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Design and manufacturing of a prototype of a lightweight robot arm

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Abstract

The aim of this work is to manufacture a prototype of a lightweight robot arm with a low cost budget, fully functional. This prototype is used to test and fix the elements for driving and controlling. During the development process, several tests and studies were performed, such as, strength simulations, dimensional effects after a post-process treatment with acetone, adjustment of control parameters to improve the accuracy, testing of behaviour of transmissions, etc. The prototype must have a low weight overall and a right operation. The results and conclusions, related with material, reinforcements, geometry/shape of the parts, etc., become recommendations for the manufacture of the final lightweight robot arm. The one that will not be prototype.

Keywords: Rapid prototyping; light robot arm; Fused Filament Fabrication; 3D printing

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1. Introduction

The main purpose of this work was to shorten the development cycle of a prototype of a lightweight robot arm, increasing the overlap between the stages of this cycle, in order to allow the concurrent work of different multidisciplinary teams.

These teams are in charge of design, manufacturing, control [1], integration with the patient [2], etc., so, it is important to have a functional prototype in each of its development stages. Although, this prototype is not going to have real application, it will be the basis for the development of new one, able to assist people with disabilities.

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The choice of the prototyping technique is usually strongly influenced by the material that the technique can process and by its total cost. In this case, the prototype was made of plastic to reduce weight, using a low-cost prototyping technique and with a short time for processing each part [3].

The 'low cost' to manufacture the prototype includes redesign and reprocessing for some of the parts for their right fit in the final assembly. The request for modifications may come from any of the teams.

The structural parts were obtained using a 3D printing, based on fused deposition, FFF: Fused Filament Fabrication. Simple steel parts were used for drives, shafts and couplings, they were made with a lathe and a milling machine.

The prototype of lightweight robot arm includes the shoulder, arm and forearm, with a total of two degrees of freedom, an image is shown in Fig. 1. (a). The robotic hand [4] will offer the other three degrees of freedom.

Although the prototype of the hand was made in a different project, features, as the fit with the forearm and the space for the power and control wires, were taken into account.

One of the disadvantages of using FFF is the lack of low tolerances close to the required ones. Nevertheless, the use of plastic materials (like ABS, Acrylonitrile Butadiene Styrene), that can be easily reprocessed by machining or using chemicals products, allowing to fit any part in an easy way. An experimental study was made in order to control the behaviour of the ABS under a chemical exposition, and the dimensional changes due to the use of chemicals.

Another peculiarity to have in mind is the way that the 3D printing system works. Due to the superficial melting of the layers and filaments directions, the strength of the manufactured structure differs considerably from that expected according with the mechanical properties of the plastic material used [5]. This point adversely affects the quality of the obtained product. To solve it, the parts were reoriented to leave the filaments favourably oriented to withstand the efforts, and post-process treatments were made.

This paper shows and tests the manufacturing process of a functional prototype of a lightweight robot arm, made by 3D printing of ABS. The materials and elements used are the most similar possible to those that will be used in the final product. The ultimate goal was to realize about all the disadvantages that could arise, find the causes and their implications in the product, and search for suitable solutions.

2. Experimental procedure

The methodology followed can be outlined in these steps:

- To make 3D designs in an environment that allow to check part of the requirements, as well as the feasibility of the final assembly.
- To manufacture at a low cost, without the traditional process-plan and without any type of ancillary.
- To analyse the causes of lack of precision to feed back the design and manufacturing stages, in order to avoid post-process adjustments for other parts and modifications.
- To perform post-process adjustment to meet the requirements, if it is necessary.

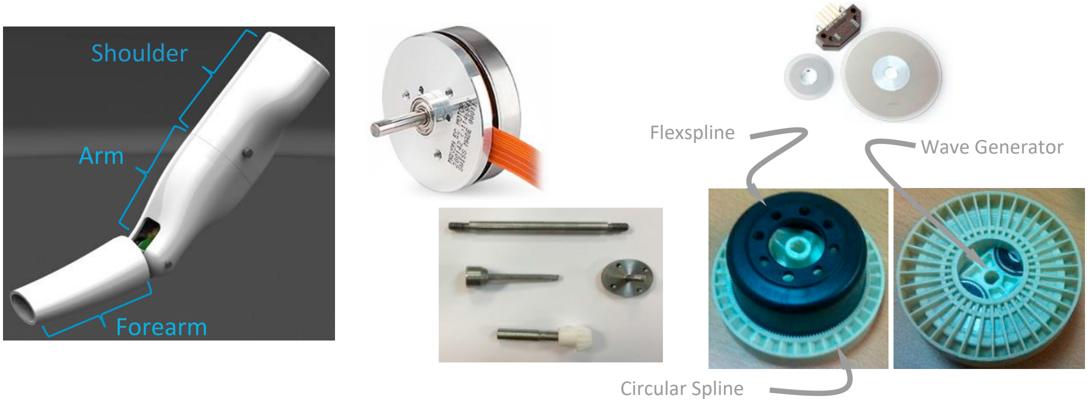
The components used for driving and controlling the arm had a strong influence on its geometric shape and dimensions. Even so, the final shape was soften using splines, trying to improve its appearance, Fig. 1. (a).

Being a low-cost prototype, some components were reused, such as brushless motors, Fig. 1. (b) up. Nevertheless, other elements such as drive shafts, gear reducers, sensors, etc., have been chosen or designed, see Fig. 1. (b) down, trying to compact each part and maintain a proportional dimensions on the final product.

The main start restrictions were:

- Search for a low weight for the arm, and therefore for the elements used [6]. The use of scaffolds made with a different material to the shell of the arm parts were avoided.
- A work volume of 200x200x200mm available in the 3D printer. The forearm, arm, shoulder and coupling elements have confined their dimensions to this volume.
- Use optical encoder sets before and after each gear reducer (harmonic drives), Fig. 1. (c). This was necessary for the control tests.
- Compulsory use of wheels coupling connectors (flexible couplings) between the brushless motors and gear reducers to absorb misalignments.

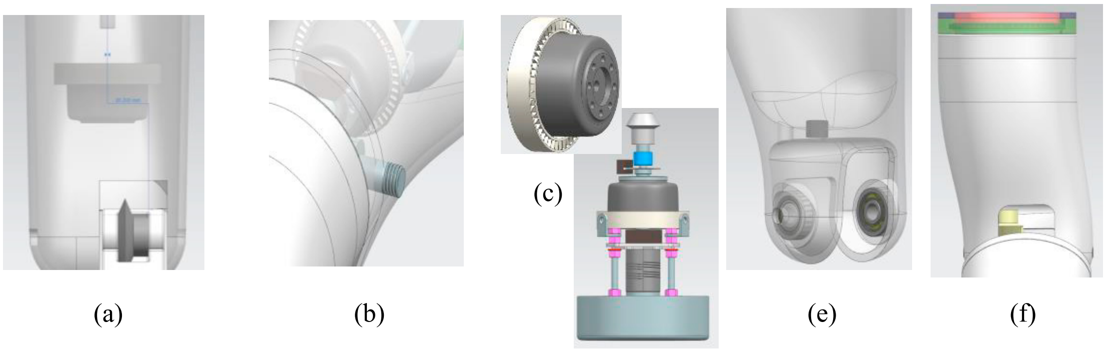
- The requirement of an easy assembly and disassembly of all parts. It is a prototype, and it is used to make tests, adjustments and improvements.



(a) (b) (c)

Fig. 1. (a) image of the light robot arm; (b) brushless motor, shafts and coupling joints; (c) optical encoder and harmonic drive.

All the components were modeled and assembled in a CAD application, Siemens NX, in order to check dimensions, movements and assembly sequences. This helped to choose, among different proposals, those ones that worked properly. In other words, electromechanical components, their shapes and dimensions and the required distances between them, determined the design of the parts. For example Fig. 2. (c), (d) and (e) shown 3D models of some conditioning elements. Fig. 2. (a) shows the minimum distance and alignment for one of the transmission axis. Fig. 2. (b) shows the position of the harmonic and one of the encoders relative to the shoulder joint. Fig. 2. (f) shows the necessary deviation of the external shape to allow alignment between pinion (shown in yellow) and crown.



(a) (b) (c) (d) (e) (f)

Fig. 2. Examples of 3D models of parts and components for the robot arm.

Taking advantage of the 3D models made, some simulations to check the stress behaviour in the critical parts were run, for instance, the arm-forearm joint shown in Fig. 3.

For this purpose NX Nastran, FEM solver included in NX Siemens, was used. Once the joints were selected properly, one by one, all the parts were put through to their corresponding loads to obtain numerical results and critical zones.

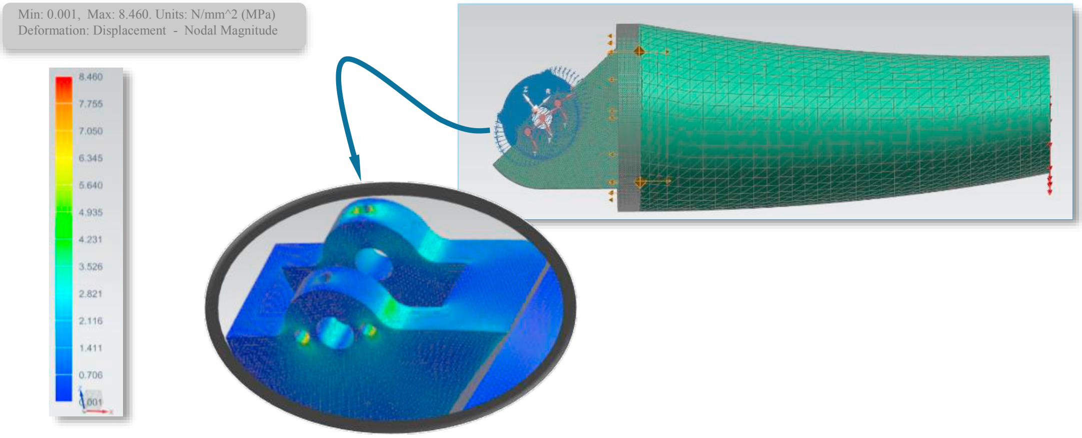


Fig. 3. Structural analysis of the arm-forearm joint.

Once all the models were validated, each part were printed. Since the parts were re-orientated to avoid the scaffolds during their manufacturing, the use of them was decreased considerably. Another corrective action was to redesign some transitions between surfaces to make them progressive, giving them certain slope, to make the layers self-supporting. See Fig. 4. (b) 'Printing first part of the arm'.

After the printed parts were reprocessed (drilling them, cutting them, making acetone primers, etc.) all the parts were assembly in the final set. Fig. 4. shows some examples.

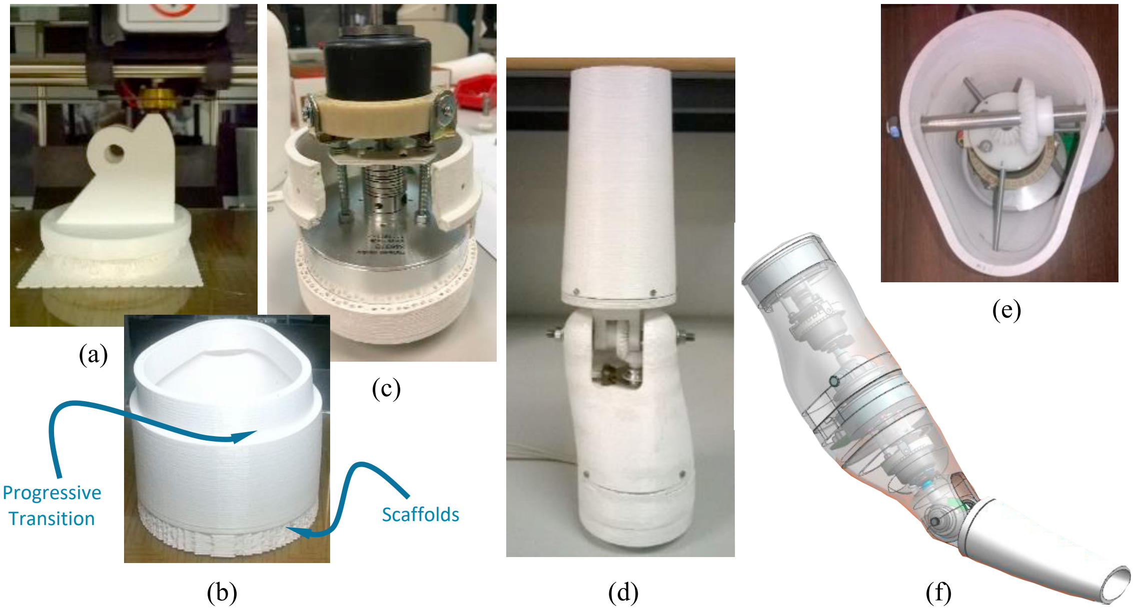


Fig. 4. (a) printing the arm-forearm joint; (b) printing first part of the arm; (c) motor–gear reducer assembly using a flexible coupling; (d) arm-forearm assembled; (e) view of the 3 points to adjust crown-pinion union; (f) interior view of the arm and shoulder.

3. Results and discussion

3.1. Computer stress simulations on the 3D models and structural cohesion in the real models

The computer strength simulations had a partial validity, since the direction of the plastic threads in the layers and the melting between layers, strongly affect the final characteristics of the part. The simulation software considers the part as a consistent and continuous element and it is not real.

Before processing the most critical parts of the arm, a right orientation for each part was chosen, in order to leave the direction of the plastic threads compatible with the direction of efforts application. Nevertheless, one of the characteristic more relevant is the right level of melting (interlacing) between the layers.

Changing 3D-printing parameters as, temperature, layer height, density of refilling and extruder speed, the melting between layers can be improved, [7], but better results can be achieved if acetone is used to dissolve and improve adherence. In this way, the behaviour of the parts were closer to the computer simulation results.

For example, the requirement for the arm is to withstand a force of 30N in cantilever, in the free side of the forearm. This situation causes a maximum strength of 13.31 MPa on the prototype, far from the material breaking stress which is 40MPa.

After manufacturing, two operations on the parts were made to improve structural cohesion in them:

- Treating the parts with heat to release strains.
- Using acetone to increase the level of adherence between layers [8].

Acetone can be diluted with water, before applying it, to reduce its effects. When submitting a part to acetone bath, the part suffers superficial roughness changes and dimensional changes.

In order to have an order of magnitude, regard to the effects of acetone in the parts, a study was made. This study focused on dimensional changes on 30 rectangular samples of 45 mm of length, 15 mm height and 0.5, 1, 2, 3, 5 and 10 mm of thickness. Five samples with each thickness.

The dissolution used was 90% acetone, 10% water, and the time of the bath was 300 seconds. Table 1 shows a summary of the maximum percentages of length, height and thickness variations.

The minus sign means a decrease in that dimension. If the percentage increases, that means the sample absorbs water and the density of ABS increases too, and therefore the dimension. The ABS used absorbs 0.3-0.7% of water at 24 hours, with acetone this percentage increases.

Table 1. Maximum dimensional variations in %.

Samples set	Length	Height	Thickness
0.5 mm thickness samples	-6.23%	-7.3%	76%
1 mm thickness samples	-3.4%	-6.9%	46%
2 mm thickness samples	-0.3%	-0.6%	23.5%
3 mm thickness samples	0.06%	-0.3%	21.6%
5 mm thickness samples	0.22%	1.06%	9.4%
10 mm thickness samples	0.24%	1.3%	4.7%

The samples more affected are those ones with less thickness. This is due to the time of exposure inside the dissolution, because the attack, instead of being superficial, affects the whole part. The part ends up losing its shape.

Leaving apart the 0.5 and 1mm thickness samples, in the other ones, the percentages shown represent a unitary variation, in the worst case, of 0.648mm. Therefore, the cohesion between layers improves, but the dimensional accuracy in the processed parts gets worse in values around tenths of a millimetre.

The recommendations, after the studio, are to use thickness higher than 3mm and acetone baths less than 300 seconds time. Another possibility is using walls with fill structures. This means, little wall-thickness, around 1mm, and a shortest bath time, around 20 or 30 seconds only.

3.2. Process parameter related to accuracy

Even having properly fix and calibrate the printing platform, Fig. 5. (b), and having a robust gantry configuration in the printer machine, the accuracy in these low-price devices are low, usually of tenths of millimetre.

The 3D printed used was Da Vinci 1.0 from XYZprinting Netherlands B.V. This device offers four levels of layer resolution: standard 0.2mm, speed 0.3mm, ultrafast 0.4mm and custom 0.1-0.4mm. Its nozzle diameter is 0.4mm.

The final accuracy can be improved choosing appropriate parameters as, diameter of the extruder, layer height and the right orientation of the part [9]:

- A small extruder diameter allows a better dimensional adjustment, on the contrary, processing time increases.
- The layer height, jointly with the diameter of the extruder and the temperature selected to melt the filament, let limit the side expansion of the deposited filament. Nevertheless, this situation decreases the bond strength between layers. Parameters used: 0.2mm layer height, 210ºC extruder temperature and 90ºC print bed temperature.
- Part orientation that minimizes the routes of the extruder in which the combination of axes X and Y is necessary. This way the dimensional accuracy improves.

Definitely, the lack of process accuracy forces to do local modifications in the parts to be able to assembly them together. Sandpaper was used to adjust the parts, acetone to soften specific surfaces, and some removing material operations, as re-drilled of small diameter holes, to remove excess of plastic that almost left them closed.

The adjustment process of the platform is done manually. As the reading points (where the 3D printer makes the measurements) Fig. 5. (a), are not the same as the set points, Fig. 5. (c), the calibration process turns slow and tedious. The calibration process is cyclic, because when you adjust one of the points, the others turn slightly *misaligned.*

Besides, due to the movements on the platform to take off manually the part once impressed and its posterior cleanness for a new printing, readjustments from time to time were needed. Any misalignment between the platform and the working plane of the extruder (plane XY) causes geometric and dimensional mistakes in the processed parts.

(a) (b) (c)

Fig. 5. (a) reading points; (b) real platform showing one of the set screw; (c) set points.

The 3D printer let a small degree of misalignment in the three reading points. However, if this gap can be minimized, the final accuracy improves. Therefore, knowing the dimensions of the platform, the distances between the reading points, the set points and the adjustment screws pitch, a specific software application was developed to help with the calibration process. The program tells the number of turns, fractions of turn and the direction of rotation in each point to make minimum the final gap.

3.3. Choosing the right shapes

Other relevant aspect was the decision to build the parts as closed shells, only opened at the ends. This type of construction is more rigid, but it forces to have a strict sequence of assembly for internal components, with very few alternatives.

As a rule, the assembly sequence is, to fit the engine, to fit the coupling shaft with the glass code-wheel for the first rotary encoder, to fit the harmonic drive, to assemble the shaft extension for the pinion and the second glass code-wheel and, by last, to assemble the source-detector enclosed package for each code-wheel.

In the case of a prototype, this sequence is a drawback, because to access to the pieces placed in the first positions, e.g. the motor or the first glass code-wheel, is necessary disassembly all the chain elements. So much so that, in the case of the arm, a side access was cut to be able to radially fit the source-detector enclosed package with the code-wheel. Specifically, it is referred to the encoder placed after the motor and before the harmonic drive, Fig. 4. (c).

Special tools were made, for example, a long fixed spanner to access inside the parts and help to close the screw joints, for the assembly between the forearm and the joint-part that connects with the arm.

3.4. Material behaviour

The nature of ABS (elongation of rupture 45%, modulus of elasticity between 2.1 and 2.4 GPa, etc.) and the thickness chosen to lighten weight, need an intermediate guidance system for the transmission-axes. Besides, due to the level of compaction of all the system, it was necessary to use metallic materials for the transmission elements to bear the required efforts.

The arm shell plays the role of support structure. Some internal components are fixed using screw connections. Because of the manufacturing process, it is compulsory to use teeth washers. This way the washer lock and distribute efforts, avoiding the separation of the plastic filaments.

The filling structure of the walls was used to shut some nuts, fixed them with a specific glue for ABS. This way the tasks of assembly and disassembly were simplified.

3.5. Transmissions behaviour

To adjust the transmission shafts and keep together the crown-pinion transmissions, small spiles with cylindrical bearings were used, fixed to the shell through several points (three points located at 120 degrees between them) and with screws to allow adjustments, Fig. 4. (e).

In the joints, commercial low-weight crown-pinion transmissions were used, made of POM (Polyoxymethylene). This plastic material has a good wear-behaviour, nevertheless, due to the required small dimensions; only crown-pinion transmissions with straight teeth were available.

Using straight teeth slightly increase the gap between the parts and besides the level of noise in the transmission increases as well. This gap was corrected through the adjustable screw elements commented.

On the other hand, being able to modify easily the place where the motors are placed and the location of the gear reducers to improve alignment between them, the way that harmonic drives work makes necessary to use flexible couplings.

If flexible couplings are not used, the shaft that joint the motor with the harmonic drive end up taking out the ‘flexspline’ from the inside of the ‘circular spline’, Fig. 1. (c). This is due to the coaxial error between the motor and the harmonic drive axes.

4. Conclusions

The functionality of the prototype, nearest the real one, is the main advantage reached in the arm-prototype. This functionality (movements, reaches of the arm, supported loads, etc.) has allowed the concurrent work of different teams. The development time was decreased, and some behaviours and setups that need to be corrected for the manufacturing of the final robot arm were made evident.

The manufacturing technique chosen, 3D printing: FFF, allowed the quick processed of the parts, and their re-processed in case to be necessary, keeping always a low-cost. Nevertheless, the behaviour of the plastic material selected and the model construction by layers forced to make post-manufacturing operations. This way, mechanical characteristics were improved and the lack of accuracy supplemented.

Once the 3D model was made, the time to manufacture a main part varies between 6 and 10 hours. The manufacture was performed at night autonomously. After manufacture a part, it was necessary around 45 minutes to make post-process operations and adjustments and 2 hours to insert and fix components and connections. After this, the part was ready to start working.

After having manufactured, analysed the behaviour of the parts and tested the real operation (assembled in the set, with the expected load, sweeping the workspace through controlled movements, testing the inertias for control issues…), the main aspects that should be taken into account for the final robot-arm are:

- Raw material: to use a plastic material, but reinforced with fibres. This way, the wall thickness is kept low and high the required structural firmness, without a negative influence on the total weight of the arm. To accomplish this, will be necessary to change the manufacturing process to the one called ‘vacuum infusion process’, [10].
- Metallic reinforcements: during the construction of the arm shell, local reinforced elements must be included. This way, the process of assembly/disassembly parts is easier, and the guided and adjustment of the transmission elements are more efficient, with a minimum impact on the final weight.
- Accessibility: in order to guarantee this characteristic, the shoulder shell, the arm shell and the forearm shell should be divided in two parts along its horizontal plane. This way, the access to any drive and control elements is guaranteed.
- Flexible couplings: it is compulsory to use gear reducers to have the necessary torque without having to increase the size of the motors. The most light gear reducers in the market are the harmonic drive type. These are specially recommended for this type of devices. Nevertheless, taking into account the way they work, a lack of alignment between the in and out shaft causes the disassembly of the gear package. To avoid this situation flexible couplings are required.

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