FINAL REPORT

DESIGN OF A PROSTHETIC ARM

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ADVANCE REPORT I
DESIGN TASK AND NEEDS

- INTRODUCTION

A prosthesis is an artificial device that replaces a missing body part, which may be lost through trauma, disease, or congenital conditions. The prosthesis related to arms and legs requires a rehabilitation, this is primarily coordinated by an inter-disciplinary team of health care professionals including physiotherapists.

The typical prosthetic device consists of a custom fitted socket, an internal structure (also called a pylon), belts that attach it to the body, prosthetic socks that cushion the area of contact, and, in some cases, realistic-looking skin. Prosthetic limbs design is currently undergoing changes on many levels, some of which concern the choice of materials and the implementation of electronic actuators.

Going back in time, the oldest known prosthesis is the Capua Leg, which was discovered in a tomb in Capua, Italy. The leg is made out of copper and wood and is dating back to 300 BC. In the early Christian period, limb loss was the result of trauma or 'nonsurgical' removal, and survival was generally regarded as very low chances. Then in 15th century, there were a period of surgical experimentation, mainly on gangrenous limbs or those already terribly damaged, where the patient was given a choice with the aim of saving their life and achieving a healed stump, despite the difficulties with infection and the lack of effective control for pain or blood loss. The survival rate was still small as many succumbed to shock and infection.

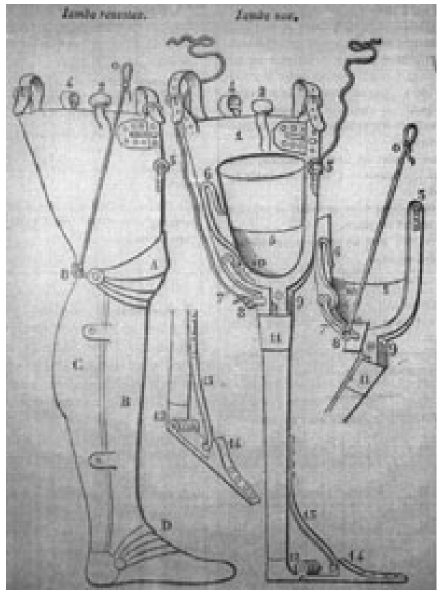


Figure 1. 16th century leg design.

The main area of development came in the 19th century along with the development of anesthetics and later infection control. In the American Civil War many men lost limbs due to canon and rifle shot, which would shatter bone sections making it impossible to repair the fracture. This led to well off people looking at means to replace the lost limb. Below is the patent for a wooden replacement leg, but this would have been a very heavy device.

Nowadays, if we talk about materials selection, the aim is to look for a lightweight prosthesis; hence, much of it is made from plastic. Lightweight metals such as titanium and aluminum have replaced much of the steel in the pylon. Alloys of these materials are most frequently used. The newest development in prosthesis manufacture has been the use of carbon fiber to form a lightweight pylon and the use of 3D printers for manufacture a hand.

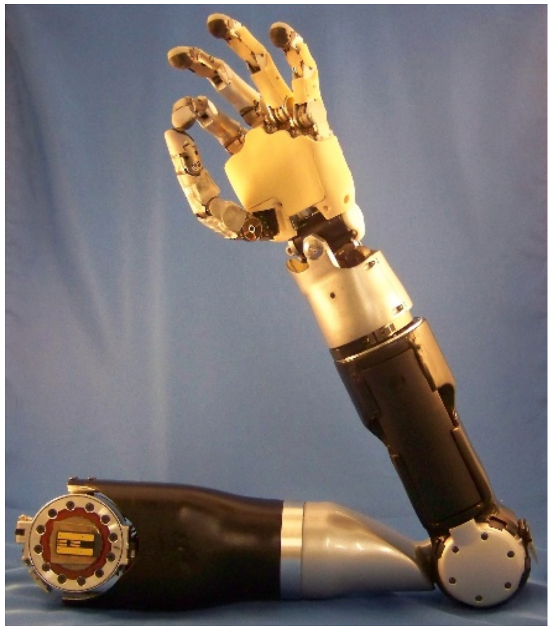


Figure 2. Modern arm prosthesis.

Certain parts of the limbs (for example, the feet) have traditionally been made of wood (such as maple, hickory basswood, willow, poplar, and linden) and rubber. Even today the feet are made from urethane foam with a wooden inner keel construction. Other materials commonly used are plastics such as polyethylene, polypropylene, acrylics, and polyurethane. Prosthetic socks are made from a number of soft yet strong fabrics. Earlier socks were made of wool, as are some modern ones, which can also be made of cotton or various synthetic materials.

Physical appearance of the prosthetic limb is important to the amputee. The majority of endoskeletal prostheses (pylons) are covered with a soft polyurethane foam cover that has been designed to match the shape of the patient's second limb. This foam cover is then covered with a sock or artificial skin that is painted to match the patient's skin color.

The other developed area it’s the communication and here is when the electronic it’s a fundamental part of the prosthesis. Recent advances permit the brain to send signals to a computer and then execute a movement with the prosthesis. Furthermore, the aim it’s to stablish a continuous communication with the brain, by capturing signals from the prosthesis, send it to the brain, process the signal and then send the response to complete the cycle.

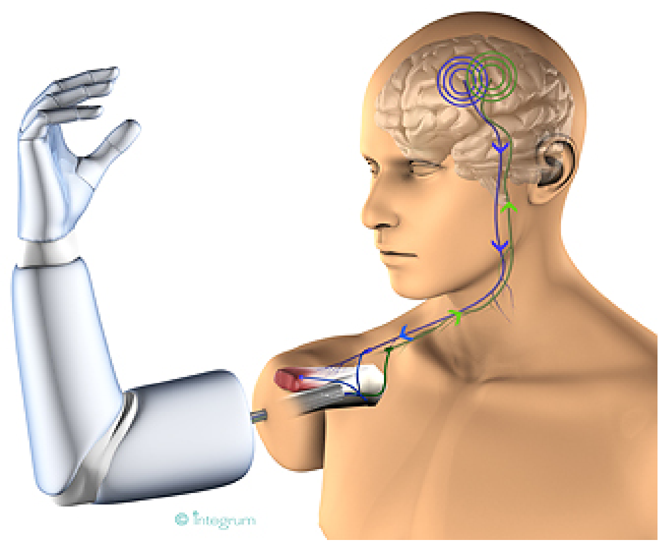


Figure 3. Scheme of brain-prosthesis communication.

➢ OBJECTIVE

The aim of this project is to design an above elbow adjustable prosthetic arm for people between 18 and 50 years old. The prosthetic arm is intended for low to middle income population. The prosthetic arm has to have an attached hand that allows the users to perform day to day basic activities such as holding different forms, rotate, use computers and touch screen devices.

<u>Customer needs:</u>

- Light weight but still very durable
- Not painful when applying or taking it off
- Aesthetically similar to the look of an actual human arm
- Good battery life, at least one full day with a single charge
- Low charging time
- User friendly
- Low maintenance costs
- Water proof and resilient to high and low ambient temperature

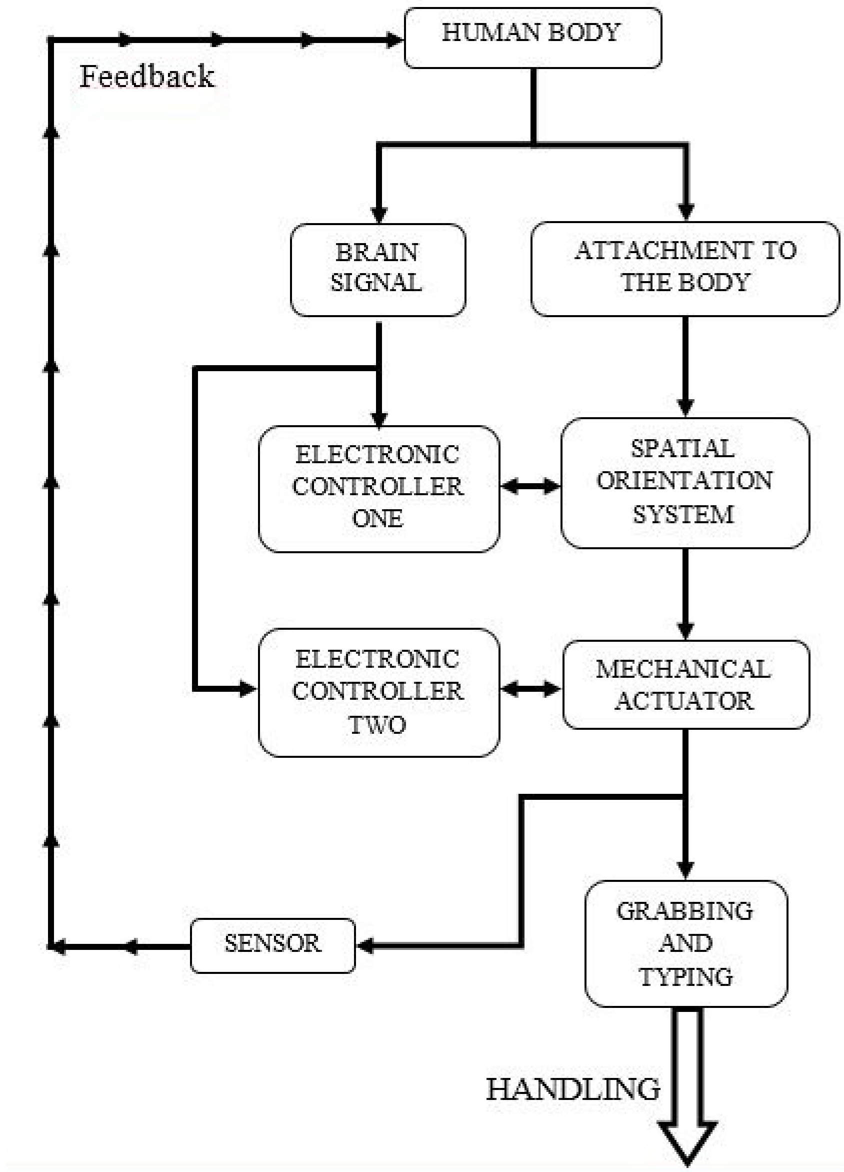
➢ FUNCTION & SUB-FUNCTION

The primary function of the prosthetic arm is to let the patient grab and handling objects and perform basic activities such as typing on a computer keyboard or utilising a touch screen device.

Table *1*. List of functions & subfunctions.

Essential function: Handling	
Essential Subfunctions	**Means of Achieving Subfunctions**
Attachment to the body	Link the body to the prosthesis
Spatial orientation system	Orientate the end effector
Activate the mechanical actuator	Make the forces to grab and typing

- FLOW SCHEME OF FUNCTIONS & SUB-FUNCTIONS



ADVANCE REPORT II
FUNCTIONS ANALYSIS AND DESIGN SPECIFICATIONS

The essential function of the prosthetic arm is to enable the patient to manipulate object and be able to handle everyday tasks, such as open doors and windows, utilize touch screen devices, and manipulate objects.

- FUNCTIONS ANALYSIS

We can identify two essential sub-functions from the main function.

- Attachment to the body:
  The function consist in linking the prosthesis to the body of the patient, the attachment must be compliant with the normative.

  Other specifications are defined by comfort, the attachment system must be comfortable for the patient, because it must be used for long periods of time, such as an entire day before be removed.

- Spatial orientation system:
  The spatial orientation system has the task to permit to the patient to orientate properly the prosthetic arm and the hand, in an independent way each other.

REQUIREMENTS

We enlist here the requirement needed for our prosthetic arm, based on a survey on taken on a number of patients.

Basic requirements

- Production**:** the prosthetic arm must be able to be produced in every country in which it'll be sold
- Cost: the cost must be adequate to let the prosthetic arm be bought by middle class patients
- Comfort: the prosthetic arm must be comfortable to wear

Technical requirements

- Weight and mass center: The prosthesis should have less, or at least, the same weight and mass center of an 18-50 year old.
- Easy installation: the installation and removal must not require surgery, and the patient must be able to do it by himself.
- Environment resistance:
  - Water proof
  - Wide range of operating temperature (-10 to +45°C)
- Battery performance: the battery must last at least for an entire work day, for example from 7:00 to 19:00 with normal usage with no need to external power sources.
- Loads: the assembly must withstand the stresses of a load generated by holding and manipulating relatively heavy objects like water bottles or shopping bags.

Marketing requirements

- External looks: the prosthetic arm must have a superficial finish that resemble human skin, and the shape too must be as similar as possible to a human arm.
- Additional features: final product must have additional feature to appeal the customer, like a hook for attach shopping bags or a USB port to charge mobile devices like phones and tablets.

<table>
<tr><td>Politecnico di Milano</td><td colspan="2">Prosthetic arm.</td><td>Date: 12.1212.12

Page: 11 of 2</td></tr>
<tr><td>Changes</td><td>D
W</td><td>Requirements</td><td>Responsible</td></tr>
<tr><td>31/10/2014

31/10/2014

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31/10/2014</td><td>
D
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D
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W</td><td>1) <u>Geometry</u>
- Length elbow-finger ≈ 500 [mm]
- Diameter of the forearm ≈ 75 [mm]
- Similar shape of a human arm and hand

2) <u>Kinematics</u>
- At least 3 degrees of freedom
- Precise positioning
- Low noise.

3) <u>Forces</u>
- Weight carried by the hand ≥ 1 [kg]
- Weight carried by the prosthesis ≥ 4 [kg]
- Weight of the prosthesis ≤ 7 [kg]

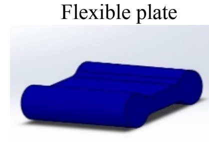
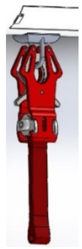
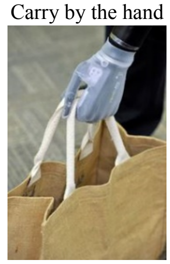
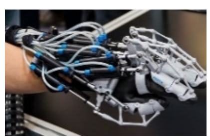
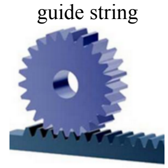
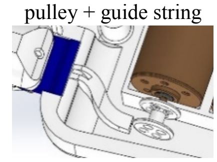
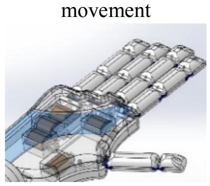
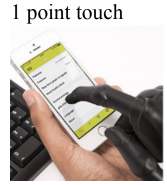
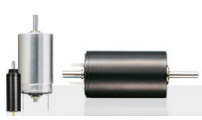
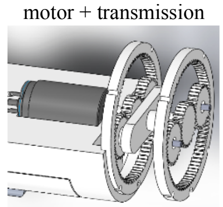
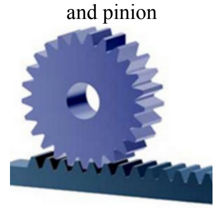
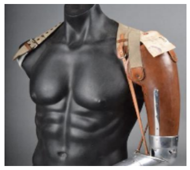
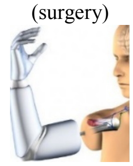
4) <u>Energy</u>
- Long autonomy ≥ 12 [hr]
- Reload easily

5) <u>Safety</u>
- Safety mechanism to prevent undesired rotations or malfunction.
- Nontoxic materials (Medical laws)
- Isolate danger rotating parts from the operator
- Isolate the electronic parts from the operator
- Water proof</td><td>
Polimi Team</td></tr>
</table>

Politecnico di Milano		**Prosthetic arm**.	Date: 12.1212.12 Page: 2 of 2
Changes	**D W**	**Requirements**	**Responsible**
31/10/2014	 **W** **D** **W**	6) **Ergonomics** - Design must be adaptable for different size of persons - Installation without surgery - Comfortable to wear	 Polimi Team
31/10/2014	 **W** **D**	7) **Production** - Not for mass production - Technologically able to be produced worldwide	
31/10/2014	 **D**	8) **Operation** - Operating temperatures [-10 , +45] [°C]	
31/10/2014	 **W** **W**	9) **Maintenance** - Easy to repair or replace any part - Easy to assemble and disassemble	
31/10/2014	 **D**	10) **Cost** - Budget of [2500-5000] [€]	

ADVANCED REPORT III
CONCEPTUAL DESIGN IDEAS AND CONCEPT SELECTION

- CONCEPTUAL DESIGN IDEAS

	Solutions			
Functions	1	2	3	4
A - Finger retracting mechanism	Flexible string 	Torsional spring 	Flexible plate 	Actuating motor 
B - Carry Mechanism	Connector at the forearm 	Carry by the hand 	Replace hand for a hook 	Suction pressure 
C - Fingers movement	Pneumatics pistons 	Electrical pistons 	Rotational rotor + rack and pinion system + guide string 	Rotational rotor + pulley + guide string 
D - Write/touch-screen mechanism	5 finger touch and movement 	Holding pen 	1 point touch 	
E - Wrist and elbow rotation mechanism	1 high torque rotational Motor 	1 low torque rotational motor + transmission 	Lineal actuator + rack and pinion 	
F - Body-prosthetic arm connection	Attached to the shoulder 	Pressure made by deformation 	Screwed to the body (surgery) 	

In the previous table it's shown the possible solution for each type of sub-function needed for design a prosthetic arm, by selecting each sub-solution we get a several conceptual solutions for the prosthetic arm assembly presented below.

Solution 1: A1 + B2 + C3 + D2 + E1 + F1

Solution 2: A2 + B3 + C2 + D3 + E3 + F3

Solution 3: --- + B4 + ---- + ---- + E1 + F1

Solution 4: A3 + B1 + C4 + D1 + E2 + F2

- CONCEPT SELECTION

The selection process must be done in an objective manner because we have to ensure that the selection it's not dictated by personal preferences.

This are the parameters that we have decided to evaluate for our selection:

A) COST

B) AUTONOMY

C) HOLDING CAPACITY

D) RESISTANCE TO ENVIRONMENT

E) SAFETY

F) ERGONOMICS

G) EASY TO BUILD

H) PERFORMANCE

I) LOW MAINTENANCE

J) ADDITIONAL FEATURES

In the first step we have to discard some of the solution because they don’t comply at least the 80% of our selection parameters

Solutions	Parameters of Selection										Comments	Decision
	A	B	C	D	E	F	G	H	I	J		
SOL1	+	+	+	+	+	+	+	+	+	-		+
SOL2	+	-	+	+	+	+	+	-	-	+	Can’t use surgery	-
SOL3	+	+	-	+	+	+	+	+	-	-	Can’t use touch screen or old different shapes	-
SOL4	+	-	+	+	+	+	+	+	+	+		+

- \+ = positive
- \- = negative

From previous table, we can notice that SOL1 and SOL4 comply at least 80% of the parameters for selection. The following step it’s to choose between this two solutions seeking the best of them

- BEST IN CLASS SOLUTION

In this part, we compare all solutions by using an AHP analysis for a more precise evaluation. This method consist in create a square matrix for the comparison between all the parameters of selection. The comparison its done by giving a score ranging [0 , 5] each parameter and then divide his value with the value of the others. In the following table, we can see the final result of the matrix.

	A	B	C	D	E	F	G	H	I	J
A	1.000	1.000	1.125	1.125	0.9	0.900	1.125	0.900	1.125	1.500
B	1.000	1.000	1.125	1.125	0.9	0.900	1.125	0.900	1.125	1.500
C	0.889	0.889	1.000	1.000	0.800	0.800	1.000	0.800	1.000	1.333
D	0.889	0.889	1.000	1.000	0.800	0.800	1.000	0.800	1.000	1.333
E	1.111	1.111	1.250	1.250	1.000	1.000	1.125	1.000	1.125	1.667
F	1.111	1.111	1.250	1.250	1.000	1.000	1.125	1.000	1.125	1.667
G	0.889	0.889	1.000	1.000	0.800	0.800	1.000	0.800	1.000	1.333
H	1.111	1.111	1.250	1.25	1.000	1.000	1.125	1.000	1.125	1.667
I	0.889	0.889	1.000	1.000	0.800	0.800	1.000	0.800	1.000	1.333
J	0.667	0.667	0.750	0.750	0.600	0.600	0.750	0.600	0.750	1.000

In this point it’s necessary to multiply the matrix for itself and summing the elements of the row it can be obtain a column vector, then this vector it’s normalized. The final value indicate which among this parameters are the most important for the design.

Cost	A	0.918
Autonomy	B	0.918
Holding capacity	C	0.816
Resistance to environment	D	0.816
Safety	E	1.000
Ergonomics	F	1.000
Easy to build	G	0.816
Performance	H	1.000
Low maintenance	I	0.816
Additional features	J	0.612

We now find the best solution combining the index for the parameters with the parameters selection matrix.

Abbiamo dato a un voto per ciascun parametro per ogni soluzione (nella tabella 1), sommati i valori lungo le righe e valutato cosi le varie soluzioni in base anche ai pesi dati ai vari parametri. Si ottengono quindi i seguenti voti per le rispettive soluzioni.

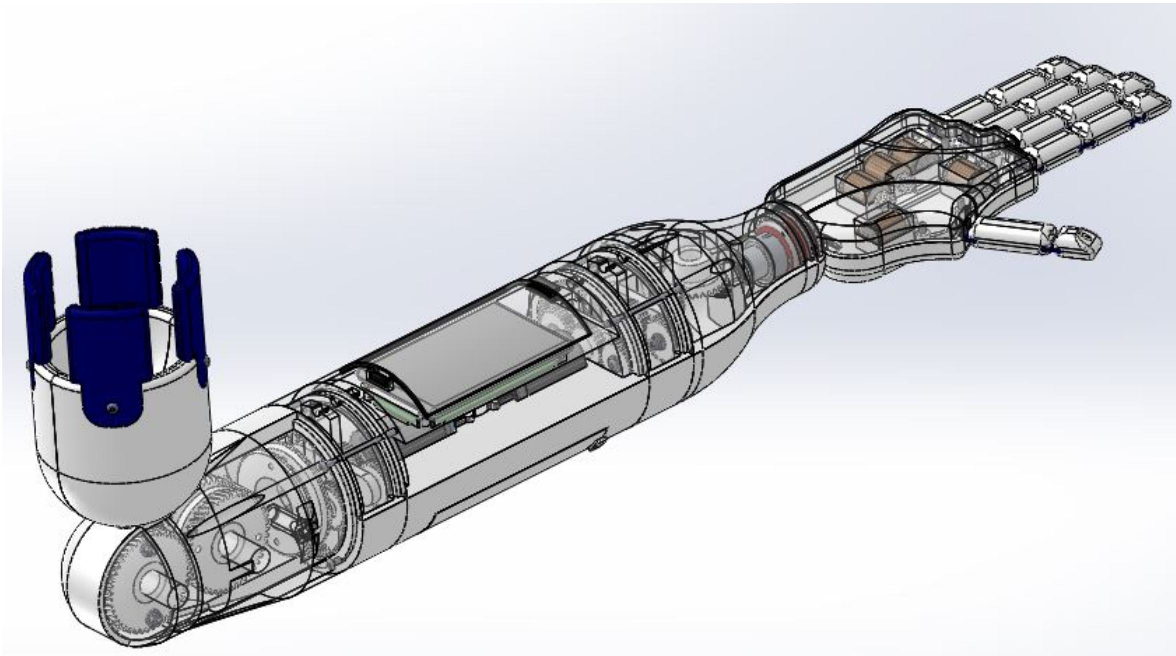
At this point we give a score to every parameters for each solution (table 1), sum the values on the row and so evaluating all solutions also taking in account the different wheights given to different parameters.

Doing so we obtain the following values for the respective solutions :

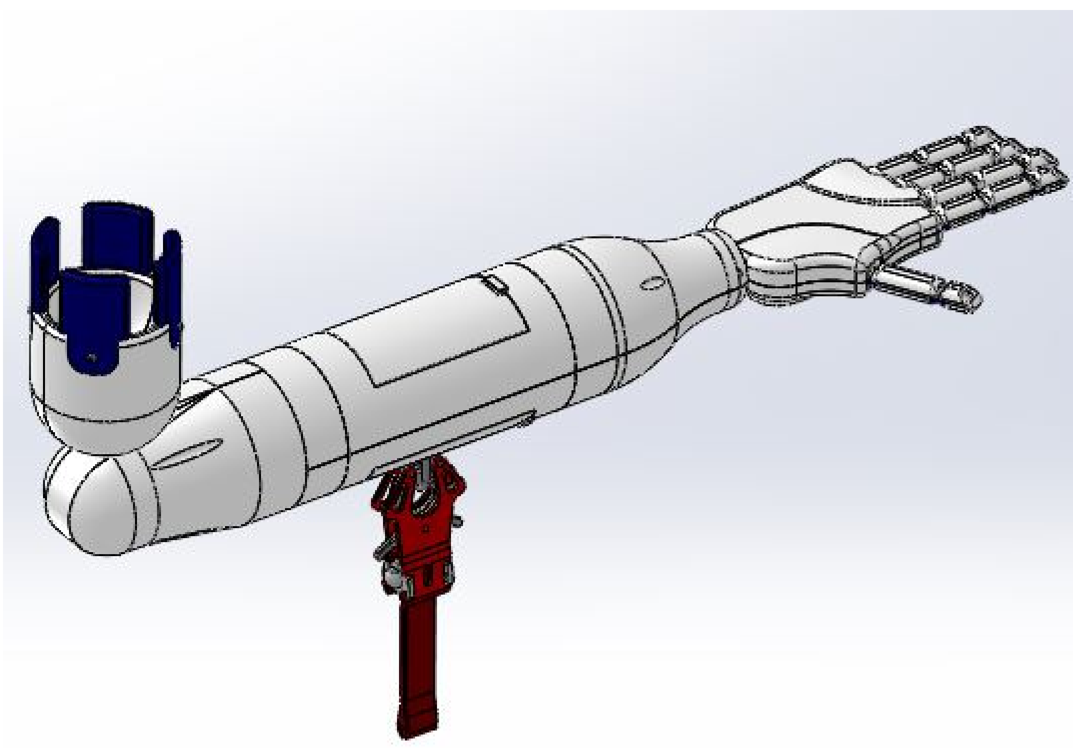
SOL1	0.0758
SOL2	0.0573
SOL3	0.0642
SOL4	0.0871

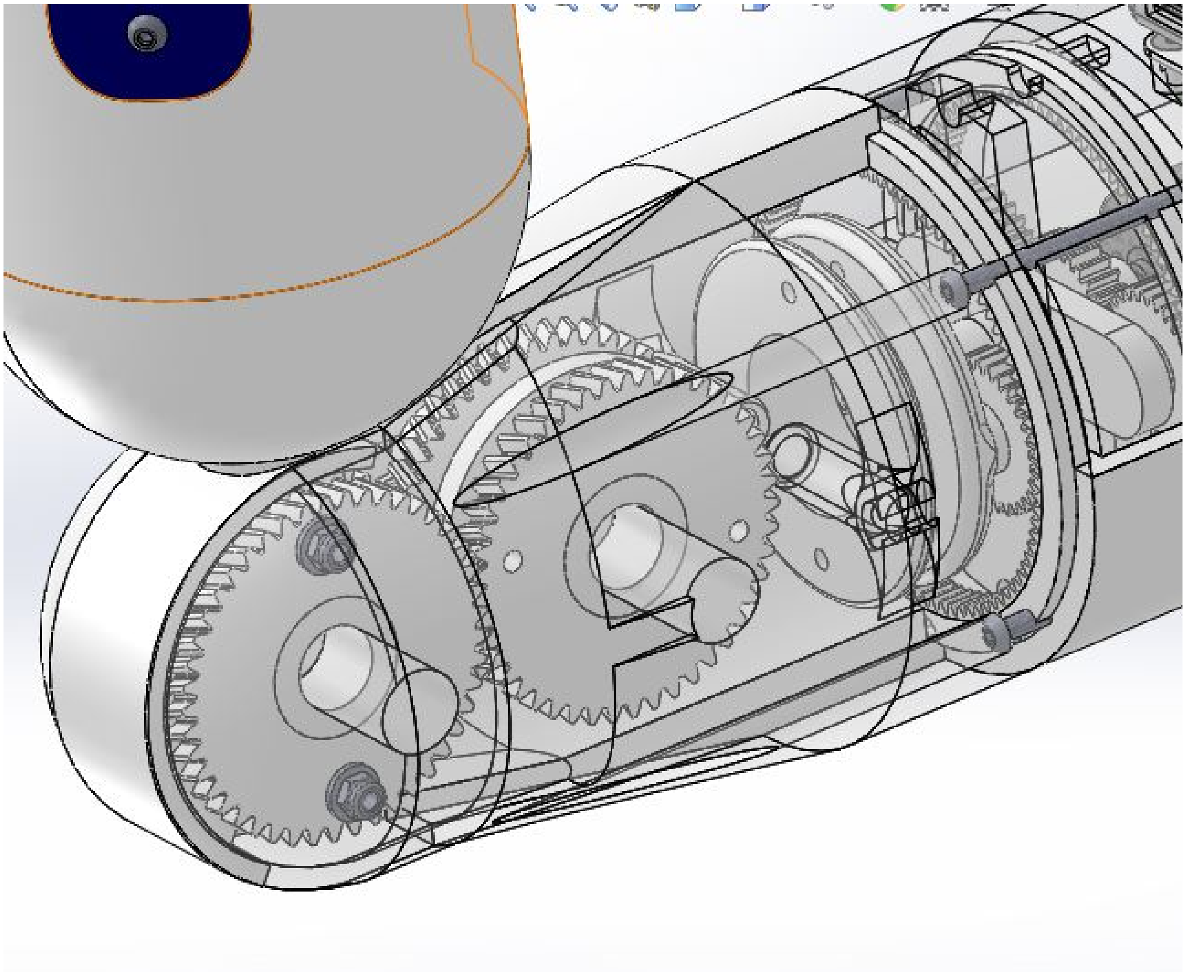
The final solution is SOL4.

- DETAILS OF THE SOLUTION

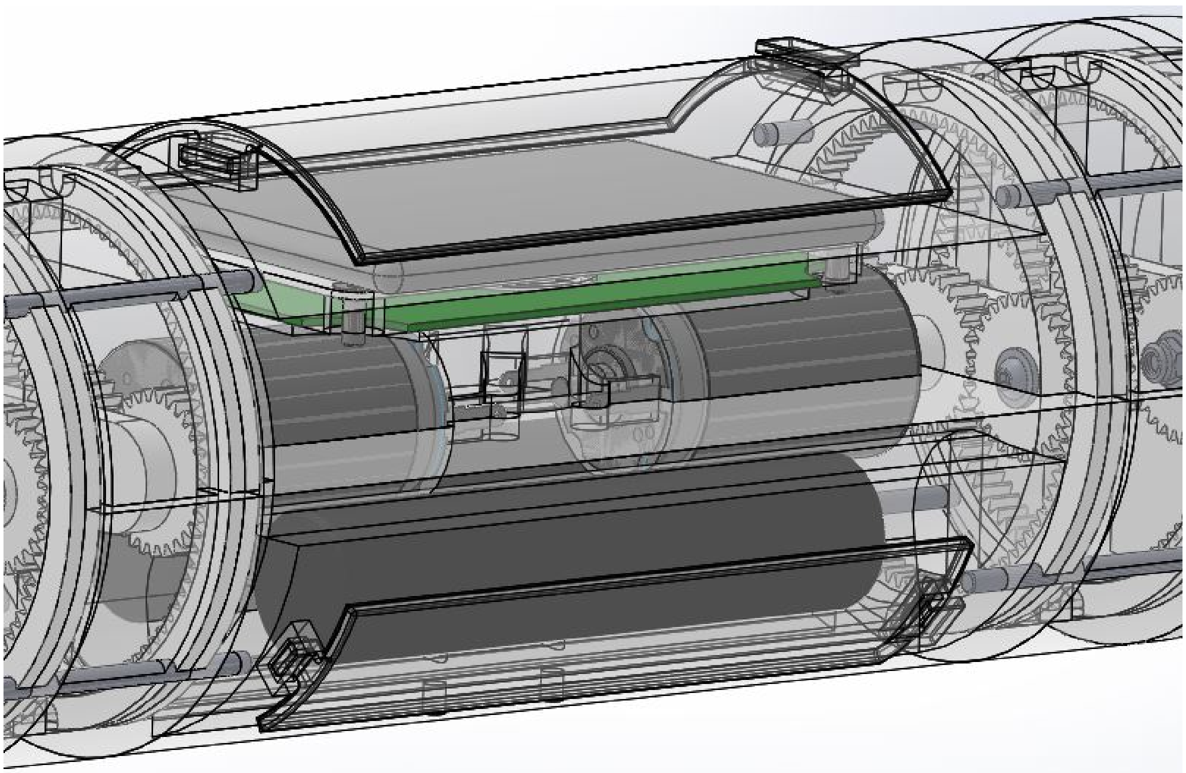


View of the assembly (top), view of the assembly with the hook (bottom)

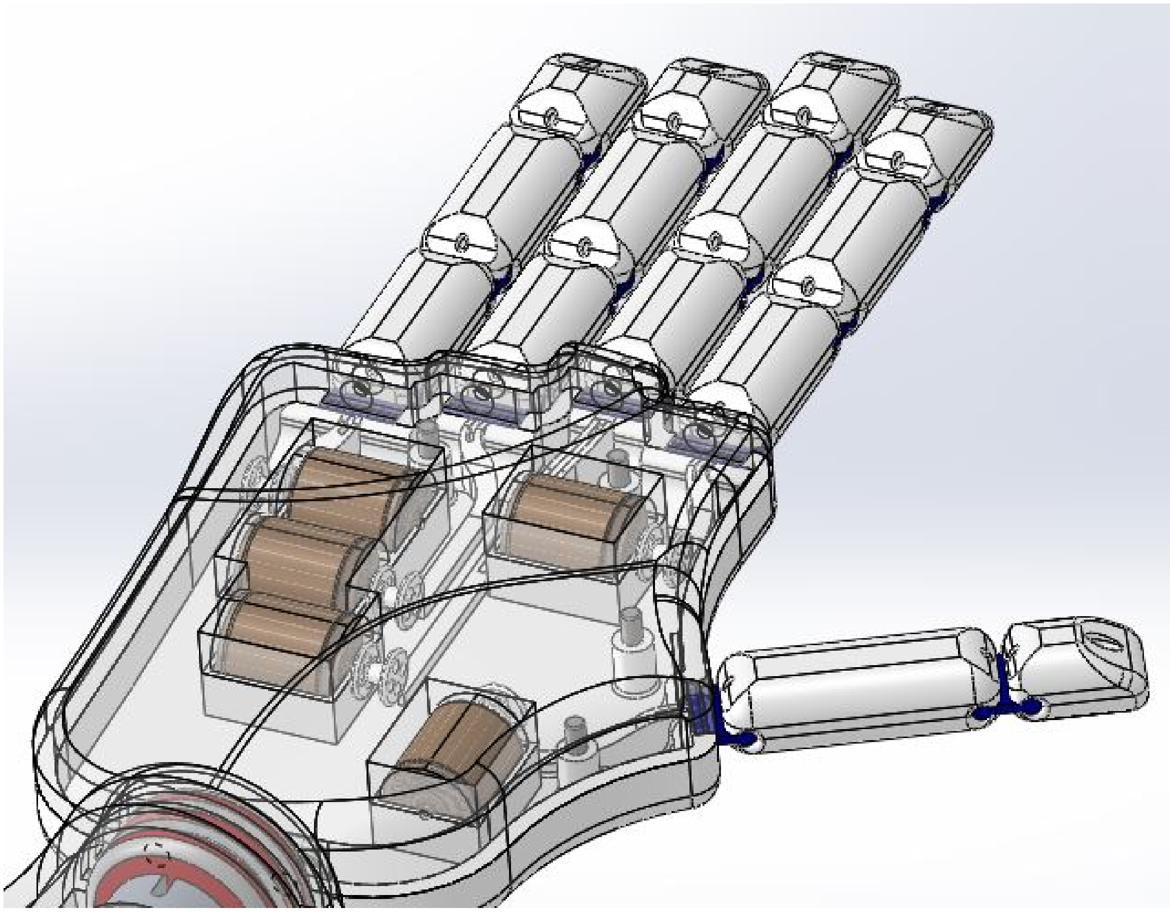




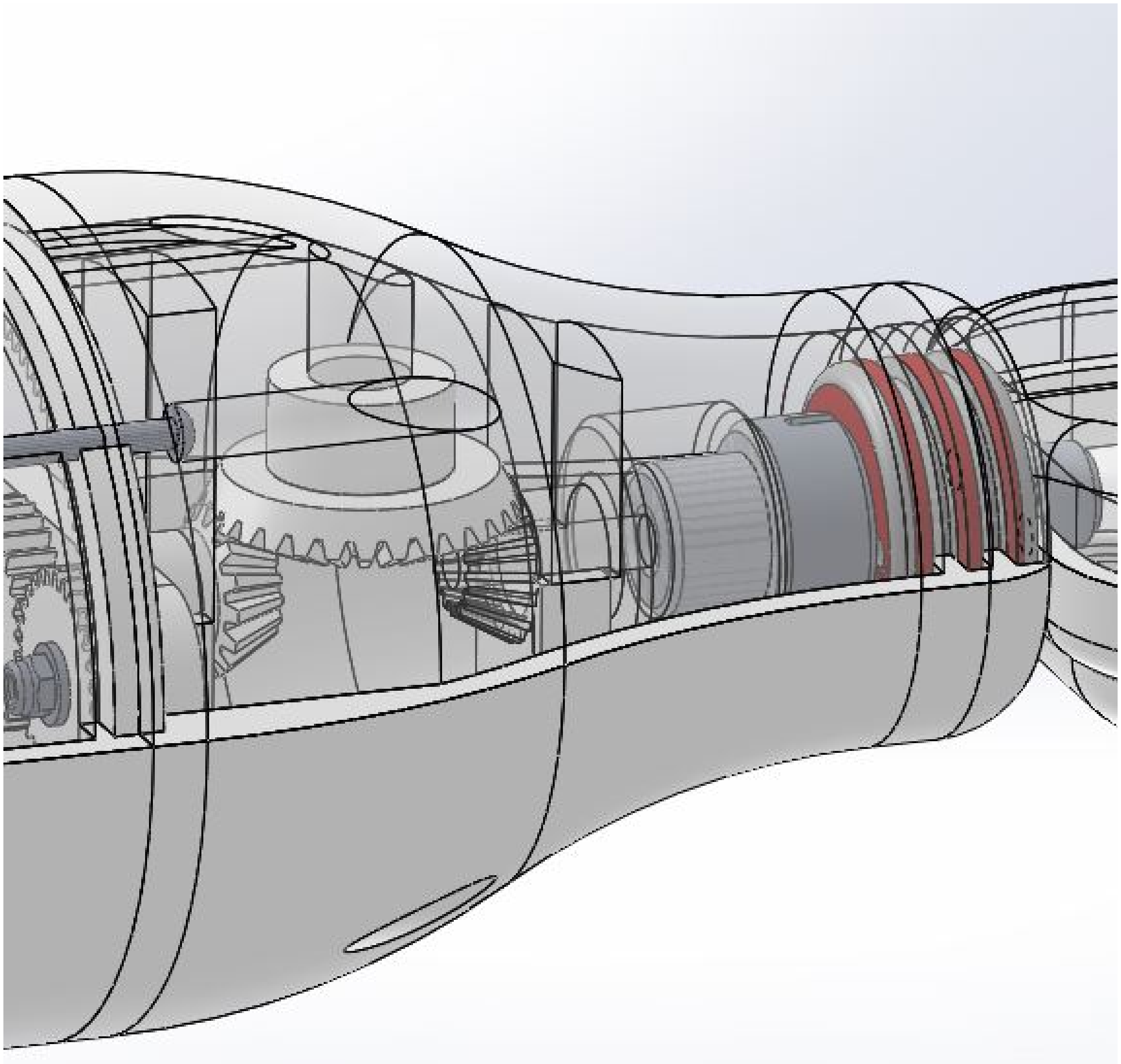
particular of the elbow



particular of the forearm



hand assembly



wrist mechanism

CONCLUSIONS

Mechanical characteristics

Prosthesis	Characteristics
Servo motors of the hand	Type: Stepper motor Steps: 24 steps per revolution Current: 0,45 [mA] Maximum holding torque: 10 [Nmm] Quantity: 5 Weight:12 [g]
Servo motors of the forearm	Type: DC Micromotor Current: 92 [mA] Maximum torque: 144,6 [Nmm] Maximum velocity: 5800 [rpm] without load Quantity: 2 Weight:114 [g]
Transmission at the forearm	Type: Epicyclic transmission of straight teeth with two stages Ratio per stage: 1/4 Final ratio: 1/8
Movement of fingers	5 finger movement
Rotation of the hand	180° movement (electronically controlled)
Rotation of the forearm	90° movement (electronically controlled)
Battery for hand or forearm	Capacity: 2600 [mAh] Voltage: 5 [V] Type of connection: USB Quantity: 2 (1 hand and 1 forearm) Weight: 64 [g]
Battery for emergency	Capacity: 1020 [mAh] Voltage: 5 [V] Type of connection: USB Quantity: 1 Weight: 32 [g]
Material used	ABS Flexible material for tendons and body attachment: NinjaFlex (printed material)

Numerical results of the final solution

Characteristic	Value
Estimate cost	3d printer: 600-3600 [€] Raw material: 25-40 [€/kg] Servomotor: 30-60 [€/motor] Battery: 10 [€/battery] Electronic controls: 40-50 [€/control] Total estimated cost: 970-4230 [€]
Weight carried by the hand	Each finger: 5 [N] or 0.5 [kg] All hand: 2.0 – 2.5 [kg], depends on the position of the hand
Weight carried by the prosthesis	It has to me measure at the moment when the prosthesis it's attached, because it varies depending the person using the prosthesis.
Weight of the prosthesis	1917 [g]
Autonomy for the hand	Assuming that closing the hand for 5 second and 20 times per hour, the autonomy is up to 53 hours.
Autonomy for the forearm	Assuming a rotation for the two motors at the same time for 5 seconds and 20 times per hour, the autonomy is up to 211 hours.

Additional features:

- All made of printed materials: if it break you can print it, if you want to make a redesign you can print it, if you want to chance the hand for making a more specific function you can print it.

- Commercial cellphones external power bank: this type of batteries offers an advantage to the prosthesis, with the capability to be recharged by a USB port.

- Additional hook: the current design it's adapted to use a hook connector to carry heavy things.

- External sensitive cover: cover made of a skin look-like material could be applied over the whole prosthesis with pressure sensors to simulate the touch sense. The use of this cover allow a communication between the brain and the prosthesis, but at this moment it only can be done by adding by surgery an electronically device in the body.