

# 3D PRINTING FOR FEASIBILITY CHECK OF MECHANISM DESIGN

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## ABSTRACT

In this paper 3D printing is presented as useful means for checking design feasibility of mechanism structures for robots. A procedure is outlined for rapid prototyping that can produce scaled prototypes for experimental validations since early stages of robot developments. An example from LARM activities for developing LARMbot humanoid is illustrated to show the soundness and practical implementation of the proposed procedure.

Keywords: Robot design, Prototyping, 3D Printing, Experimental Validation

## 1 INTRODUCTION

Prototype construction and validation testing is a fundamental activity in machine developments and particularly for robot designs. This activity is often time consuming and expensive, although necessary to achieve proper final design as pointed out in [1-3]. Thus, before a final production, it is required to work with prototypes that can be used for design checks and performance testing. Since early 1990s the technique of Rapid Prototyping has been developed by using scaled prototypes even with materials with fairly easy manufacturing. This has led to the development of 3D Printing whose practical feasibility has reached maturity only in the late 2000s. In recent years, new solutions have been proposed and are available in the market for fairly cheap printers and procedures. Thus, Rapid Prototyping with 3D print can be reconsidered even since early stages of the product designs. 3D printing as additive manufacturing is a process of making three dimensional solid objects from a digital file. A 3D printed object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object. Several different 3D printing processes have been invented since the late 1970s. The printers were original large, expensive, and highly limited in what they could produce [4]. Today a large number of additive processes are now available. The main differences among different processes are in the way that layers are deposited to create parts and in the materials that are used.

Some methods melt or soften material to produce the layers, e.g. selective laser melting (SLM) or direct metal laser sintering (DMLS), selective laser sintering (SLS), fused deposition modeling (FDM), while others cure liquid materials using different sophisticated technologies, e.g. stereolithography (SLA).

In laminated object manufacturing (LOM), thin layers are cut and joined together (e.g. paper, polymer, metal). Each method has its own advantages and drawbacks, and this is why some companies consequently offer a choice between powder and polymer for the material to build the object, [5-9]. Other companies sometimes use standard, off-the-shelf business paper as the build material to produce a durable prototype. The main considerations in choosing a machine are generally speed, cost of the 3D printer, cost of the printed prototype, cost and choice of materials, and color capabilities, [10-11]. In this paper, the problem of using 3D printing with speedy low-cost procedure is proposed for a rapid prototyping of mechanism for robots that can be used since early stage of robot development to check the feasibility of the mechanism solution through its functionality and feasibility even in mechanical design.

## 2 RAPID PROTOTYPING VIA 3D PRINTING

Rapid Prototyping (RP) is a term used to describe a variety of processes, which are aimed at quickly creating three-dimensional physical parts from virtual 3D computer models using automated printing machines. The parts are built directly from a 3D CAD model and can match a model within the precision limits of the chosen process. All RP processes are additive since parts are built up by adding layer by layer, depositing, or solidifying one or more material in a horizontal layer process.

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In addition to additive production processes, the possibilities of subtractive processes such as CNC (Computer Numerical Control) machining and laser cutting can be considered. These subtractive processes can help the optimization of the printed prototype improving its quality and the precision quitting burrs and errors due to chosen process and technology, [12]. 3D printable models can be created with a computer aided design (CAD) package or via a 3D scanner or via a plain digital camera and photogrammetry software. The manual modeling process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting. Regardless of the used 3D modeling software, a 3D model (often in .skp, .dae, .3ds or some other format) needs to be converted to either a .STL or a .OBJ format, in order to allow the printing software to be able to read it. Before printing, a 3D model must first be examined for "manifold errors".

This step is called the "fixup". Especially STLs that have been produced from a model obtained through 3D scanning, often have many manifold errors in them that need to be fixed. Examples of manifold errors are surfaces that do not connect, and gaps in the models. Examples of software that can be used to fix these errors are netfabb and Meshmixer, or even Cura, or Slic3r. Once created, the .STL file needs to be processed by a software called a "slicer" which converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer (FDM printers). This G-code file can then be printed with 3D printing client software, (which loads the G-code, and uses it to instruct the 3D printer during the 3D printing process. It should be noted that, the client software and slicer are often combined into one software program. Several open source slicer programs exist, such as Skeinforge, Slic3r, and Cura as well as closed source programs such as Simplify3D and KISSlicer.

Examples of 3D printing clients are Repetier-Host, ReplicatorG, Printron/Pronterface. There is one other piece of software that is often used by people using 3D printing, namely a G-Code viewer. This software lets one examine the route of travel of the printer nozzle. By examining this, the user can decide to modify the G-Code to print the model in a different way (for example in a different position, e.g. standing versus lying down) so as to save plastic (depending on the position and nozzle travel, more or less support material may be needed). Examples of G-Code viewers are G-code Viewer for Blender and Pleasant3D.

A 3D printer follows the G-code instructions to lay down successive layers of liquid, powder, paper or sheet material to build the model from a series of cross sections. These layers, which correspond to the virtual cross sections in the CAD model, are joined or automatically fused to create the final shape. The primary advantage of this technique is its ability to create almost any shape or geometric feature. Printer resolution refers to layer thickness and X-Y resolution in dots per inch (dpi) or micrometres ( $\mu\text{m}$ ).

Typical layer thickness is around 100  $\mu\text{m}$  (250 DPI), although some machines such as the Objet Connex series and 3D Systems' ProJet series can print layers as thin as 16

$\mu\text{m}$  (1,600 DPI), where X-Y resolution is comparable to that of laser printers with the particles (3D dots) around 50 to 100  $\mu\text{m}$  (510 to 250 DPI) in diameter. Construction of a model can take from several hours to several days, depending on the used method, size and complexity of the model. Additive systems can typically reduce this time to few hours, although it varies widely depending on the type of machine, size and number of pieces being produced simultaneously.

Traditional techniques like injection molding can be less expensive for manufacturing polymer products in high quantities, but additive manufacturing can be faster, more flexible and less expensive when producing relatively small quantities of parts. 3D printers give designers and R&D teams the ability to produce parts and concept models by using a desktop size printer, [13- 15].

Some additive manufacturing techniques are capable of using multiple materials in the course of constructing parts. Some others are able to print in multiple colors and color combinations simultaneously. Supports are removable or dissolvable upon completion of the print and are used to support overhanging features during construction.

No matter which approach a 3-D printer uses, the overall printing process is generally the same. A procedure can be outlined for a suitable speedy efficient 3D printing of mechanism structures thorough a procedure that is summarized in Fig. 1:

*Step 1: CAD Modeling* - It is aimed to build a 3D model by using computer-aided design (CAD) software. The software may provide some hints related to the structural integrity that is expected in the finished product by using data of certain materials in virtual simulations and how the object will behave of certain conditions.

*Step 2: Conversion to STL* - The objective is to convert the CAD drawing to STL format. STL (Standard Tessellation Language) is a file format developed for 3D Systems in 1987 for use by stereolithography apparatus (SLA) machines.

*Step 3: Transfer to AM (Automatic Machine)* - A user copies the STL file to the computer that controls the 3D printer. There, the user can designate the size and orientation for printing choosing the best orientation.

*Step 4: Parameter setup of the printer* - Printer requirements include refilling the polymers, binders and other consumables the printer will use. It also covers adding a tray to serve as a foundation or adding the material to build temporary water-soluble supports. It is needed to check if the parameters of the printer such as the temperature of the extruder and the platform are compatible with the chosen material and the dimensions of the designed prototype are compatible with the printer characteristic and working space.

*Step 5: 3D printing of elements* - The build process is mostly automatic. Each layer is usually about 0.1 mm thick, though it can be much thinner or thicker. If quality of the printing is not satisfactory parameters should be changed or the CAD model should be changed to adapt the structure to the 3D printer capabilities.

*Step 6:* Polish and assembly - Safety precautions are necessary in removing the printed object from the printer platform in order to avoid injury by using wearing gloves to protect from hot surfaces or toxic chemical. Activities for polishing and assembly are required on printed object for brushing off any remaining powder and removing any support material.

*Step 7:* 3D Prototype – At the end, the prototype is ready for testing activity.

The above proposed procedure has been thought with sequential phases in order to have checks during the process permitting adjustments and optimizations even in the mechanical design of the parts.

The sequential steps of the 3D printing permits also a parallel activity in design optimization and numerical simulation of the adjustment during the prototype construction.

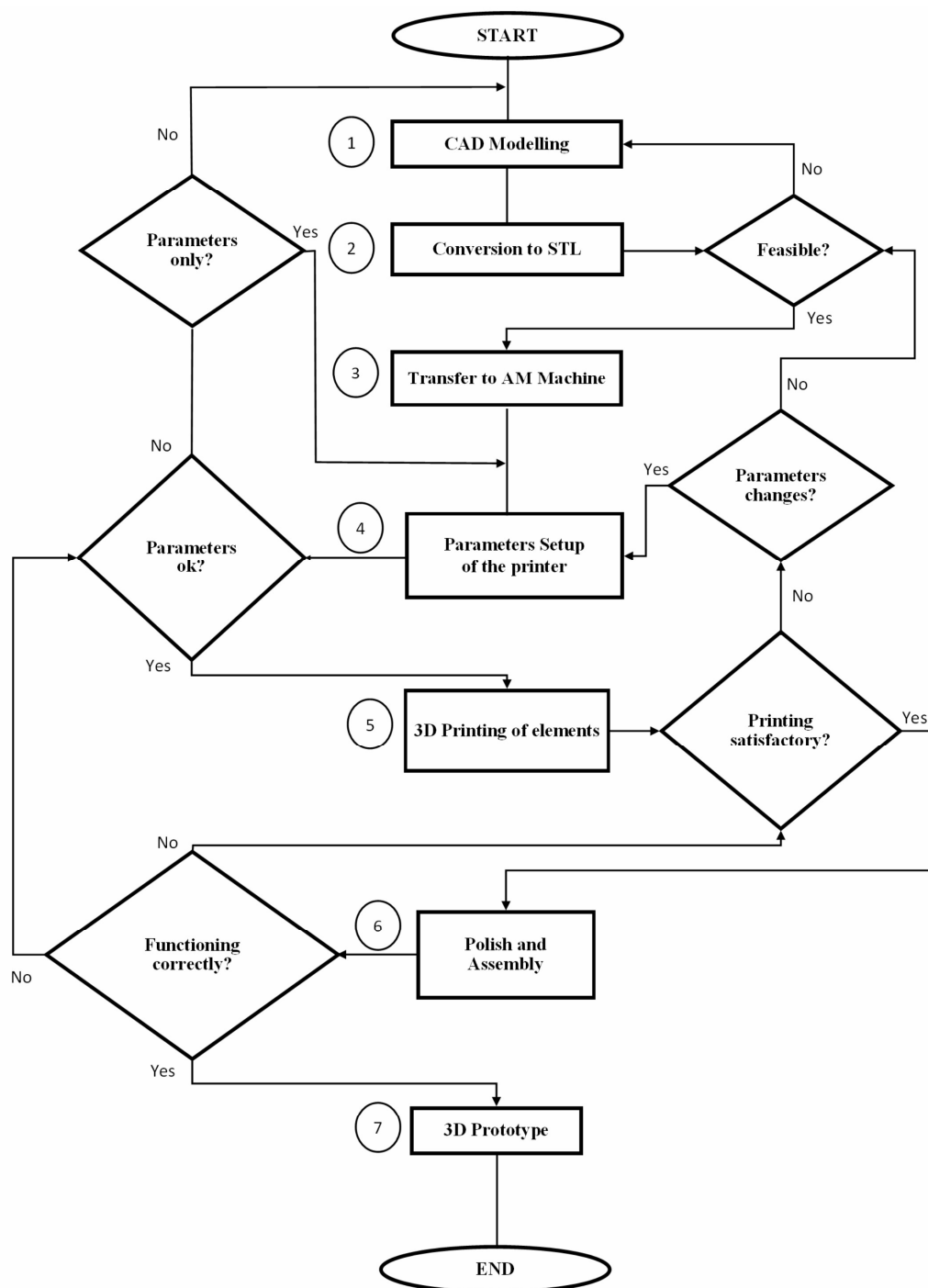


Figure 1 A scheme of a 3D printing procedure for rapid prototyping of robot mechanisms.

### 3 3D PRINTING ISSUES

Rapid prototyping via 3D printing is a very useful technique that can improve the developing of a new design. Nevertheless, its result is influenced by the equilibrium between several parameters. Thus, during the procedure several main issues can occur.

Figure 2 shows what happens if the plastic is not sticking to the bed. It is very important that the first layer of the print is strongly connected to the build platform so that the remainder of the part can be built on this foundation. This problem can happen for several reasons. The build platform can be not leveled since many printers include an adjustable bed with several screws or knobs that control the position of the bed. If the bed is not level, one side of the bed may be too close to the nozzle, while the other side is too far away. Achieving a perfect first layer requires a level print bed. Choosing a correct speed is very important. If the first layer is printed too fast, the plastic may not have time to bond to the build platform. For this reason, it is very useful to print the first layer at a slower speed so that the plastic has time to bond to the bed. Plastic tends to shrink as it cools from a warm temperature to a cool temperature. If the extruder prints ABS at 230 °C, but it is deposited onto a cold build platform, it is likely that the plastic would quickly cool down after leaving the hot nozzle. Some printers also include cooling fans that speed up this cooling process when they are being used. If this ABS part cooled down to a room temperature of 30 °C, a 100 mm wide part would shrink by almost 1.5 mm, so the plastic will tend to separate from the build platform as it cools. This is an important fact to keep in mind for the first layer. If the layer seems to stick initially, but later separates from the print bed as it cools, it is possible that the temperature and cooling settings are to be changed.

It is important to choose a good build platform surface since different plastics tend to adhere better to different materials. Several printers use a build task sheet on the top of their bed that tends to stick very well to PLA. Other manufacturers opt for a heat treated glass bed such as Borosilicate glass, which tends to work very well for ABS when heated. There are several types of tape that stick well to common 3D printing materials. Strips of tape can be applied to the build platform surface and easily removed or replaced with a different material. For example, ABS tends to stick better to Kapton tape known as Polyimide film. Sometimes when a very small part is being printed, it does not have enough surface area to stick to the build platform surface. Adding a Raft under the part provides a larger surface for bed adhesion.

Another important characteristic that a prototype should have is a good stiffness. To save plastic, most 3D printed parts are created to have a solid shell that surrounds a porous, partially hollow interior.

Figure 3 shows an overheating problem starting from a filament in normal condition on the left going through the overheating until burning it. Furthermore, the plastic that is under the extruder may be at any temperature between 190 °C and 240 °C.

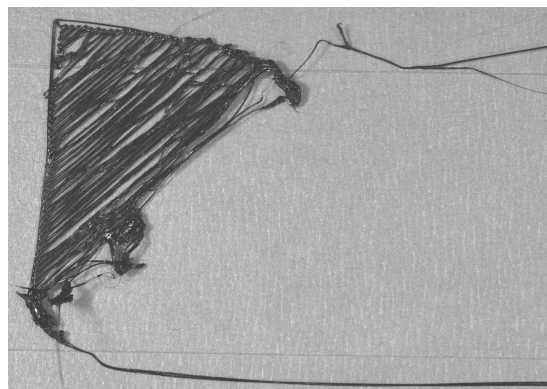


Figure 2 Example of plastic not sticking to the bed.

While the plastic is still hot, it is pliable and can easily be formed into different shapes. However, as it cools, it quickly becomes solid and retains its shape. A correct balance between temperature and cooling is needed so that the plastic can flow freely through the nozzle, but it can quickly solidify to maintain the exact dimensions of the 3D printed part. If this balance is not achieved, the exterior of the part is not as precise and defined as expected.

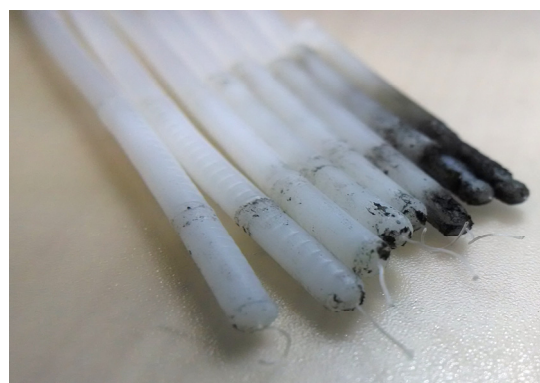


Figure 3 Example of overheating plastic filament.

The most common cause for overheating is that the plastic is not cooled fast enough. When this happens, the hot plastic is free to change shapes as it slowly cools. For many plastics, it is much better to quickly cool the layers to prevent them from changing shape after being printed. If the plastic is extruded at a lower temperature it will be able to solidify faster and retain its shape. 3D printing works by building the object one layer at a time. Each successive layer is printed on top of the previous layer. If the layers do not bond together well enough, the final part may split or separate, as shown in Figure 4. Warm plastic will always bond together much better than cold plastic. It may happen that the filament needs to be printed at a higher temperature to create a strong bond. For example, if ABS plastic is extruded at 185 °C, the layers of the part will easily break apart. This is because ABS typically needs to be printed around 220-240 °C to create a strong bond between the layers.

The success of the Rapid prototyping via 3D printing is straightly related not only to the output of the plastic filament but also to its input. Most 3D printers use a small drive gear that grabs the filament and sandwiches it against another bearing. The drive gear has sharp teeth that allow it to bite into the filament and push it forward or backward, depending on which direction the drive gear spins. The one of the most important component of the 3D printer is the extruder that can be clogged as mentioned above.



Figure 4. Example of layer separation.

The 3D printer must melt and extrude many kilograms of plastic over its lifetime. All of this plastic must exit the extruder through a tiny hole that is only as big as a single grain of sand. It may happen that jams or clogs are usually due to something inside the nozzle that is blocking the plastic from freely extruding. Figure 5 shows a clogged extruder. To solve this problem heating the extruder and manually pulling the filament out. If the process efficiency during printing is maintained, Rapid prototyping can be used as a satisfactory method for a feasibility check of a mechanism design.

The 3D Printing procedure can be used to check:

- Shape design;
- Joint design reliability;
- Assembly coherence and feasibility.

Shape design is a very important step during prototyping.

Each shape has a different behavior depending on the field of use. With 3D printing it is possible to check if the design requirements are fulfilled. Furthermore, its stiffness can be tested and some modifications can be elaborated to improve the characteristics of the prototype. During the design of the prototype it is difficult to check if the desired joints will move as expected. Manufacture them may help to check their reliability and their behavior and possible undesired friction. Furthermore, this last step is useful to check if the assembly is feasible and its coherence. Assembling the prototype will help to have new ideas to improve its performance realizing its real behavior. All these details in combination with commercial components have been taken into account to build a mechanical structure for the LARMbot humanoid prototype.



Figure 5. Example of clogged extruder.

#### 4 A CASE STUDY: LARMBOT

The aim of the proposed novel humanoid is to mimic human anatomy and performance using mainly parallel architectures due to their characteristics that permit a proper stiffness, payload capability and smoothness in movements. For a first configuration of the Humanoid robot the LARMbot in Cassino the CAUTO humanoid torso design has been assembled. The human-like behavior and shape of CAUTO (Cassino hUmanoid TOorso) [16] and its configurations had been an inspiration for the design and construction of a new humanoid. CAUTO is a hybrid cable-driven structure. The structure of the proposed humanoid torso for robots consists of 4 discs that replicate the function of the vertebrae in the human spine. The vertebrae are interconnected with each other by means of flexible couplings that behave as spherical joints allowing the rotation  $\theta$ ,  $\Phi$ , and  $\psi$  around X-axis, Y-axis and Z-axis. The trunk is fixed on the spine through a vertebral disc. The spine is also connected to the abdomen using another vertebral disc. The pelvis is connected to the abdomen and houses 5 actuators 4 of which allows the 3 d.o.f.s of the humanoid spine. Four cables are fixed to the platform through the trunk, they pass through the holes of the other vertebral discs reaching the cables are pulled by the actuators. Moving the actuators antagonistically, the humanoid spine can bend right, left, forward and backward. When a cable is pulled, the corresponding is released. In addition, a circular motion can be performed thanks to the combination of the two above-mentioned movements.

LARM tripod Locomotor is a biped locomotor based on parallel leg mechanisms, [17]. The biped locomotor consists of two 3-DOF leg mechanisms and a waist. Two leg mechanisms are installed on the waist, and between the waist and feet there are two tripod mechanisms of six identical prismatic pairs with U-joints at each end.

Legged locomotion has a number of advantages as compared with conventional wheeled and crawler-type locomotion, such as higher mobility, better obstacle overcoming ability, active suspension and so on, especially when it operates in rough or unconstructed environment.



Table I - Specification parameters of the 3D Printer Creator, [18]

<i>Extruder Model</i>	<i>Printing Material</i>	<i>Software</i>	<i>Input File Format</i>	<i>Compatibility</i>
Dual-extruder	ABS&PLA 1.75-1.8 mm	Relicator G	STL/X3G	Linux, Mac and Windows
<i>Machine Dimension</i>	<i>Build Size</i>	<i>Print Precision</i>	<i>Positioning Precision</i>	
320×467×381 mm	225×145×150 mm	0.1-0.2 mm	0.0025 mm on Z axis; 0.011 mm on XY axes	
<i>Flow Velocity</i>	<i>Layer Thickness</i>	<i>Extruder Temperature</i>	<i>Heated Build Platform Temperature</i>	
Approx. 24 cc/hr	0.1-0.5 mm	Maximum 230 °C	Maximum 120 °C	

The above prototypes have been built starting from a 3D model has been elaborated in SolidWorks® environment and the corresponding 3D prototype has been built by printing all the components and assembling them with commercial components. The 3D printer used in this case is FlashForge Creator [18], whose specification parameters are listed in Table I. Based on the built 3D model, the corresponding STL format file of each component can be directly generated in SolidWorks® environment.

By using the required RP program, Replicator G, and considering machine parameters like temperature, build size, printing precision, and printing speed, the proper G-code can be generated and then transferred to the 3D printer. G-Code is the name for the most widely used numerical control programming language; it is defined by instructions on where to move, how fast to move, and along which path to move. To allow the printer to print offline disconnecting it from the computer the G-code has been converted to X3g format and transferred to the SD Card of the printer. X3g is a binary file that the machine reads, and which contains all of the instructions for printing.

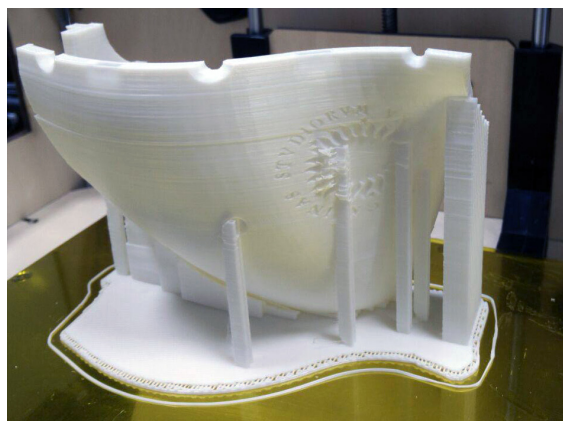
The interior of the pieces was filled with a rhomboidal grid with an infill of 80%, an infill perimeter overlap ratio of 0.3 and an infill solidity of 0.1. During parameter setting in Replicator G, the first two factors that should be considered are the build size of the 3D printer and the temperatures of extruder and build platform. In this case, each component is scaled down to 0.25 value by comparing with the original

size of designed CAD model, and the temperatures of extruder and build platform are set as 208 °C and 63 °C, respectively as PLA has been chosen as printing material for the chest and the pelvis, while ABS for the spine and the locomotor setting the extruder and the platform respectively to 245 °C and 110 °C. Travel feed rate has been set to 55 mm/s and flow rate has been set equal to 40 mm/s.

Before choosing the final material of each part and the above parameters some preliminary prototype have been manufactured and tested with several printing configurations to improve the performances of the humanoid structure.

The key-parts of the novel torso CAUTO are the chest where pulling forces coming from the servomotors act and the humanoid spine that will transmit the motion through all the structure. A shape design check has been carried out starting from the chest. The first version of the torso have been built in 4 different shells assembled together using ABS plastic. Figure 6 shows the results of the printing. Figure 6a shows a torso shell part with its support structure. Figure 6b shows the defective part.

Layer separation due to an incorrect shape design can be noticed, this will affect the stiffness of the prototype under pulling forces. Thus, the structure has been improved going through a full redesign of the part. The novel chest has been designed using only one part to improve the stiffness and the inside of the structure have been filled with material. Figure 7 shows the new printed structure.



a)

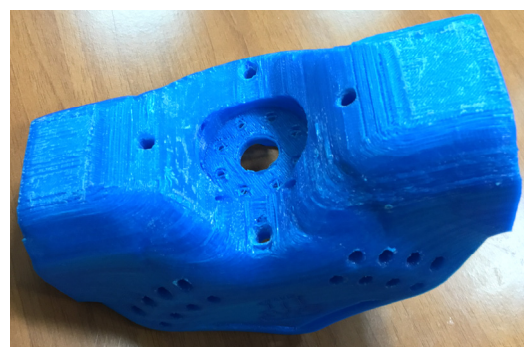


b)

Figure 6. CAUTO preliminary Chest Test: a) Printed chest shell part with support material, b) Printed chest shell part layer separation issue.



a)



b)

Figure 7 CAUTO preliminary Chest Test: a) Printed chest using ABS with overheating issue, b) Printed chest using PLA.

The first attempt is shown in Figure 7a. The high temperature and the long time needed for the printer have produced an overheating issue. This can be seen in the upper part of the chest. Figure 7b shows another attempt, the material has been changed to PLA avoiding overheating since the PLA needs lower printing temperature. Furthermore, PLA reacts to compression forces better than ABS. The second key-part of CAUTO is the spine so a joint design reliability and an assembly coherence and feasibility check have been worked out. Figure 8 shows the spine preliminary test layout. The 4 vertebrae have been printed in ABS and connected between each other using commercial multi-beam aluminium multi-helix flexible beam coupling. Four servo-motors have been stored on the base platform and have been connected to the upper platform using nylon cables. The joint design reliability has been checked by controlling the servo-motor using Arduino, by presenting a satisfactory motion behavior assembly coherence. Considering the locomotor, several attempts for joint repeatability and assembly coherence have been made to improve its behavior and check its stiffness. These tests are fundamental since in the design requirements the locomotor is the part that will afford the major payload.

Printing parts with orientation based on the Z axis of the 3D printer has been identified as a key factor that affects printing quality. Generally, it is recommended to choose printing orientation as based on the principle that a relative large contact area provides more support material on the build platform. However, when there is coaxiality requirement of the components during the assembly, the axial direction should be considered as the printing orientation. For instance, each prismatic pair in this case consists of an upper tube part, a lower tube part, a ring connector and the rod part, as shown in Figure 9, where the tube part is divided into two parts by considering the verticality along axial direction as well as convenient assembly with the rod part. In order to choose the proper printing orientation, the lower tube part has been printed in two directions, as shown in Figure 10. It can be noticed that the print precision and the stiffness of the tube along the axial is much higher than the other one along the radial direction.

When all the components are printed, the next step is to polish and assemble them. In order to achieve the aim of simple polishing and convenient assembly, the supporting material is planned as little as possible during the parameter setting, and the size of each pin is designed with 0.2 mm less than the corresponding hole by considering the print precision. Once all the parts have been ready and adjusted they have been assembled.

The preliminary prototype satisfactory fulfills the requirements so that the final one has been built. ABS has been chosen as the material for the final version for its characteristics to better absorb the impact forces compared to PLA. Having found suitable parameters, the final version of the prototypes has been manufactured.

Figure 11a shows the CAD Design of CAUTO and Figure 11b shows the production of the prototype using Rapid prototyping technology via 3D Printing.

Figure 11a shows the CAD Design of LARM tripod Locomotor and Figure 12b shows the 3D printed prototype of the locomotor. Analyzing the figures, it can be appreciated how the manufactured prototype satisfactory reproduce the CAD Design.

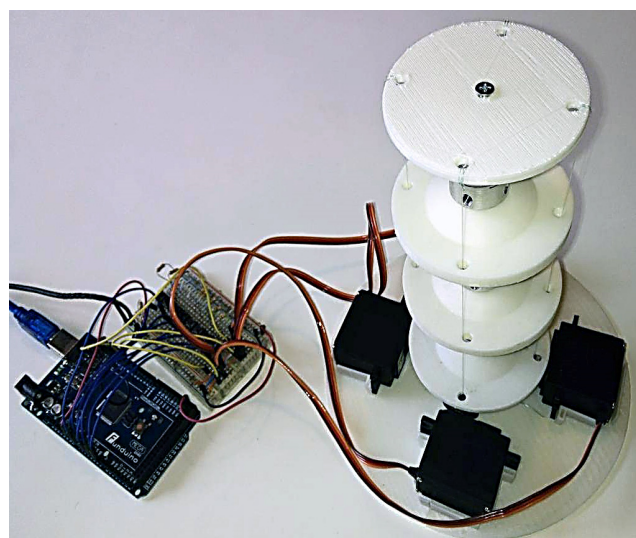


Figure 8 CAUTO spine preliminary test layout.

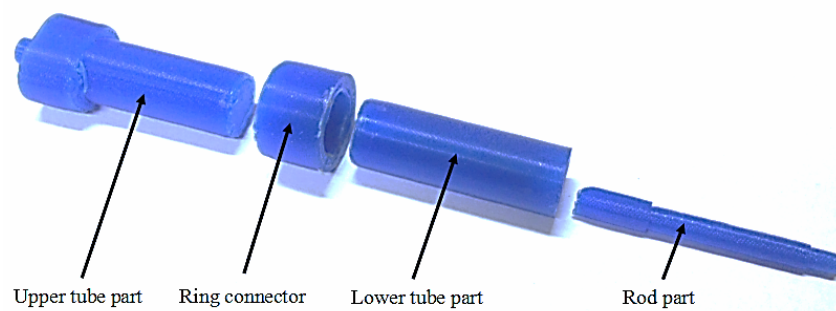


Figure 9 A preliminary printed prismatic pair for the LARM tripod Locomotor.

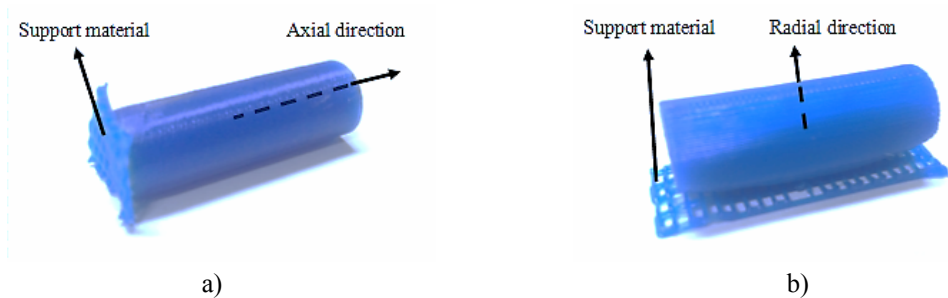
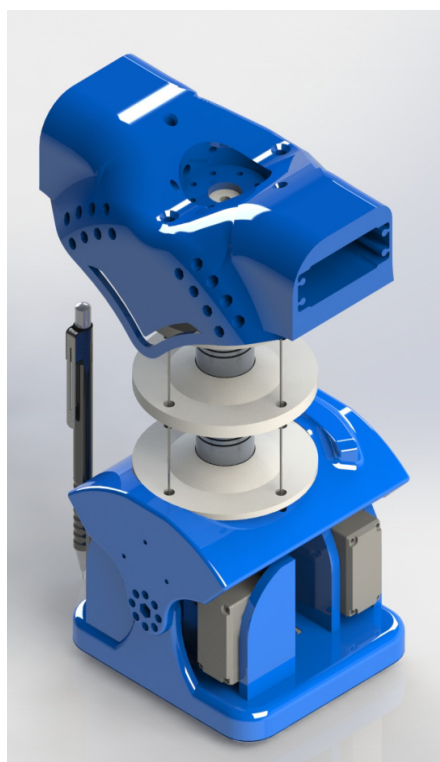
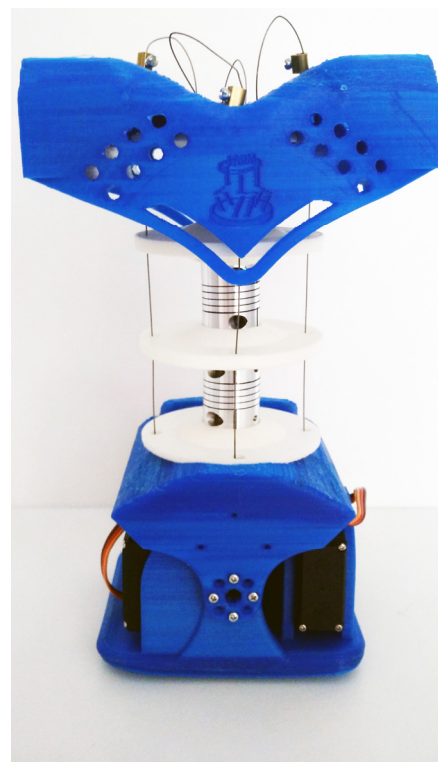


Figure 10 A preliminary printed tube part of a prismatic pair when printed: a) axial direction; b) radial direction.



a)



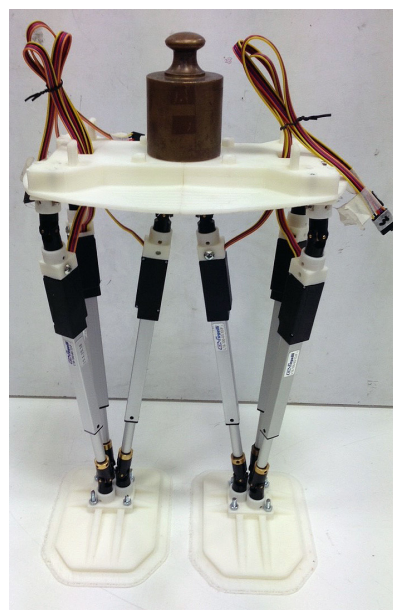
b)

Figure 11 CAUTO Prototype: a) CAD Design, b) 3D printed prototype.





a)

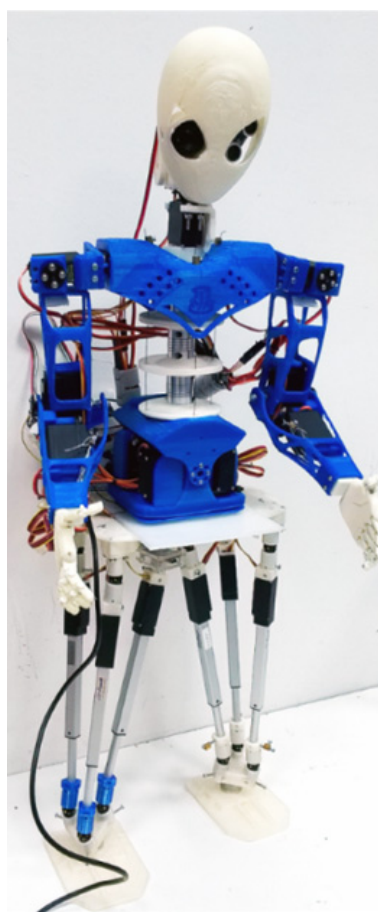


b)

Figure 12 LARM tripod Locomotor: a) CAD Design, b) 3D printed prototype.



a)



b)

Figure 13 LARMbot humanoid: a) CAD Design, b) 3D printed prototype.

The final assembly of the humanoid is shown in Figure 13. Figure 13a shows a CAD Design of the LARMbot, while Figure 13b shows the Final assembled prototype. This robot can be used in social fields helping people in daily operation or in industries to do dangerous tasks and among other applications. It is obstacle avoidance feature and Wi-Fi monitoring can be used to implement a software for remote operations.

## 5 CONCLUSIONS

In this paper 3D printing is recognized as a useful means in a design process with rapid prototyping of robot mechanisms through a procedure that permits a feasibility check of design solutions since early stages of robot developments. Specific experiences at LARM are presented as related to ongoing development of CAUTO and LARM tripod Locomotor. Finally, LARMbot humanoid is presented as an assembly of the two prototypes to show a practical convenience and soundness of using the proposed procedure of 3D printing prototyping for specific designs of mechanisms in humanoid robots.

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