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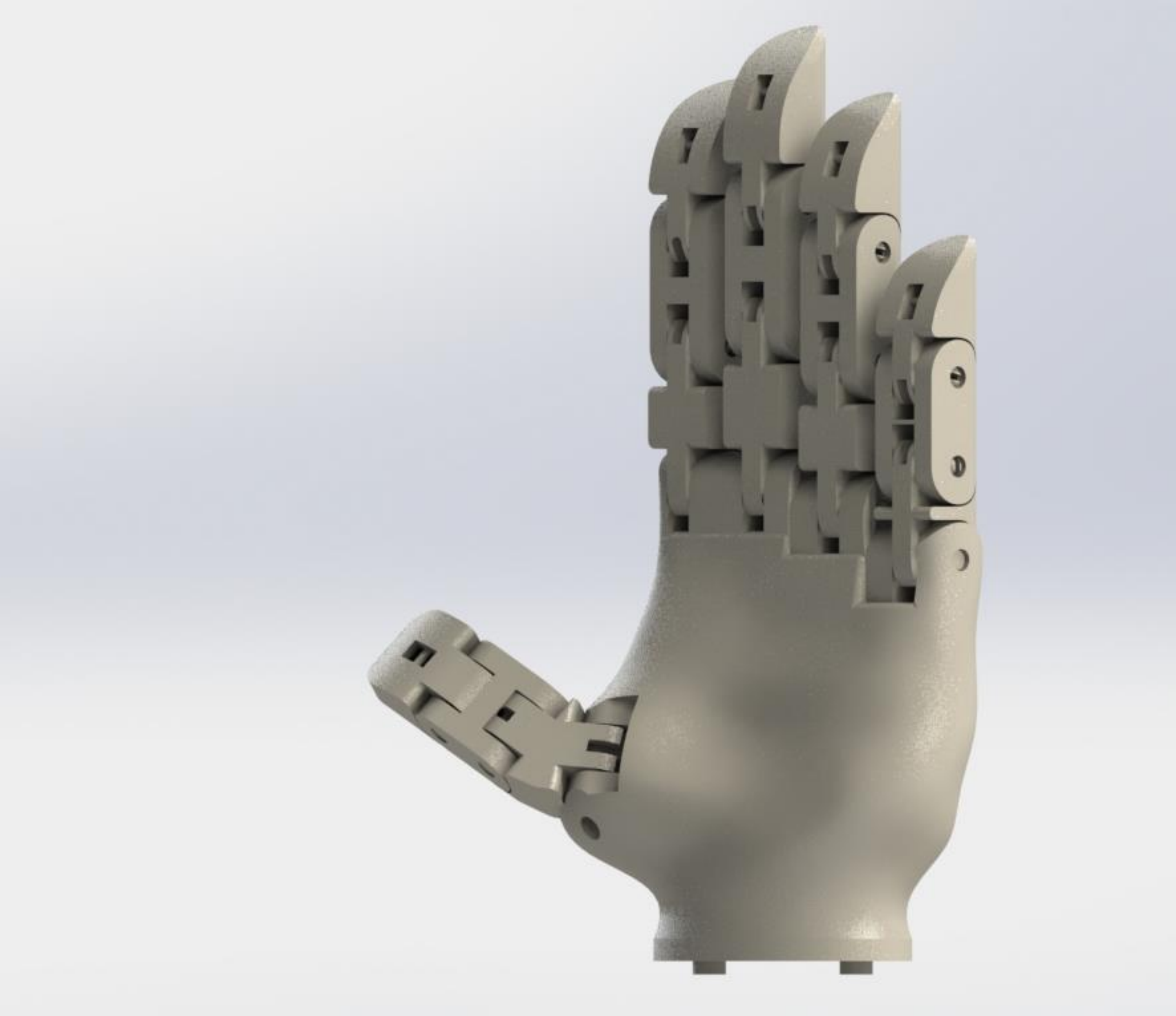

Research, Design and Construction of a Prosthetic Appendage

An investigation into the pros and cons of the prosthetic hand – with a solution to improve on past designs

By Dylan Fitzsimmons, Steve Foy, Diego Guijarro and Albert Martin

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Master in Mechatronic Engineering
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Chapter 1 – Introduction

The following document is a collection of work produced by 4 Erasmus students: Dylan Fitzsimmons, Steve Foy, Albert Martin and Diego Guijarro; who together, form as part of the European Project Semester. The EPS programme allows multiple students from different engineering disciplines and cultural backgrounds to integrate into a new study and working environment, learning and adapting skills that are important in today´s global economy. The effects of globalisation and the liberalisation of foreign economic markets has opened the world to an almost infinite amount of engineering opportunities; fuelled by the unprecedented investment in industries such as energy, manufacturing, technology and ambitious infrastructure projects from countries across Asia and Europe. For this reason, it is imperative to adapt the interpersonal communication skills learned throughout the Erasmus programme if our engineering knowledge is to stay prevalent and achieve international success. EPS helps to expand on these by producing a relaxed working ambience with helpful core staff who are dedicated to the benefits of the learning experience.

The project as briefly mentioned above, is the research, design and construction of a prosthetic appendage. The appendage, in our case a hand, is an important instrument in everyday life; yet the technology has not advanced with the remainder of other medical breakthroughs. The overall objective of the group was to find out what the issues were surrounding the design and the potential methods of solving these problems. Previously, there have been many attempts at designing and building the complex fluid shapes of the prosthetic hand through techniques such as injection moulding, although the process can be very expensive. To make the technology available to a wider target audience, the team had to focus on low budget methods of creating the hand; using the 3D printer. 3D printing technology is the future of manufacturing, being able to build a range of shapes in a matter of hours; the solution offers not only a lower budget prosthetic but an easily accessible product. Fuelled only by our knowledge and will to succeed, the team worked on these cheaper solutions – refining each design to reach the desired outcome that recipients look for in their prosthetic.

Chapter 2 – Research

2.1. Aim of Research and Objectives

The aim of the project was to design, construct and test a prosthetic hand which conducts human actions – shaking hands, picking up objects. The idea is that the design, which is completely open source, can be modified by any other engineers to suit the medical needs of the individual who requires the artificial appendage. The new design builds upon the common method of electrically actuated hands, whilst improving the negative design aspects of current models: bulky, heavy, expensive and aesthetically unappealing. To achieve these objectives, most of the prosthetic was created using a 3D printed filament; substantially reducing costs and the need for outsourcing all components. All of which began on 03/03/2017 and was to be completed by 06/06/2017.

Limited only by budget and timescale, the project was undergone by a research team consisting of 4 multinational and multidisciplinary students – offering experience from mechanical and industrial design engineers. Each student provided a different perspective on how to meet the project objectives and come to the final solution, due to the varied knowledge and socio-cultural backgrounds; of which resulted in a congregation of new ideas and techniques.

2.2. Design Specification

Using the Mojo 3D by Stratasys to print all plastic components of the product, the team could place a limit on the dimensions of the largest printed piece – the palm. As the palm was the largest individual section, it was to provide the basis for the fingers, thumb and wrist; which would stay relative to its size, whilst remaining true to the research on anthropometrics (discussed in section 2.7). Based on the $112.7mm^3$ working area within the printer, the team agreed upon the following dimensions:

	Size (mm)
Maximum height of palm	110
Maximum finger length	110
Maximum Wrist length	100
Component wall thickness (minimum)	3

Table 2–1

Each dimension is the idealised approximation of what is possible by the printer; 1 printing layer amounts to 0.178mm, which in turn amounts to 56 layers at 9.968mm (closest value to 10mm). However, these differences are too miniscule to have any effect on the strength of the design, and can be considered negligible.

2.3. Project Management

To make efficient use of the allocated time and to monitor the effectiveness of each members input – a project plan was first established. The bulk of the work was divided into 4 segments:

- Initial planning and research
- Conceptual and detailed design
- Printing and assembly
- Testing and presentation

To monitor progress and keep on track with the schedule, a Gantt chart was created and modified throughout – **appendix 1**.

Furthermore, a flowchart was created to help maintain steady progress on the initial design focused research – **appendix 2**.

2.3.1. Task

Member	Type
Dylan Fitzsimmons	Initial design research, market research, anthropometrics research, material research
Diego Martin	Initial design research, design of thumb, wrist and programming of electrical components
Albert Martin	Initial design research, design of palm, wrist and thumb
Steve Foy	Initial research, design of fingers, wrist and palm

Table 2–2

2.4. Initial Research

Staying precise to the mechanics of the product, it was important to gather the necessary and detailed research into the way prosthetic hands operate. The basic principle of the prosthetic appendage is to help the recipient achieve the common everyday tasks that they would usually accomplish without the disability. To effectively collect all vital information, the team were tasked with finding the accompanying information:

2.4.1. Types of Actuation

Before a type of design could be pursued by the team, sufficient information was gathered on 3 types of actuation: pneumatic, hydraulic and electric.

Pneumatic actuation – works by pressurising air through a series of sealed chambers to contract and retract the hand in a clasping motion. In the most common designs, each finger and thumb represent the hollow chamber which the air is fed into; desired pressures are attained using a series of pressure relief valves, negating the use of sensors to maintain gripping force. Pressurised with an air compressor, and power by a small DC motor. To obtain a more intricate distribution of freedom for each finger and thumb, valves are placed at the entrance to each chamber – operated by a closed-loop control system.

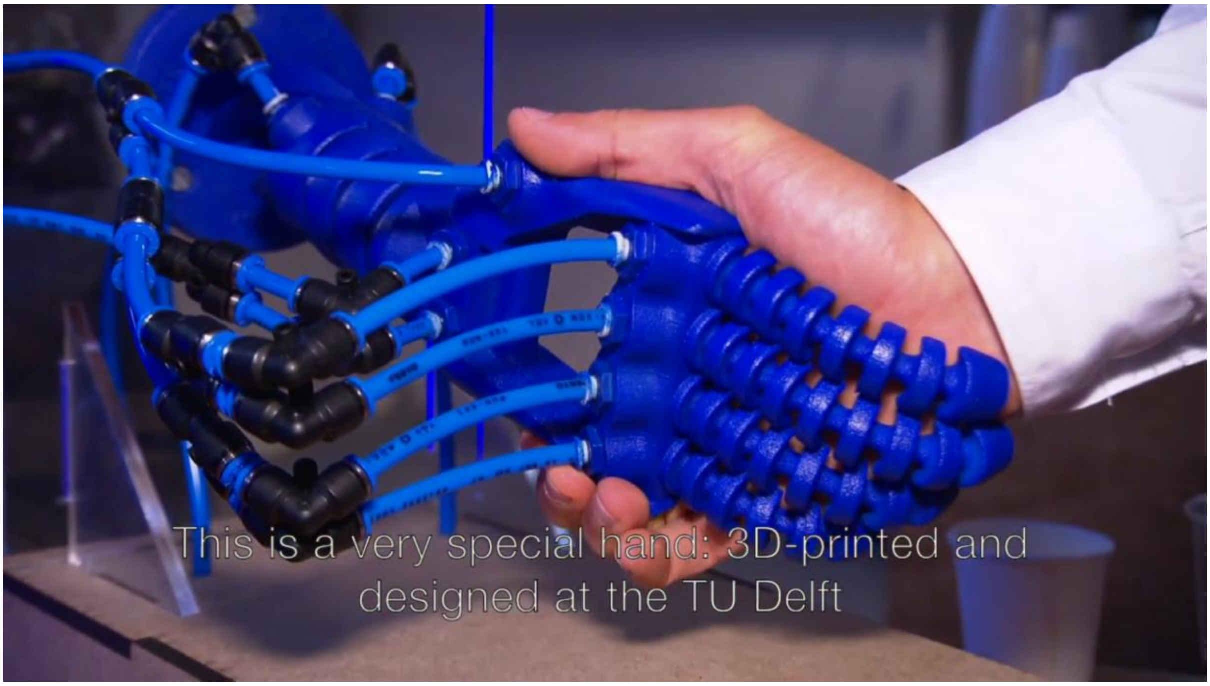


Figure 2-1 (3D printed Soft Robotic Hand, 2016), developed by Rob Scharff, Delft University of Technology

Hydraulic actuation – like the pneumatic design, hydraulic builds on the same principle apart from using a fluid instead of a gas.

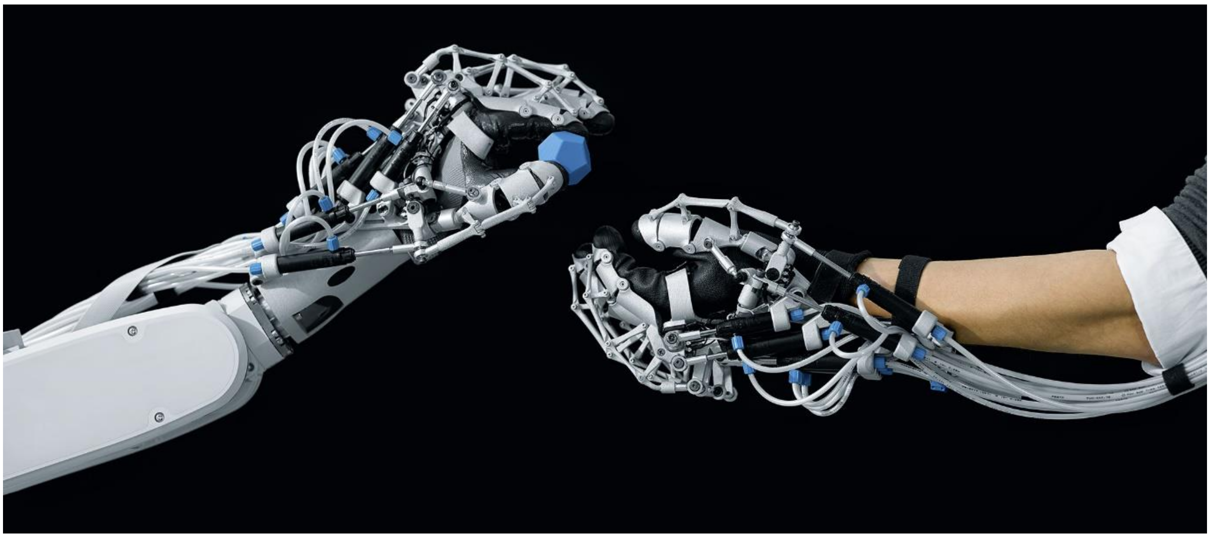


Figure 2-2 (hydraulic ExoHand, 2017), developed by Festo

Electrical actuation – works using motors to transfer electrical energy from a power source to mechanical work, pulling on cables that replicate muscle tendons to open and close each finger. The most common and favoured method of actuation – the hand can be powered multiple ways depending on design and purpose. As only 1 motor is required for one distribution of freedom, the most basic design (opening and closing the entire hand) needs only 1 DC motor: the fingers contract as the motor pulls the cable, and retract when the direction is changed. And, building on that principle, each distribution of freedom requires 1 motor; for example, 1 for each finger movement and 2 for the thumb would require 6 motors. This makes electrical actuation unique to the other types, as with multiple sources of power we can conduct multiple finger and hand movements with greater ease.

Figure 2-3 (2016), by Zhe Xu and Emanuel Todorove, University of Washington

2.4.2. Key Differences

Despite all 3 designs achieving the same result, there are some fundamental differences in their operation and the benefits that each type provides. Whilst pneumatic and hydraulic operate faster than electric – in addition to saving energy in the process – they are prone to leaks and require frequent maintenance: compressors require changing, resulting in a less cost-effective product. Furthermore, as the electric model provides the most aesthetically pleasing design (all components can be concealed within the casing) many recipients prefer it; opposed to pneumatic and hydraulic, in which all pressurised cables protrude the appendage. On the other hand, hydraulic can operate at greater pressures than the other models, although the delivered forces are superfluous to the requirements of the prosthesis. Hydraulic also weighs the most, which makes it an undesirable option to children or amputees that do not possess the necessary strength to use it.

2.5. Rationale on Chosen Design

It was vital to decide as a team which method of actuation was suitable for the product; achieved using a design matrix. The chosen design was based on a group analysis of the most important factors that must be considered for each type:

Safety (10) – a crucial aspect of the product, it is important to put the recipient's safety as our top priority.

Cost (9) – the second most important factor; the budget is non-negotiable and is one of the few limits placed upon the project. It is essential to lower the costs of the appendage as much as possible as to make the finished product available to a great volume of recipients.

Energy efficiency (8) – as most current designs are not particularly energy efficient, the team thought it was imperative to improve upon this factor in the new design as to offer something better than what is widely available.

Manufacturing capability (8) – it is necessary to first be able base the design around what it physically possible to construct; taking our tools and technical experience into consideration.

Durability (8) – the appendage must be made to last for the benefit of the customer and the design team, as the brand must come with a degree of reputation to ensure the recipients know the quality of our product.

Lifespan (8) – it is essential that the product is made to last, however the expectation of a plastic device used throughout a person's daily life is that eventually it will fail due to fatigue. Material choice will compensate this issue, although some designs tend to have greater lifespans than others.

Maintenance (8) – throughout the products lifespan there will be necessary maintenance checks and improvements, however the extent to this process in terms of time and resources is independent to the method of actuation.

Aesthetics (7) – the least important factor in the process yet still an extremely relevant one, aesthetics is a factor that has a large impact on sales and whether the recipient wishes to wear the device.

2.5.1. Design Matrix

The factors were placed into a design matrix, where they were multiplied by the rating agreed upon by the group. For example, safety was given a factor rating of 10 and pneumatic was given a 4 for safety on a scale of 1 to 10 (1 being the worst, 10 the best); the total rating is then 40. Each design was rated on each factor and the sum of each was compared – the higher the number the better the overall design in relation to our objective.

Factor	Importance	Pneumatic	Hydraulic	Electrical
Safety	10	4	3	9
Cost	9	6	6	5
Electrical efficiency	8	7	7	5
Manufacturing capability	8	7	7	9
Durability	8	5	4	8
Lifespan	8	7	6	9
Maintenance	8	4	4	8
Aesthetics	7	5	5	9
Total	-	**369**	**343**	**510**

Table 2-3

2.5.2. Matrix Evaluation

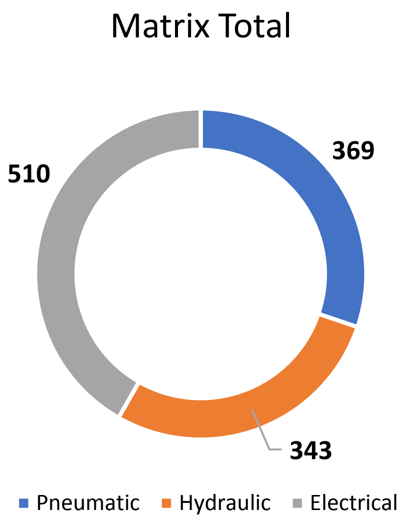


Figure 2-4, 2017

Ranking 2nd on the matrix, pneumatic received high scores in electrical efficiency, manufacturing capability and product lifespan. In terms of electrical efficiency, the only use for electrical energy is the small motor which powers the compressor and the control system (if incorporated into the design); in comparison to electrical actuation, which requires more energy as it contains more electrical components. In relation to manufacturing capability, the team is more than capable of dealing with the pneumatic technology – as 2 members have experience in this line of work. And, for lifespan, the pressurised substance (air) does not operate at high enough pressures to be considered corrosive to the inner tubes and chambers of the prosthesis, giving it a higher rating than hydraulic; which does contain a pressurised corrosive substance. The pneumatic design failed to score high on factors such as safety, durability and maintenance – due to the protruding pressurised tubes and their prone to leakage.

Last on the scale was the hydraulic design, which failed to score high in areas such as safety, durability and maintenance for the same reason as pneumatic. The design is less safe than pneumatic as unlike air, the level of pressurised water necessary to grip objects with the hand could damage the recipient if they were to fail. And, like pneumatic, the hydraulic design is as efficient – its most desirable factor – as electrical energy is only needed for few components.

The type of actuation that scored the highest on the matrix was the electrical, which can be seen on figure 2-4 as holding a greater share awarded points. This is due to its high scores in safety, manufacturing capability, lifespan and aesthetics. The design scored high in safety due to its lack of hazardous components, unlike the other 2 which are prone to leaks and failure which can cause damage. All electrical components are safely placed into the wrist or the palm of the design, secure from contact with the recipient; in case of failure, the product would simply stop working. In relation to manufacturing capability, all team members have access to all the necessary equipment and are experienced in working with electronics, 2 have further studied the use of control systems that is essential in its operation. And, as all components can be stored within the prosthetic, the aesthetics of the product is limited only by the designer's imagination – scoring it the highest of the 3. However, the method of actuation failed to score as high as the others in the cost and electrical efficiency factors. This is due to the initial high price in outsourcing electrical components, and the need to power them to activate movement within the appendage.

2.5.3. Design Justification

Based on the results of the design matrix and the in-depth analysis conducted by the research team, the chosen method of actuation was electrical. As previously stated, electrical holds more benefits than the other choices – which is why its universally the most favoured design for prosthetics. It has negatives such as efficiency and initial cost, however that is an aspect that can be improved upon by the team: a more efficient design and saving costs by 3D printing most of the components.

2.6. Market Research

Prior to any decisions by the group on which direction to take the product, research was conducted into the prosthetic hand market to discover what exact qualities the recipients were looking for in an appendage.

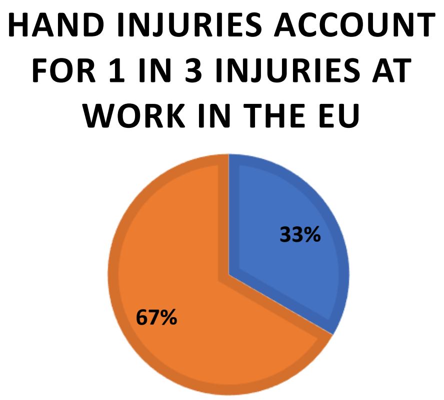


Figure 2-5, 2017

The human hand is an important tool in everyday life and its loss can cause severe psychotic problems for those so unfortunate, as amputees lose the ability to use body language gestures and their will to physically express instinctive emotions. In the US, there are 61,100 people with this issue, making it the most common amputation. Moreover, in the EU, 57% of all upper body amputations are transradial. For the most part, the cause of the amputation is due to ill health: infection, tumours, and cardiovascular problems. Although, a minute portion are attributed to traumatic accidents – less than 0.1% in the EU occur in the workplace, however 1 in 3 are hand related.

The prevalent issue with the prosthetic hand is that large portion of amputees choose not to use their appendage, due to its poor cosmetic appearance and low functionality – a recent study found that somewhere between 30% and 50% of recipients refuse to use their prosthesis based on these issues.

2.6.1. Past Designs

To better accustom the team with what else was available on the market, we took inspiration from the following designs, shown in figure 2-6. All the designs were open source, however none of the CAD files were used in the team's new design.

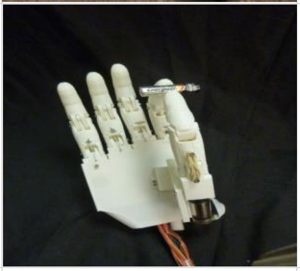
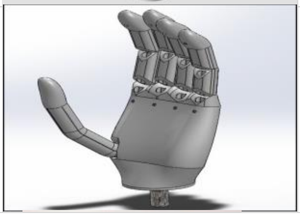
Name	Pictures	Types of Files	Potential Actuation	Finger Movement	Comments	DoF
Inmoov		Stl, STEP	Servos(5)	Cables, independent movement for each finger	Servos out of the hand (in the arm), mechanics parts, slow movement	1 each finger and 2 thumb
Hookhand		Stl	5 servos with rolled cables.	Cables and servos for actuating, memory shape plastic for returing to original shape.	Good way to join the parts of the finger using memory shape plastic instead of elastic cables.	1 for each finger
FlexyHand		STP, STEP	1 motor required to close all fingers	Fingers open automatically, no return tendons or springs needed	Frictionless articulation and adaptive grip on irregular objects	1 for each finger
Raptor		Stl	No actuator, cables, wrist movement closes fingers	Grasping motion	Wires are uncovered over the palm, no need actuators	1 for each finger
Tact		no files	5 scap 16 Coreless DC Gear motor with rolled metal cables.	 Interesting mechanism, that needs little movement to actuate every finger.	All the motors inside the palm.	1 for each finger and 2 for the thumb
Prosthetic hand		STEP	Cables	Fingers are moved by shoulder abduction, no actuators	Operated manually	1 for each finger,
Mechanic hand		STEP	Cables	Cables to actuate by shoulder harness worn by the amputee	Good finger movement	1 for each finger

Table 2-4, 2017, comparison chart

Favoured most by the team in terms of aesthetics was the first design by InMoov. It is also the most professional looking and thorough tested design on the list, the mechanics are what is needed in the future of bionics due to its variability in human action. On simplicity of automation and functionality, the team showed interest in design 3 by FlexyHand. Although it only has a single degree of freedom for its thumb, in contrast to InMoov's two, it offers a good base point for further development.

It is also important to mention the interested shown for the Tact design, as its ingenious method of mechanical function made the use of cabled obsolete, however we were unable to source the specialised screw motor to actuate the fingers.

Design 6 and 7, Prosthetic hand and Mechanic hand, were studied on their appearance and functionality as opposed to their methods of actuation. Particularly the fingers, as their frictionless closure helps to restrict the effects of fatigue on the joints.

Lastly, Raptor helped to solve an easy solution to the snap pins to hold the joints, and HookHand to shape the palm. The inspiration of these designs can be easily recognised later in the design.

2.6.2. Quality/Success Criteria

Criteria	Description of conditions for failure or success
Functional	Given the expectations and performances by other prosthetic hands on the market, the new design must remain fully functional, more efficient and save the recipient on cost in the process. Moreover, it is important that the product can function for a reasonable amount of time with low-to-no maintenance, as to maximise customer satisfaction of the device and to maintain comfort in its everyday use. Failure to do so will result in failure of the research team's objectives.
Maintainable	The product is designed in a manner which makes it simple to maintain and replace broken printable components. The palm is a single piece which can be cheaply and easily replaced when damaged, along with the fingers which can be detached and reattached in minutes if the spares are available. Likewise, the wrist can be opened to expose any faulty electrical components, a process that is simple and takes no expertise. Components under the most stress, cables and snap pins, must be supplied in spares as they are the most likely to fail under fatigue. The success of the appendage depends on the simplicity of maintaining the device, as anything too complicated is likely to fail.
Favourable	To appeal to the target market, the device must achieve and retain a favourable opinion by all recipients. To ensure this, the product must offer something new and/or improve on the downsides of current options. Failure to do so, meaning failure to offer something different, would hinder the chances of meeting the research team's objectives.
Co-operation	Co-operation is imperative for the success of the product as its essential to discover the needs of the individual and meet the general needs of recipients. It would be logical to partner with other engineers and medical professionals (including research and technology sharing) in the future when taking the prosthetic to the next design stage. To achieve our objectives in the long-term, this process will need to be revaluated along each step of co-operation.

Table 2-5

2.6.3. Considerations for New Design

In relation to the results gathered by the design matrix and the market research, the team proposed a list of potential design improvements to incorporate into the new prosthesis:

- Lightweight and visually appealing
- Easy to maintain
- Remain cost effective (advanced bionics range from €30,000 – €100,000, cheapest €2000)
- Efficient material selection (best suited for purpose)
- Innovative sequence of electric components to cut back on energy demands

2.7. Anthropometrics

Anthropometric data is the study into the measurement and proportional averages of the human body. This data proved useful for the prototype in establishing a basis for component sizes and how to attach the corresponding actuating parts in a common manner to the product. After the common sizes are modelled, it is simpler to adapt that model to the individual later.

The following table represents a study by the DTI, 2002, conducted into the hand anthropometry of men and women:

–	Gender	5th percentile (mm)	50th percentile (mm)	95th percentile (mm)
Hand length	Male	173 – 175	178 – 189	205 – 209
	Female	159 – 160	167 – 174	189 – 191
Palm length	Male	98	107	116
	Female	89	97	105
Thumb length	Male	44	51	58
	Female	40	47	53
Thumb breadth	Male	11 – 12	23	26 – 27
	Female	10 – 14	20 – 21	24
Index finger length	Male	64	72	79
	Female	60	67	74
Hand breadth	Male	78	87	95
	Female	69	76	83 – 85

Table 2-6

The data presented above helped to create the measurements for our prosthesis in accordance with the printer's specification. For example, the 50th percentile of the male hand stands at 107mm, whereas the printer's cubic area of operation was 112.7mm; 110mm being the approximated midpoint. The excess also allowed room for post process reduction, which has the potential to remove 1mm to 2mm of material whilst remaining within the anthropometric range of measurements. Figure 5 below allows the reader to better understand the details of each set of dimensions:

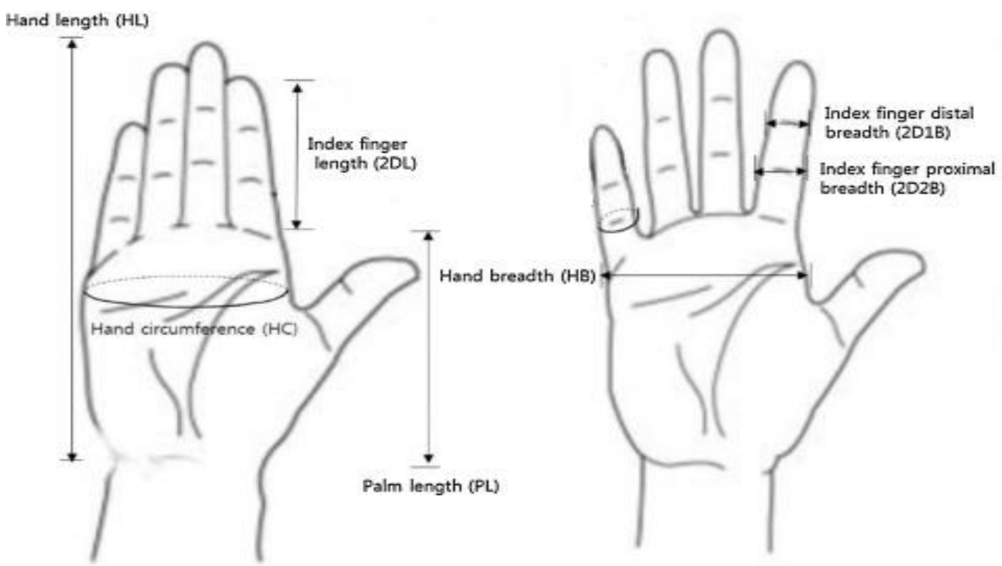


Figure 2-6, 2015, by Forensic Science International Journal

2.8. Materials

Prior to the selection of the printing filament, sufficient research was conducted to find the best solution for the requirements; taking into consideration the budget and resource availability. The following materials were investigated:

Plastic filament	Properties	Strength	Durability	Printing temp ℃	Heated bed temp ℃
Acrylonitrile Butadiene Styrene (ABS)	Durable, slightly flexible, easily extruded and lightweight.	★★	★★	210 – 250	50 – 100
Polylactic Acid (PLA)	Biodegradable, moderate strength and durability.	★★	★★	180 – 230	N/A
Polyamide (Nylon)	High strength and flexibility, lightweight, wear resistant and non-soluble.	★★★	★★★	220 – 260	50 – 100
Polyethylene Trimethylene Terephthalate (PETT)	Transparent, high strength, biocompatible, lightweight, impact resistant and flexible.	★★★	★★★	235 – 240	N/A
Polyethylene Terepthalate Glycol (PETG)	Biocompatible, lightweight, high impact resistance and extremely durable.	★★	★★★	220 – 235	N/A
Polycarbonate (PC)	Great strength and impact resistance, tough, can withstand high temperatures and tough.	★★★	★★★	270 – 310	90 – 105

Table 2-6

ABS – a cheap impact resistant thermoplastic, the filament offers the quality standard required in the design. However, ABS can produce intense and damaging fumes during the printing process and must be compensated for with the necessary ventilation equipment.

PLA – the most favoured filament for unexperienced manufacturers, and common for food storage since its derived from natural materials like corn starch and sugar cane, PLA contains moderate durability and strength properties. However, the material possesses a high surface hardness and is prone to snapping at yielding stress due it its high level of brittleness.

Nylon – very cost effective, the material contains high strength and durability properties (less brittle than ABS). However, the filament quickly absorbs humidity from the environment and should be protected from such an occurrence. Furthermore, some shrinkage is to be expected upon setting and must be compensated for in the design.

PETT – as the material is transparent, the design possibilities are heightened; or consequently, could alienate potential customers as they might not want a robotic looking appendage. However, as the material is biocompatible, it makes for a good prosthetic filament. Also, like nylon, shrinkage is to be expected upon setting.

PETG – with greater flexibility and durability than ABS, PETG seems a more favourable option. However, it is considerably more expensive and requires greater time and skill to print. The filament is also prone to deformation if exposed to humid environments, in addition to weakening when exposed to long periods of UV light.

PC – offers the greatest strength and impact resistance properties out of the other filaments, PC can also withstand ambient temperatures of up to 100℃. However, the finished product shrinks when cooled, and requires an enclosed chamber for slow cooling – preventing warping and deformation.

In addition to the above materials, the research team also considered the use of **Shape Memory Polymers (SMPs)**. SMPs can change shape under the influence of an external stimuli: temperature, light, electricity, and magnetic fields. To achieve shape memory effects (SMEs), the polymer should have one transition point, such as glass transition temperature, crystal-melt transition, etc. To achieve triple or multi-shape changes in SMPs, two or more reversible transition points are needed, triple-shape memory structures can be achieved by fabricating the composites materials which have well-separated glass transitions points.

2.8.1. Rationale

Based on the two project limitations – cost and time – it was not possible to use shape memory polymers, polycarbonate or PETG. SMPs require a large amount of time and resources to find the correct solution, which unfortunately the team did not possess; PC and PETG were out of budget. Moreover, PETT and nylon are particularly difficult to print and require extensive design tweaks and testing – taking up too much of the projects time scale. Nylon remains a reliable and cost-effective material which could be used in future designs depending on time restrictions. Leaving only ABS and PLA: the materials are the cheapest and the most available printing filaments on the list. However, as PLA is too brittle to maintain the stresses acting on the product, it could not be considered in the design. Ultimately, it was ABS that satisfied all the necessary design characteristics with its properties.

Chapter 3 – Design Stage

3.1. Concept Sketches

An integral part in every design process, concepts were used prior to the initial design and throughout the course of the project when tweaks were made to enhance performance. Concepts help the designer visualise an end product, eliminate waste and achieve the most realistic model to fit the design criteria.

Figure 3-1 below best illustrates this issue. The component shown is one designed to improve the aesthetic look and functionality of the thumb as it is connected to the palm.

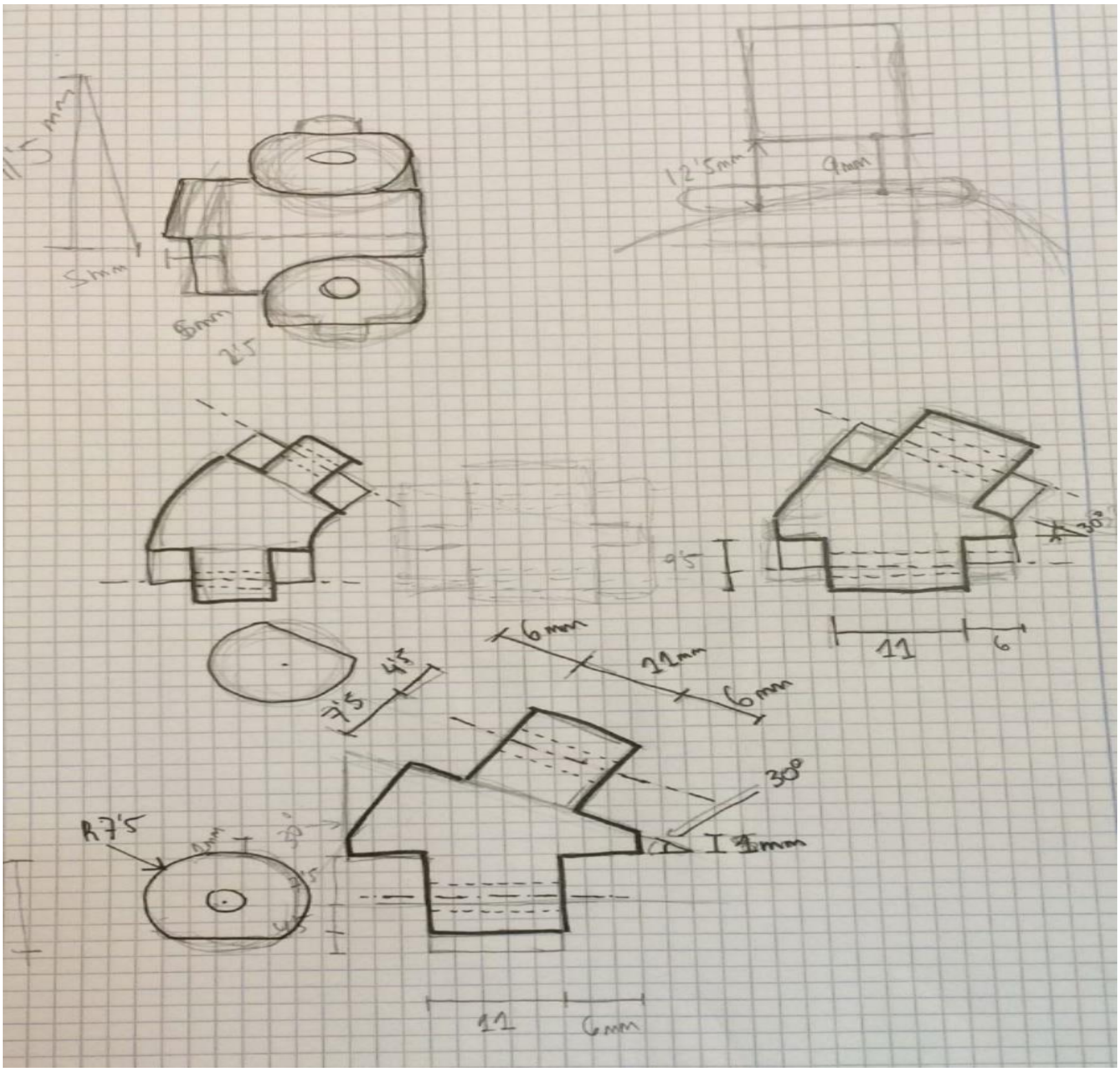


Figure 3-1

Sketches like those shown in figure 3-1 were created for all functioning parts, in addition to the electrical components.

3.2. CAD Design

3.2.1. The Palm

To secure the most accurate design for the palm, in accordance with the anthropometric data, the component was created using the plane-by-plane technique; building from the bottom to the top with a change in dimensions every 10mm. At this stage, the palm was modelled on SolidEdge, and, with the addition of the created layer, the software could connect both to produce a solid shape within the given 4 guidelines. An example of which can be seen below:

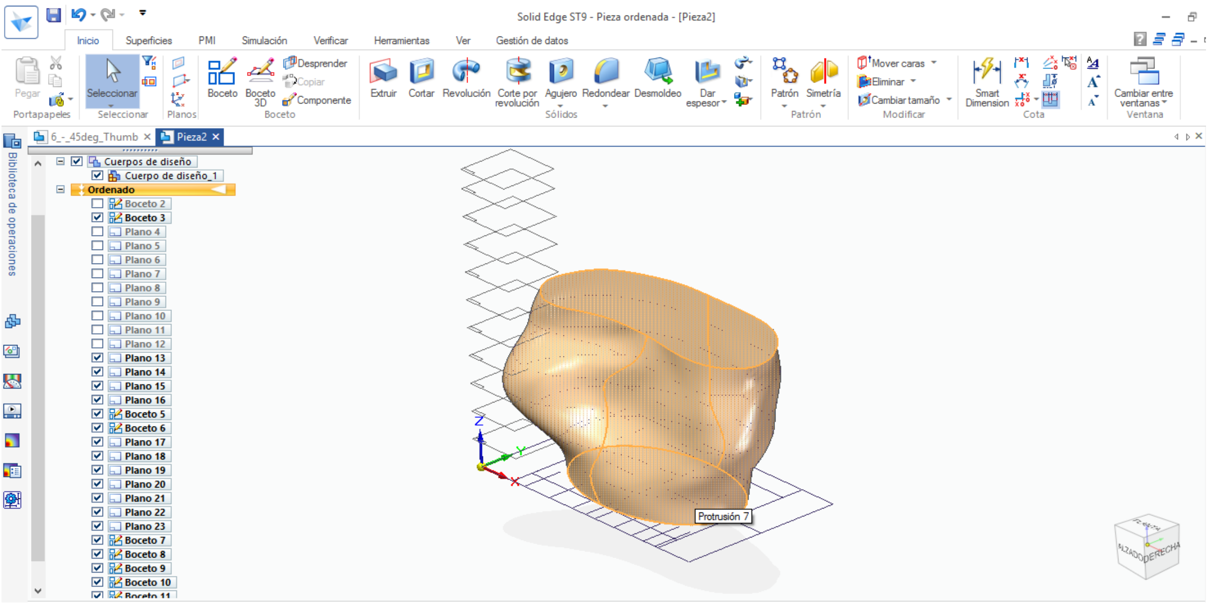


Figure 3-2, 2017

The design was created using the previous anthropometric data and the following mean sizes of an adult male, shown below:

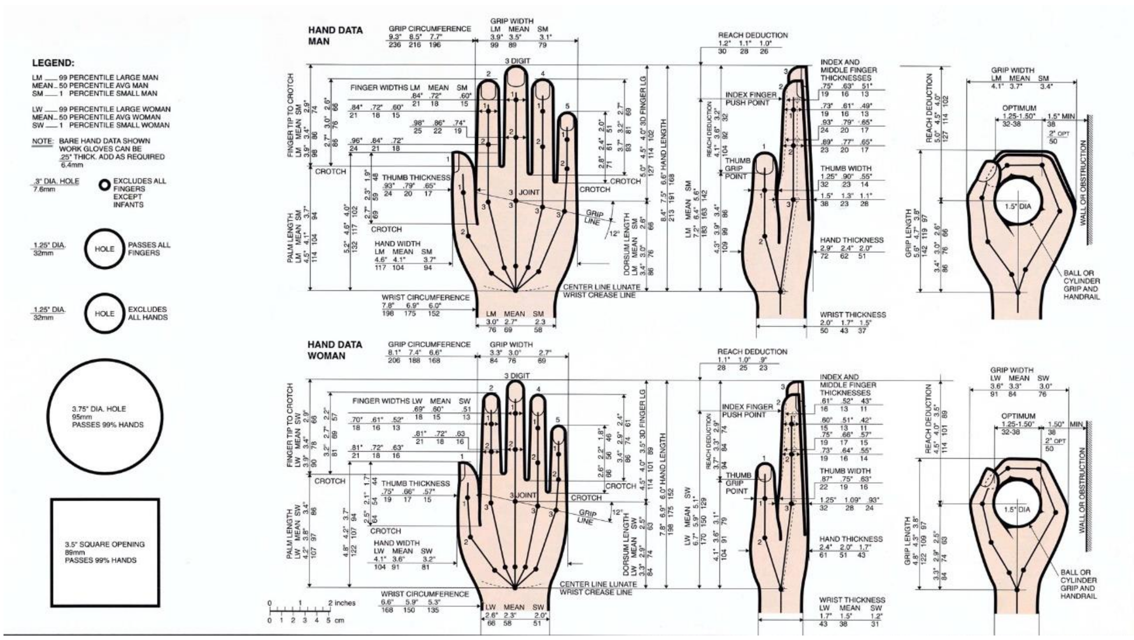


Figure 3-3, 2017

The design of the palm was then transferred to the SolidWorks CAD software to allow editing by the other members of the design team, and to build upon the structure further.

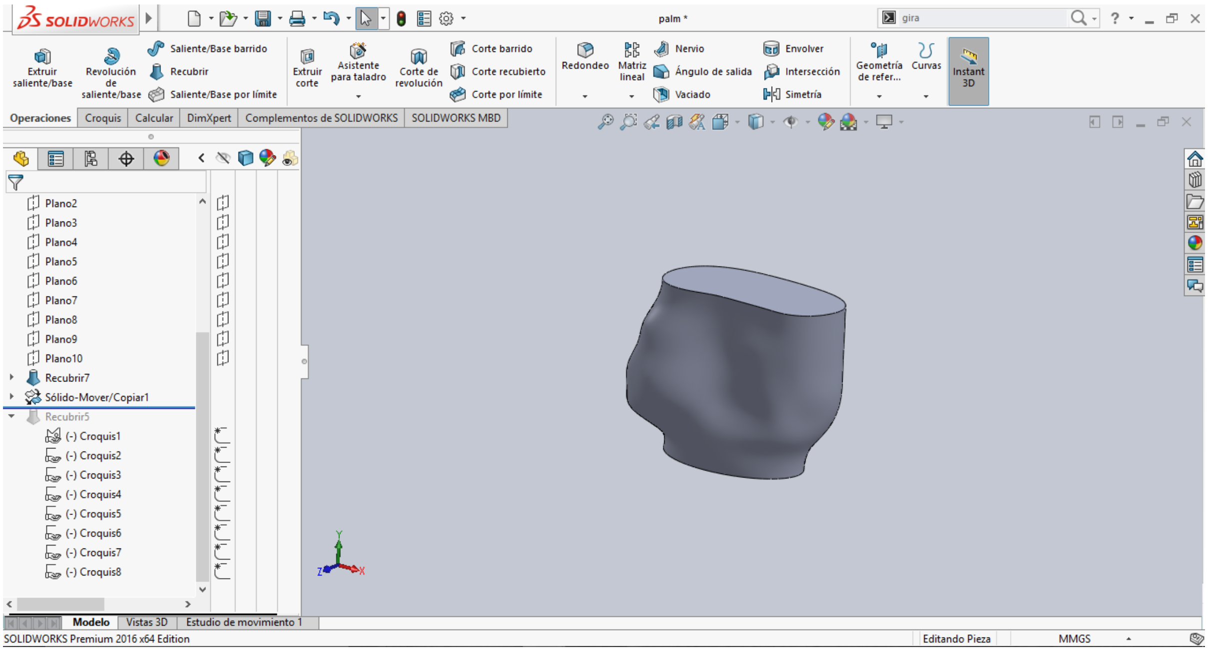


Figure 3-4, 2017

Shown adjacent is the attachment of the 'knuckles' which would connect the fingers to the palm. And, as you can see, the initial dimensions of the palm did not meet with the width of the fingers as the design failed to taper towards the top.

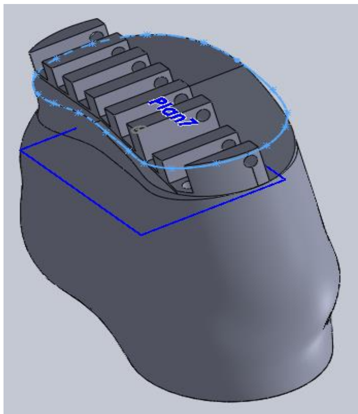


Figure 3-5, 2017

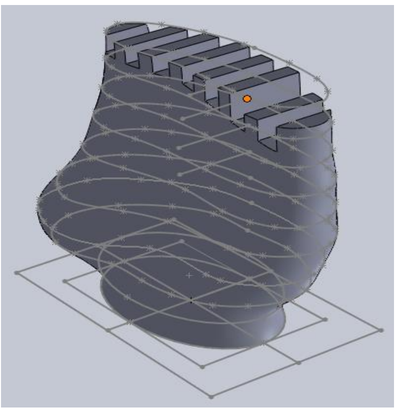


Figure 3-6, 2017

To compensate for this issue, a redesign was created to accommodate the connection of the fingers through the 'knuckles'. The tapered design incorporates a more fluid shape, still in line with the anthropometric data, with additional ergonomic and aesthetic considerations.

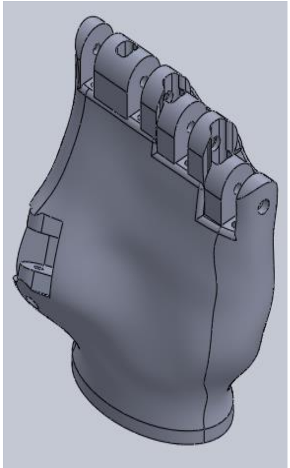


Figure 3-7, 2017

Within that redesign, the team could add the port for the connection of the thumb. Furthermore, shown in figure 3-7 is the new design for the connection for the fingers at the 'knuckles'. The connections allow for the fingers to be slotted into the palm and locked into place using snap pins. And, Finally, the last step was to create the space inside the palm to accommodate the cables, shown as the void in figure 3-8.

All engineering drawings for this component can be found in the **appendix** section.

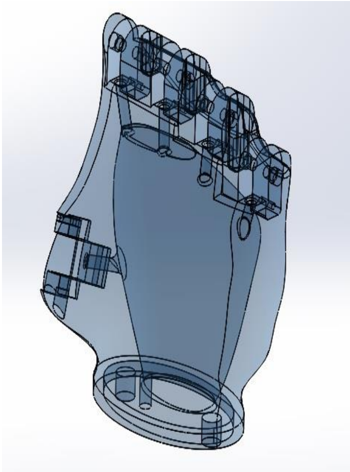


Figure 3-8, 2017

3.2.2. The Fingers

Firstly, to create the design of each finger, the same anthropometric data was used that formed the palm – securing an accurate mean size of the adult male. As can be seen below, the fingers possess three phalanxes: lower, middle and top; all equal in size. This is the same for each finger, which range in size from 90mm, 110mm, 100mm and 75mm respectively from the index to the little finger. Shown below, all examples used are of the index finger, as the same principle of the design is the same for each.

For each finger, there were two versions:

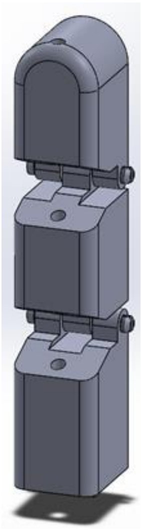


Figure 3-9, first version

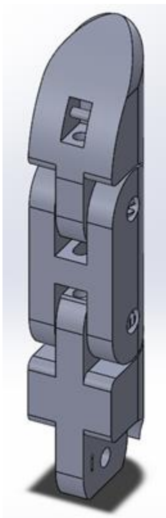


Figure 3-10, second version

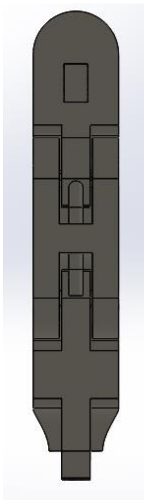
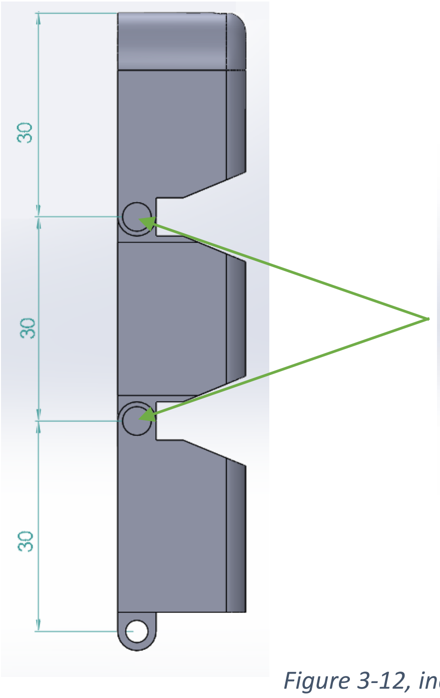


Figure 3-11, final version

Originally, the dimensions of the finger were the 90mm length divided into 3 equal sections; one phalanx equalling 30mm. Then, snap pins were put in place to adjoin the sections and to allow the finger to retract and contract.



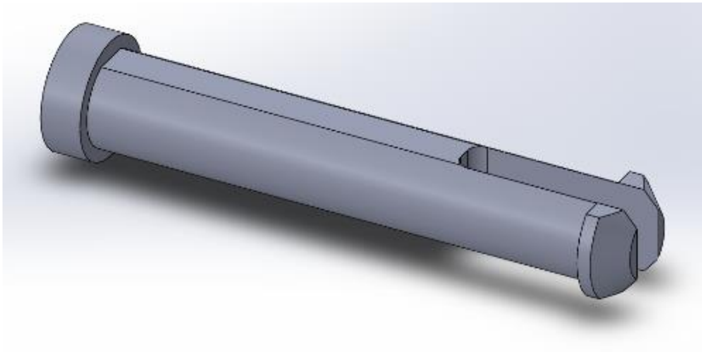


Figure 3-13, snap pin

Figure 3-12, index finger first version

Later, in the second design, a new shape was incorporated to resemble a more realistic finger; an aesthetic requirement necessary, discovered from the market research. And, to allow the finger to contract and retract back to its original position, 2 parallel holes were created inside the component. One cable for the contraction, and another for the retraction. Both cables in this case are concealed, again, allowing the recipient to feel at ease with a realistic looking appendage; as opposed to one looking robotic. The contracting cable is connected via the motor, and the cable for retraction at the knuckle of the palm: when the motor releases the pulling force, the tension in the retracting cable pulls the finger back to its original position.

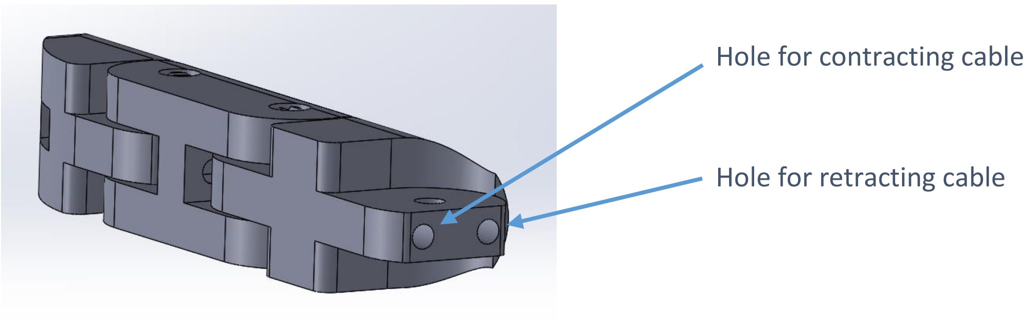


Figure 3-14, holes for each cable

The final version, which can be seen in figure 3-11, shows 2 small alterations on the rear of the finger – 2 sections of material removed to reduce friction from the cables during contraction.

To secure the cables at the top of each finger, two holes were created inside the tip of the finger, shown below:

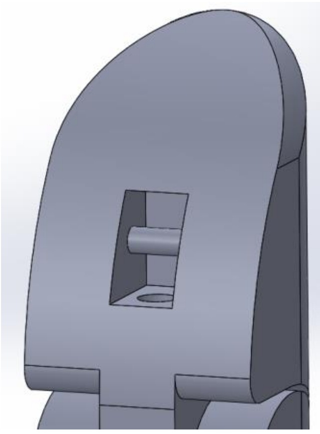


Figure 3-15

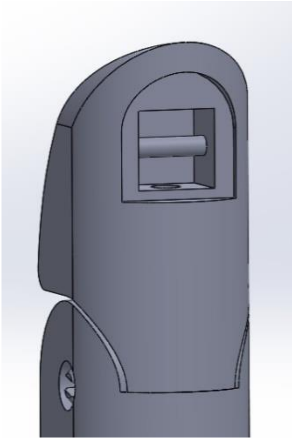


Figure 3-16

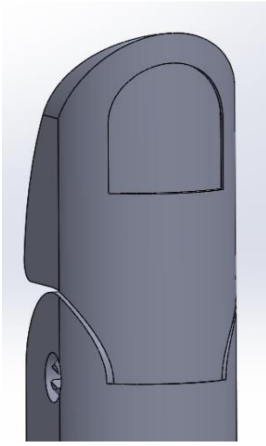


Figure 3-17

Again, adhering to the aesthetic requirements, the design must conceal these sections of the finger as to retain its realistic appeal. To solve this, a finger nail section was created that would clip into the finger after the cables were attached, shown in figure 3-16.

All engineering drawings for this component can be found in the **appendix** section.

3.2.3. The Thumb

Similar to the finger design explained previously, the thumb was created using the same technique of taking the male adult mean sizes from the anthropometric research in unison with figure 3-3 and splitting it into 3 equal sections. The initial design can be seen below as figure 3-18:

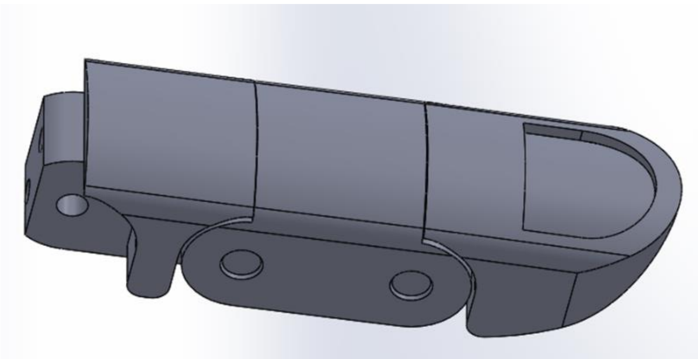


Figure 3-18

Later, after the prototype was printed and evaluated for mistakes and improvements, the thumb was subject to 2 improvements which would give it a more realistic and human-like appeal. The first alteration was a change in the angle in which the thumb protruded the palm – rotating the component 30 degrees; the aesthetic and ergonomic benefits are recogised in the following comparison:

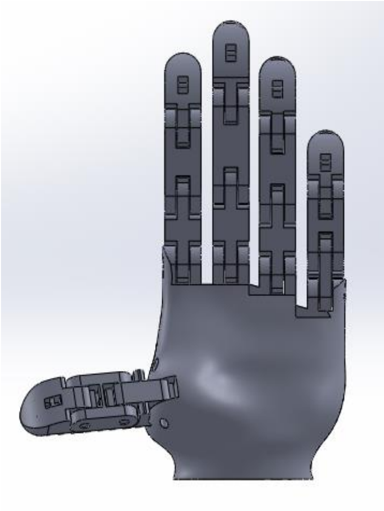


Figure 3-19

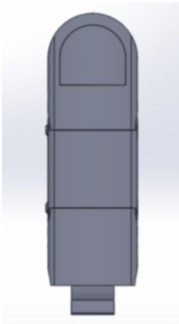


Figure 3-20

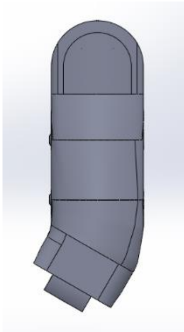


Figure 3-21

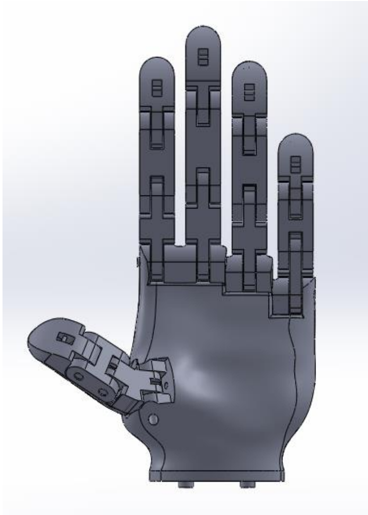


Figure 3-22

Figure 3-21 represents the new design, which when connected to the plam (figure 3-22) allows the hand to achieve a more accurate grip on objects whilst improving the overall look. The second alteration was the shape of the thumb, which is easily noticable in the comparison between figure 3-23 and 3-24. Again, the change allowed the design to take on a more appealing look by avoiding right angles; one of the design considerations taken on by the team after the market research was conducted.

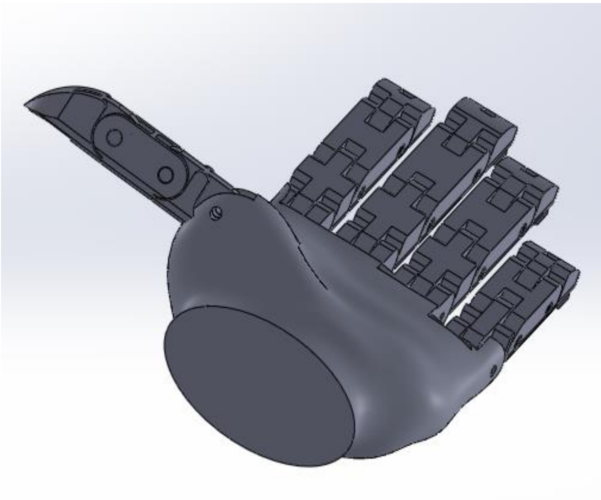


Figure 3-23

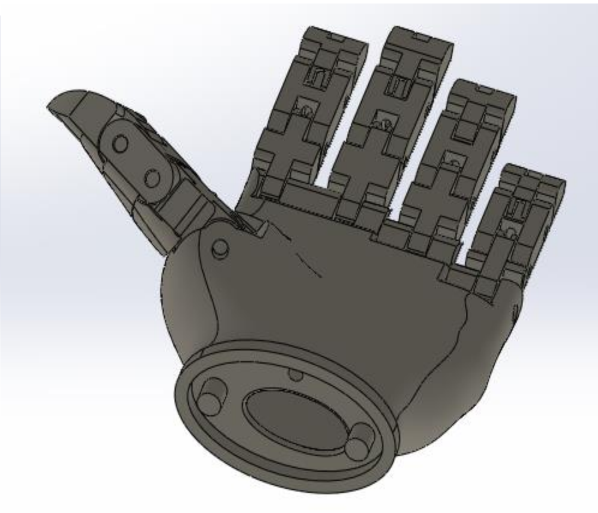


Figure 3-24

All engineering drawings for this component can be found in the **appendix** section.

3.2.4. The Wrist

To accompany the hand, a 'wrist' was designed to house the electrical components. The wrist, which would also help the hand remain stable in an upright position, plays an important role in concealing such components as the motor and controller – reducing the robotic look. The design, however, was a practical choice in this early development stage; whereas in the future if the recipient was to receive the product, the components would be redesigned to suit their needs individually.

When designing the wrist, the team was limited in resources and as a result had to recycle materials previously used in an old printer. Those materials were:

- Steel bar: ø6mm with 400mm length
- Step motor: 12V at 1.1A
- Gear: ø25mm
- Belt

Firstly, 5 holes of ø1mm were drilled into the steel using a pillar drill which would connect the cables from the fingers to the bar. The bar was then connected to the gear where it would later be attached to the motor via the belt. However, it was realised that as the steel bar rotated it would slowly erode the plastic within the wrist and that bearings were needed – which we did not possess. To counter this issue, a new printable component was designed that would exchange the frictional wear away from the wrist and onto itself, and as the component is ABS it could be easily reprinted. This is only a short-term solution. Shown below in figure 3-25 and 3-26 is the steel bar, gear and friction reduction casing:

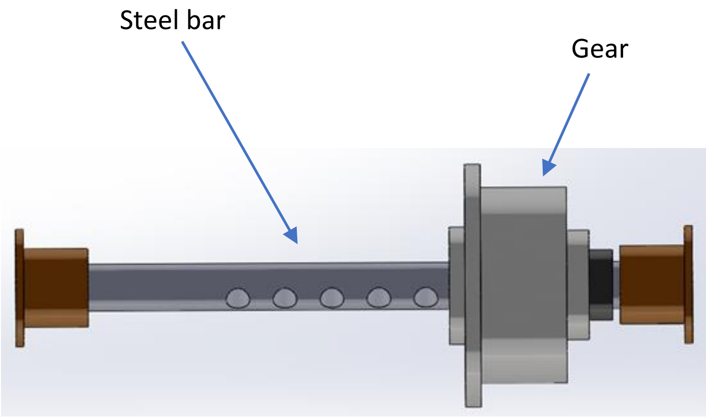


Figure 3-25, 2017

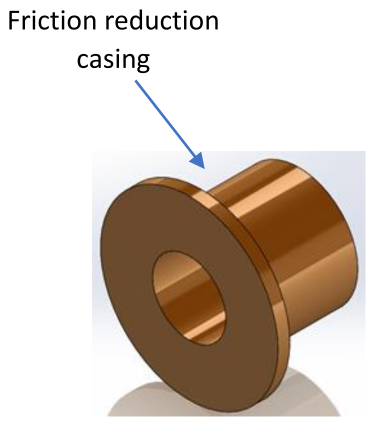


Figure 3-26, 2017

After these issues were solved, the wrist had to fit both the component pictured above and the motor in the same design, whilst minimising space and material. To achieve this, the motor would be situated 28mm away from the gear, which was the working length of the belt, and fixed to the wrist by 4 screws. The complexity of the design held the motor in a fixed position, allowing the hand to rotate in any direction and still operate under ordinary conditions. Shown as figure 3-27 and 3-28:

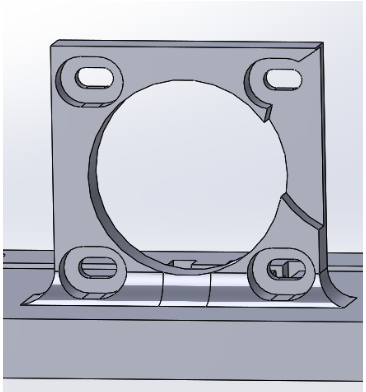


Figure 3-27,2017

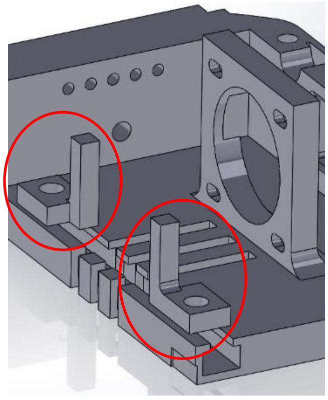


Figure 3-28, 2017

In figure 3-29 and 3-30 below, the design of the motor and connecting components is shown as a section view from above and from the left side:

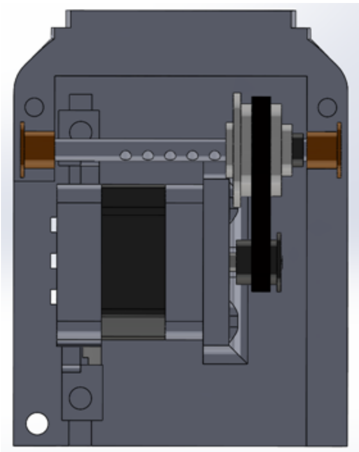


Figure 3-29, 2017

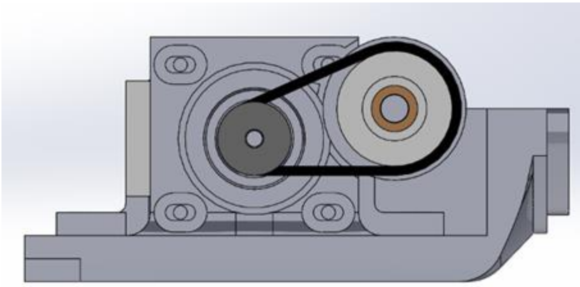


Figure 3-30, 2017

Next, due to the heat produced over long exposure by the motor, the design had to incorporate a cooling method to prevent overheating. To achieve this, a fan was installed on the roof above the motor, and cooling vents by the side of the motor, shown as figures 3-31 and 3-32.

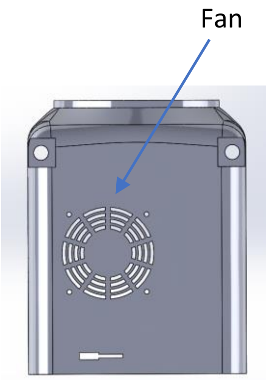


Figure 3-31, 2017

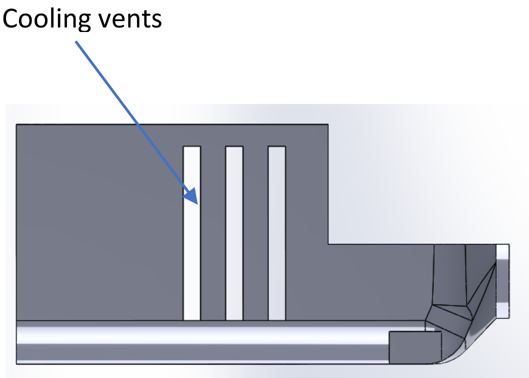


Figure 3-32, 2017

After the issues with cooling were corrected, the next problem was how to control the actuating parts from the controller inside the wrist. The solution to this was to design slots for 3 buttons and 1 switch:

- Green button: contract fingers (movement stops when button is released)
- Yellow button: retract fingers (movement stops when button is released)
- Red button: reset program, returning the hand to its original position
- Switch: power supply, ON and OFF

An example of which can be seen below in figures 3-33 and 3-34:

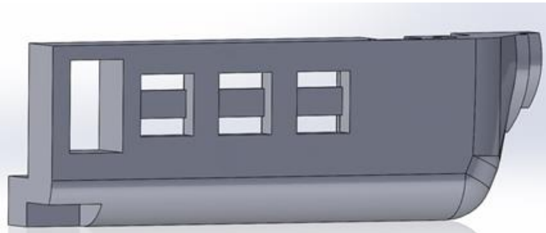


Figure 3-33, 2017

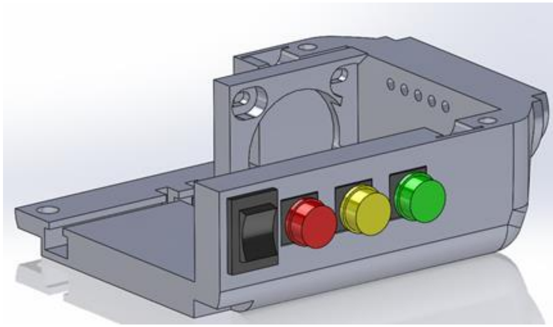


Figure 3-34, 2017

Lastly, and now that all components were in place and the design was complete, a final adaptation was made to split the shell of the component into 2 shapes for ease of assembly. To assemble the part, all the electrical components would be placed in the lower half, seen in figure 3-36, before screwing the top piece into place with 4 M6 screws, shown in figure 3-35.

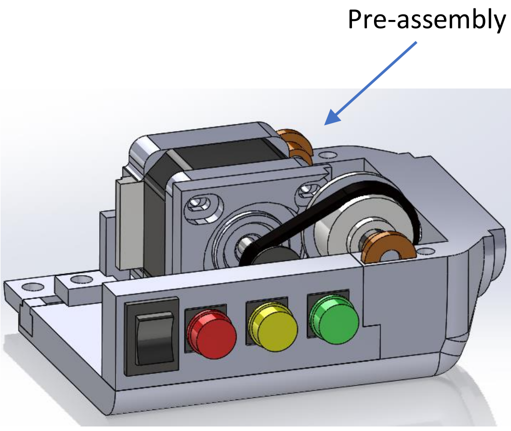


Figure 3-35, 2017

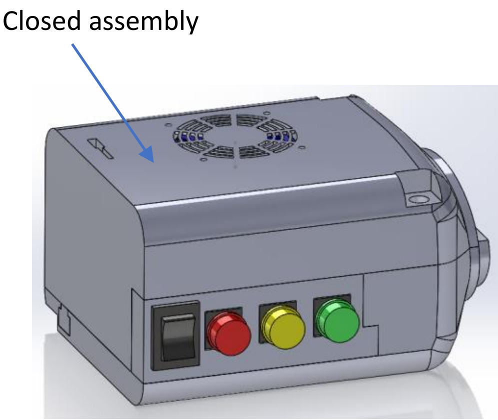


Figure 3-36, 2017

All engineering drawings for this component can be found in the **appendix** section.

3.2.5. 3D Assembly

Presented below is the final assembly if the prosthetic, piecing together the designs from each member and incorporating the 4 main aspects of the device: fingers, thumb, palm and wrist.

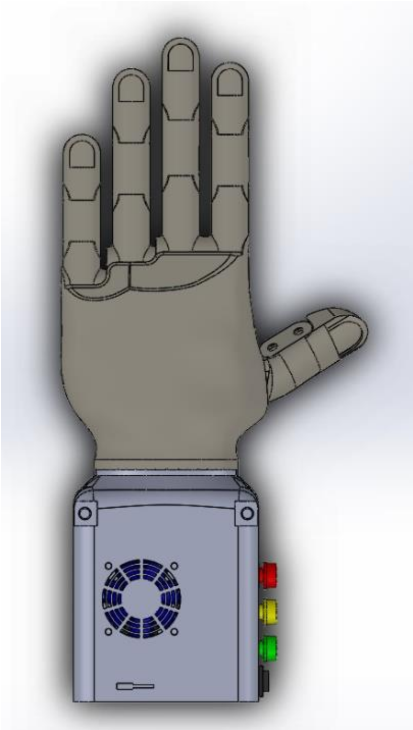


Figure 3-37, 2017

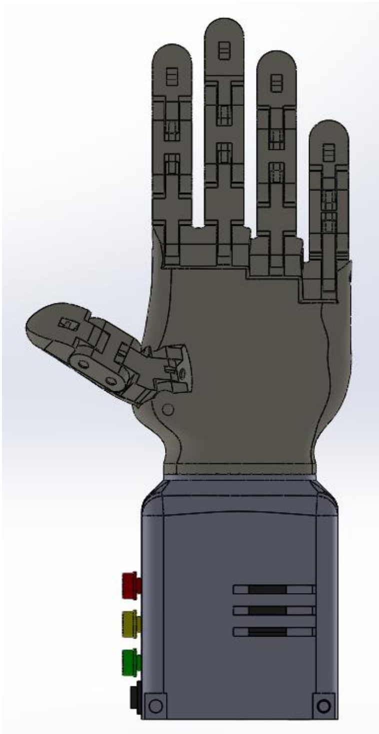


Figure 3-38, 2017

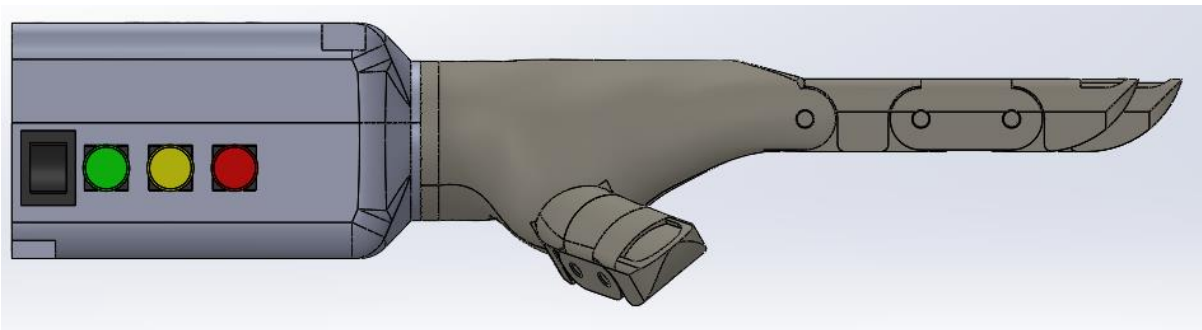


Figure 3-39, 2017

3.3. Printing

Using the Mojo 3D printer, the team could print the entire hand using the ABS filament. And, as the printer operates in a sealed area, the printing fumes were channelled away safely with no human contact.

The shortest print was 1 individual finger, shown as figure 3-40 without the snap pins, which took approximately 3 hours.

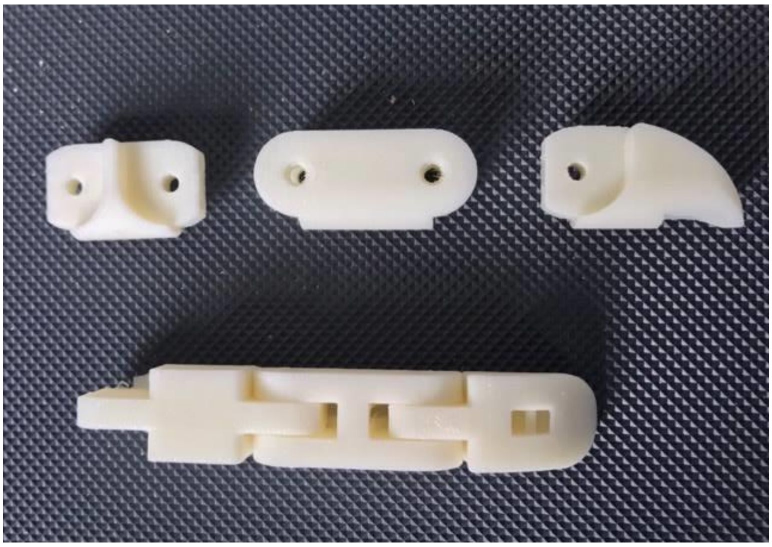


Figure 3-40, second design, 2017

The longest print was the palm and thumb, shown in figure 3-41 which took approximately 19 hours.

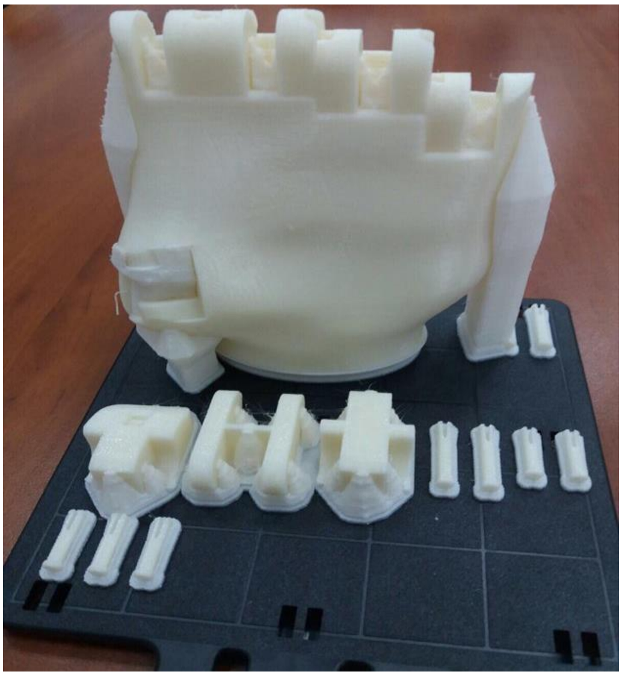


Figure 3-41, palm and thumb first design, 2017

As can be seen above, the palm and thumb do not resemble the 3D design. This is due to the still attached support structure connecting the components to the heat bed.

3.3.1. Post Processing

Following each print, the support structure was removed from the components using a solution provided by Mojo. The solution, which came as a compressed powder in tablet form, was submerged in the Stratasys' wave wash support cleaning system at high temperature with the component until the support structure had dissolved – approximately 2 hours, however this varied depending on the amount used within the print.

An example of the support structure can be seen here in figure 3-42. The rough material surrounding the top and middle section of the thumb is not excess ABS; rather it is the support structure. And, although the excess material on the outer edges of the components can be sanded or filed away, the material within the channels of the components cannot – hence the need for the material removing solution.

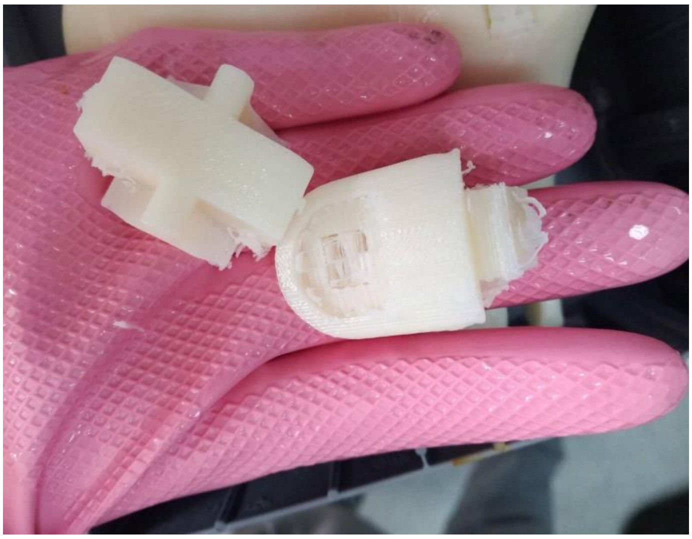


Figure 3-42, 2017

Figure 3-43, 2017

Furthermore, some design issues were encountered throughout the printing and inspection of the components; an example of which can be seen in figure 3-43. In this instance, a problem arose with the cables within the channels of the fingers as they rubbed against the joint at the middle section – not allowing the assembled finger to contract under actuation. The frictional resistance, in addition to the blocking at the joint, prevented the finger from achieving the required closure necessary for successfully gripping objects; the solution was then developed to remove the material by manually cutting. Through this experiment on the component, it was realised that all fingers and thumb would need the same correction, and that the final solution was to change the CAD designs for the next print – shown previously for the finger in figure 3-11.

3.4. Actuating the Prosthetic

To control the motor within the wrist, the team used an Arduino Mini. The controller, which was programmed using the IDE software supplied by Arduino, was based on C language and structured into 3 parts:

- Declaration of variables
- Mode of peripheries (set-up)
- Main loop

Only 2 digital pins were required to control the driver, in addition to 2 buttons (green and yellow); as the red would be used to reset the board and the switch to determine the supply of power depending on the position of the motor. Figure 3-44 and 3-45 helps to show the structure of the programming, the entirety of which can be found in the **appendix**.

```
const int green = 8;
const int yellow = 9;
const int dirPin = 5;
const int stepPin = 6;
```

Figure 3-44, declaration of variables

```
void setup() {

  Serial.begin(9600);
  pinMode(stepPin,OUTPUT);
  pinMode(dirPin,OUTPUT);
  pinMode(green,INPUT);
  pinMode(yellow,INPUT);

}
```

Figure 3-45, programme set-up

To simplify the work of the actuator, the addition of a driver (model A4988) would help to supply power to each coil of the step motor at the correct moment and in the desired sequence. The full step sequence was chosen as it maintains the highest output of torque and does not require a substantial amount of accuracy. Examples of full step and half step can be seen below in figures 3-46 and 3-47 respectively:

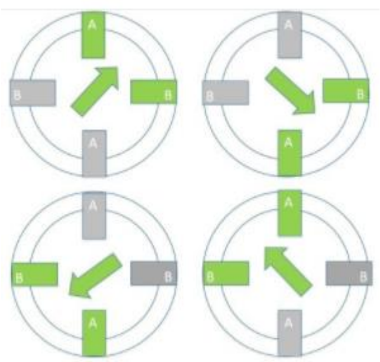


Figure 3-46, full step

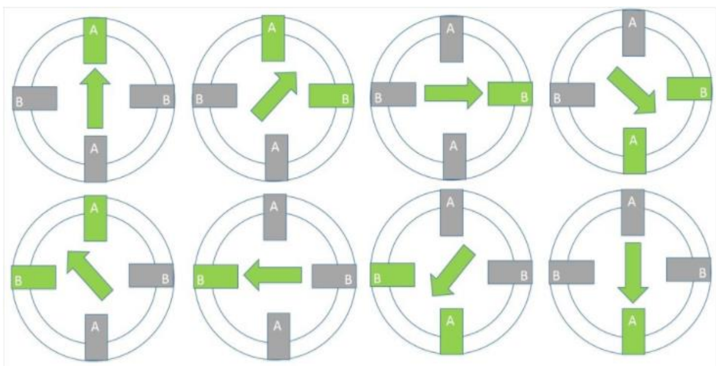


Figure 3-47, half step

With the aid of the driver, the system only needs 2 digital pins to control the motor: one to indicate direction and the other for the steps. The step of the 12V DC motor is 1.8°, which means if the motor is to revolve a full turn (360°) 200 pulses must be sent. Depending on how fast the motor is required to rotate, the driver will supply shorter or longer pulses. In the case with this design, the pulses will occur every 5 seconds as the team do not want to put too much stress on the cables; resulting in slow operating a speed.

Following this began the programming of the main control loop:

1. When activated (and held in position), the green button will close the hand
2. When activated (and held in position), the yellow button will open the hand
3. When the pressure is removed from the green or yellow button, the motor will stop
4. When activated, the red button will reset the program

An example of the code described above can be seen below in figure 3-48:

```
void loop() {

  while (digitalRead(yellow)==0 && (digitalRead(green)==1)) {

    digitalWrite(dirPin,LOW);
        for(int x = 0; x < 10; x++) {
           digitalWrite(stepPin,HIGH);
           delayMicroseconds(5000);
           digitalWrite(stepPin,LOW);
           delayMicroseconds(5000);
        }
  }
                                                              1)
  while (digitalRead(green)==0 && (digitalRead(yellow)==1)) {

    digitalWrite(dirPin,HIGH);
       for(int x = 0; x < 10; x++) {
            digitalWrite(stepPin,HIGH);
            delayMicroseconds(5000);
            digitalWrite(stepPin,LOW);
            delayMicroseconds(5000);
       }
  }
                                                              2)

  // in case there is not buttons pressed motor will not work
  digitalWrite(dirPin,LOW);
  digitalWrite(stepPin,LOW);
                                                              3)
}
```

Figure 3-48, main loop of the program

In the last operation (number 4 on the list), there was no requirement to programme the software as the red button is connected to the reset pin from Arduino to the ground directly. The entirety of this code and diagrams of the electrical circuit can be found in the **appendix**.

3.5. Final Assembly

Figure 3-49, final assembly

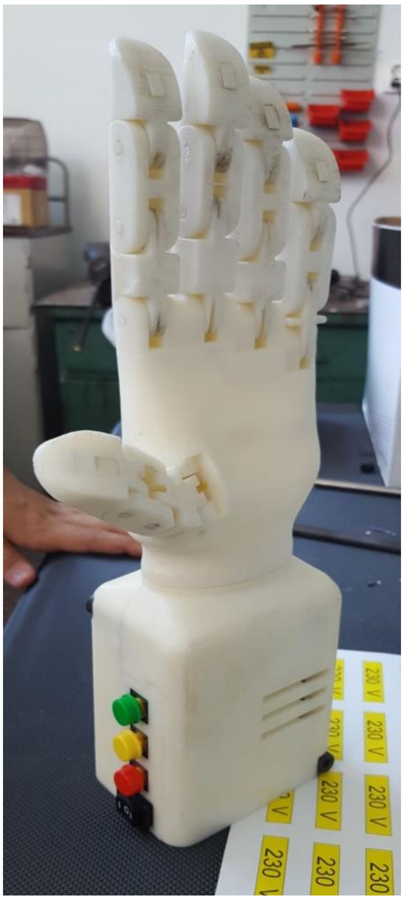


Figure 3-50, final assembly

Figure 3-51, final assembly

3.6. Component List and Bill of Materials

Component	Quantity	Cost (Euros)
Palm (104.65cm^3)	1	52.33
Index finger (19cm^3)	1 (7 pieces)	9.50
- Upper section	1	-
- Middle section	1	-
- Lower section	1	-
- Joint snap pins	2	-
- Finger nail	1	-
- Rear finger cover	1	-
Middle finger (23.24cm^3)	1 (7 pieces)	11.62
- Upper section	1	-
- Middle section	1	-
- Lower section	1	-
- Joint snap pins	2	-
- Finger nail	1	-
- Rear finger cover	1	-
Index and middle finger knuckle snap pin	1	-
Ring finger (21.16cm^3)	1 (8 pieces)	10.58
- Upper section	1	-
- Middle section	1	-
- Lower section	1	-
- Joint snap pins	2	-
- Finger nail	1	-
- Rear finger cover	1	-
- Ring finger snap pin	1	-
Little finger (15.85cm^3)	1 (8 pieces)	7.93
- Upper section	1	-
- Middle section	1	-
- Lower section	1	-
- Joint snap pins	2	-
- Finger nail	1	-
- Rear finger cover	1	-
- Little finger snap pin	1	-
Wrist (192.36cm^3)	1 (2 pieces)	96.18
- Upper section	1	-
- Lower section	1	-
Thumb (19.24cm^3)	1 (8)	9.62
12V DC step motor	1	-
Cooling fan	1	-
2:1 ratio gear	1	-
Belt	1	-
Arduino Mini controller	1	5
A4988 driver chip	1	9
Cables	10	-
M6 screw	4	-
Total	**61**	**211.76**

Table 3-1

Chapter 4 – Testing

4.1. Quality Control

Inspection – a final inspection of the product was carried out after completion to ensure that the hand complied with the build specification, as well as adhering to the necessary safety regulations. Firstly, a visual inspection was implemented to check the prosthetic was fit for purpose. Furthermore, each component was measured to confirm its accuracy in relation to the Engineering Drawings. Next, through a process of physical manipulation, the fingers were closed; paying attention to any irregularities such as an uneven closure or any concerning frictional resistance by the components. It was important that the wrist supports were secured to avoid any chance of danger to any personnel during the event of failure. Finally, all bolts and snap pins were secured and held in position. These techniques were applied to find any unwanted characteristics; best achieved through observation.

Analysis – the group analysed the final product with evidence gathered through a brainstorming process, which included such techniques as logical thinking and the theoretical calculation of function probability. Each scenario was full evaluated in relation to conformance with the original operation expectations.

Similarity – checks conducted to retain assurance that the final design of the product is not replicated from former or similar models. Evidence was gathered by comparison of comparable hand designs – through feedback and research.

Demonstration – a set of tests conducted in conditions like the environment which the product will be operational. Used as a method of verifying that the prosthesis is fit for purpose; the results were measured against the correlation to its predetermined outcome.

Testing – conducted upon the product under controlled conditions to authenticate its position in terms of its competence to performance expectations and functionality. Tests were conducted using equipment that measures electrical power input, in addition to whether the force applied was capable of gripping and holding a bottle of water weighing 0.5kg.

Sampling – a quality control technique which is used throughout the process of selecting a means of verifying that the product is attuned to the technical specification in relation to tolerances and additional printing or machine characteristics.

4.1.1 Quality Corrections

As explained in greater detail previously in section 3-2 and 3-3, there were changes to the design to improve the overall attributes of the final product. Shown below on table 4-1 is a brief list of all the corrections made throughout the design, printing and quality control processes to the prosthetic.

Component	Change
Palm	Larger area inside the palm for less cable friction and increased weight reduction, larger distance between the hole and the wrist connection
Thumb	More aesthetic and realistic shape (width and lower phalanx redesign)
Fingers	Material removed to reduce friction, components numbered for ease of assembly
Wrist	Change in design to a larger structure to accommodate wider motor and steel bar

Table 3-1

4.2. Forces and Transfer of Torque

In able to apply the necessary force by the motor to retract the fingers and thumb of the hand, a force test was conducted. The findings of said test were that each finger required approximately 4.91N to close, totalling at around 24.5N. However, to grip and hold objects, the force would need to be increased; around 30N. An example of the test calculations can be seen in section 4.2.1.

In relation to the transfer of torque, the speed chosen for the rotation of the motor was 48 RPM. This speed was chosen as it is the slowest speed that offers the highest torque value, found on the manufacturer's specification for the motor. However, as the 0.26Nm value was not great enough to operate at the found gripping force, it was necessary to install a gear with a 2:1 ratio into the design. The results of the calculation can be found in section 4.2.3. below.

4.2.1. Calculation Prefix

Variable	Symbol	Units
Power	P	Watts
Force	F	Newtons
Mass	m	Kg
Acceleration	a	$\mathrm{m}/_{s^2}$
Torque	T	Nm
Speed	N	RPM
Gear teeth	Z	N/A
Pi	π	N/A

4.2.2. Force Calculations

As 1 finger required 0.5kg at gravity to close:

$$F = ma$$

$$F = 0.5\ X\ 9.81$$

$$F = 4.905N$$

As the same force was required for each finger and thumb:

$$F = Force\ of\ 1\ finger\ X\ 5$$

$$F = 4.905\ X\ 5$$

$$F = 24.525N$$

However, an additional newton of force was added for gripping:

$$F = (4.905 + 1)\ X\ 5$$

$$F = 29.525N$$

Gripping force $\cong 30N$

4.2.3 Torque Calculations

When connecting the motor to the gear, it was important to calculate the transfer of torque. First, it was necessary to find the power:

$$P = \frac{T_1 \; X \; 2\pi \; X \; N_1}{60}$$

$$P = \frac{0.26 \; X \; 2\pi \; X \; 48}{60}$$

$$P = 1.307W$$

Then, using the value of power, we could calculate the speed of the gear using the gear ratio:

$$N_2 = N_1 \; X \; \frac{Z_1}{Z_2}$$

$$N_2 = 48 \; X \; \frac{20}{40}$$

$$N_2 = 24 \text{ RPM}$$

Finally, using the power and the rpm of the gear, the torque transferred by the gear could be calculated:

$$T_1 = \frac{60 \; X \; P}{2\pi \; X \; N_2}$$

$$T_1 = \frac{60 \; X \; 1.307}{2\pi \; X \; 24}$$

$$T_1 = 0.52Nm$$

The results from the calculations and the changes to the programming of the motor's output can be seen in practice below, in figure 4-1, as the hand grips and holds a 0.5kg bottle of water:

Figure 4-1

Chapter 5 – Conclusions

5.1. Product Review

Overall, when considering the limitations (budget and time), the team still managed to produce a project of favourable quality. In comparison to the research on past designs, the model contains some of the better characteristics of those on the list – such as the snap pins from Raptor and the realistic look of FlexyHand. Using these, and the information gathered from the additional research, the considerations for the new design: lightweight and visually appealing, easy to maintain, remaining cost effective; were all met. Furthermore, to a certain extent the design consideration of innovating the electrical components to cut back on energy demands was somewhat met, as the power to actuate the hand is minimal – however this is a direct result of its relatively low functionality. Function was a factor in the quality/success criteria, described as imperative to the relevance of the prosthetic in the market, which to some degree it does achieve – in terms of low-to-no maintenance, although no tests have been conducted on fatigue and the longevity of the product. Moreover, in relation to maintenance, as the prosthesis is almost entirely printed it makes it quick and simple to replace broken sections (which should last for a considerable period due to the durable and impact resistant qualities of ABS). In addition, when compared to other models in terms of price, the product remains one of the cheapest options available, remaining favourable to those which cannot afford the expensive bionics currently on the market. More information on this aspect in section 5.1.1. And, when testing the device, quality control measures were taken to ensure the final product was fit for purpose. These included: visual inspections, physical manipulation and performance testing; all of which was met with a favourable outcome.

Ultimately, the product did achieve the objectives set out by the team at the beginning of the project: shaking hands and picking up objects. The results of which are shown in Chapter 4 – testing.

5.1.1. Cost Analysis

In any prosperous business venture or research and design project, the budget is placed as a forefront concern when trying to produce something of substance and/or importance whilst remaining relevant to the market. And, described in the beginning as a limitation of this project; the budget was a major factor in achieving this success.

With the more advanced bionic models costing anywhere from €30,000 to €100,000, the need for a cheaper alternative is imperative. To reduce these costs, research teams and other bionic enthusiasts have begun to look for new manufacturing methods – mainly 3D printing. However, the typical 3D printed prosthetic available online still ranges somewhere above the €2,000 mark. To compensate for this issue, it was our task to produce a completely new design whilst offering the less expensive product that recipients required.

Ultimately, the team succeeded in this task, as the prosthesis is completely open source and the above cost is lower than those previously mentioned. Although, it is important to mention that due to budget restrictions on the project, some components were recycled. This means that the bill of materials is not entirely accurate for the product, however the difference would not be substantially higher and the objective of creating a cheaper product would still have been met.

5.1.2. Improvements

Despite the success of the finished product, there is the need for further improvements that would enhance the performance and favourability in the market if the team had more time. Those include:

- Modifying the wiring system so that all wires are elastic – this would allow the fingers to continue closing even when one finger has already clasped the object, as the steel bar would continue to turn, increasing the gripping force delivered by the hand.
- Using two motors for the thumb – this would increase the freedom of movement to 2, which is useful when gripping odd shapes, in addition to giving the thumb a more realistic function.
- Using 1 motor for each finger – this would allow a range of different hand movements and increase the level of function on the prosthetic.
- Printing the electrical circuit board and including it inside the design of the wrist.
- Using batteries instead of a power supply (LM7805 voltage regulator).

5.2. Reflections

From the beginning to the end of the project, the team continued to learn new and adapt past skills – whether that be from knowledge learned through research or by experimenting in the workshop. In addition to the knowledge gained, the team also built upon interpersonal skills and international communication, which was the purpose of the EPS programme. Throughout the entire programme which lasted approximately 4 months, new methods were learned by the team from taking inspiration and sharing techniques; valuable expertise that can be applied in future educational or workplace roles.

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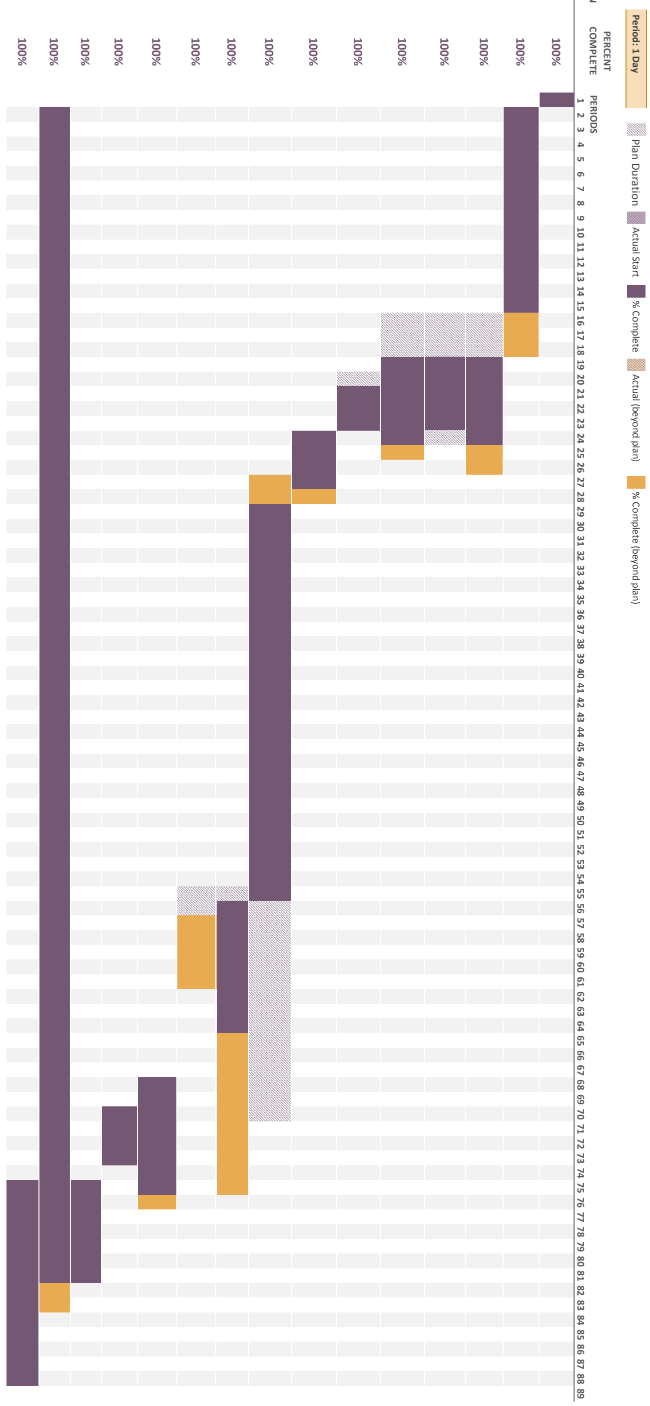
Appendix

Gantt Chart

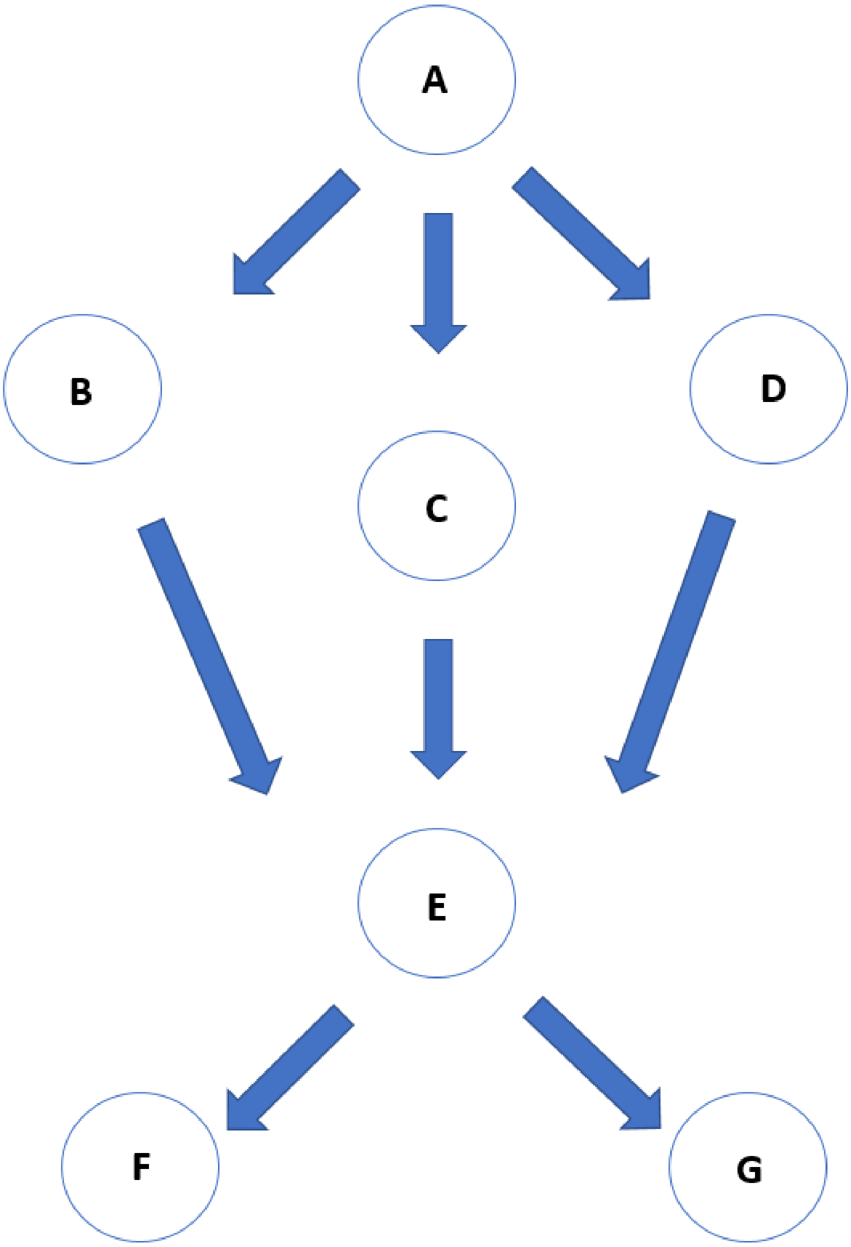
Project Planner

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Allocating tasks	1	1	1	1	100%
Initial research	2	14	2	17	100%
Further design research	16	9	19	8	100%
Component research	16	9	19	5	100%
Market research	16	9	19	7	100%
Concept design	20	4	21	3	100%
Material research	24	4	24	5	100%
CAD design process	29	42	27	29	100%
Printing	55	10	56	20	100%
Programming controller	55	2	57	5	100%
Post processing	68	8	68	9	100%
Assembly	70	4	70	4	100%
Testing	75	7	75	7	100%
Report	2	80	2	82	100%
Presentation	75	14	75	14	100%

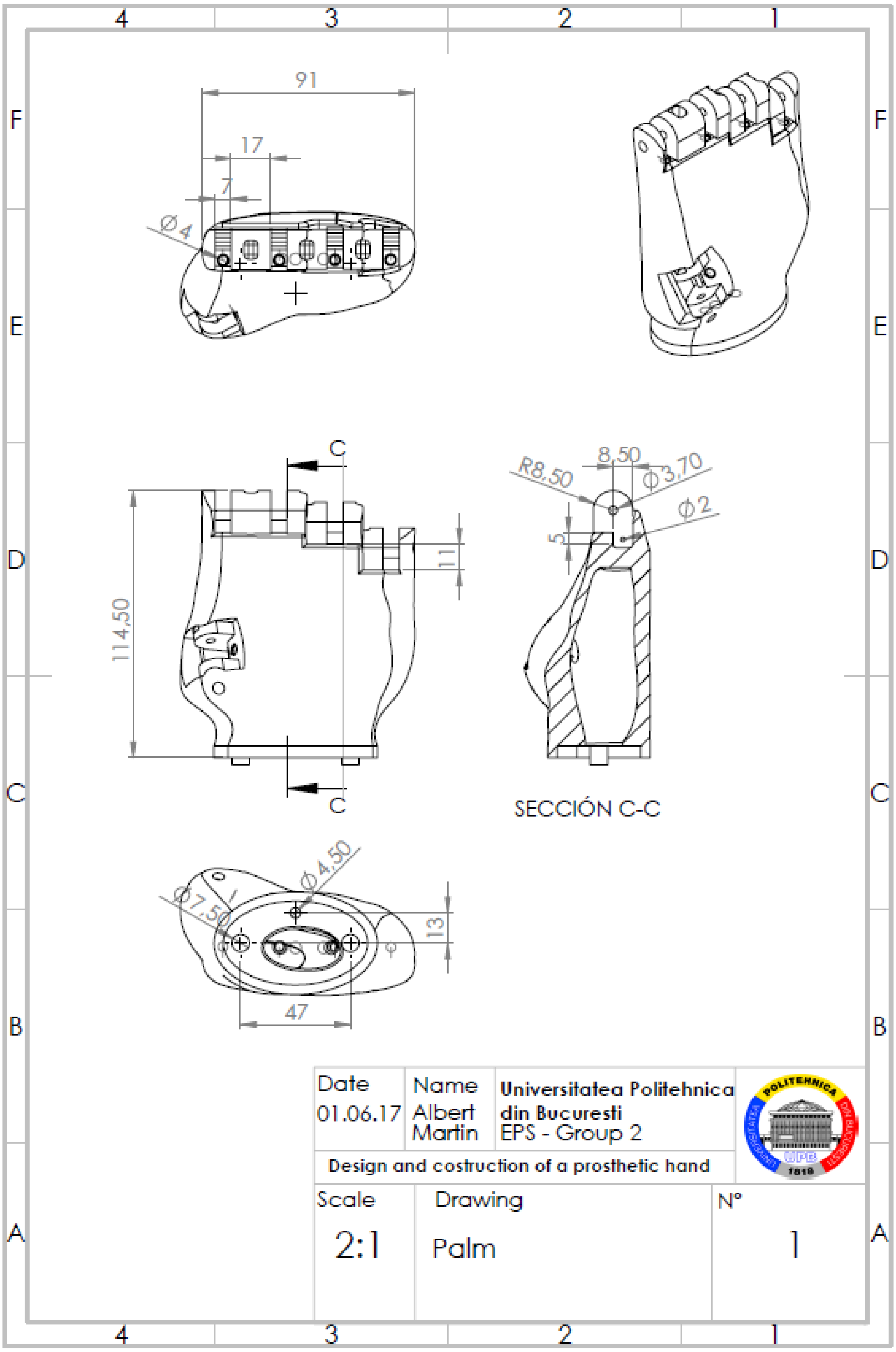


Flow Chart

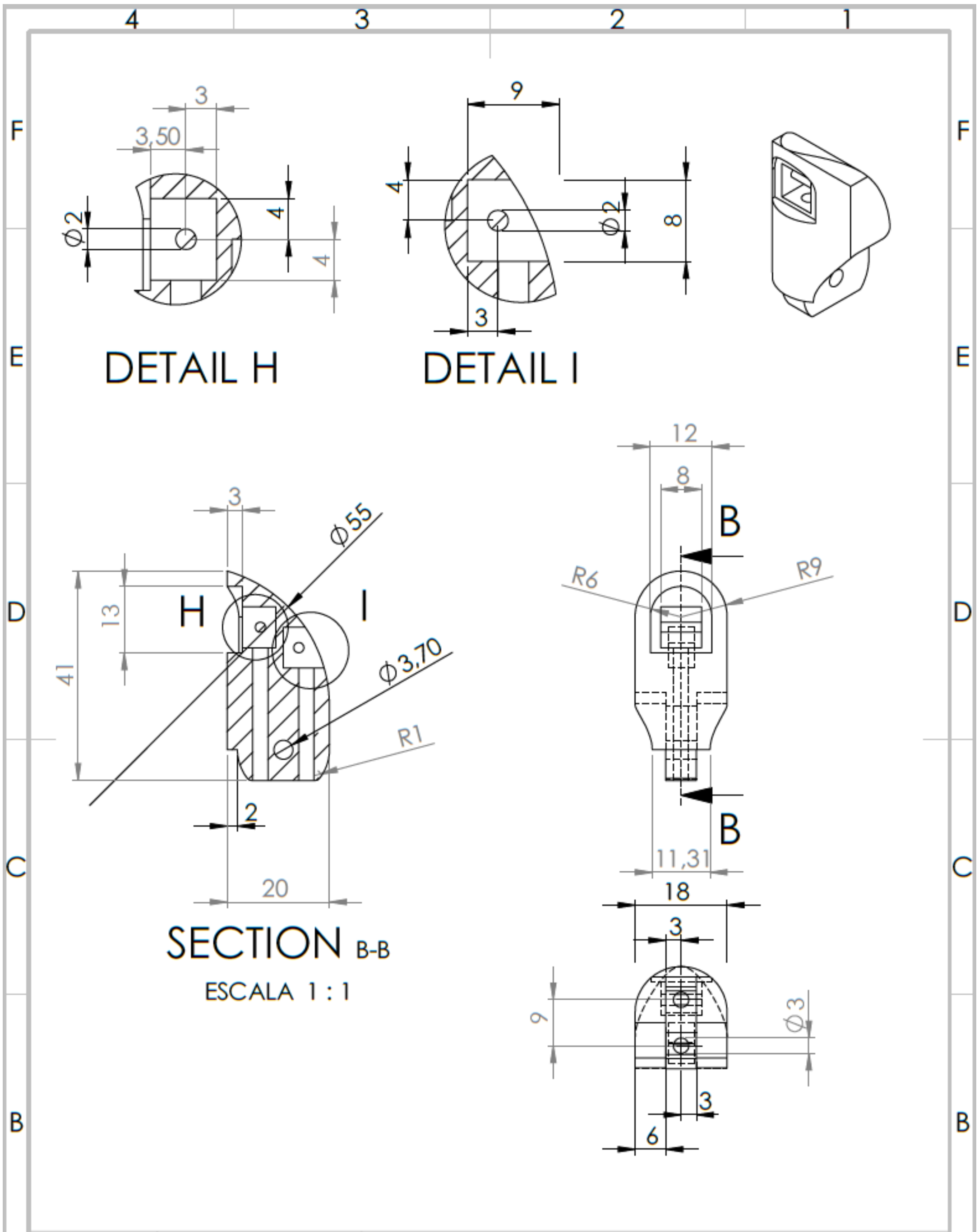
Activity	Member	Duration (days)
A – Initial design research	All	14
B – Further design research	Steve, Albert	9
C – Component research	Diego	9
D – Market research	Dylan	9
E – Design approval	All	1
F – Design process	Steve, Albert, Diego	27
G – Material research	Dylan	4



The Palm Engineering Drawing

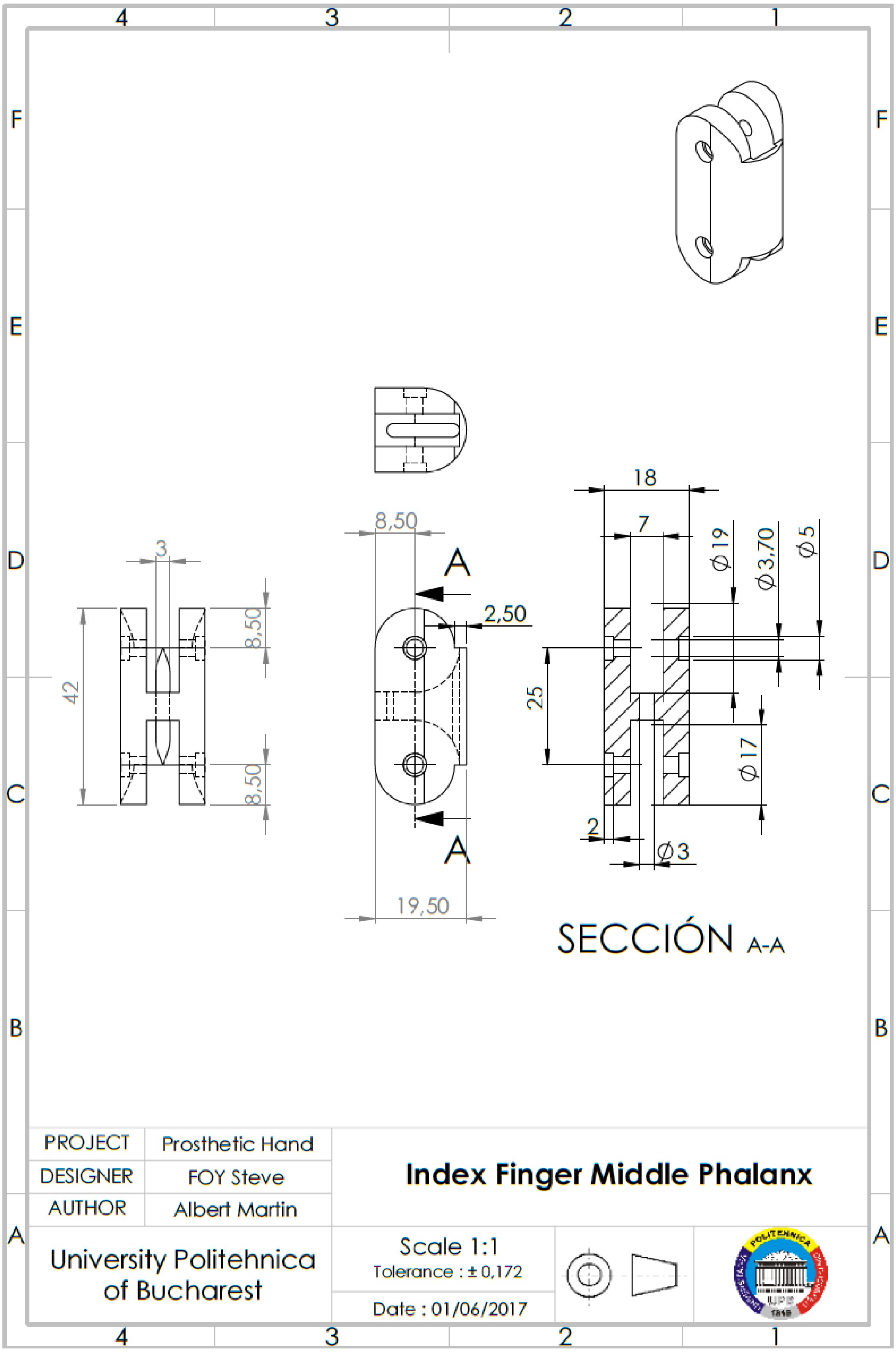


Finger Engineering Drawing (Index, 1)

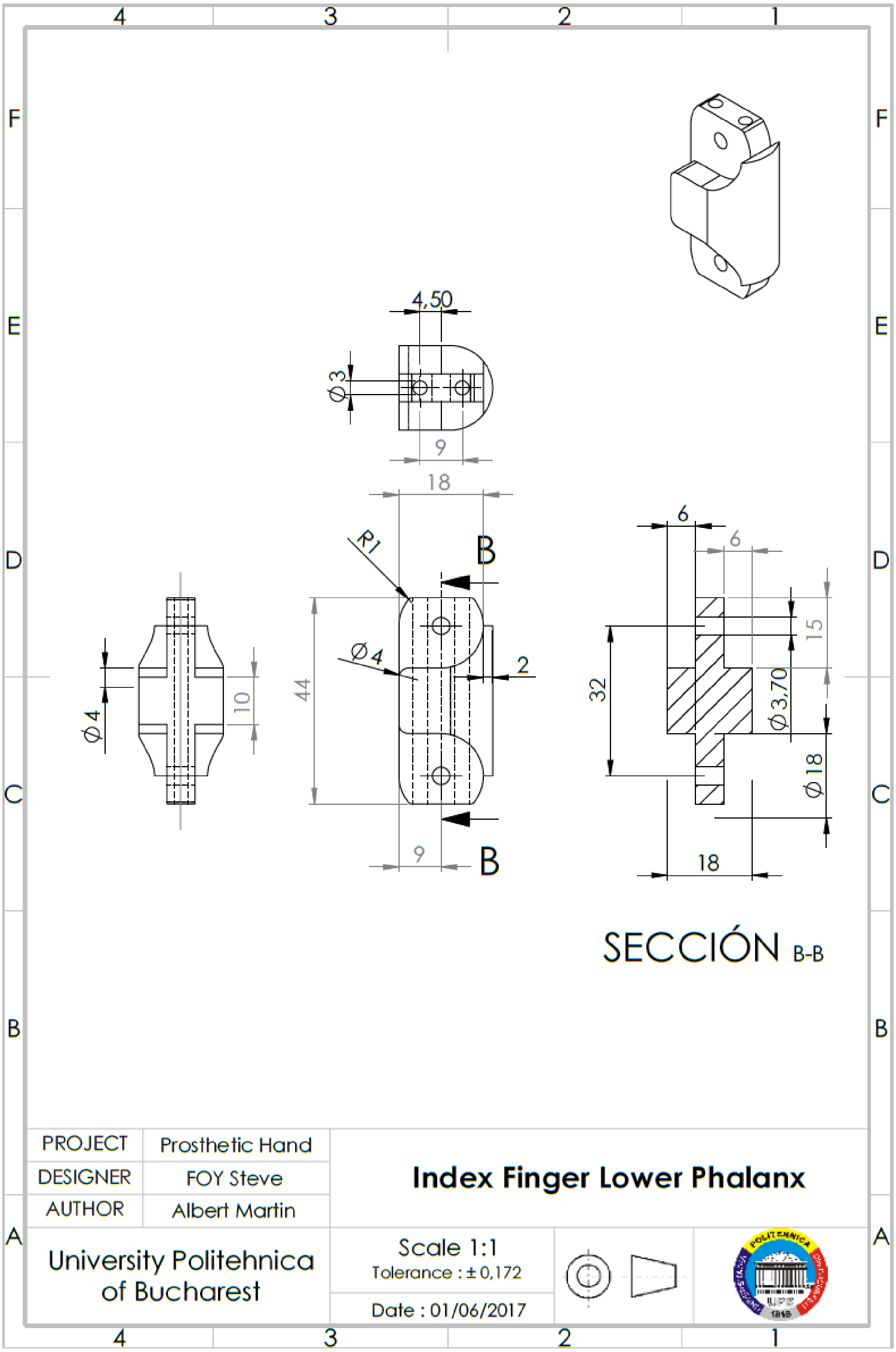


PROJECT	Prosthetic Hand	Index Finger Top Phalanx
DESIGNER	FOY Steve	
AUTHOR	Albert Martin	
University Politehnica of Bucharest	Scale 1:1 Tolerance : ± 0,172 Date : 01/06/2017	

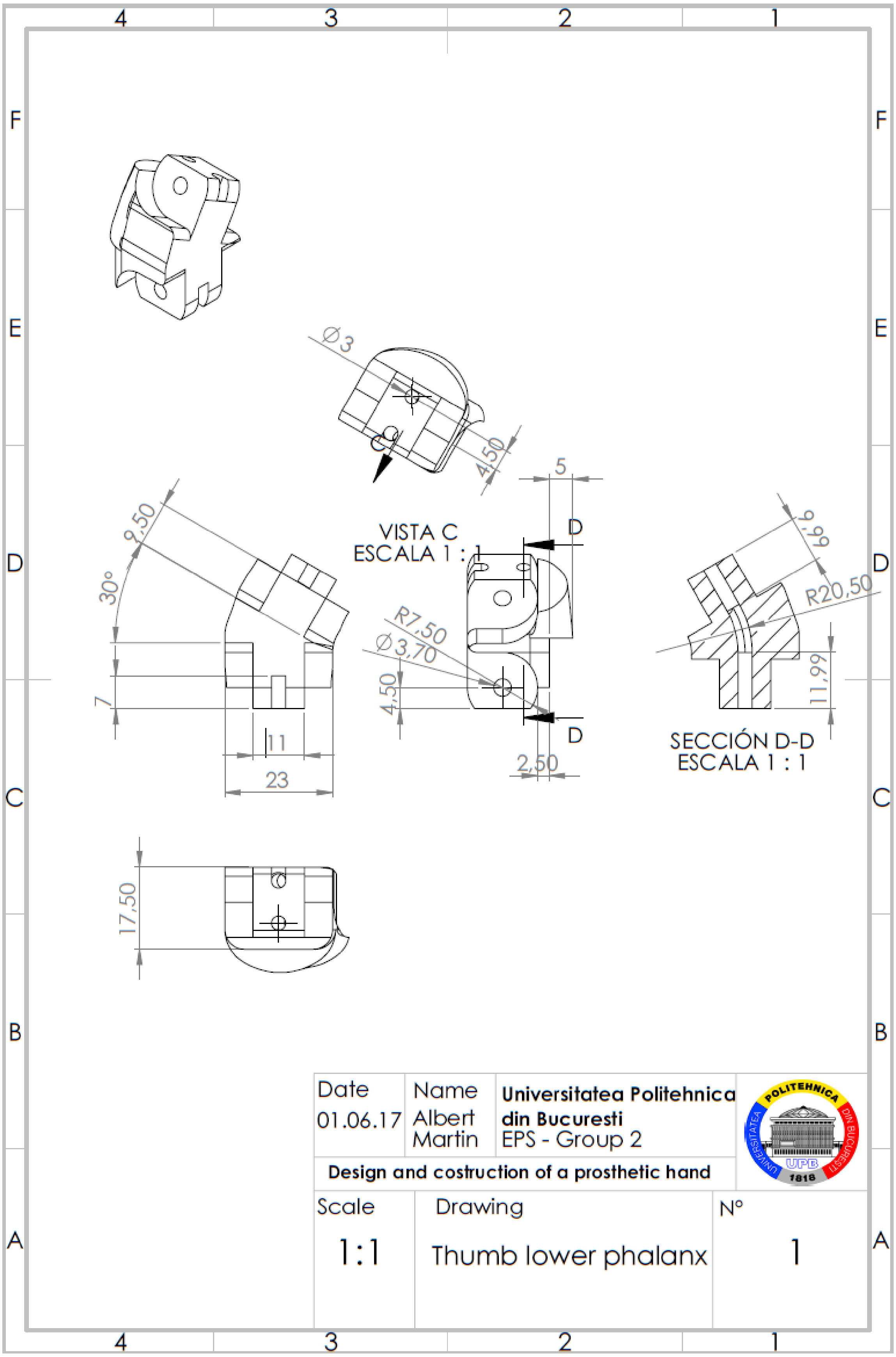
Finger Engineering Drawing (Index, 2)



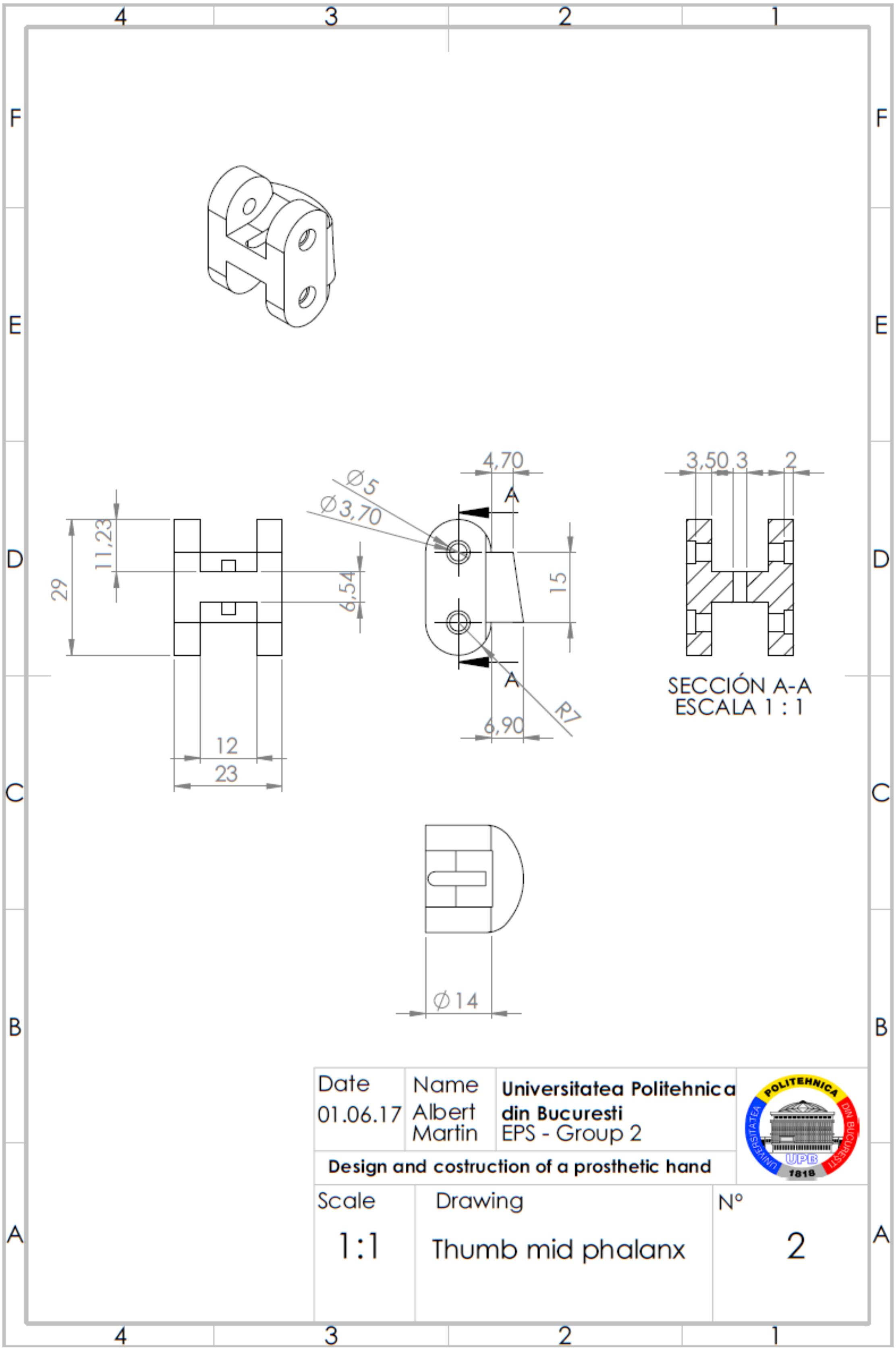
Finger Engineering Drawing (Index, 3)



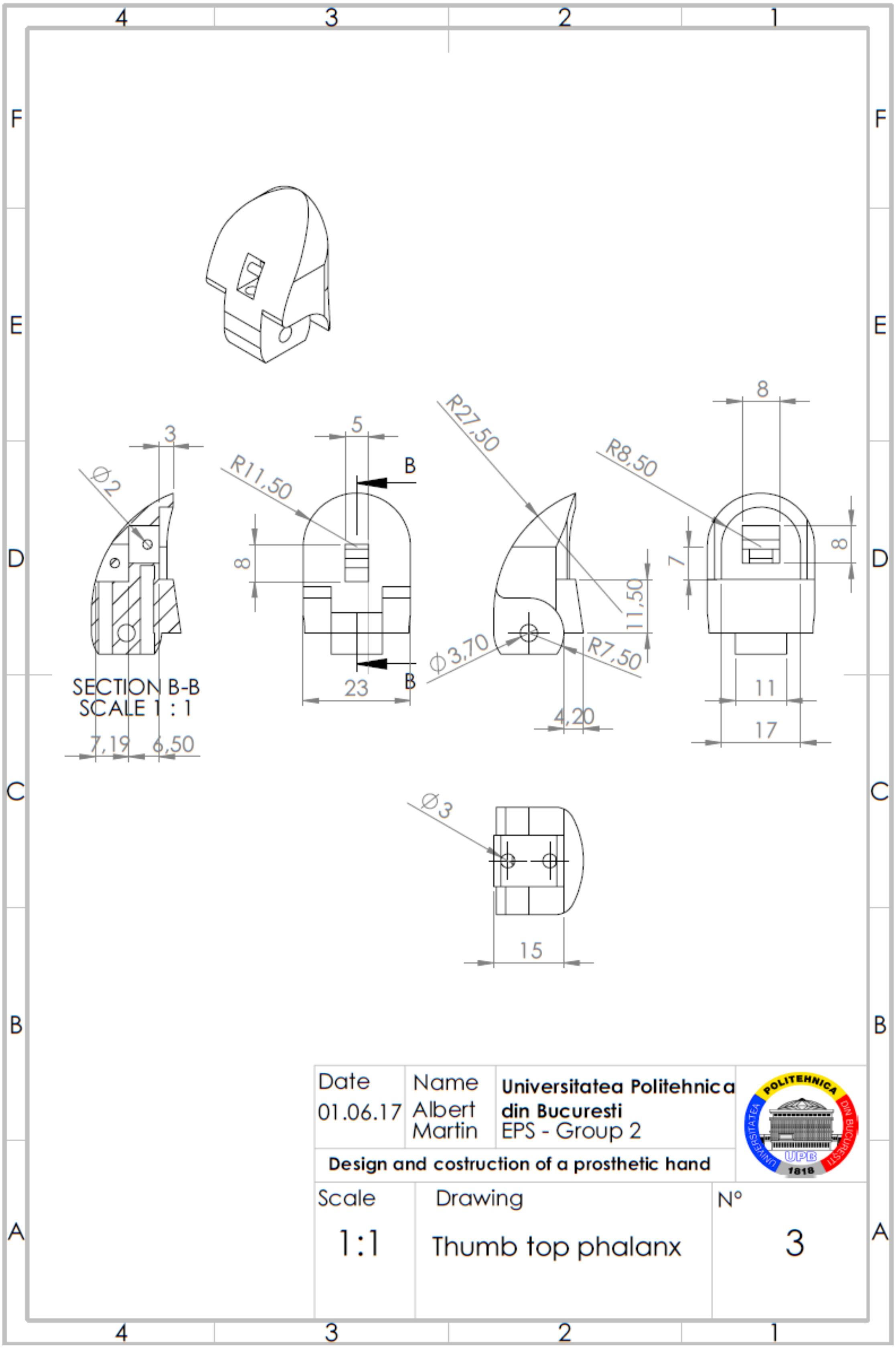
The Thumb Engineering Drawing (1)



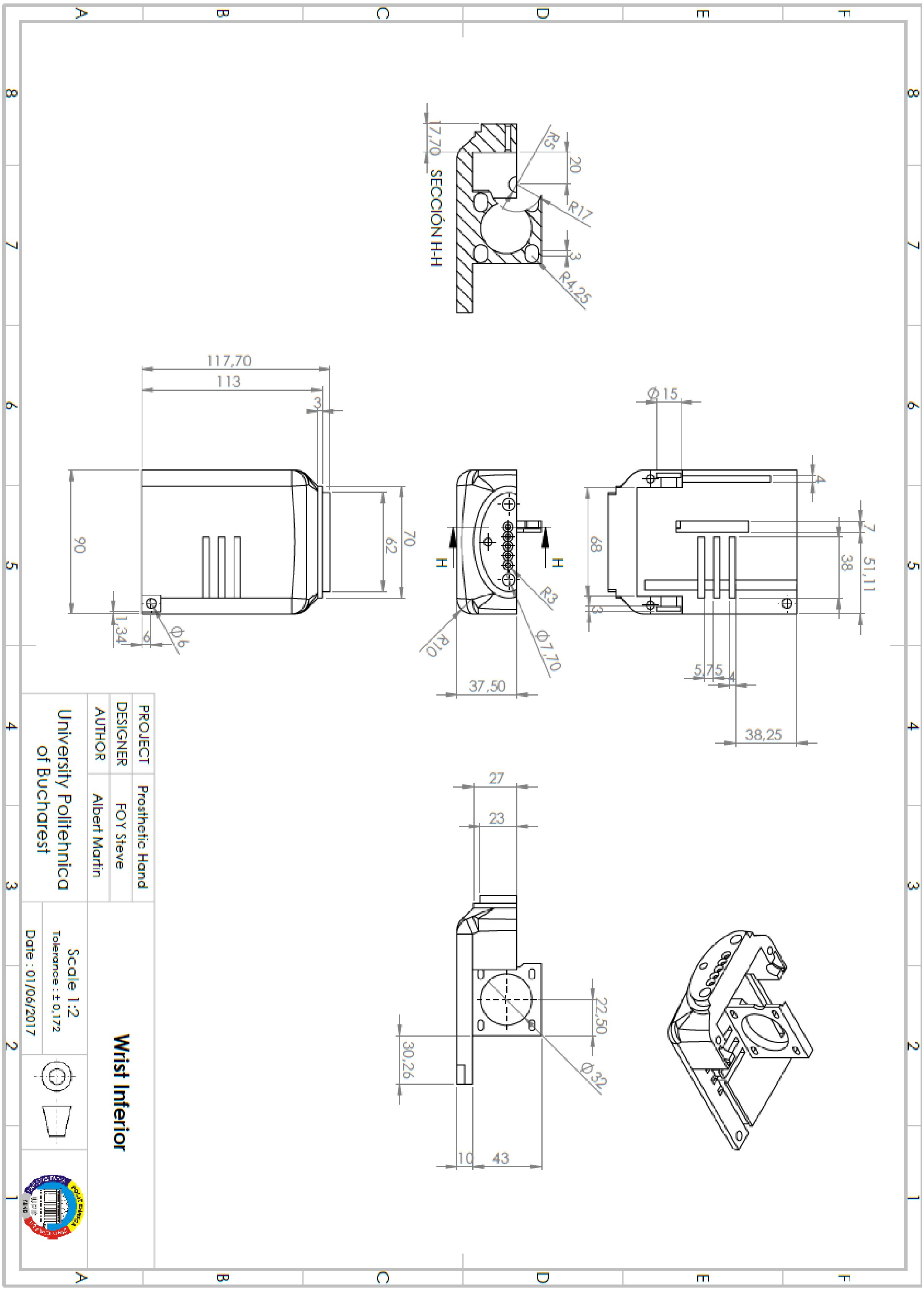
The Thumb Engineering Drawing (2)



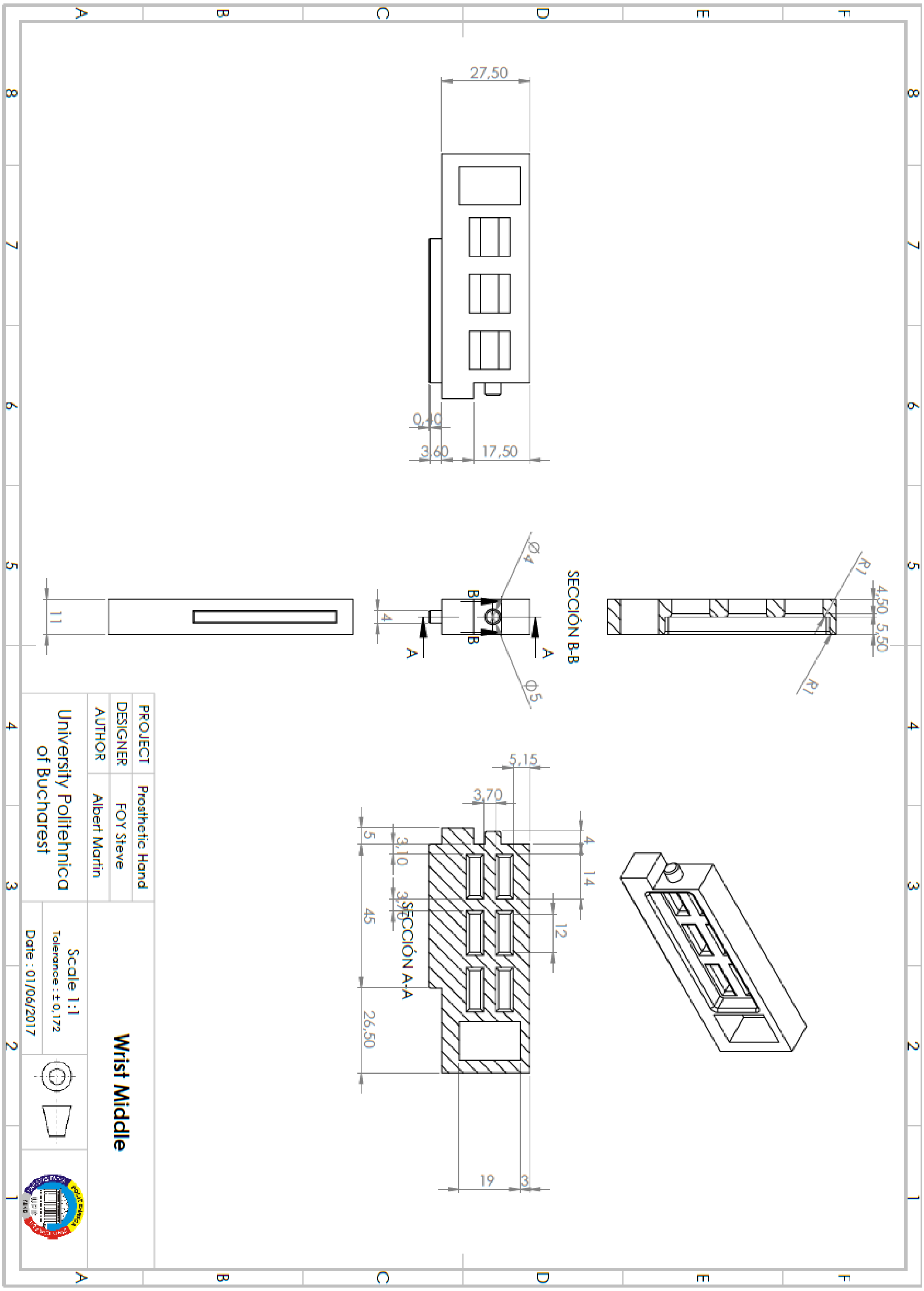
The Thumb Engineering Drawing (3)



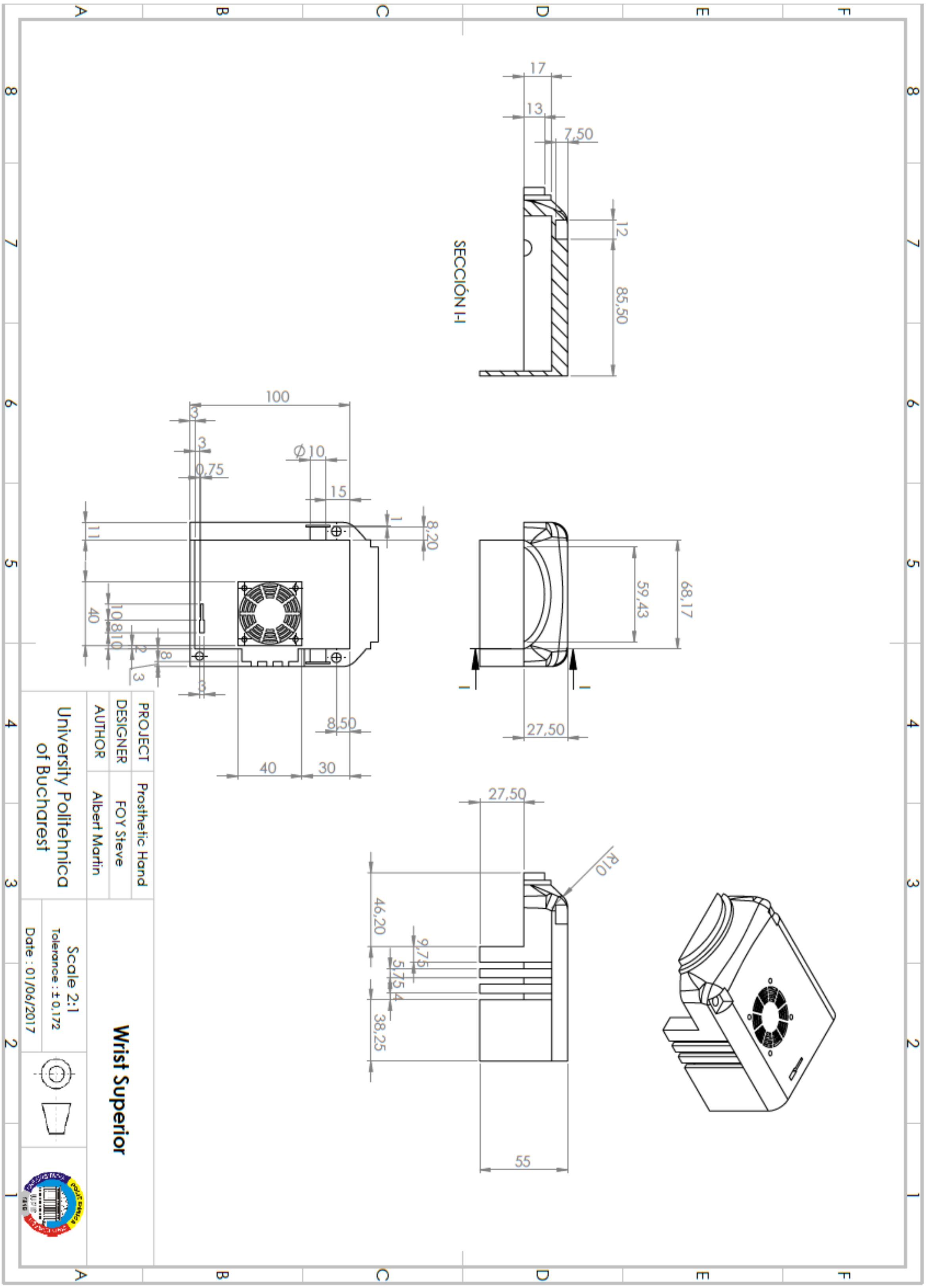
The Wrist Engineering Drawing (1)



The Wrist Engineering Drawing (2)



The Wrist Engineering Drawing (3)



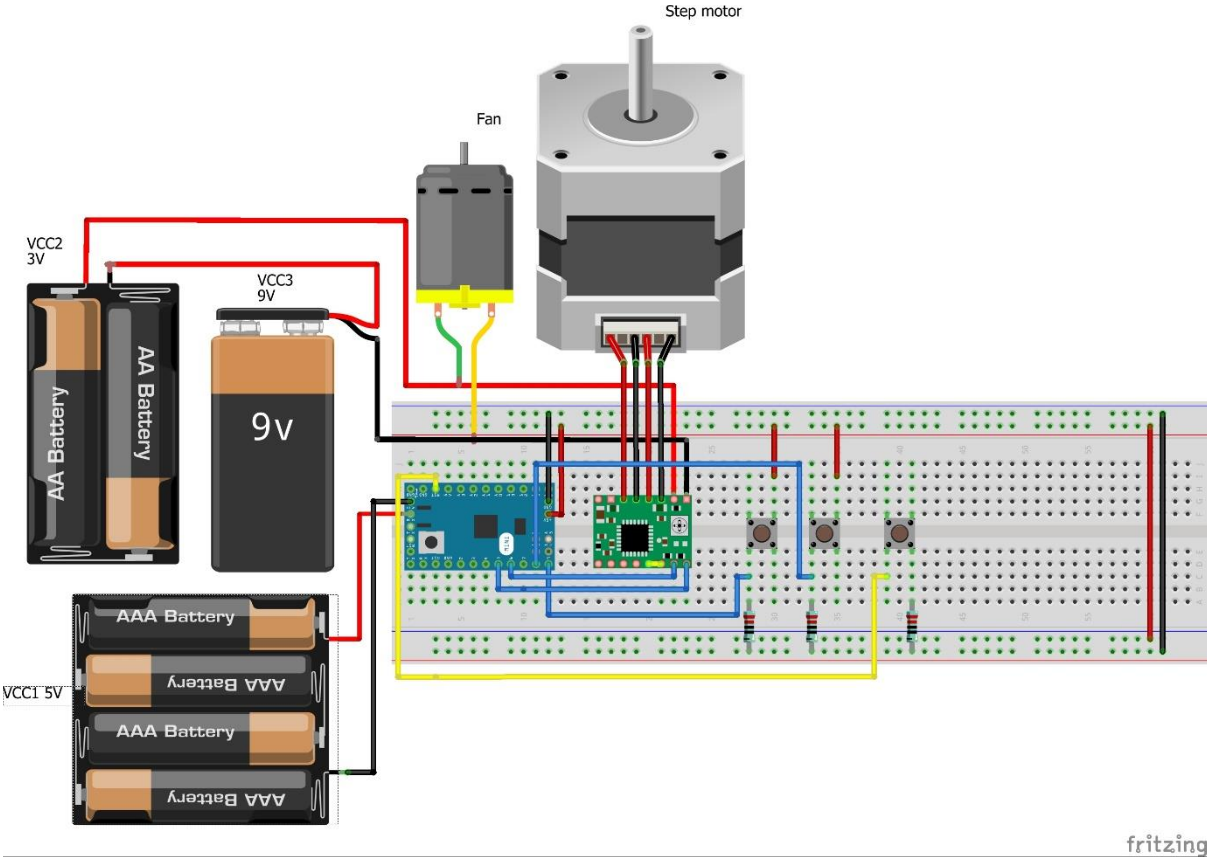
Controller Programming (part 1)

```
/*
  Control of a step motor for a prothesic hand
  Author: Diego Guijarro Martin
  Date:04/06/2017

 */

const int green = 8;          // pin 8 connected to green button
const int yellow = 9;         // pin 9 connected to yellow button
const int dirPin = 5;         // pin 5 connected to the direction pin in the driver A4988
const int stepPin = 6;        // pin 6 connected to the step pin in the driver A4988

void setup() {

  Serial.begin(9600);         // data rate in bits per second (baud)
  pinMode(stepPin,OUTPUT);    // initialize the digital pin as an output.
  pinMode(dirPin,OUTPUT);     // initialize the digital pin as an output.
  pinMode(green,INPUT);       // initialize the digital pin as an input(green button).
  pinMode(yellow,INPUT);      // initialize the digital pin as an input(yellow button).

}
```

Controller Programming (part 2)

```
void loop() {

  while (digitalRead(yellow)==0 && (digitalRead(green)==1)) {      // green button pressed and yellow button not pressed, while it's being pressed motor close the hand

    digitalWrite(dirPin,LOW);                                       // pin to detereminate the direction of the motor
        for(int x = 0; x < 10; x++) {                               // for loop to make 10 pulses or steps
           digitalWrite(stepPin,HIGH);
           delayMicroseconds(5000);
           digitalWrite(stepPin,LOW);
           delayMicroseconds(5000);
        }
  }

  while (digitalRead(green)==0 && (digitalRead(yellow)==1)) {      // yellow button pressed and green button not pressed, while it's being pressed motor open the hand

    digitalWrite(dirPin,HIGH);                                      // pin to detereminate the direction of the motor
       for(int x = 0; x < 10; x++) {                                // for loop to make 10 pulses or steps
            digitalWrite(stepPin,HIGH);
            delayMicroseconds(5000);
            digitalWrite(stepPin,LOW);
            delayMicroseconds(5000);
       }
  }



  // in case there is not buttons pressed motor will not work
  digitalWrite(dirPin,LOW);                                         // when dirPin and stepPin are in LOW motor stops
  digitalWrite(stepPin,LOW);

}//end of loop
```

Electrical Circuit



Electrical Circuit Diagram