cc}^{ci} = \frac{4{,}39\times123^2}{6\times193000\times2270{,}81}(123 - 3\times123) \cong -0{,}006213\ mm$$

$$\delta_{cc}^{gl} = \frac{wx^2}{24EI}(4lx - x^2 - 6l^2) =$$

$$= \frac{13{,}734\times10^{-3}\times123^2}{24\times1{,}93000\times2270{,}8}(4\times192{,}5\times123 - 123^2 - 6\times192{,}5^2) =$$

$$= -0{,}00282\ mm$$

That results in a total deflection of 0,014 mm in module.

For the deflection of the platform module glass, another approach had to be made has this element is subjected to the force resulting from the weight of the deposited material that, in the case of ABS and considering a build volume of 200 mm x 200 mm x 250 mm, can reach 102 N. Adding this to the weight of the glass and transforming it into pressure it was obtained a result of 0,002647 MPa. Introducing this values in Siemens NX in order to make a finite element analysis, as shown in Figure 12, the results were obtained as it is shown in Figure 13.

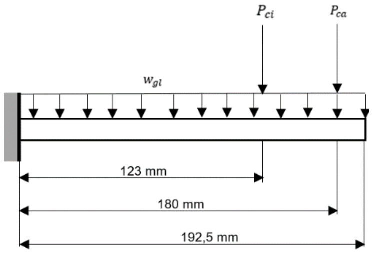

Figure 11 – Forces diagram of the rail aligned with the *x* axis.

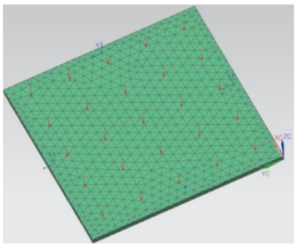

Figure 12 – Finite element analysis of the glass.

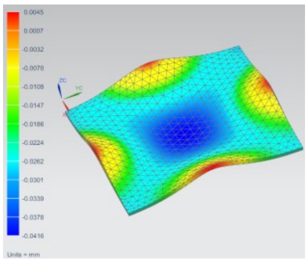

Figure 13 – Results of the glass analysis.

The calculations made in order to evaluate the instability of the vertical members showed that the forces applied in them weren't even closed to the required force to do so, meaning this isn't a critical evaluation to be made in a system like this.

However, in order to make these calculations, the maximum number of deposition modules that could be inserted in the system simultaneously had to be defined. Due to the dimensions of them, the length of the rails aligned with the *y* axis has to be equal to 500 mm, in which only 432 mm are useful. To avoid collisions between two deposition modules adjacent along the *y* axis they must have a minimum distance of 92 mm. Dividing 432 by 92 it's obtained that the maximum number of deposition modules in each pair of rails is four. As there are two sets of these the maximum number in the system is eight.

The number of both modules that was accepted as a concept validation was three for each one. But since the system has space for four platform modules and eight deposition modules it's interesting to study the worst case scenario.

The sum of the deflection results of the superior zone of the structure, the inferior zone of the structure and the glass of the platform module showed that the maximum deflection occurs in the center of the glass and its value is 0,093 mm, which is inferior to the limit of 0,1 mm defined in the specifications. The deflection of each individual member is always bellow the limit of 0,2 % of its length. Adding this to the fact that there aren't any instability problems it's concluded that the structural members were well projected.

Moreover, all the specs of velocity and acceleration of the printing heads were validated with the choice of the motors and the transmission components, allowing this system to fabricate parts in an approximated time to similar parts in a much smaller scale fabricated in the most common systems, when linked to a software that optimizes the printing heads trajectories, avoiding collisions between them.

As the system represented in Figure 6 is constituted by many platform modules and many deposition modules, whose fixation elements to the system are minimal to guarantee the required precision, and because there are many positions for each modules, it can be concluded that this system is reconfigurable. For a deposition volume of 400 mm x 400 mm x 250 mm, the weight of the entire system is 41,63 kg and its general dimensions are 654 mm x 570 mm x 944 mm.

6. Conclusions and future works

This document is the result of the conception, design and development of an innovative AM modular system with multiple printing heads and multiple build platforms, each independent from each other. This innovative system is in the process of a submission for patent protection.

The objective of this innovative system is to improve significantly the fabrication time of a part with large dimensions or many parts with small dimensions, without compromising their quality. This is obtained with the cooperation of multiple printing heads in the fabrication of a single part simultaneously without risking any collisions.

The independence of the platform modules also carries another benefit, since it allows, for certain geometries, to reduce the need of support materials. Another extra point is that with few changes to the software, it can allow a part to begin production after others already started, as long as there are available platform modules.

The system's versatility and scalable structure allow it to be utilized in industries like automobile and aeronautics, both in rapid prototyping and in rapid tooling. And also, by enabling the fabrication of multiple small dimensions parts simultaneously it brings AM technologies one step closer to the mass production industries.

Next steps will involve prototyping the designed concept to verify the effect of assumptions on the produced part, adjusting the limits imposed after the analysis.

Although the designed system in this document refers only to FDM, with some adaptations it can be exploited in most processes that involve material deposition. It even allows the utilization of multiple technologies simultaneously.

The devised system opens some roads to further development the AM technology in general, specially addressing one major gap: fabrication of parts of bigger dimension, maintaining quality within a certain time to fabricate.

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