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Combined 3D Printing and Part Assembly Manufacturing

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"There is no such thing as a long piece of work,
except one that you dare not start."
— CHARLES BAUDELAIRE

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ABSTRACT

Despite its irrefutable potential to change the way goods are produced, 3D printing technologies are, nowadays, employed to an insignificant amount of manufacturing processes in the production chain. While additive manufacturing, as the technology is also known, can be used for building objects of any shapes in a wide range of materials, the resulting products usually require costly post-processing steps for the incorporation of non-printable parts that provide the object with useful functionalities. Such technologies could play a more important role in the manufacturing sector if they were enhanced so that these post-processing steps would be addressed during the building process and the resulting object would already be equipped with its final set of features. Aiming to add more functionalities to the parts produced by 3D printing techniques, this study introduces improvements to be applied to additive manufacturing machines. The technology introduced and demonstrated in this research, named Combined 3D Printing and Part Assembly (CPPA), merges the versatility of 3D printing with techniques to assemble external parts to the printed object in building time, allowing the manufacturing of products with functionalities beyond the ones provided by classic additive methods. While traditional 3D printing technologies can only create objects in a limited variety of materials, CPPA machines are capable of merging any sort of external parts to 3D printed structures.

Keywords: 3D Printing. manufacturing. non-printable parts. enhancements.

RESUMO

Apesar de seu irrefutável potencial de mudar o modo como bens são produzidos, a tecnologia de impressão 3D são empregadas em uma insignificante parcela dos processos de manufatura na cadeia produtiva. Ao mesmo tempo que a manufatura aditiva, como a tecnologia também é conhecida, é capaz de gerar objetos de qualquer formato em uma imensa gama de materiais, os produtos resultantes frequentemente necessitam de etapas de pós-processamento altamente custosas para a incorporação de partes não imprimíveis que proporcionam funcionalidades úteis ao objeto. Tais tecnologias poderiam exercer um papel mais importante no setor de manufatura se passassem por melhorias que permitissem que essas etapas de pós-processamento fossem executadas durante o próprio processo de impressão, de forma que o o objeto resultante já estivesse equipado com o seu conjunto de funcionalidades final. Visando adicionar mais funcionalidades aos objetos produzidos com técnicas de impressão 3D, esse estudo apresenta aperfeiçoamentos a serem aplicados em equipamentos de manufatura aditiva. A tecnologia denominada *Combined 3D Printing and Part Assembly* (CPPA) introduzida e demonstrada nessa pesquisa tem por objetivo combinar a versatilidade da impressão 3D com a anexação de peças externas ao objeto em tempo de impressão, de modo a criar produtos com funcionalidades além das fornecidas por métodos aditivos clássicos. Enquanto tecnologias tradicionais de impressão 3D criam objetos com uma variedade muito limitada de materiais, máquinas CPPA são capazes de incorporar peças externas de qualquer tipo a estruturas impressas em 3D.

Palavras-chave: impressão 3D, manufatura, peças não imprimíveis, aprimoramentos.

LIST OF ABBREVIATIONS AND ACRONYMS

CPPA	Combined 3D Printing and Part Assembly
CAD	Computer-Aided Design
FDM	Fused Deposition Modeling
DCEL	Doubly Connected Edge List
USB	Universal Serial Bus
SLA	Stereolithography
UV	Ultraviolet
CNC	Computer Numerical Control
IoT	Internet of Things

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1 INTRODUCTION

Although the 3D printing technology started to gain visibility very recently, the first patent regarding this technology was issued in the 1980's, when Charles Hull invented the stereolithography apparatus (SLA) (3D Printing Industry, 2014). Following Hull's creation, many other technologies with the same purpose of additively manufacturing a three-dimensional object virtually represented in a computer were developed. Due to the speed, the cost-effectiveness and the level of customization of such manufacturing processes, 3D printing became a method mostly used for creating prototypes for product development within industry, being known then as Rapid Prototyping (3D Printing Industry, 2014).

Even today, additive manufacturing, as the technology is also known, is largely employed in prototyping projects, but it has been found to be useful also for movie companies, advertising offices, amusement parks, and other business that often require simple products in small quantities but with high level of customization. It has not reached many regular consumer houses yet, as current 3D printing methods are not capable of providing much more than simple objects that do not aggregate functionalities other than the ones related to its shape.

Additive manufacturing is indeed a powerful manufacturing technique as it allows objects of almost any shape to be fabricated in a wide range of materials at low cost (CUMMINS, 2010). However, the materials that a 3D printer is able to print are limited by its manufacturing technology, which makes the range of materials that a single 3D printed object may have fairly small. In addition, many things can not be manufactured by any additive manufacturing technique due to its size or physicochemical properties. These limitations are the factors that narrow the functionalities that can be embedded in a 3D printed object without posterior intervention.

Rick Smith, a 3D Printing Entrepreneur, predicts that in a near future the 3D printing technology will allow localized production for consumer and industrial goods (SMITH, 2015). That means that many goods will no longer be manufactured in industries and purchased in stores, but downloaded from the Internet and synthesized by the consumers themselves, with a 3D printer. In the industrial level, that means that many digital 3D printing factories will be connected in a global production network, allowing the goods to be fabricated closer to their point of use. For all those advances to take place it is necessary to overcome the limitations faced by additive technologies and build machines capable of creating objects with additional features and less restrictions.

In this research we introduce an original concept in additive manufacturing named *Combined 3D Printing and Part Assembly Manufacturing* (CPPA). The enhancement of 3D printing platforms with concurrent part assembly capabilities proposed by such concept allows the creation of objects whose features go beyond the ones obtained by traditional additive manufacturing techniques. For instance, the creation of a simple plastic pendant embedded with a stone could not be fully accomplished solely by traditional 3D printing methods. The plastic frame can be created by the printer, but the stone can only be assembled in a posterior, additional process. Meanwhile, the same object could be created in a single manufacturing process by CPPA technology, as it allows the assembly of external items to the part being printed during the printing process. In order to establish the relevance of the proposed concept, we also demonstrate the technology by extending the functionalities of a regular 3D printer with basic CPPA premises.

2 3D PRINTING

3D printing refers to various methods of making three dimensional objects from computer models using additive processes (3DPrinting.com, 2012). The 3D printing process starts by creating the virtual design of the object that will be manufactured, either by modeling it from scratch using a CAD application or by making a digital copy of an existing object with a 3D scanner. Once the virtual representation of the object is ready, it must be sliced up into a set of cross sectional layers, which are printed out one on top of the other, until they build up into a complete 3D printed object (BARNATT, 2013). Figure 2.1 depicts the three stages of any additive manufacturing process.

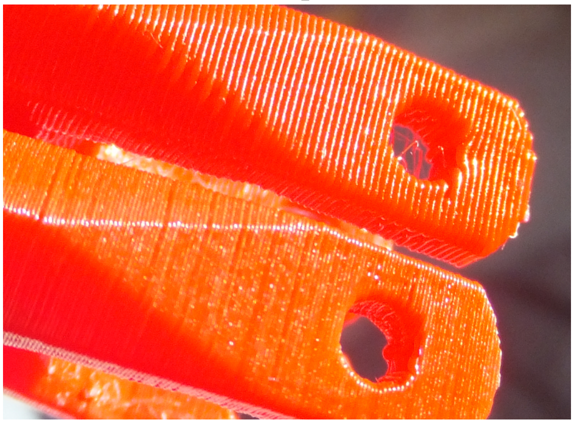
Figure 2.1: The three stages of 3D printing

Source: hotmess3d.com

The quality of a 3D printed part is defined by the resolution the manufacturing machine can accomplish. The resolution of a 3D printer can be defined by two variables: the minimum feature size of the XY plane and the Z-axis resolution (layer height) (Formlabs, 2016). This distinction must be defined because usually the mechanism that controls the Z-axis movement is very different from the one that controls the other axis. Due to technology restrictions, the layer height tends to be the characteristic that limits the perceived sharpness of a 3D printed object. Thus, such variable is used more often to describe the resolution of a machine. Figure 2.2 shows how layer thickness affects the sharpness of 3D printed objects.

Besides 3D printing, many other manufacturing technologies are employed in the design of objects in industry. Subtractive manufacturing and molding are popular techniques considerably more developed than additive manufacturing technology, making them a usual safer choice for companies. Despite the advantages of other methods, 3D printing has found to be useful for several applications, and, from time to time, new improvements to the technology make it more robust and beneficial to different manufacturing processes.

Figure 2.2: Difference between 0.3mm (top) and 0.15mm (bottom) layer thickness



Source: blog.protoneer.co.nz

Subtractive manufacturing is a process by which 3D objects are fabricated by selectively removing material from a solid block of such material. This manufacturing technique is widely used in the industry to create either metallic and plastic objects, and can replace 3D printing in many situations. While subtractive manufacturing can usually produce objects faster and with a better resolution than its additive counterpart, the waste of material intrinsic to the process highly increases the cost of production and impacts the environment. Due to these disadvantages and with the constant improvements of additive methods, some subtractive manufacturing processes are being replaced by 3D printing, revealing that this technology still has a good potential to spread.

Molding is another manufacturing technique very popular in industry and injection molding is the method of choice for the creation of large batches of plastic parts. In the molding manufacturing process, liquid or pliable raw material is shaped using a mold, which is done incredibly fast and reliably in the most advanced methods. The resulting objects usually have high sharpness and almost no material is wasted in the process. The main limitation of molding lies in its cost-effectiveness for small batches. Once the creation of molds is expensive and time consuming, the dilution of this cost between the total number of copies manufactured will determine the cost-effectiveness of the process. Therefore, molding and 3D printing are best employed in different situations.

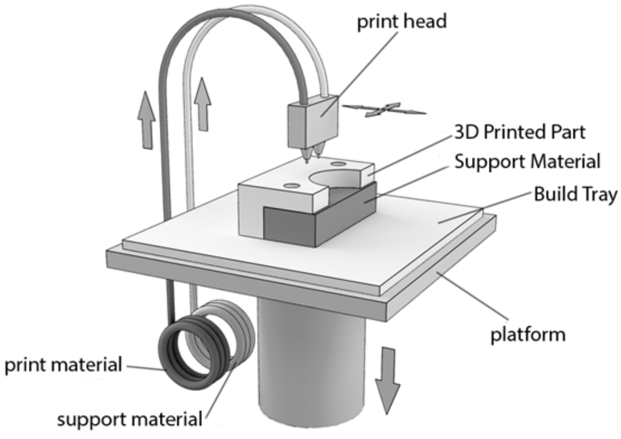
2.1 Additive Manufacturing Technologies

There are many technologies that use additive manufacturing principles in the creation of three-dimensional parts and almost all of them can be classified in one of the three categories described by Barnatt (BARNATT, 2013). The first category, called *extrusion printers*, creates objects by extruding molten material such as thermoplastic, metal, or even edibles from a nozzle. Secondly, there are the printers that create each layer by selectively solidifying a photopolymer exposing it to a light source, as such, they are called *photopolimerization printers*. Object can be created inside a tank of such photopolymer or the liquid can be jet out to make thin layers. Finally, the third category selectively sticks together successive layers of very fine powder either by jetting a glue or by fusing the granules together. Such printers are called *powder printers*. Each one of these categories has its own pros and cons and fits better in a particular application. The following subsections provide a brief review of these techniques.

2.1.1 Extrusion printers

Such machines create 3-dimensional objects by depositing layers of molten material over a build tray, where it cools down and solidifies. The most common type of extrusion printing technology is FDM (Fused Deposition Modeling), in which thermoplastic filament is loaded on a spool and continuously supplied through a nozzle. The nozzle heats up the filament and extrudes a hot, viscous strand (like a hot glue gun) while moving along the x- and y-direction. After each layer is finished, the build tray is lowered to produce the next layer. Support structures are normally printed out of the same material as the object, requiring physical removal after the process has finished. In more expensive systems, a second nozzle can carry a soluble support material that is easily dissolved afterwards. Figure 2.3 illustrates the functioning of an FDM 3D printer.

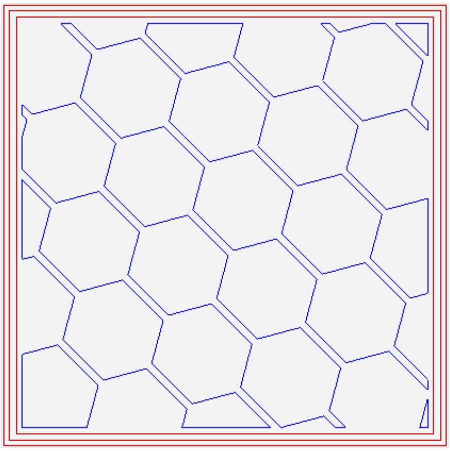
Figure 2.3: FDM 3D printing schematic



Source: engatech.com

In order to save material and decrease the building time, FDM printers usually do not create completely solid objects. The interior of the part is filled with hollow structures that provide a good balance between strength and material economy. The most common infill structure, that mimics the shape of honeycombs, is depicted in Figure 2.4. Note that the blue lines represent the infill structures while the red ones are the perimeters of the layer. The perimeters are the outermost portions of the layer and form the surface of the object, providing the overall look and finishing of it.

Figure 2.4: Honeycomb infill structures in a square layer



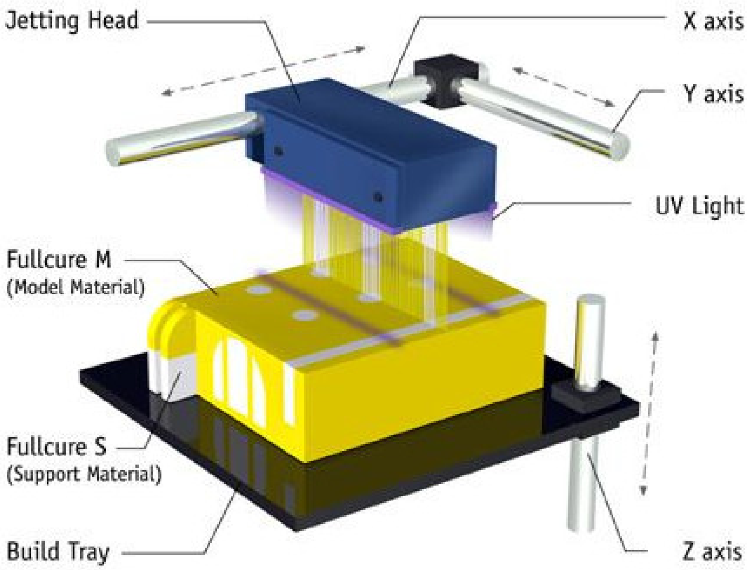
FDM has become the most popular technology for 3D printing due to the cost-effectiveness of the whole printing process (including machine and raw material), decent printing quality and small size of the machinery (office friendly). There are many commercial FDM 3D printers available in the market, both for home and business applications, produced by big companies like 3D Systems and Stratasys. In 2004, Adrian Bowyer, a Senior Lecturer in mechanical engineering at the University of Bath in England, conceived the idea of a low-cost, self-replicating 3D printer, and created the RepRap project. The goal of the initiative is to develop and give away the designs for a cheaper machine with the capability of creating copies of itself. Due to the accessibility of FDM printers, the technology was chosen for the development of the RepRap project.

2.1.2 Photopolymerization printers

Photopolymers are special kinds of polymers that change their properties when exposed to light. The materials used in photopolymerization printers are hardened when exposed to specific wavelengths. The machines in this category create objects by solidifying thin layers of the photopolymer one on top of the other. The shape of each layer is defined either by selectively depositing the photopolymer or by selectively hardening it. Depending on the way the layers are shaped, two classes of 3D printers can be defined.

The first class of machines use print heads with many tiny nozzles to selectively jet droplets of photopolymer that are cured by UV light. The build tray can move in the Z axis, allowing for the print heads to deposit material on top of the previous layer. Model material and support material come from different nozzles, and the support material is usually a wax or a gel that can be physically removed. Figure 2.5 depicts the operation of a PolyJet machine, a technology developed by Stratasys.

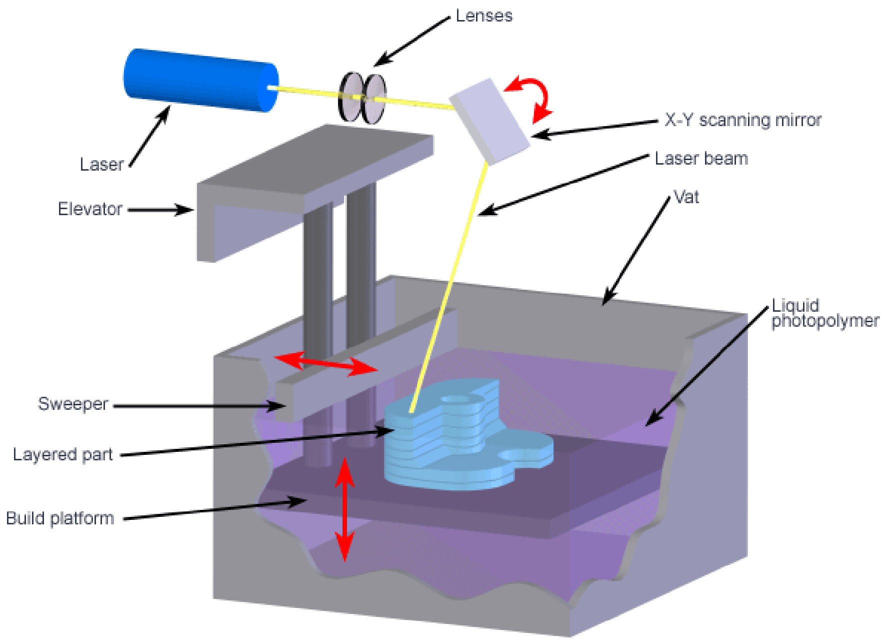
Figure 2.5: PolyJet 3D printing schematic



Source: stratasys.com

The second class of photopolymerization printers create each layer by selectively hardening thin portions of the photopolymer inside a vat. In this technology, known as stereolithography (SLA), a scanning laser or a 2D projector is used to solidify either the surface of the material or its bottom (through a transparent window). The hardened portions remain fixed to a structure that moves in the Z axis, allowing the next layer to be solidified. Since the part is built inside a tank of the raw material, only one kind of photopolymer can be used for each print, thus the whole object must be constructed with one single material, including its support structures. Figure 2.6 shows the schematic of a 3D printer of the second class of photopolymerization machines.

Figure 2.6: Stereolithography 3D printing schematic



Source: custompartnet.com

2.1.3 Powder printers

In this class of 3D printers, a thin layer of powder is spread over the working area and some parts are selectively solidified by jetting a binder from an inkjet print head or by sintering or melting the granules together. The working area then moves downwards, a new layer is added and the process is repeated until the piece has built up. Support structures are not needed for this process since the unsolidified media fills all the gaps not occupied by the object. After the object is removed from the working area, all the remaining powder can be recycled and used for other prints.

Machines that stick the powder together by jetting binder can use plaster or resin powder. The binder can be dyed, thus allowing the printing of colored objects. Usually the resulting piece of this process is structurally weak, which can be improved with wax impregnation.

For melting or sintering the material either a laser or an electron beam is generally used as heat source. The materials compatible with this technique are metals and polymers and the resulting objects usually have a rough finishing, requiring a post-processing to smoothen the surfaces.

3 COMBINED 3D PRINTING AND PART ASSEMBLY

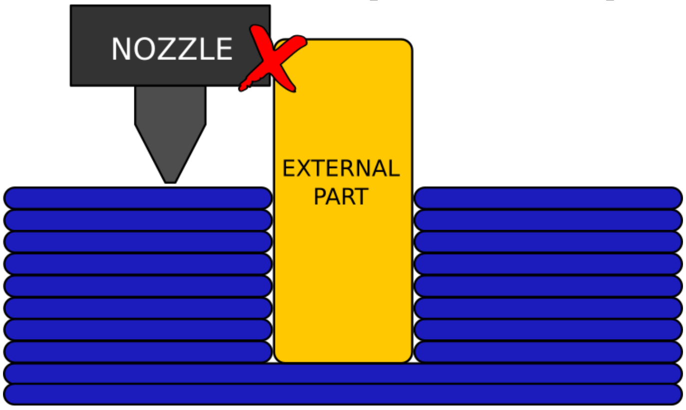
Given the limitations of current additive manufacturing technologies regarding the variety of functionalities that can be embedded into a manufactured object, it is safe to assume that 3D printing by itself, as it is conceived today, is not powerful enough to induce real changes in the way we create and use the objects of our daily life. With that in mind and seeking to expand the capabilities of 3D printing, the concept of a Combined 3D Printing and Part Assembly (CPPA) manufacturing system is introduced in this research.

The central idea of CPPA technology is to assemble non 3D-printable parts to an object while it is being printed, embedding functionalities that otherwise could not be obtained in a 3D printed object. The ideal CPPA machine would be able to place parts in any orientation, anywhere within the printing area, at any time during the printing process. For that to be done, besides the regular additive manufacturing capabilities, the machine must be equipped with a robotic arm capable of positioning the external parts to be assembled. The two systems that compose the machine (3D printing subsystem and part placement subsystem) must not interfere the operation of one another. Sections 3.1 and 3.2 detail the CPPA subsystems.

In addition to the two subsystems, software that controls and synchronizes them both is necessary for the operation of a CPPA machine. The software is responsible for taking a model composed by printable and non-printable parts and outputting a set of commands for the machine, operating the subsystems so that the printable parts are built by the 3D printing subsystem and the non-printable parts are placed by the part placement subsystem. The control software must decide the best moment for positioning the external parts during the printing process, avoiding interferences between the subsystems. Section 3.3 provides a deeper explanation of the control software.

Despite the straightforward concept of CPPA, its implementation is quite challenging, mainly because of the interference between the 3D printing and the part placement subsystems. 3D printers create objects layer by layer, sequentially. If an external part is placed in such a way that a portion of it is higher than the last printed layer, the printing process will very likely be disrupted, as depicted in Figure 3.1. Besides that, if a particular part must be placed in a way it is not self supported, the object placement mechanism should hold it in place until the printing process make it self supported. The simultaneous activity of both mechanisms in the printing zone would also be disruptive in most of the cases.

Figure 3.1: Interference of an external part in a FDM 3D printing process



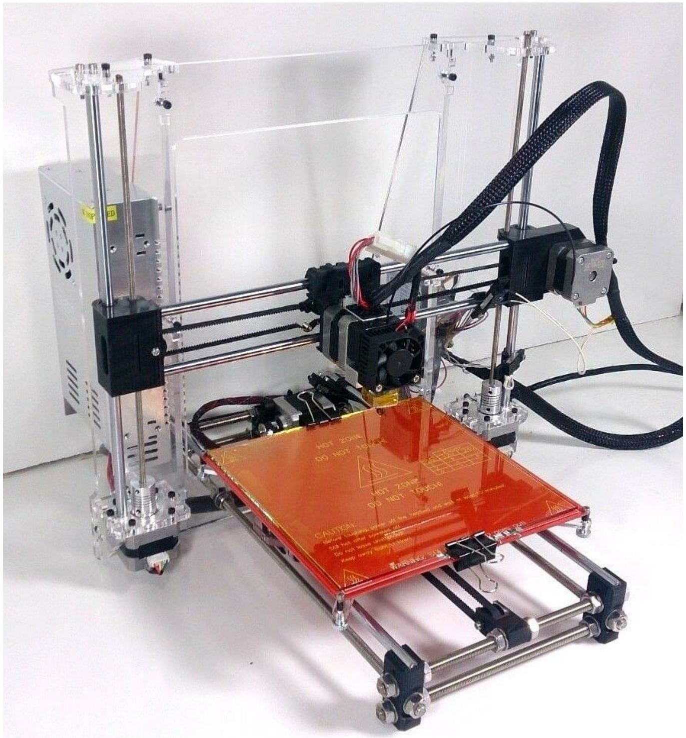
In order to establish the concept of CPPA technology, a demonstrative machine was developed. Due to time and technology restrictions, a simplified version of a CPPA machine, without automatic part placement capabilities, was created. Thus, the focus of the demonstration was the development of a CPPA control software capable of generating commands for a regular 3D printer that, besides printing the printable objects, interrupts its process for the manual assemble of the non-printable parts. The development of such software is covered in more details in section 3.3. Despite its simplicity, the machine was able to print objects with embedded non-printable parts, demonstrating the potential CPPA technology can accomplish.

3.1 The 3D Printing Subsystem

This subsystem is responsible for building all the printable parts included in the model using additive manufacturing processes. Any traditional 3D printing technology can be employed for this task, but FDM (refer to section 2.1.1) stands out as the best choice for the development of this project, given its outstanding cost-effectiveness, accessibility and simplicity. A regular FDM 3D printer can serve as the base for a CPPA machine, fully providing the 3D printing subsystem. In this case, the part placement unit must be constructed on top of the printer to complete the CPPA machine, as detailed in section 3.2.

An extrusion printer from RepRap project, model Prusa i3, was used to build the demonstrative CPPA machine. The project of this printer, including hardware and firmware, is completely open source and many of the parts necessary to assemble the printer can be 3D printed themselves. The Prusa i3 is controlled by an Arduino board, which is connected to the USB port of a computer for the communication of the printing commands. The firmware in the controller can be freely modified and replaced, which is essential for customizing the printer operation. Besides being a low-cost alternative for 3D printing enthusiasts, this machine is known for generating high quality objects and for being durable and user friendly. All these characteristics make the Prusa i3 an excellent choice of 3D printer to be used as base for the development of a CPPA machine. Figure 3.2 shows a RepRap Prusa i3 3D printer.

Figure 3.2: RepRap Prusa i3



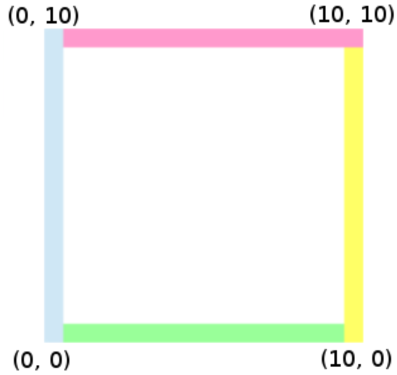
Source: all3dp.com

Most of FDM machines, including the RepRap used in this project, are managed by simple digital controllers without great computing power. In order for these machines to print complex objects, the building process must be previously broken into a set of basic operations that can be handled by the printer. These basic operations are standardized by a numerical control programming language known as G-Code, which is adopted not only by 3D printers but many other CNC machine as well. The G-Code programming language has a procedural, imperative paradigm (Electronic Industries Association, 1979) and is composed by a set of simple commands that translate into actions such as moving the print head, extruding material, heating the build tray and pausing the printing process. Figure 3.3 illustrates a simple G-Code program and the printed structure it creates.

Figure 3.3: Simple G-Code program and the resulting printed structure

```
1: G1 X0.0  Y0.0
2: G1 X10.0 Y0.0  E2.0  F900.000
3: G1 X10.0 Y10.0 E4.0
4: G1 X0.0  Y10.0 E6.0
5: G1 X0.0  Y0.0  E8.0
```

(a) G-Code instructions



(b) Structure generated by the code

In the code depicted in (a), G1 is a move/extrusion instruction where: X and Y are the absolute coordinates where the movement will end; E is the amount of material to be extruded during the movement (cumulative); F is the rate the material will be fed to the extruder (thus, defines the movement speed). Each step is detailed below:

1: Print head is moved to start position (0, 0) without extruding any material;

2: Print head is moved to position (10, 0) while extruding 2mm of material at 900mm/min;

3-5: Print head moves to (10, 10), (0, 10) and (0, 0) respectively and at each step 2mm of material is extruded. The extrusion rate does not change from step 2.

3.2 The Part Placement Subsystem

The part placement subsystem is responsible for assembling non-printable parts to the 3D printed objects during the building process. It takes parts (e.g., electronic components and/or mechanical parts) at locations specified in the design description and places them at the intended object position. The external parts are fed to the subsystem by an automated mechanism or by a human operator that places them in a predetermined location before the building process starts.

A robotic arm integrated to the 3D printing subsystem performs the placement of external parts. The robotic arm either can be attached to the print head positioning system of the 3D printer or it can be completely independent from the 3D printing subsystem. In the first case, the moving mechanism of the 3D printer is used to place the external parts in the correct location. The robotic arm only needs to grab the part and release it when appropriate. While this approach simplifies the machine, it also limits the freedom of the part placement subsystem and potentially reduces the available printing area. The implementation of the second approach is more sophisticated, as a robotic arm with three degrees of freedom using an independent coordinate system must be created and attached to the printer. Misalignments between the coordinate systems of both subsystems can induce errors during the building process, so calibration is a sensitive point in this approach. On the other hand, independent moving mechanisms allow for simultaneous operation of part placement and printing units, ensuring more flexibility to the machine.

Apart from the implementation strategy of the robotic arm, the control system of the part placement subsystem must be synchronized with control system of the 3D printing subsystem. To fulfill such requirement, the most appropriate solution is the integration of the robotic arm management software into the 3D printer controller. It is necessary to extend the set of commands the controller handles, including instructions for moving the arm, grabbing and placing parts.

For the machine built to demonstrate the concept of CPPA technology no robotic arm was developed, instead, a manual version of the part placement subsystem was used. The control software pauses the printing process whenever an external part must be assembled and a human operator places the object at the appropriate location, thus simulating the operation of a robotic arm.

3.3 The Control Software

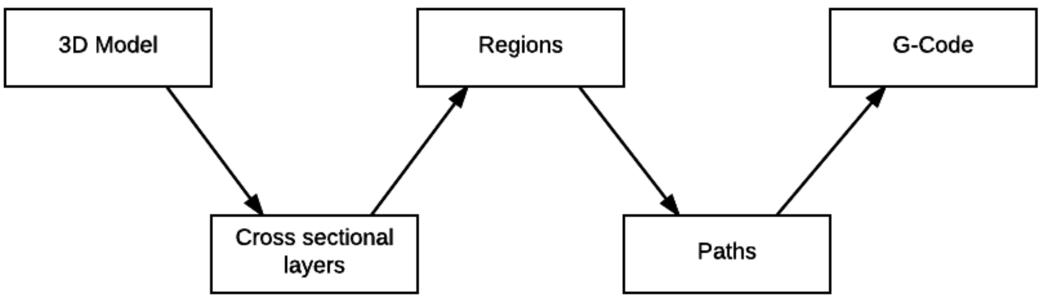
As both 3D printing and part placement subsystems are provided with rather simple control units that only interpret elementary commands and translate them into basic operations, a software that compiles complex 3D models into a set of appropriate commands is necessary. From the information of printable and non-printable objects present in the model, the program must output instructions for synchronizing the two subsystems that compose the machine.

The CPPA control software must take the printable parts of the model and compute their cross sectional layers, in a process named *slicing*. In many cases, the slicing algorithm must also generate supporting structures to keep "floating" parts from falling down during the printing process. Each layer must be converted into a set of movement and extrusion commands for the 3D printing subsystem. On the other hand, the commands for controlling the part placement subsystem are generated based on the arrangement of the non-printable parts. The software is responsible for electing the best moment during the printing process for performing the placement of external parts, in an effort for reducing the interference between the two subsystems.

For the machine created for the demonstration of CPPA technology, a control software provided with a customized slicing algorithm was developed from scratch. As the machine is not equipped with a mechanized part placement unit, the G-Code commands generated for controlling that subsystem simply pause the printing process at the proper moment and let the operator manually assemble the external part. C++ was the programming language adopted for developing the application, as it offers good performance while providing powerful object-oriented features. The part of the program responsible for slicing the printable parts was deeply inspired by regular slicing software solutions, specially *Slic3r*[1], an open source application widely used by the 3D printing community.

The complex process of generating the control commands (G-Code) from a 3D model can be split into a set of simpler operations as depicted in Figure 3.4. This data flow chart was specially designed to facilitate the development of the control software used in the demonstrative CPPA machine. The remainder of this section deals with detailing the implementation of said software.

Figure 3.4: Data flow chart of the CPPA control software



The first data structure in the data flow depicted in Figure 3.4 is the 3D model representing the object to be printed. The model was implemented as a mesh of triangles in the three-dimensional Euclidean space. A mesh of any kind of polygons could be used to define a 3D object, but the property that, unlike polygons with more sides, triangles are always planar, simplifies the mesh processing. Also, all main file formats used to represent 3D objects for 3D printing follow the same approach (ASTM/ISO, 2013; 3MF CONSORTIUM, 2015; 3D Systems, Inc., 1988), therefore, importing files is easier when using triangle meshes.

The internal triangle mesh structures are loaded from STL files (3D Systems, Inc.,

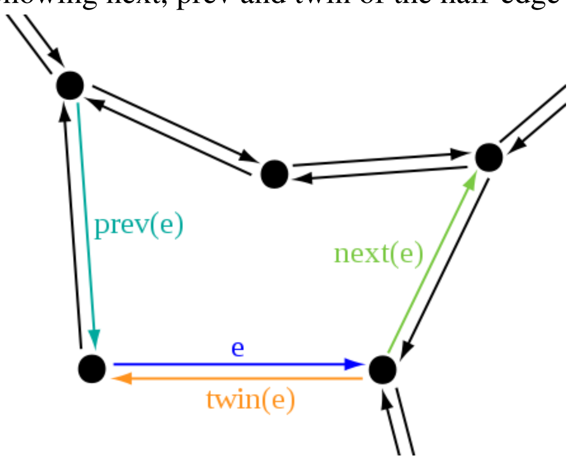
[1] Available at <http://slic3r.org/>

1988) provided by the user. This file format is compatible with most of the CAD softwares in market, thus, a wide variety of 3D modeling programs can be used for creating models for the control software implemented in this research. In addition, as STL file type do not contain information about the nature of the part (if it is printable or not), the user must provide the software with that information when loading objects.

The implemented triangle-mesh structure is capable of representing only manifold geometry, i.e., each edge of the mesh must be shared by exactly two triangles. Non-manifold geometry manifests itself as unbounded volumes, open shells, or thin walls. Such structures would cause many problems to the slicing process if they were present, as the thickness of thin walls and shells is undefined and they would confuse the definition of what is inside and what is outside the object. Modern file formats for additive manufacturing such as AMF (ASTM/ISO, 2013) and 3MF (3MF CONSORTIUM, 2015) do not allow non-manifold geometry as well.

To represent a triangle mesh the doubly-connected edge list (DCEL) data structure was implemented. The data structure was originally described by Muller et al (MULLER; PREPARATA, 1977) and is composed by vertices and structures known as half-edges. A set of three half-edges bound a triangle and each one of them has a pointer to the next half-edge in the same triangle, a pointer to its twin half-edge, and a pointer to its head vertex. A pair of twin half-edges form an edge and each one of them points to a different vertex of such edge. Each vertex has a pointer to one of its incident half-edges. Figure 3.5 shows the connections between half-edges in a DCEL structure (not triangular). This complex structure provides efficient manipulation of the topological information of the mesh, which is essential for the slicing algorithm.

Figure 3.5: Showing next, prev and twin of the half-edge *e* in a DCEL



Source: wikimedia.org

A large integer type was chosen to represent coordinates in the Euclidean space rather than a floating point type. A floating point type contains two fixed size fields, a significand (s) and an exponent (e), and its value v is defined as follows:

$$v = s \times b^e$$

where b is the base (usually defined as 2 or 10). For instance, using decimal numbers, lets assume $b = 10$, s is a four digit, generic number and e is a one digit number. Varying the value of e from -3 to -1, v is given as follows:

$$v = WXYZ \times 10^{-3} = W.XYZ$$

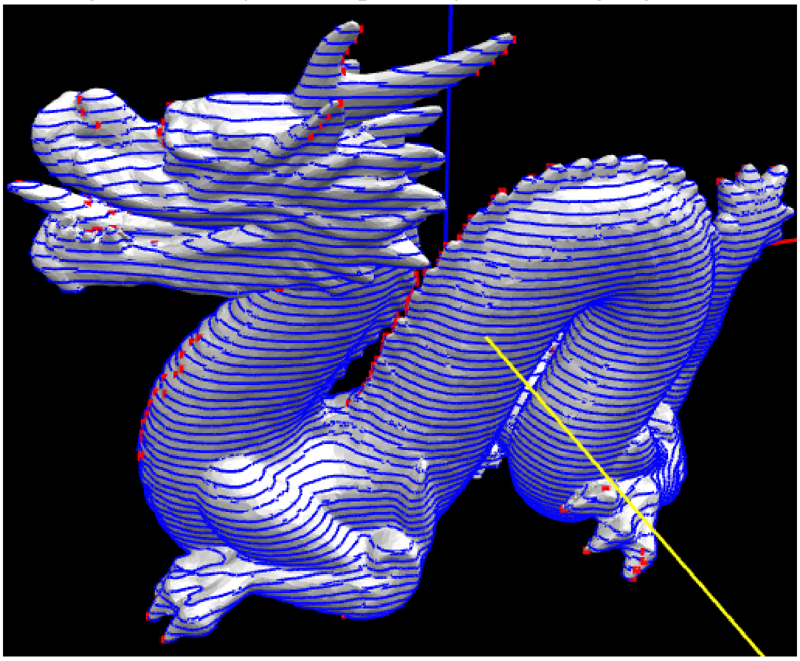
$$v = WXYZ \times 10^{-2} = WX.YZ$$

$$v = WXYZ \times 10^{-1} = WXY.Z$$

Notice that the accuracy of the value varies according to the scale of the number, getting lower as the number gets bigger. The point moves to the end of the representation as the number gets bigger, limiting the accuracy. Closer to its upper limit, the value of a floating point variable can be dozens of units distant from the actual value, so, in a floating point coordinate system, objects whose coordinates are big numbers could suffer major distortions.

The triangle mesh is provided as input for an algorithm that computes its intersections with a given set of parallel planes, generating a set of cross-sectional layers, the second data type in the control software flow depicted in Figure 3.4. The cross-sectioning algorithm starts at any edge of the mesh, calculating the intersections of such edge with the given planes, and expanding to its neighbor edges, which also have its intersections calculated. The algorithm continues iteratively expanding the set of edges that have its intersections calculated until the last edge is processed. At each iteration, each intersection point is connected to the neighbor that lies on the same plane, gradually building a linked list until it forms a loop. The resulting circular linked lists compose the set of cross sections. Figure 3.6 shows the set of layers computed for the model of a dragon.

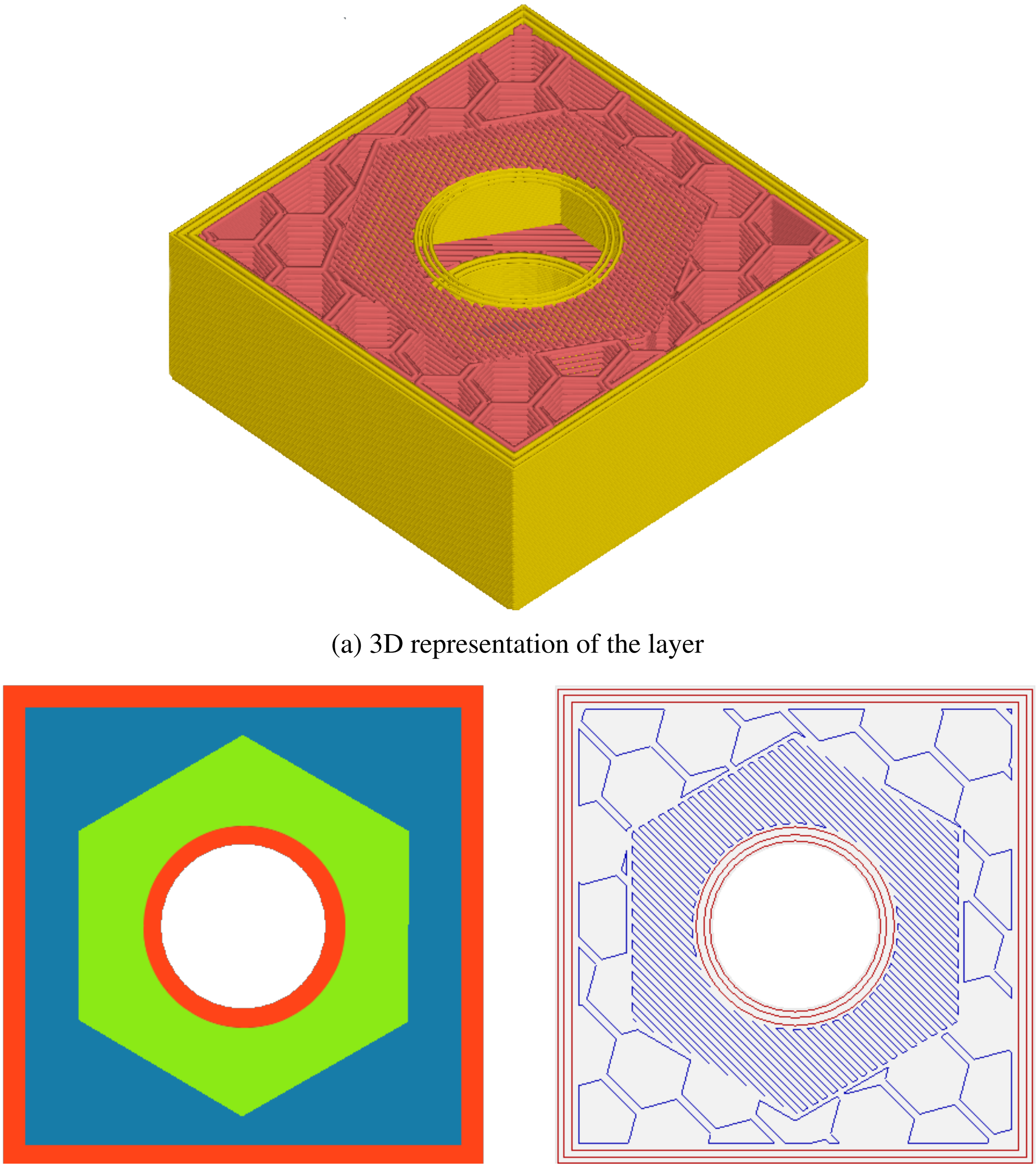
Figure 3.6: Layers computed by the slicing algorithm



The next step represented in the flow chart is the conversion of each of the cross-sectional layers into a set of regions. There are three types of regions: perimeters, surfaces and infill. Perimeters and surfaces constitute the shell of the printing object. Perimeters are the outermost regions of the polygons that compose the layer, while surfaces are central regions that do not have a layer above or below. Infill is the internal region that receives hollow filling structures. Perimeter regions are generated by performing an offset operation in the polygons of the layer, while surfaces are the result of the subtraction of the upper and lower layers. The remaining regions are infill. Figure 3.7b shows the regions of the layer depicted in 3.7a.

After the regions are defined they must be filled with path structures, as one can notice in Figure 3.4. A path structure is a set of points that describe the movement of the print head during the printing process. Each path has a particular width and thickness, which are defined based on the configuration provided for the slicer and the region the path fills. Paths in the perimeter region are calculated by applying multiple offset operations in the polygons. Surface regions receive a linear pattern of paths that completely fills the region, providing a good finishing to the object. Infill regions are filled by a honeycomb pattern in order to save material, as mentioned in Section 2.1.1. Figure 3.7c shows a set of paths filling the regions identified in Figure 3.7b.

Figure 3.7: Regions and paths of a layer



(a) 3D representation of the layer

(b) Regions of the layer: perimeter (red), surface (green) and infill (blue)

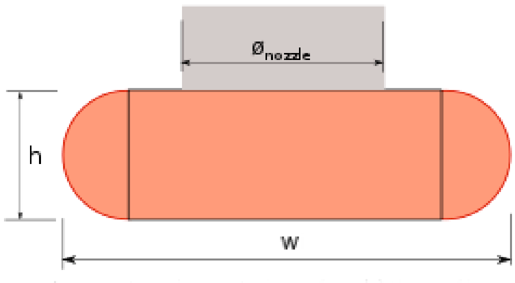
(c) Regions filled with the appropriate path pattern

The final step in the slicing process is the compilation of the set of paths into control instructions for the printer, the last data type of the flow chart. The previous preprocessing operations make the generation of G-Code commands that translate the structure of the intended object quite straightforward. Path structures can be easily compiled into a set of commands for moving the print head along the defined path while the right amount of thermoplastic is extruded. The extrusion flow rate is calculated given the thickness and width of the path, following the model employed by *Slic3r* (HODGSON; RANELLUCCI; MOE, 2013). Analyzing Figure 3.8, which depicts the cross section of a printed path, the correlation between the width and thickness of the path and the extrusion flow rate can be determined. Taking the area of the cross section we obtain the volume of molten thermoplastic that should be extruded per unit of traveled length in order to obtain a path with the given dimensions. The result is the following equation:

$$FR = (w - h)h + \Pi(h/2)^2$$

where w is the path width, h is the path thickness and FR is the extrusion flow rate (in volume units per path length units). Note that for this model to be accurate the path width should not be much bigger than the nozzle diameter and the path thickness should be smaller than its width.

Figure 3.8: Cross section of a printed path



w = width of the path

h = thickness of the path

Source: slic3r.org

The order in which the paths are printed is also defined in this step. Perimeter paths are created first, followed by surface paths and finally infill paths. Inside each category the printing order is selected so that the minimum amount of non-extrusion movements are performed, shortening the overall printing time.

In this stage is also necessary to generate the commands for controlling the part placement subsystem. As in the machine developed in this research is not equipped with automatic part placement mechanism, the commands generated simply pause the printing process and move away from the object the print head, allowing the operator to manually position the external part. The moment for such action to be performed is defined by the position of the external part. The commands are included immediately after the first layer above or at the same level of the external part is printed, so the assembled object will be completely below the printing level of the next layer. This restriction ensures that the 3D printing subsystem will not be disrupted by the external part positioning. The printing process is restarted shortly after the part is placed.

All the G-Code commands generated for controlling the printing process are saved into a text file and stored in the computer. For sending the commands to the printer a third party software is used, an open source application widely known in the 3D printing community named *Repetier-Host* [2]. It takes a G-Code file and sends the commands one by one to the printer through the USB port. When an external part must be placed, a pause command with a predefined expiration time is issued, so the object can be manually placed during the printing process.

[2] Available at <https://www.repetier.com>

4 RESULTS

Many manufacturing processes can benefit from the CPPA concept, given that the technology facilitates the building of an expressive extent of parts. Not only non-printable mechanic parts can be assembled to 3D printed parts but also electronic circuits, with sensors, actuators and displays. If combined with conductive 3D printable materials, CPPA machines are capable of creating circuits completely integrated to the object, possibly automating the whole manufacturing process. This could represent the next step of Internet of Things (IoT) applications, as the development of *things* with embedded electronics would be greatly simplified.

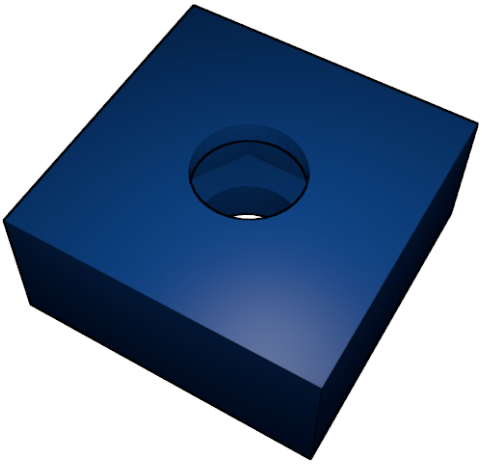
The control software developed to extend the functionalities of a regular 3D printer, allowing for the demonstration of CPPA technology, was able to generate G-Code instructions for 3D printing simple objects with manually assembled parts. Even that this demonstrative application is not capable of achieving the full potential of the technology, some useful objects with otherwise impracticable features could be created.

Threads are intricate structures for 3D printers to build, as the helical protrusions are usually narrow and must tolerate high pressures as well as friction. 3D printed threads commonly break or wear out after some usage, so external parts like screws and nuts are assembled to the models. In order to demonstrate an application of CPPA technology, a simple model, depicted in Figure 4.2, was created. The model is composed by a 3D printable parallelepipedal structure with an internal cavity housing a regular, non-printable nut. When inputted to the control software, the model is converted into a set of G-Code commands, with convenient travel and pause instructions right after the first layer higher than the nut model is completed.

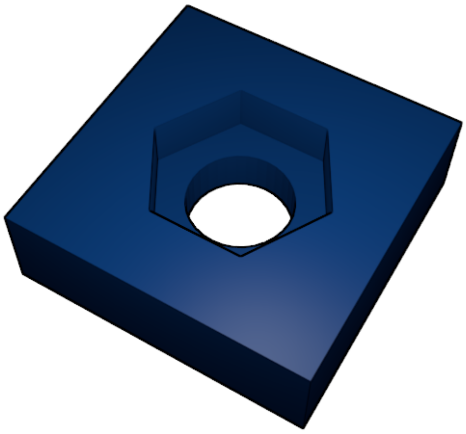
As expected, the printing process guided by the instructions generated by the control software proceeded regularly building the 3D printable part, until the last layer before the one that covers the nut was finished. At this point, the print head moved away from the part and the printing paused, allowing for the nut to be manually positioned in the cavity. The printing process restarted immediately after the nut was placed and the next layers covered the assembled part, permanently holding it on place. The resulting CPPA part, shown in Figure 4.2, presented quality compatible with objects created by analogue additive manufacturing technologies. Furthermore, the nut remained tightly in place and a bolt can be easily screwed onto it.

In addition, a second model was created to illustrate the functioning of CPPA

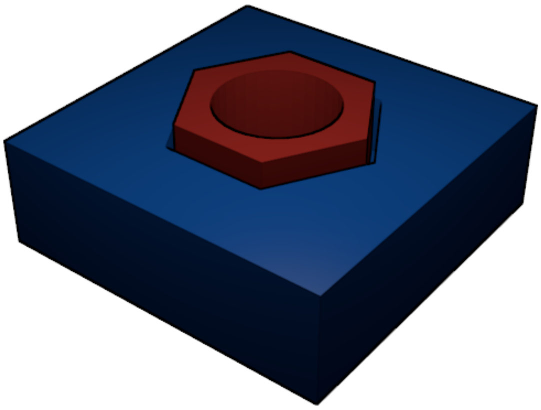
Figure 4.1: Model of a nut enclosed by a 3D printed structure



(a) The complete 3D printable part of the model

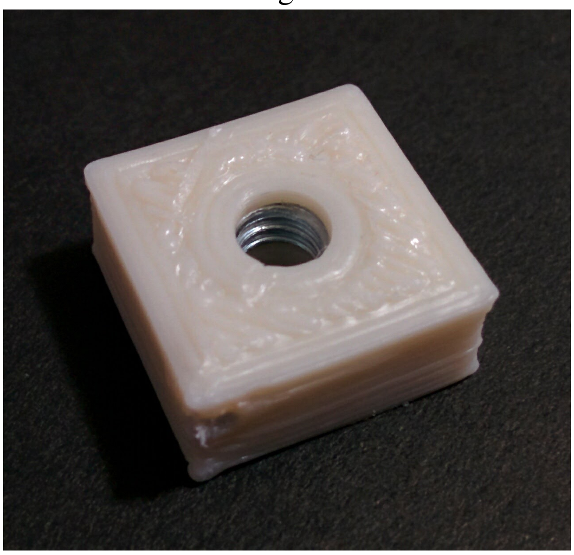


(b) Cross section of the model, showing the internal cavity

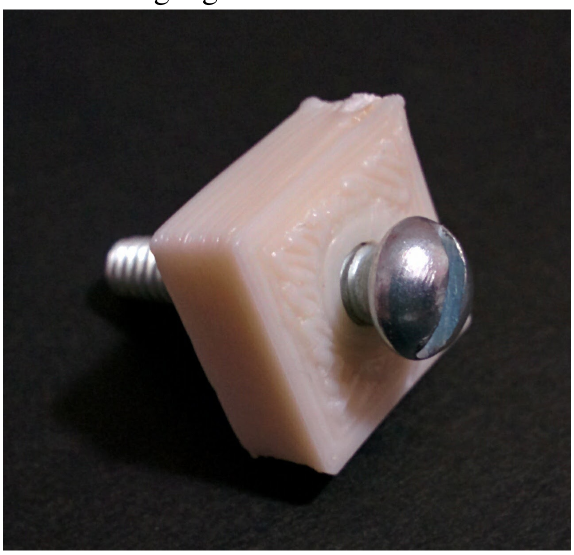


(c) Cross section of the model with the nut in place

Figure 4.2: Printed structure enclosing regular nut



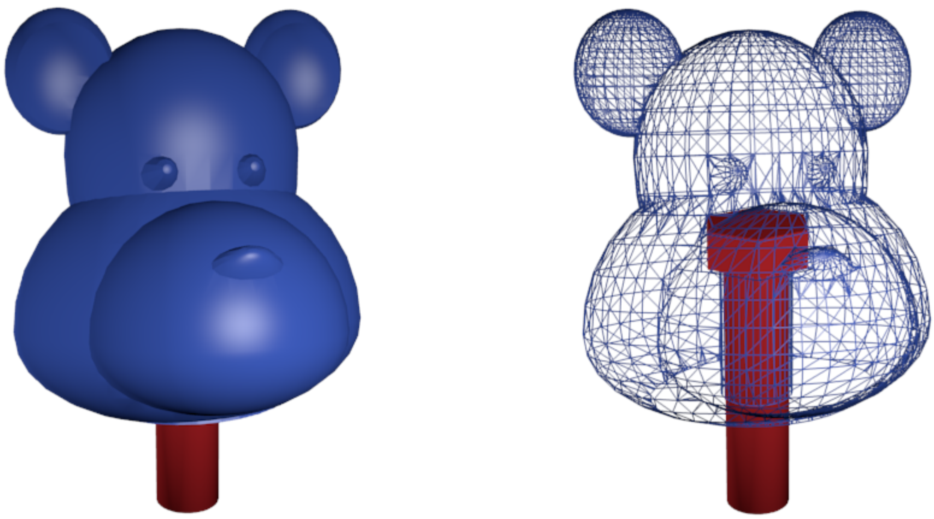
(a) 3D printed structure with nut partially visible



(b) Screw fastened to the object

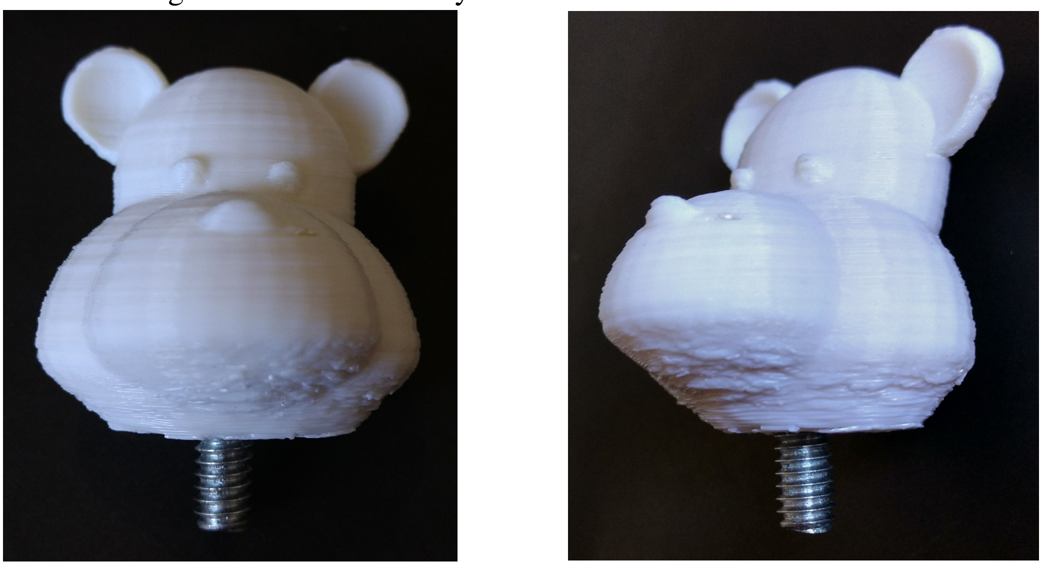
technology. This model, which is more complex than the previous one, is composed by a Teddy Bear head with a regular screw coming out from the neck region. Figure 4.3 depicts the model. As it can be noticed, the screw is partially below the lower level of the head, which would prevent it from being properly assembled to the part. In order to overcome this issue, a supporting structure was included below the head, elevating its level and providing space for the screw to be placed. The printing process went smoothly and the screw was successfully positioned in the designated cavity. Similarly to the first experiment, the printing quality was compatible with regular FDM machines and the screw remained in place after the printing was over. The resulting part is depicted in Figure 4.4.

Figure 4.3: Model of a screw inside a Teddy Bear head



(a) Head with screw partially visible (b) Screw visible inside Teddy Bear head

Figure 4.4: Printed Teddy Bear head with screw assembled



5 CONCLUSION

3D printing already changed the way objects are fabricated, acting as a fast, simple, and cost effective method for creating highly customized parts. Besides its benefits, many functionalities can not be achieved by additive manufacturing processes, requiring heavy post-processing of the 3D printed part. The CPPA concept was conceived with the objective of overcoming some of the limitations of classic additive manufacturing technologies, providing means for embedding non-printable parts to 3D printed structures during the building process.

The demonstration of CPPA concept was achieved by developing a software that extends the functionalities of regular 3D printers, allowing external parts to be manually assembled during the printing process. Such demonstration has shown that the technology is capable of, within one single manufacturing process, generating complex objects with functionalities that otherwise would require multiple post-processing steps. In addition, the overall quality, strength and finishing observed in the printed portions of CPPA objects are comparable with the ones obtained with analogue 3D printing processes. These results indicate that the technology can bring benefits to the manufacturing of several goods and, therefore, has a positive economic value.

Further improvements to the current demonstrative machine should be developed in order to achieve the full potential of CPPA technology. The human intervention currently necessary to assemble non-printable parts can be overcome by the installation of a robotic arm capable of placing external parts anywhere in the printing zone. This automation of the part placement subsystem is essential for the application of CPPA methods in real manufacturing processes, as it would eliminate the necessity of humans operators, improving the build time and reducing production costs.

Even with the complete automation of the manufacturing process, the disruption potentially caused by the simultaneous operation of both 3D printing and part placement subsystems can hardly be avoided in the current conception of CPPA. Such restriction can make it impossible to build certain structures. The only way to reduce the impact of this problem is developing a completely new additive manufacturing strategy to implement the 3D printing subsystem. It must be capable of printing even with parts above the printing level and while the part placement mechanism is holding a part in place. Such improvement is beyond the scope of this study, but it is an extremely interesting subject that should be addressed in future works.

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