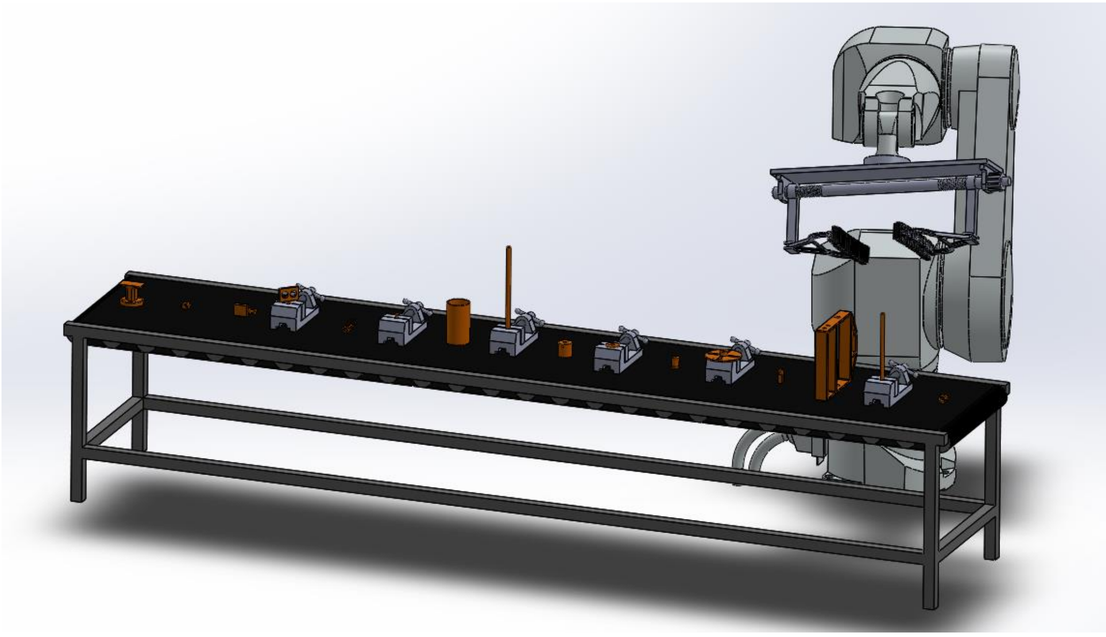
NATIONAL TECHNICAL UNIVERSITY OF ATHENS

INTERDISCIPLINARY POSTGRADUATE SPECIALIZATION PROGRAMME “AUTOMATION SYSTEMS”

MASTER OF SCIENCE THESIS

DESIGN OF A ROBOT’S RECONFIGURABLE GRIPPER FOR INDUSTRIAL PART HANDLING



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PREFACE

In the last decades several factors such as the increasing cost of human labour, the spread of automation and the decreasing cost of robotic systems have pushed both industry and academia towards the development of new grippers and robotic hands. While in the past robot hands and industrial grippers were oriented to different goals, nowadays it is often difficult to distinguish a simplified robotic human-like hand from a complex industrial gripper. The fast growth in the field and the development of new grasping technologies merits a review of grasping devices and methods in production processes. In addition the world economic crisis is pushing automation towards new frontiers asking for more flexible, versatile, lightweight and small grippers able to perform more complicated functions.

There are numerous applications of where robotic grippers can be used. This highlights the importance of reviewing the recent developments that are accuring in research and the future directions of designs and applications. This work provides a broad perspective on the different types of grippers being used for known and unknown environments. The literature overview conducted focuses on emerging applications, new design developments in this field and future directions of the trending grippers' designs. Then, based on this acquired knowledge a smart gripper is designed designated for industrial applications. Various features are selected to be implemented on the design that give functionality and flexibility to the gripper.

At this point I would like to thank the Professor of the School of Mechanical Engineering of National Technical University of Athens (NTUA) Mr. G.-C. Vosniakos for the trust he showed me with the assignment of the current Master Thesis and for his guidance. Additionally, I would like to thank the laboratory of Manufacturing Systems of NTUA and specifically Doctor Mr. N. Galanis for his contribution on the manufacturing process of the work. Moreover, I want to express my gratitude to my parents and sister for their continued support, which has enabled me to successfully complete my studies. Finally, I want to thank my friends and colleagues for the support and creative years we spent together.

ABSTRACT

Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially grippers. Grippers are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object with respect to other equipment. There are several ongoing attempts to improve grippers mainly in two fields, performance and flexibility. An extensive literature review has been conducted as part of this work and the gripper designs that were most worth mentioning are presented.

The mechanical design process is a combination of engineering and creative design processes. The systematic procedure widely known for designing and constructing a component involves three stages: conceptual, configuration and parametric design. The current work presents the concept of a new gripper solution for industrial applications. The goal of this project is to design and analyse a smart gripper capable to deal with a relatively wide range of industrial component types. Taking into account the identification of the parts to be manipulated and their orientation in space, the gripper should change its shape in order to effectively grab the components to be handled. Based on the above specifications and restrictions the need of a gripper capable of manipulating components with various geometric particularities, designated for various tasks and able to comply with special environmental conditions is obvious.

Three alternative design concepts have been developed inspired by the literature review conducted in this Thesis. These ideas try to fill up design gaps noted in terms of the objectives, specifications and restrictions of the current project. However, to design a product properly, it is important to know the customer requirements coupled with the integration of corporate functional groups. The customer desires were translated into design characteristics during product development. In order to achieve this, several tools have been used, notably Quality Function Deployment method (QFD) and Failure Mode Effects Analysis (FMEA). The design concepts were evaluated and the key parameters according to which the design can be improved were determined.

As the last step of the analysis comes the computational evaluation of the structural characteristics of the designed gripper, in order to ensure the operation functionality of the design.

A detailed bill of materials and in-house manufacture of several parts on CNC machinery completed the development process.

ΠΕΡΙΛΗΨΗ

Ο αυξανόμενος ανταγωνισμός μεταξύ ρομπότ και ανθρώπου για εργασίες που συνήθως εκτελούνται από ανθρώπους, έχει οδηγήσει στην ανάγκη για αποτελεσματικότερο βιομηχανικό εξοπλισμό χειρισμού και πιο συγκεκριμένα για εξελιγμένες βιομηχανικές αρπάγες. Οι αρπάγες είναι υποσυστήματα μηχανισμών χειρισμού που παρέχουν προσωρινή επαφή με το αντικείμενο που πρέπει να συλληφθεί. Εξασφαλίζουν τη θέση και τον προσανατολισμό του κατά τη μεταφορά και τη συναρμολόγηση του αντικειμένου . Όλες οι προσπάθειες εστιάζονται στη βελτίωση των βιομηχανικών αρπάγων κυρίως σε δύο τομείς, την απόδοση και την ευελιξία. Στα πλαίσια αυτής της εργασίας, έχει διεξαχθεί εκτενής βιβλιογραφική ανασκόπηση και παρουσιάζονται διάφορες ενδιαφέρουσες ιδέες βιομηχανικής αρπάγης που συναντώνται στην αγορά.

Ο μηχανολογικός σχεδιασμός είναι ένας συνδυασμός διαδικασιών μηχανικής και δημιουργικού σχεδιασμού. Η συστηματική διαδικασία που είναι ευρέως γνωστή για το σχεδιασμό και την κατασκευή ενός στοιχείου περιλαμβάνει τρία στάδια: εννοιολογικό, διαμορφωτικό και παραμετρικό σχεδιασμό. Η τρέχουσα εργασία παρουσιάζει μία νέα ιδέα αρπάγης για χρήση σε βιομηχανικές εφαρμογές. Στόχος είναι να σχεδιασθεί και να αναλυθεί ένα έξυπνο εργαλείο που μπορεί να χειριστεί ένα ευρύ φάσμα βιομηχανικών εξαρτημάτων. Λαμβάνοντας υπόψη την ταυτοποίηση των προς χειρισμό αντικειμένων και τον προσανατολισμό τους στο χώρο, η αρπάγη θα πρέπει να αναδιαμορφώνεται προκειμένου να αρπάζει αποτελεσματικά τα προς χειρισμό εξαρτήματα. Με βάση τις παραπάνω προδιαγραφές και περιορισμούς είναι προφανής η ανάγκη για ανάπτυξη ενός μηχανισμού ικανού να χειρίζεται εξαρτήματα με διάφορες γεωμετρικές ιδιαιτερότητες, που προορίζονται για διάφορες εργασίες.

Έχουν αναπτυχθεί τρεις εναλλακτικές σχεδιαστικές λύσεις που στόχο έχουν να καλύψουν τα κενά σχεδιασμού που εντοπίζονται στην βιβλιογραφία και σχετίζονται με τους στόχους, τις προδιαγραφές και τους περιορισμούς της τρέχουσας μελέτης. Ωστόσο, για τον σωστό σχεδιασμό ενός προϊόντος, είναι σημαντικό να είναι γνωστές οι απαιτήσεις των καταναλωτών. Οι επιθυμίες του τελικού καταναλωτή μεταφράζονται σε χαρακτηριστικά σχεδιασμού κατά την ανάπτυξη του προϊόντος. Προκειμένου να επιτευχθεί αυτό, χρησιμοποιούνται αρκετά εργαλεία, όπως οι μέθοδοι Quality Function Deployment method (QFD) and Failure Mode Effects Analysis (FMEA). Οι έννοιες σχεδιασμού αξιολογούνται και βάση αυτών καθορίζονται οι βασικές παράμετροι σύμφωνα με τις οποίες μπορεί να βελτιωθεί ο σχεδιασμός.

Το τελευταίο βήμα της ανάλυσης είναι η υπολογιστική αξιολόγηση των δομικών χαρακτηριστικών του σχεδιαζόμενου μηχανισμού, προκειμένου να διασφαλιστεί η αποτελεσματική λειτουργία του. Τέλος, καταστρώνεται μία λίστα με τα απαραίτητα εξαρτήματα για το τελικό προϊόν και η κατασκευή διαφόρων τμημάτων σε μηχανήματα CNC ολοκληρώνουν τη διαδικασία ανάπτυξης του τελικού προϊόντος.

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CHAPTER 1 INTRODUCTION

Human labour has always been associated with the acquisition of specific skills, methods and tools, making the work and its environment easier and more effective. The more or less evolved mechanisms mimicking human motions devised before the early 1900s, the worldwide explosive industrial development including information technology and its deployment in the control of working equipment have triggered, as a natural consequence, the creation of robots [1].

Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially prehension tools (more commonly called “grippers”). However, industrial robots are not simply a substitute for people. Their relevance is more often in applications beyond the normal ability (physical or temporal) of conventional manpower. Examples include, dirty, hazardous and repetitive work environments. Just as human hands are the organs of human manipulation, so are robot grippers usually the only parts in direct contact with the workpiece [2].

Over the past decades, automation solutions have seen a large shift away from traditional, hard-tooled lines to reconfigurable, reprogrammable robotic cells. Corresponding to this, in manufacturing systems an increasing importance has been placed on end-of-arm tooling, making the design one of the most crucial components of an overall assembly system. A proper gripper design can simplify the overall assembly, increase the overall system reliability and decrease the total cost of implementing the system. The importance of the gripping system design is evident and a large new research field has been emerged in the industrial sector [3].

1.1 Mechanization and Robotics

Over the last decades the manufacturing landscape has changed worldwide. The changes can be attributed mainly to the variations at the level of trade barriers and the development of more efficient modes of transportation and communication. Moreover, the level of innovation has dramatically grown to such an extent that, in order for firms to be familiar with the best products, processes, materials and technologies, they must have access to international operations. In 2002, the share of total global manufacturing trade was 18% for the European Union, while the US had 12% and Japan 8%. However, besides the main regions, which have been traditionally active in the manufacturing world, today, there are a lot of other spots all over the globe that significant manufacturing activities take place [4].

Technological advancements, new competitors, global sourcing and industry restructuring result in great challenges for the industrial sector. The transition from mass production to mass customization is based on the need for more customized products, providing many variants using fewer resources in the shortest time possible. Increased complexity in the assembly technologies, requires a holistic perspective of the main manufacturing attributes that need to be considered when manufacturing, decisions as regards cost, time, quality and flexibility [5].

All of the above justify the increasing trend of robots being moved into environments originally designated for human use. In industry, robots of human size are expected to replace human workers without major redesigns of the workplace. The ability to use human and robot workers interchangeably is thought to be the key to low-cost, flexible automation. As robots used in hazardous environments increase, so does the need for robots that are well adapted to these intrinsically human-centric environments. More advanced robots designs are expected to act and manipulate objects in ways similar to humans [6].

Robot users demand versatility in their processes as a result the role of robot end-of-arm tooling has never been more important. Manufacturers are under pressure to deliver flexible, intelligent end-of-arm tooling that adds value to the overall system. In robotics technology, grippers belong to the functional units having the greatest variety of designs. This is due to the fact that, although the robot is a flexible machine, the gripper performs a much more specific task. Nevertheless, these tasks are not limited to prehension alone which is why the more generic term “end-effector” is often used [2].

The great number of different requirements, diverse workpieces and the desire for well adapted and reliable systems will continue to stimulate further developments in future end-effector design. Experience indicates that in the future it will only be possible to respond to practical demands if flexible designs for assembly equipment are available. This explains why an overwhelming proportion of corresponding patent literature is devoted to prehension concepts of unconventional design. In general, end-effectors are not normally within the delivery remit of robot manufacturers. Depending on the specific requirements, they are selected as accessories from tooling manufacturers or specially designed for a given purpose [2].

1.2 Definitions

Use of the term robotics in any scientific or research endeavour carries an additional and important burden beyond what we expect from other areas of research: advancements deemed to be robotic in nature, can not only increase our collective knowledge but they must also demonstrate a path to perform useful work in the real world [7].

From the multitude of functions of the human hand, gripping stands out as the most important. According to the definition provided by the Romanian language dictionary, gripping is ‘the hand’s action of seizing by means of fingers, claws and tweezers’. While the gripping ability of limb extremities can also be found in animals, it reaches its highest functionality in humans [1].

The human gripping function entails a sequence of phases, starting with selecting the seizing modality, followed by the actual gripping and concluded with the control of the manipulated object. A wish, generated internally or externally, triggers reaction in the brain and at visual level. Consequently to such reactions the hand is positioned close to the targeted object, which it subsequently seizes and further carries out the programmed task. Figure 1.1 presents the command flow of a human gripping action [1].

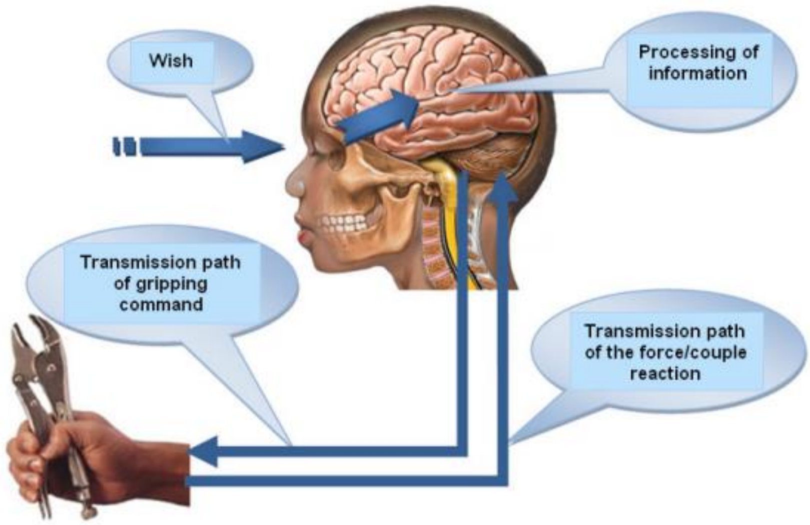


Figure 1.1 Command flows of a human hand gripping action

In robotics, gripping means contact of the effector element of a robot and a body in view of its manipulation. Grasping organs or tools constitute the end of the kinematic chain in the joint system of an industrial robot and facilitate interaction with the work environment [1].

Grippers are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements [2].

The term 'universal robotic gripper' has been used to describe a subset of robotic end-effectors that can grip a wide variety of arbitrarily shaped objects. Although universal grippers cover wide clamping ranges, in many cases they must be adapted to the specific workpiece shape [7]. As a result the term gripping is used not only for situations describing an actual mechanical seizing of an object by means of fingers, but also for the retaining of a body by means of vacuum, a magnetic or electrostatic field, by adhesion etc. [1].

The main functions of robotic gripping systems include temporary maintenance of a final position and orientation of a body in relation to the manipulation equipment, firm holding of the gripped object under static or dynamic conditions and modification of position and orientation of the gripped object depending on the requirements of the application. In Figure 1.2 a general flow-chart of a gripping system is presented [1].

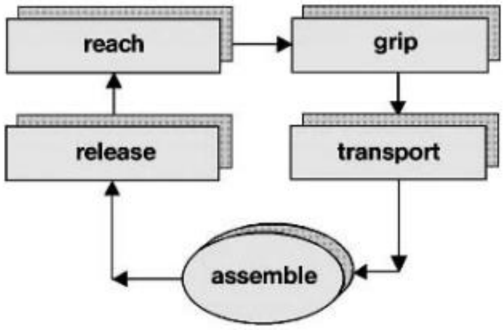


Figure 1.2 Flow-chart of a gripping system

1.3 Grasping in nature

In the course of nature's evolution many different interesting grasping mechanisms have been created. Back to the 19^{th} century many scientists analysed among others, animals' mechanisms of motions. Some characteristic examples, shown in figure 1.3, are the mouths of fish and bird's beaks which are especially used to perform prehension tasks. The use of astrictive force is also nothing new in nature. Such techniques are used by fauna as suction feet in cephalopods. Lizards possess adhesion lamellae on their toes (dry adhesion) which enable them to traverse glass plates using their surface roughness [2].

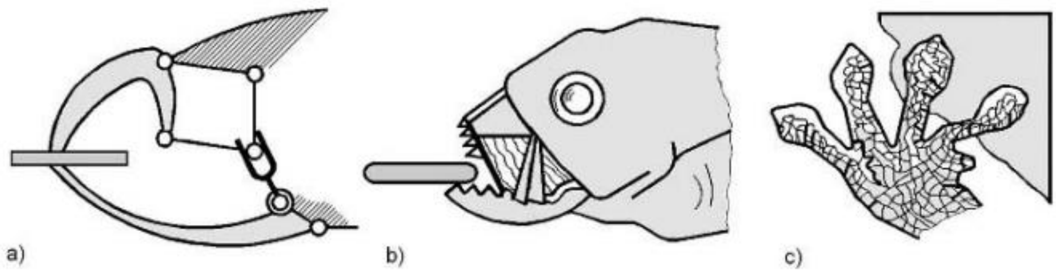


Figure 1.3 Natural grasping, holding and mastication mechanisms a) dird's beak, b) fish mouth, c) suction foot

Nature often provides fresh impetus and new approaches to solutions for industrial applications. There are in fact many grippers whose kinematic principles are strongly related to those of bird's beaks or elephant's trunks, for example in paint spraying or to encompass an object. In order to handle fragile objects, grippers which imitate the musculous hydrostates of squid tentacles are widely known. The prehension and mastication organs of insects resemble impactive grippers [8].

If one considers the osprey, it is obvious that the problem of "grasping under complicated conditions" has been solved in the course of biological evolution in a very interesting manner. The osprey is able to grasp objects whose surfaces enjoy extremely low friction coefficients during flight. More specifically, the grasping foot exhibits long-drawn and sharp claws which make it possible to catch the prey (ingressive prehension). The lower part of the foot exhibits soft pads with a high coefficient of friction (buffered impactive prehension). During grasping these pads produce a suction (astrictive prehension) effect against the smooth surface of the object. Hence, in this case several effective prehension principles are combined. Indeed, there also exist robot grippers which prehend by impactive clamping and simultaneously use vacuum suction, as shown in Figure 1.4 [2].

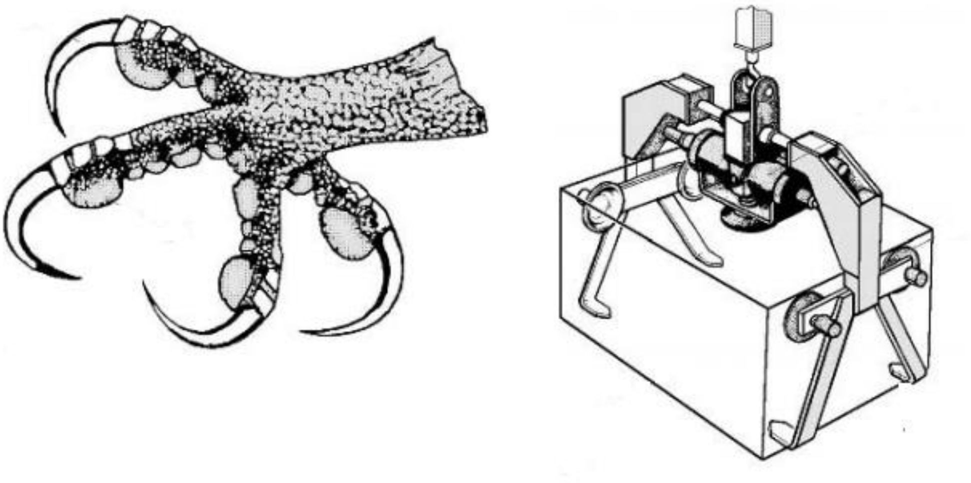


Figure 1.4 Combined grasping methods – Osprey kinematic mechanism

Crab pincers are another good example often imitated by man. The crab arms end with a robust scissor mechanism which serves for both grasping and pressing. From the point of view of kinematics, it is simply a matter of the successive coupling of two four-link spherical gears, as you can refer to Figure 1.5. The crab has developed an ingenious solution to the articulation between arm members. It is based on two spherical joints of polar cap form housed concentrically within one another. These spherical joints consist in turn of several additional shells whose surfaces serve as slip and contact areas. Such joints are of special interest for miniaturized mechanisms since joint solutions of the “fork head – pin” type cannot be arbitrarily downscaled [2].

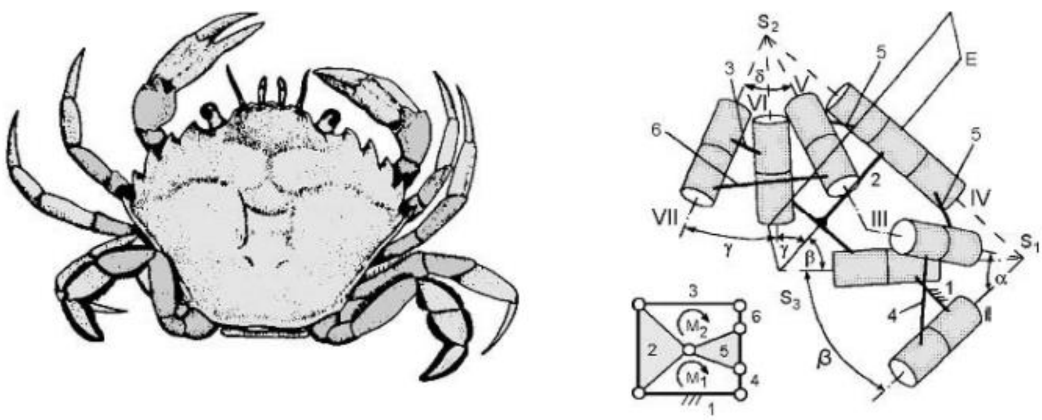


Figure 1.5 Combined grasping methods – Crab kinematic mechanism

The famous Greek philosopher Aristoteles described the hands as “the tool of all tools”. The 5-finger human hands represent a particularly flexible and useful grasping organ, particularly in conjunction with control through eye-hand feedback. There are 8 carpal bones, 5 midhand bones (one for each finger), and 14 links (two for the thumb and three for every other finger). This anatomic constellation enables a total of 22 degrees of freedom in which as many as 48 muscles are involved. The above assembly mechanism is involved in practicing, memorizing, retrieval and variation in a tremendous number of separate grips and represents the ultimate gripping system (Figure 1.6) [2].

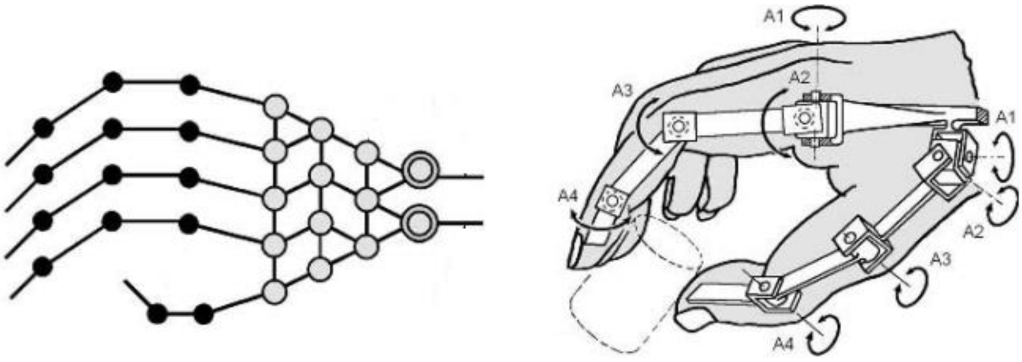


Figure 1.6 The human hand

Focusing on the activities necessary for industrial work, a direct relationship between the hand with the necessary tools and the number of fingers involved in the specific work may be observed. In other words, fingers can be replaced by tools. This relationship is illustrated in Figure 1.7 below [2].

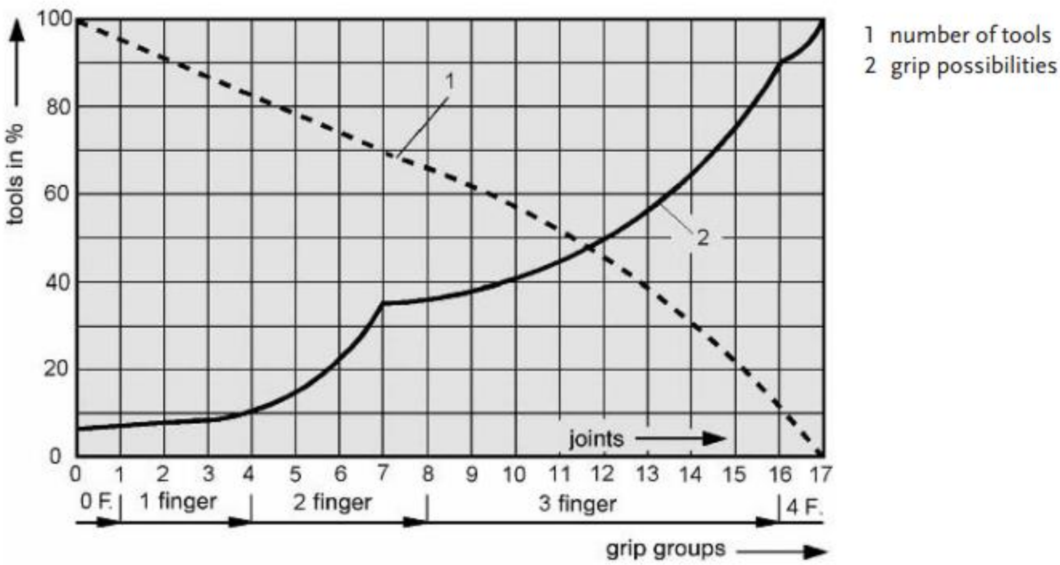


Figure 1.7 Fingers replaced by tools

Zero fingers in the graph should be understood as movement of the arm joints only. As can be seen, the addition of the fifth finger makes negligible contribution to industrial work. About 90% of the grips involved in industrial applications can be realized with a three finger hand. Furthermore, all fingers do not possess the same strength. The middle finger is the strongest one and the little finger the weakest. The strength potential is distributed as follows: index finger 21%, middle finger 34%, ring finger 27%, and little finger 18% [2].

As it is indicated above, a major source of inspiration for new knowledge and future technologies is nature. That is why the industrial sector brings bionic network into life and biology is used as a model for innovative gripping mechanisms [8].

1.4 Scope of work

The scope of the current project is to design, analyse and construct a smart gripper for industrial applications. The project will be focused on the development and combination of different features that give functionality and flexibility to a gripper. One of the main concerns of the thesis, will be the development of the best configuration that combines flexibility, simplicity and cost-effectiveness.

Taking into account the identification of the parts to be manipulated and their orientation in space, the gripper should change its shape in order to effectively grab the components to be handled. The project will be focused on the study of different industrial components with a variety of shapes, sizes and weights. Following an extensive literature review, some alternate design concepts will be developed and evaluated using Quality Function Deployment (QFD) method.

The prevalent design solution will be improved using Design for X and Failure Mode Effects Analysis (FMEA) methods. When the design will be finalized, a study of kinematics, dynamics and strength of materials will follow using CAE software. The end-effector will be constructed by purchasing as many components as possible and constructing the rest in the university's workshop. Adaptation to Staubli robot and testing of the mechanism will be the last steps of this thesis.

Therefore, the main goal of the project is to introduce a new idea of smart gripper which stands out from the ones already used in industry. Design as part of the robotics is the main challenge of the thesis, and afterwards the constructability of the mechanism is determined crucial.

1.5 Thesis Organization

As outlined above, Chapter 1 introduces the new era of industrialization and the requirements of the market and states the problem analysed in the current thesis along with its specifications and restrictions. Chapter 2 presents a literature overview on the classification of end-effectors and focuses on some interesting models present on the market. On Chapter 3, the basic design methodology is stated and the alternative design solutions developed are presented. Chapter 4 presents the main principles of selection and failure analysis techniques and details the selection system through which the above concepts are evaluated. Chapter 5 presents the analytical modelling of the prevalent mechanism. Chapter 6 includes the preliminary stages of construction of the end-effector. Finally, Chapter 7 details the conclusions and future work for this research.

CHAPTER 2 GRIPPERS

2.1 Gripping characteristics

2.1.1 The grasping process

The complexity of the grasping process is often underestimated since it looks very similar for human beings. However the automation of this process creates many problems. In fact, the design of a gripper does not depend only on the object characteristics but it is also affected by previous phases as feeding and following phases such as handling, positioning and releasing [9].

Neglecting the further requirements due to feeding and handling, the grasping process can be divided into the following phases (Figure 2.1) [2], [9]:

- Preparation for contact
  - Approaching: The gripper is positioned nearby the object
  - Coming into contact: The contact is achieved
- Prehension by establishing contact
  - Static forces and moments are increased
  - Securing: The force stops increasing when the desired degrees of freedom of the object are removed and it stops moving independently from the gripper
- Retention and object manipulation
  - Moving: The gripper and the object are joined and can be moved together
- Release at final destination
  - Releasing: The grasping force is deactivated physically or through technical releasing strategies
- Monitoring: Several sensors can be used to detect and monitor the process

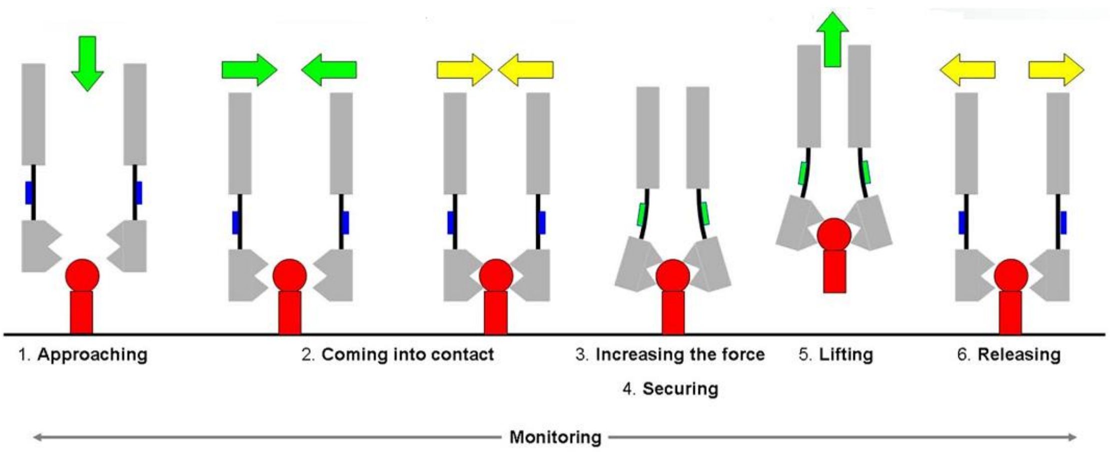


Figure 2.1 Typical phases of the grasping process

2.1.2 The grasping principles

The design of an industrial gripper must ensure a secure, robust and reliable grasping. In manufacturing technology the term 'active pairs', i.e. gripper jaw and workpiece, is often used. However, the types of the contact are also important. In the past, the classification was limited to three gripping methods: clamping, suction, and magnetic adhesion. Another categorization distinguishes between single-sided contact (vacuum suction, adhesion), double sided contact, and multilateral contact as in the case of shape adaptive gripper jaws. In addition, other physical (adhesion, interaction) forces may also be considered. The below table shows a primary classification comprising four gripping categories [2].

Active pair		
Gripping method	**Non-penetrating**	**Penetrating**
Impactive	Clamping jaws, chucks, collets	Pincers, pinch mechanisms
Ingressive	Brush elements, hooks, hook and loop (Velcro)	Needles, pins, hackles
Contigutive	Chemical adhesion (glues), surface tension forces	Thermal adhesion
Astrictive	Electrostatic adhesion	Magnetic grippers, vacuum suction

Figure 2.2 Gripping method classification

Further to the above, the grasping principle can be defined as ‘the physical principle which causes the force effect necessary to get and maintain the part in a relative position with respect to the gripping device’. Last years, the above gripping classification has been enriched due to physical and industrial advancements. Some principles are used in the macro domain while others are more effective in micro-handling applications. Below a brief description of the latest grasping principles is available, also presented in Figure 2.3 [9].

1. Mechanical grippers based on friction or on form closure are the most widespread but also intrusive grippers belong to that class.
2. Suction based and magnetic grippers dominate the metal sheet handling.
3. Bernoulli grippers work on the basis of airflow between the gripper and the part, causing a force that brings them close together.
4. Electrostatic grippers are based on charge difference between the gripper and the part.
5. Van der Waals grippers are based on the low force due to the atomic attraction between the molecules of the gripper and those of the object.
6. Capillary grippers use the surface tension of a liquid meniscus between the gripper and the part.
7. Cryogenic grippers freeze a small amount of liquid and the resulting ice produces the required force.
8. Ultrasonic grippers generate standing pressure waves used to lift up a part.
9. Laser grippers produce an optical pressure able to trap and move microparts in a liquid medium.

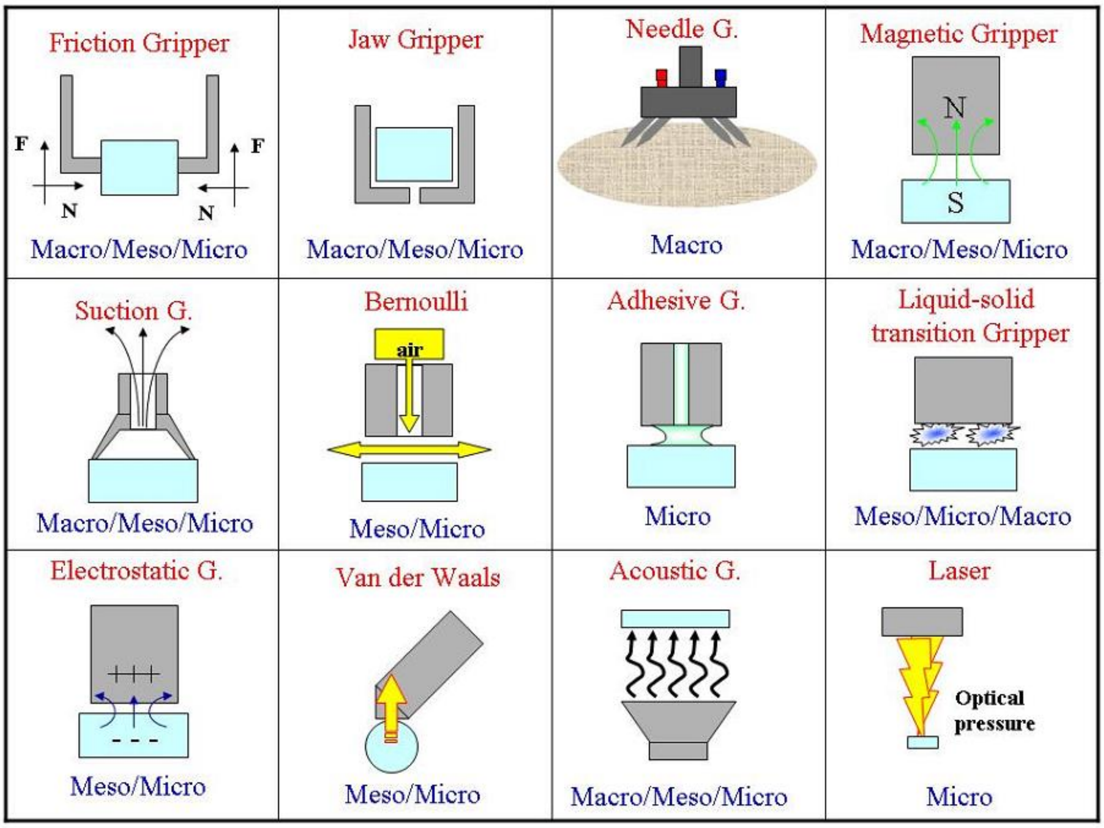


Figure 2.3 Grasping principles

2.1.3 The releasing principles

In general the releasing phase is achieved through gravity when the grasping principle is deactivated. However, in some cases gravity is not sufficient. As shown in Figure 2.4, releasing strategies can be divided into two categories [9]:

1. Passive strategies obtained by reducing surface forces
2. Active strategies where an additional force allows the gripper to release the object

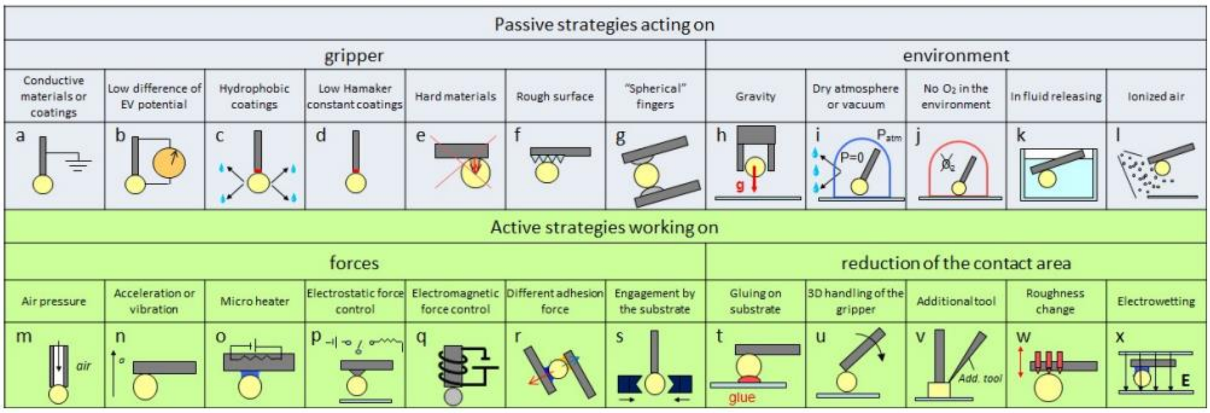


Figure 2.4 Releasing strategies

2.1.4 The monitoring principles

The presence of the object and its correct grasping are generally monitored through sensors. These sensors may be integrated into the gripper or might be mounted on an external fixture. Different kinds of sensing principles for the three main parameters (presence, force/torque and position/orientation) have been proposed. Below on Figure 2.5 an overview of sensor principles is presented [9].

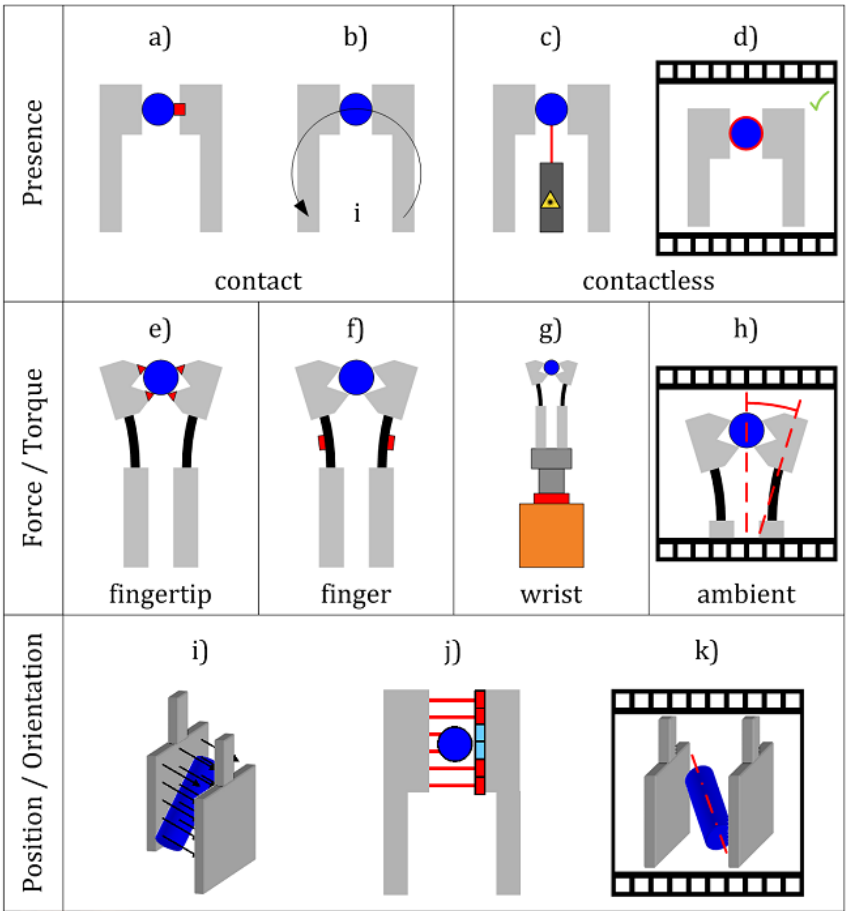


Figure 2.5 Sensing principles: a) Mechanical switch, b) Electrical sensor, c) Photoelectric sensor, d) Vision based sensor, e) Tactile sensor, f) Strain gauges, g) Force/torque sensor, h) Vision based, i) Capacitive/electrostatic, j) Led-photodiode, k) Vision based monitoring

2.2 Types of Robotic Grippers

Based on the grasping process described above, several factors such as grasping force, grasping configuration, transmission characteristics along with gripper technology, flexibility and cost effectiveness are taken into account for the design peculiarities of grippers. Consequently, there are four main types of grippers, along to their design characteristics, encountered in the literature [10].

2.2.1 Piezoelectric Grippers (Figure 2.6)

Research has focused on utilizing piezoelectric grippers for active manipulation because of the low price of piezoelectric materials. Some benefits of piezoelectric grippers are the simplicity, the ease of use, and the low power consumption compared to mechanically actuated grippers. They are ideal for micro and nano gripping as they can manipulate objects down to 50 µm with only the actuator itself. Although a wide variety of designs have been proposed with different control approaches, the main challenge that still persists is the position control and the stability of piezoelectric grippers [10].

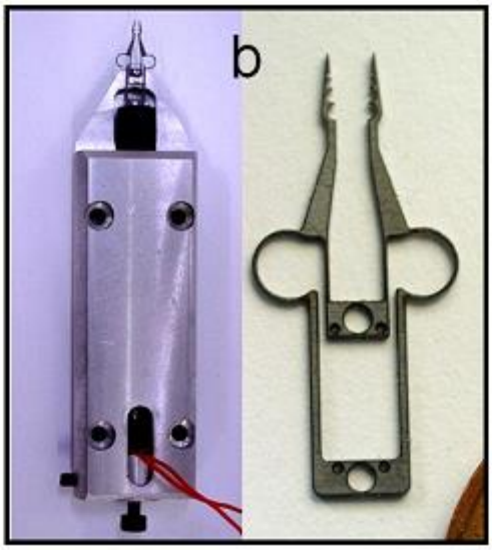


Figure 2.6 Example of piezoelectric gripper

2.2.2 Multi-Fingered Grippers (Figure 2.7)

Recent end-effectors have been developed to increase the flexibility of the parallel grippers. By using multi fingers, the available motions for the robots are increased. Fingers are made of soft materials to increase adaptability. Under-actuated mechanisms are usually used, while grasping and holding capabilities are tested on different sizes and shapes. The wide adaptability of these mechanisms makes them good applications for morphological computation principles in bio-inspired robot designs [10].

Figure 2.7 Example of multi-fingered gripper

2.2.3 Enveloping Grippers (Figure 2.8)

Grasping oddly shaped objects has been an ongoing challenge in end effector design. Some grippers were developed on enveloping and underactuated mechanisms. This new type of gripper is valuable due to its adaptability to mold around the object it is holding. The advantages of this design allow continuous clamping of smooth edged objects, as well as manipulation of objects bigger than the end-effector itself. Enveloping grippers are mainly biologically inspired and recent advancements showed that by developing such novel mechanisms, more autonomous grippers with less control effort compared to multi-fingered grippers are implemented [10].

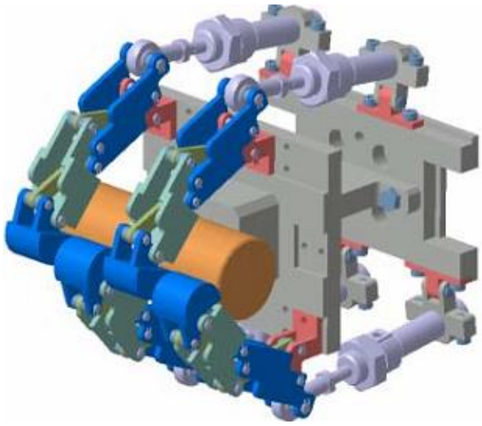


Figure 2.8 Example of enveloping gripper

2.2.4 Malleable Gripper (Figure 2.9)

Malleable grippers are made from materials that change viscosity. They are typically made from a flexible outer skin with materials inside being either: electrorheological (ER) fluid, magnetorheological (MR) fluid or pellets. The outer is pushed up against the object and it molds to the geometry. The inside is then hardened to provide an impactive force to hold the object. During release process, the inside will return to a more fluid like state to allow for free movement. These soft grippers are mainly used in shape-adaptable grippers, which are not only soft, but also strong and versatile. In summary, malleable grippers are highly flexible in grasping objects with different shapes, however their dexterity remains a design challenge [10].

Figure 2.9 Example of malleable gripper

As discussed above, the ability of the grippers to grasp different types of objects based on the categories of Impactive, Ingressive, Astrictive and Contigutive can be compared. As presented below in Figure 2.10, impactive grippers have been used in applications of picking up different types of objects from solid flat to oddly shaped and fragile. Astrictive grippers, similar to impactive grippers, have been used for different types of objects more commonly for fragile and irregular objects. No results have been reported, to the best of our knowledge, regarding employing astrictive grippers for irregular shaped objects. Ingressive grippers have been used in grasping flexible sheets. Contigutive grippers have been used in grasping solid flat objects, rigid and flexible sheets [10].

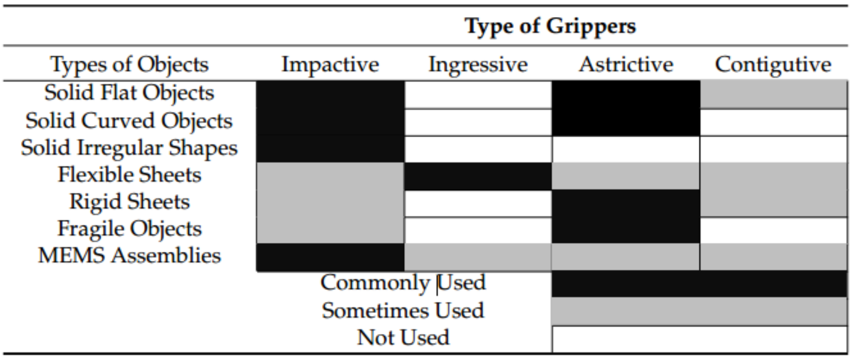


Figure 2.10 Comparison of gripper's ability to pick up different objects

2.3 Recent trends in Robotic Grippers

Further to the basic gripper types presented above, recent trends are even more enriched. Recent trends in terms of actuators and sensors technologies as well as material science have made the grippers more reliable, faster, safer and more robust. New applications have been introduced and doors for new research have been opened on employing new materials and designs or incorporating new technologies.

2.3.1 Servo Gripper (Figure 2.11)

Servo-based grippers offer the flexibility to use the minimum necessary clearance to approach a part, with a minimum stroke to pick it up. The position of the gripper's finger is totally controlled with partial opening and closing of the fingers, something that helps to pick a wider range of part sizes without compromising the cycle time. Using encoders, it is possible to determine if a part has been picked up by the gripper. This grip detection, avoids putting other sensors in the loop, simplifies integration and reduces overall cost. As the electric motor current is directly proportional to the torque it applies, it is possible to control the grip force and the closing speed applied by the gripper. The use of servo grippers reduces the operating costs as well as the cost of energy used [11].

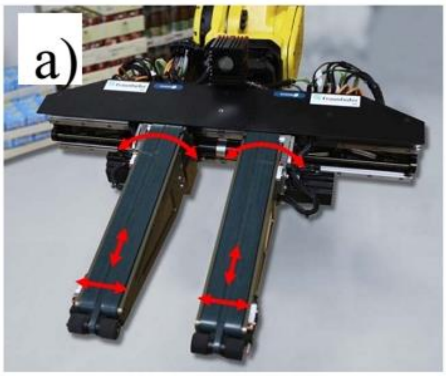


Figure 2.11 Servo gripper

2.3.2 Modular Vacuum Gripper (Figure 2.12)

Modular vacuum grippers are designed to handle various kinds of materials in varying shapes and sizes. 'Vacuum bars' as they are called, are designed to handle various materials such as wood, metal sheet, glass or plastic with different shapes, surfaces and dimensions. They can grip loads weighing up to 2000 gr regardless the product type and with process accelerations of up to 10 g. They are ideal for use in the packaging industry as the standard quick-change adapter reduces changeover times to the minimum. The materials used for their fabrication make them clean grippers, with the advantage to be used in the food processing industry too [11].

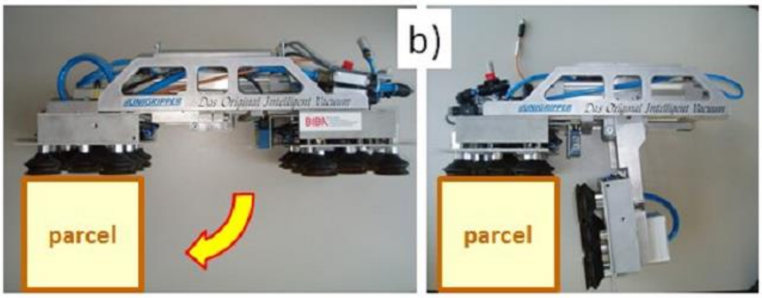


Figure 2.12 Modular vacuum gripper

2.3.3 Hybrid tooling (Figure 2.13)

Hybrid tooling combines multiple gripper technologies in one end-of-arm. The main idea behind this design is that they can grip all the products without changing tools. To accomplish that, different technologies should be combined all in one. For example, part of the tool has suction while another part has a mechanical clamping arm around it. This end-of-arm technology is ideal for high-speed, heavy weight or press tending applications [11].

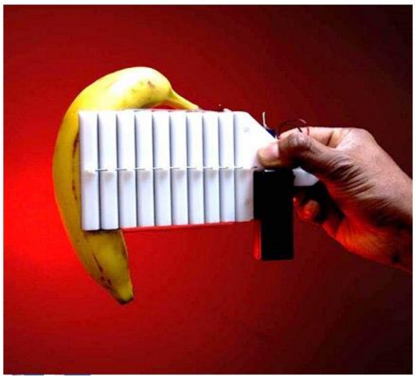


Figure 2.13 Hybrid tooling

2.3.4 Anthropomorphic and adaptable finger grippers (Figure 2.14)

These grippers are known as the 'mechanical intelligence' designed to handle a wide variety of part shapes, sizes and composite materials. The idea is that by using a single robot gripper, the user saves on tooling costs and can improve process efficiency. They are designated for use to day-to-day manufacturing where engineers want to automate labour-intensive processes with high part variability. In that case, single robot grippers achieve time saving on changeovers and reduced tooling costs. They are also valuable for advanced manufacturing and research [11].

Figure 2.14 Antropomorphic and adaptable grippers

2.3.5 Switchable magnetic technology (Figure 2.15)

This patented technology uses opposing magnetic field to effectively turn on and off a magnet or collapse the magnetic field. They can deal only with metallic gripping parts with the smallest one weighing 0.2 lb and a maximum holding force of 55 lb. They are small devices, 20 to 35 % smaller than the traditional mechanical grippers and they are capable of reducing the air consumption by around 90% [11].

Figure 2.15 Switchable magnetic grippers

2.3.1 Advanced tool changers (Figure 2.16)

Tool changers are flexible, robust and easy to use. The modular construction allows integration with applications requiring high power, coolant, servo and discrete signal capabilities by incorporating separate modules that can be mounted on any flat. In addition to the flexibility, tool changers provide many safety aspects to the operator. One of the primary benefits of tool changers is maintenance. The tool exchanger can achieve this task in 3 to 6 seconds, reducing the man-hours needed in the past for the exchange. Additionally, safety for the operator is the most important aspect of this technology, as all the changing procedure is totally automated [11].

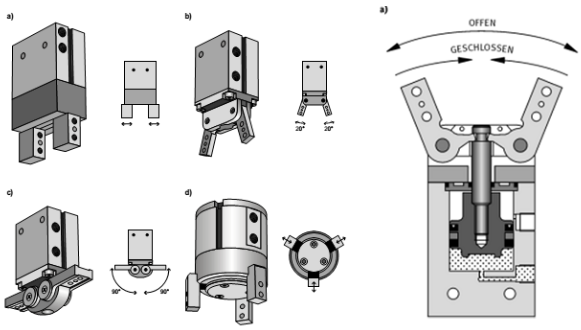


Figure 2.16 Advanced tool changers

2.4 Intelligent gripper designs

There are several ongoing attempts to improve grippers mainly in two fields, performance and flexibility. Performance indicates accuracy, speed, readability, gripping strength, robustness and flexibility denotes a variety of objects that can be grasped. Grippers with mechanical simplicity and robustness versus grippers with flexibility and adaptability are two extreme objectives in robotic gripping [10].

An extensive literature review has been conducted as part of this work and the most worth mentioned gripper designs will be presented below. Several advancements of performance and flexibility of robotic grippers will be obvious through different orientations of designs and applications.

2.4.1 A modular 3D printed underactuated hand

This project establishes the design of an adaptive four-finger hand, utilizing 3D-printed components, compliant flexure joints and readily obtainable off-the-shell parts (Figure 2.17) [12].

Figure 2.17 Modular 3D printed underactuated hand

The presented hand reproduces the functionality of a previous design, an underactuated four-finger hand with compliant flexure joints driven by a single actuator. Underactuation in robotics offers the advantage of grasping items of various shapes and sizes by passive adaption to the object's geometry. On the figure below, the two primary phases of an underactuated power grasp are shown: the sweeping phase, where the proximal finger links contact the object and the caging phase, where the distal links make contact to fully encompass the object [12].

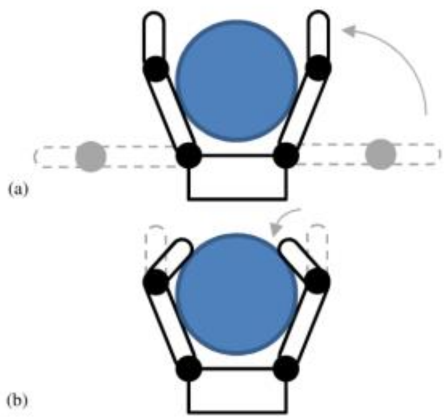


Figure 2.18 Main phases of adaptive power grasping: (a) sweeping, (b) caging

The use of a single actuator supposes that underactuation both between the fingers and within the individual fingers, is necessary in order to maximize the grasp contact such that if contact on any finger is obstructed, the others continue to move until the hand fully envelopes the object in a power grasp. Between the differential actuation mechanisms options (Figure

2.19), the current hand uses a hybrid pulley/whiffle tree differential which offers the advantage of the smallest packaging size [12].

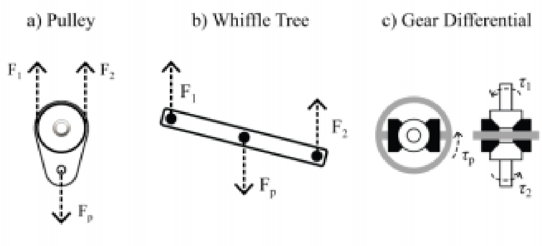


Figure 2.19 Actuation differential types

The finger design of the hand is modular and monolithic and can be easily switched out, in order to best accommodate any desired task. The rigid parts of the fingers are a single part while series of small dove-tail joints distributed along the length of the finger pad are used. The basic set of finger parameters used in underactuated fingers includes joint moment arms R, link lengths L, joint stiffness K and initial joint resting angles. In Figure 2.20, a diagram of the finger is presented where all the above parameters and characteristics are present. Then Figure 2.21, presents the manufacturing stages of the finger until it reaches its final form [12].

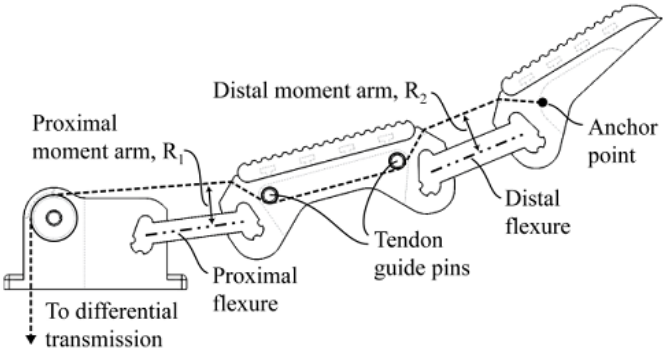


Figure 2.20 Finger design

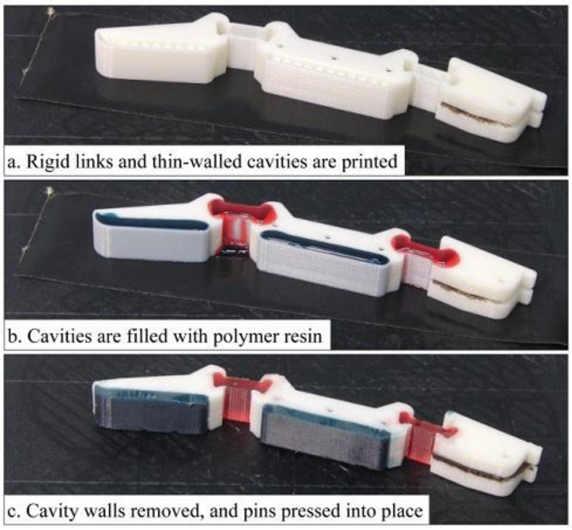


Figure 2.21 Finger fabrication process

In the context of this work, a low-cost design of an underactuated hand with compliant joints was developed through 3D printing method. This design offers the advantage of dealing with irregular shaped objects through form closure gripping. This project offers a simple and minimalistic design which can be easily reproduced and customized towards the development of innovative robotic hands.

2.4.2 A two-fingered gripper with pneumatic actuation

The goal of this work is the design of a new two-fingered gripper with pneumatic actuation and force control by using commercial components and easy operation features (Figure 2.22) [13].

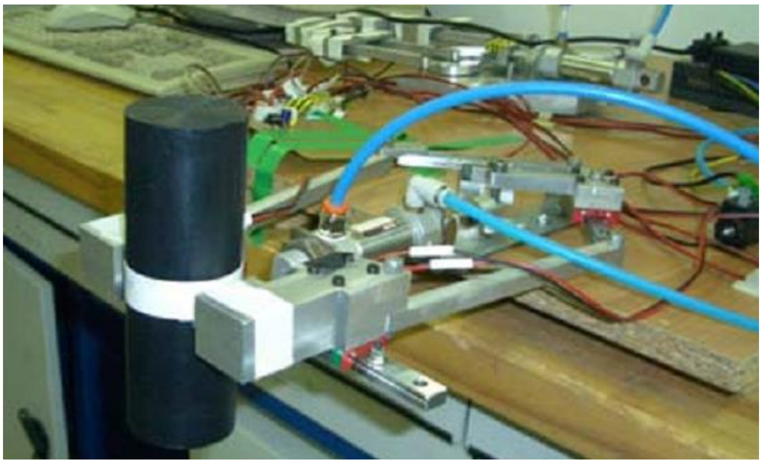


Figure 2.22 Two-fingered gripper with pneumatic actuation

The gripper uses articulated mechanisms in order to drive the movement of both fingers and a pneumatic actuation is achieved through a pressure proportional valve. According to the electronical scheme provided in Figure 2.23, an electrovalve reassures the desirable response both from kinematic and force attribution. More specifically, an acquisition card operated by a virtual instrument measures force signal from finger sensors, while a commercial PLC manages the closed-loop force control block used for the regulation of a prescribed gripping force value. Then, the signal of the force is used as feedback analogue signal as well as for monitoring the action of the grasping force [13].

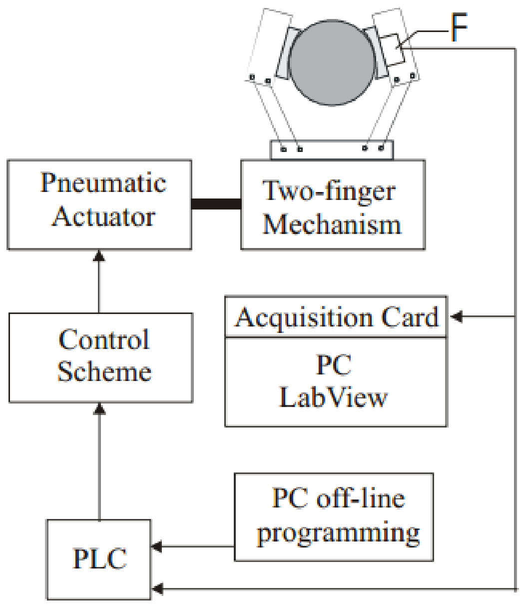


Figure 2.23 Electronical scheme

The mechanical design of the gripper prototype has been based on the kinematic model shown in Figure 2.24. Figure 2.25 also presents the 3D CAD model developed for simulation of the gripper's operational capabilities. The driving mechanism is a four-bar linkage mechanism that has been adapted for a pneumatic actuation, while actuation is achieved by connecting directly the first link of the driving mechanism to the pneumatic device. Experimental grasping tests with different objects have been carried out after the design and the operating simulation of the proposed gripper design. The maximum grasping force that has been obtained during these tests has been about 12 N [13].

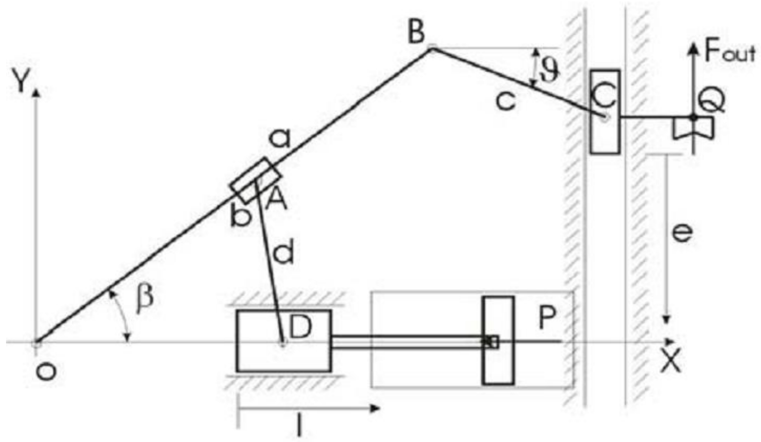


Figure 2.24 Kinematic model

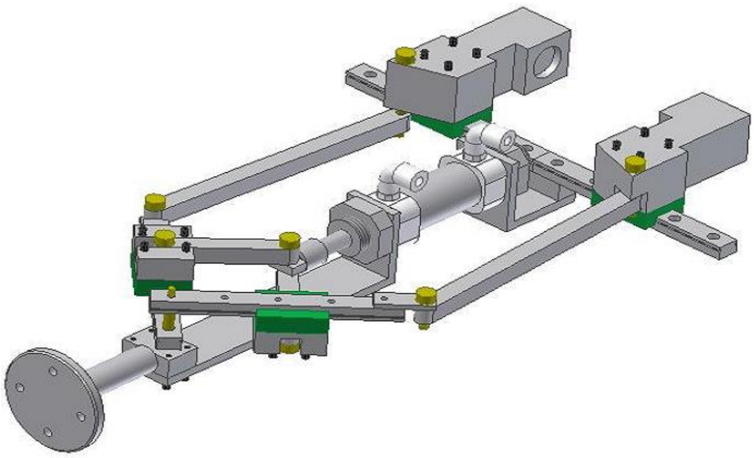


Figure 2.25 3D CAD model

The final results of experiments conducted in the context of this work, present a successful performance in friction grasping but for a limited range of objects' shapes and sizes. The mechatronic approach used can be easily designed for electrically actuated grippers by using suitable electrical and electronic components. The system design managed to maintain the simplicity of mechanical design and operation and also to keep a low-cost lay-out.

2.4.3 Dexterous robotic gripper for in-hand manipulation

In this research, a novel jaw gripper with human-sized anthropomorphic features is designed, suitable for in-hand posture transitions, such as positioning and twisting (Figure 2.26) [14].

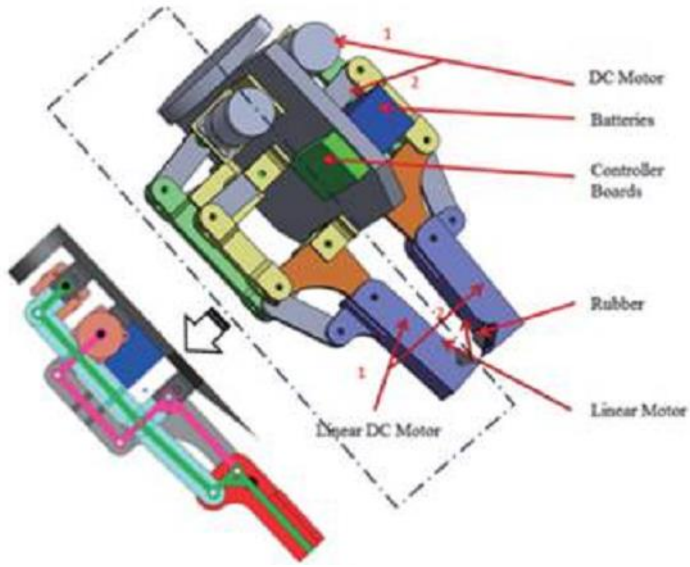


Figure 2.26 Gripper concept design

As a basic assumption in this research is that the general shape of the assembly parts is cylindrical with different surface materials. Additionally, only limited number of possible postures of assembly parts are fitting for effective assembly. The gripper consists of inner and outer fingers. By adjusting the distance between its outer fingers, the gripper can deal with almost every diameter of the cylindrical-shaped assembly parts while the inner fingers slide on the track inside the outer fingers. The system is driven by four motors whose function is to control the contact stability of assembly parts, the distance between the fingers and the twisting movement of fingers in vertical direction. Consequently, this four-degree of freedom gripper can not only open and close for positioning but also twist for effective grasping (Figure 2.27) [14].

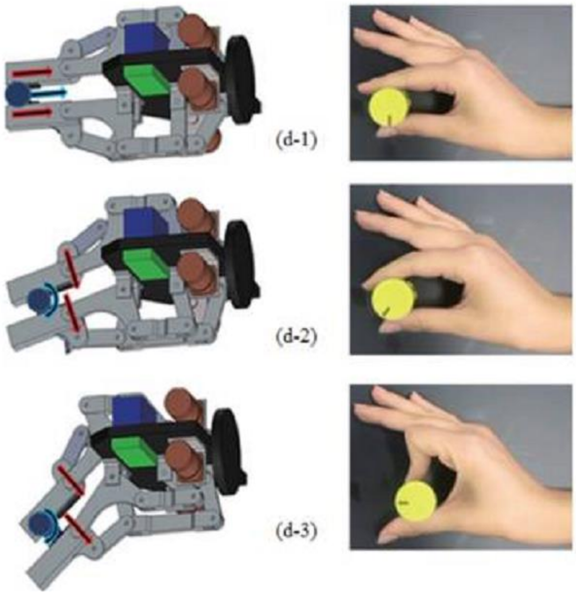


Figure 2.27 Dexterity of gripper

The kinematic scheme of the inner and outer fingers is presented in Figure 2.28. The first four bar link (inner finger) deals with vertical movement while the rotation of the fingertip is given by the second four bar link (outer finger) [14].

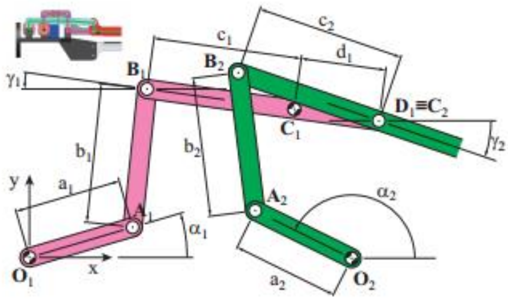


Figure 2.28 Kinematic scheme of gripper

Conclusions of the current work indicate that the developed gripper is ideal for flexible assembly to small-sized manufacturing. The mechanical design offers simplicity and dexterity, achieving precise in-hand posture transitions and effective force closure grasping for axonosymmetric components.

2.4.4 High reconfigurable robotic gripper

The gripper described into this work is designed to be modular, which means that each finger has the same mechanical design, control and electronics so it is easy to equip the gripper with two, three, four or eventually even more fingers. A three-fingered gripper is studied in this work presented in Figure 2.29 [15].

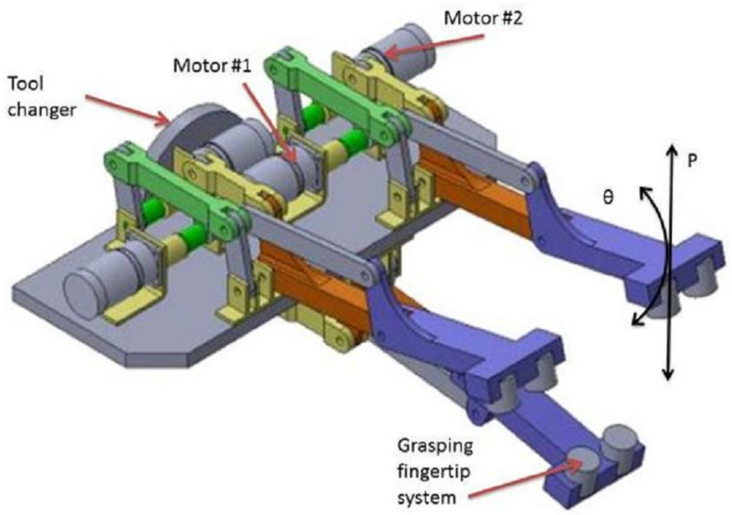
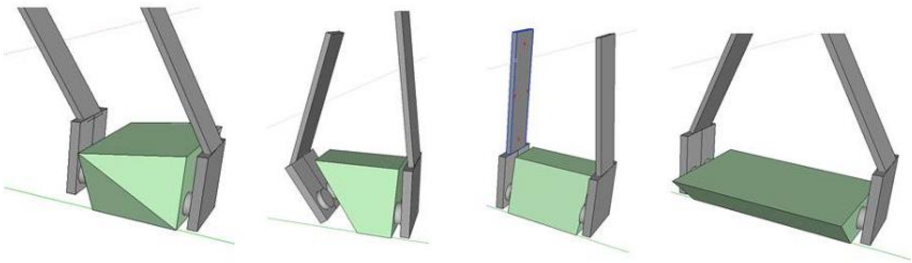


Figure 2.29 Three fingered assembled gripper

The design is based on a multi-finger setting with impactive functionality. Each finger is completely independent with two degrees of freedom, driven by two DC motors one for each DOF. The first motor is responsible for opening and closing the finger tips while the second motor allows the tips to be translated in parallel to the axis of the finger. The range of parts to be grasped is pretty wide which means various shapes, sizes and weights. Depending on the nature and material of the objects to be grasped, the gripper can arrange its shape to grasp each object, while it is also possible to fit on the fingertips electromagnets or pins to benefit from an ingressive or astrictive grasping. Figure 2.30 displays a set of possible grasping strategies for different parts, such as external grip, intermediate grip or internal grip [15].



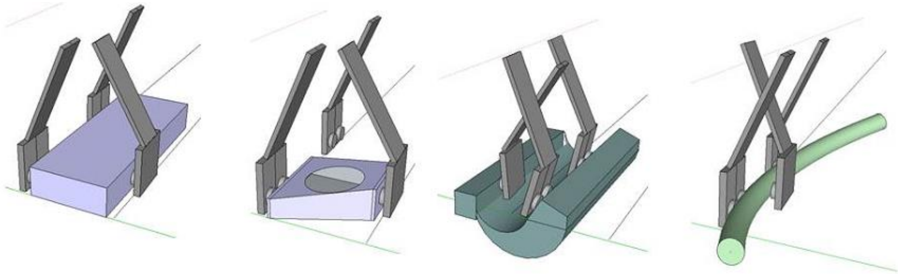


Figure 2.30 Possible grasping configurations

In this work a general-purpose gripper has been illustrated. The main advantage of the design is the multi-finger setting which enables the re-development of the gripper depending to the task designated to perform. A wide variety of pieces differing each other by weigh, regularity or size can be manipulated by installing the appropriate fingertips per case. The modularity of the gripper is perfectly matched with a simple, versatile and easily operated device.

2.4.5 Three finger conveyable gripper

In the context of this idea, a conveyable gripping device has been developed. Figure 2.31 depicts the structural parts of the design [16].

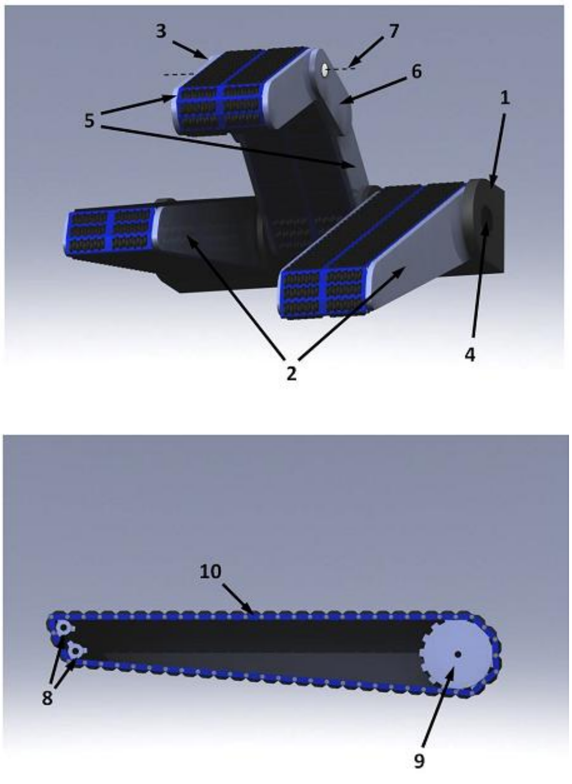


Figure 2.31 Gripper's structural description

Part 1 is the main frame of the device, the object where the gripper head is mounted. Parts 2 are the single-phalanx fingers which support every grasped object while part 3 is the double-phalanx finger which fastens the grasped object in a more secure way allowing its manipulation. Part 4 represents the axis of the fingers which can be one or more according to the design configurations. Parts 5 represent the phalanxes which permit the independent rotation. Parts 6 are the joints that connect the phalanxes. Part 7 is the axis of the second phalanx. Parts 8 and 9 represent the supportive rollers of the chain and the roller of movement respectively. The chain is obvious on part 10 and is responsible for the support of the objects, for grasping and manipulation [16].

As an operational principle, the gripper is moved close to the target object. Then the two-phalanx fingers rotate, in order that the idle rollers get closer to the lower surface of the object to be grasped. The active rollers of the two fingers are actuated and the object is lifted on their phalanges. The two-phalanx finger is adapted to the shape of the object thanks to the joint movement. Actuating all the active rollers of the three fingers, the grasped object can be translated, rotated and spun [16]. Below in Figure 2.32 a graphical view of the above described operation is presented.

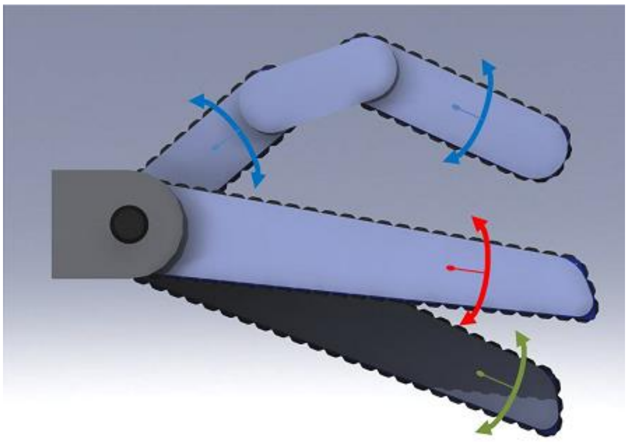


Figure 2.32 Gripper's operational principle

The subject design idea offers the advantage of manipulation and conveyance of objects. Objects of various shapes and sizes can be handled because of the translational and rotational gripper capabilities. It is a simple design offering versatile grasping functions.

2.4.6 The two-fingered 'velvet' gripper

The 'velvet' hand represents an underactuated gripper composed by two identical two-phalanges fingers of enveloping gripping capabilities developed to manipulate and convey objects (Figure 2.33) [16].

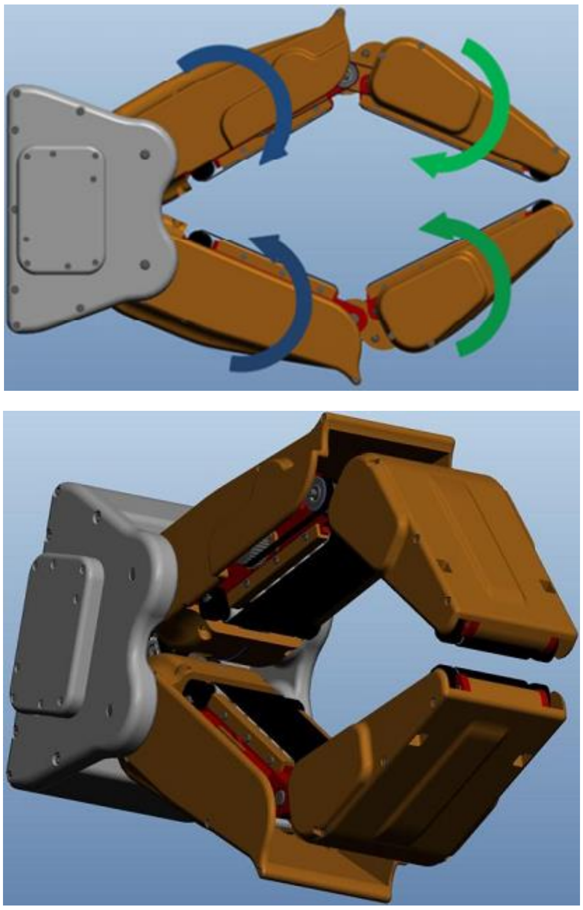


Figure 2.33 'Velvet' gripper

Each finger has a plane belt installed on the inner side which is actuated and controlled to acquire contact with the grasping objects. According to Figure 2.34 below, the individual pieces of the mechanism are presented. Part 4 shows the DC brush motor which actuates both the fingers. Parts B1, B2 are timing belts responsible of motion transmission from the motion shafts 8, 11 to the idle pulleys 20, 21 on the first joint of the finger. Concerning the second link of the finger, timing belt B3 moves the pulley 32 and tension spring 27 keeps the second link in end stroke if no external forces are present. DC brushed motor 38 finally is responsible for the actuation of plane belts PB1, PB2 through 36 motor shaft and B4, B5 timing belts. Parts 33 are the idle rolls on which the plane belts run [16].

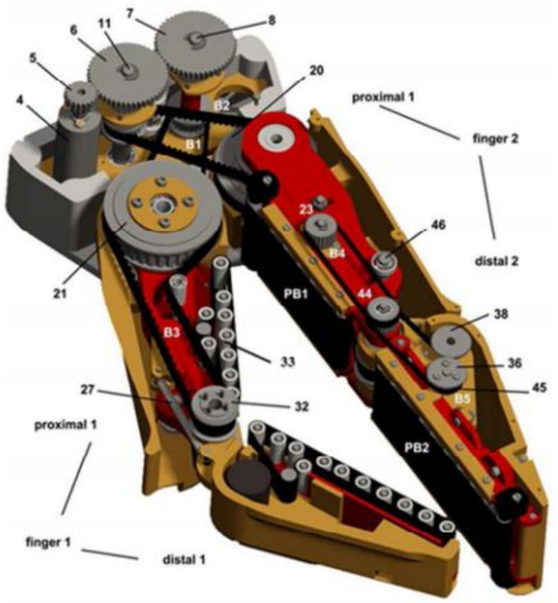


Figure 2.34 Structural description of 'velvet' finger

The kinematic model of each finger is a planar manipulator and its free closure is a V-shape. When the first link acquires contact with the body, the second one rotates until the object is completely grasped achieving an enveloping gripping. The actuated belts manipulate the grasping objects which can be translated and rotated around a controllable centre of rotation within the body, independently from the hardware structure of the gripper. As shown below in Figure 2.35, gripper's manipulation capabilities are obvious by the variety of contact points with the object [16].

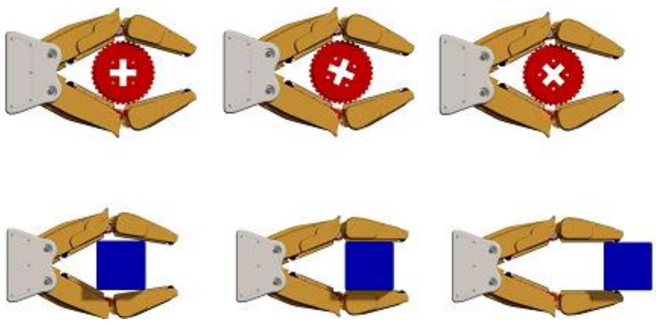


Figure 2.35 Gripper's manipulation capabilities

Velvet hand is a novel gripper design with extended manipulation capabilities. It is ideal for assembling environments while the variety of grasping and manipulated objects is limited to small objects and axonosymmetric configurations.

2.4.7 Passively adapted compliant gripper

An adaptive underactuated robotic gripper is illustrated in this research, with the ability to pick up unfamiliar objects of widely varying shapes and surfaces (Figure 2.36) [17].

Figure 2.36 Gripper prototype

The main characteristic of the present design is the embodiment of 'intelligence' into the mechanism. No sensors or complex controllers are required to perform a task since the mechanical system itself can provide the required adaptive behaviour. More specifically, the gripper has a non-uniform structure since embedded sensors are part of its structure. The main structure is manufactured by silicone rubber while conductive silicone rubber is used for the embedded sensors. A control algorithm based on the changes in embedded sensors voltage is derived to perform tasks of object detection and recognition. Simultaneously, the controller provides the input displacement signal and the gripper adapts its shape accordingly [17]. Figure 2.37 below shows the main gripper features.

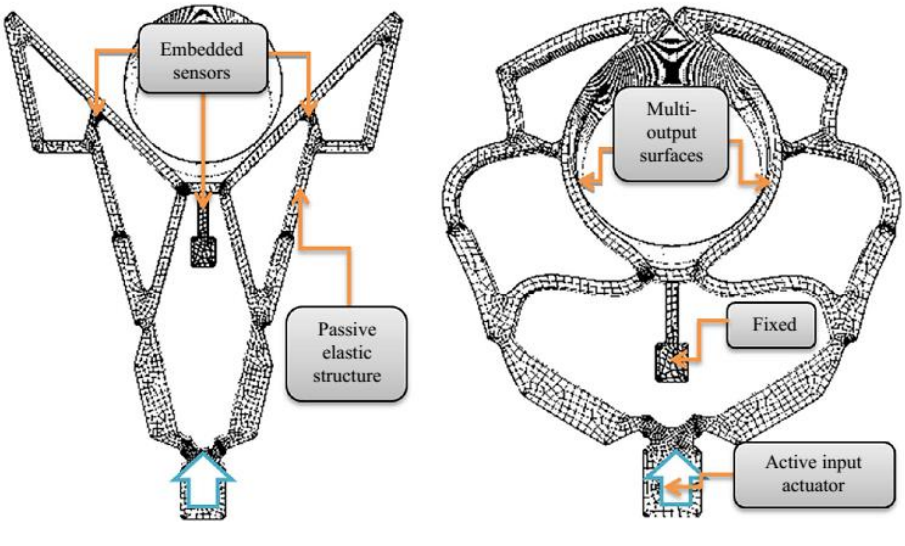


Figure 2.37 Main features of the adaptive gripper

The adaptability of the gripper to different object shapes and sizes is obvious in Figure 2.38 for a variety of different configurations.

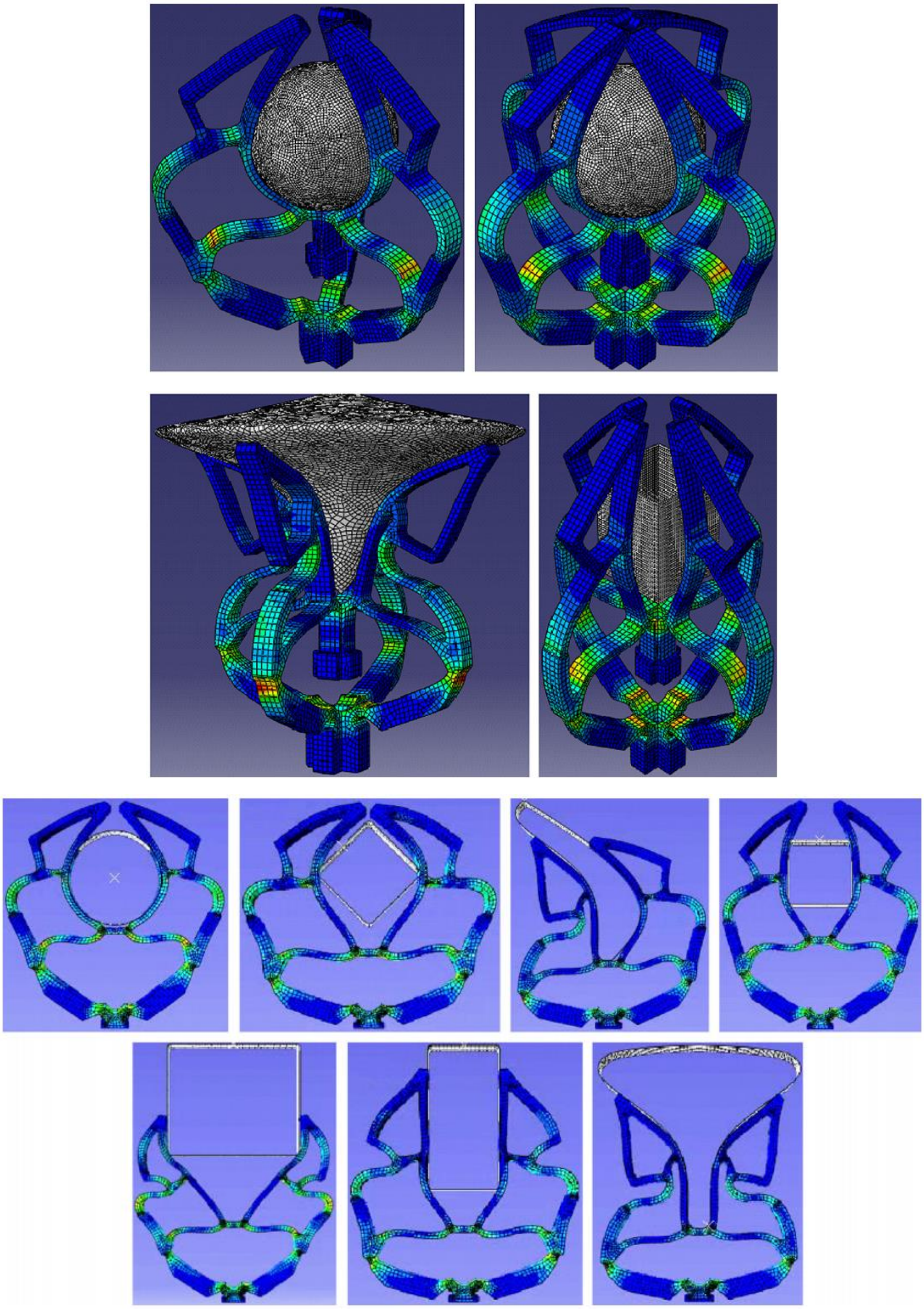


Figure 2.38 Gripper function for various object shapes and sizes

The current work introduces an unconventional passively adaptive underactuated gripper effective in the macro domain. The gripper developed, is easily adapted to any irregular object, has a low manufacturing cost and denotes good sensing capabilities.

2.4.8 Jamming gripper

The current work describes a simple passive universal gripper, consisting of granular material encased in an elastic membrane (Figure 2.39) [18].

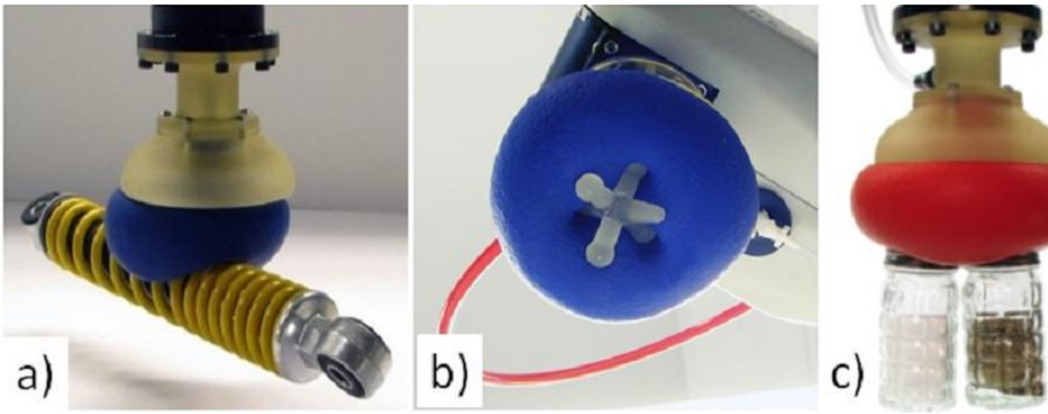


Figure 2.39 Jamming gripper

The gripper can rapidly grip and release wide range of objects that are typically challenging for universal grippers, such as flat objects, soft objects or objects with complex geometries. Using a combination of positive and negative pressure the gripper can perform the grasping process. More specifically, the gripper passively conforms to the shape of a target, then vacuum hardens to grip it, later using positive pressure to reverse this transition releases the object and returns to a deformable state. Below in Figure 2.40, an assembly drawing of the jamming gripper is available.

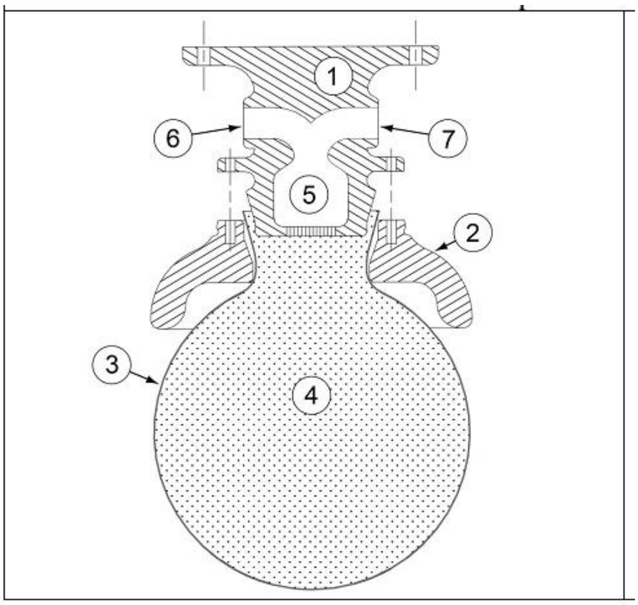


Figure 2.40 Structural characteristics of the jamming gripper

According to the drawing, part 1 respresents the gripper's connection part to the robot and also the inlet and outlet air regulation system is integrated there. Part 2 holds the balloon (part 3) and also improves the grasping performance by the guidance provided to the gripper for its conformity to the object. Part 4 represents the granular material which is contained inside the flexible balloon. Part 5 is the air filter which helps to prevent the suction of the material grains from the balloon. Finally, part 6 is used as a line port through which air is evacuated from the inside of the balloon, while part 7 is a high-pressure port used to reset the gripper shape [16].

The gripper leverages three gripping modes for operation as illustrated in Figure 2.41 below:

- Static friction from surface contact
- Geometric constraints from capture of the object by interlocking
- Vacuum suction when an airtight seal is achieved on the object's surface

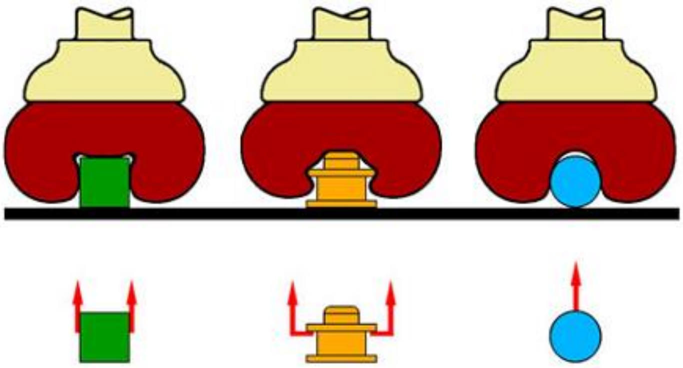


Figure 2.41 Gripping modes operated by the Jamming gripper

The jamming gripper introduced in this work proved to be a reliable and a good option for real-world applications. Such a mechanism is capable to manipulate objects of different shape, weight and fragility while multiple objects can be gripped at once maintaining their position characteristics.

2.4.9 Humanoid hand

In the current work the mechanism and the design of a new humanoid-type hand with human like manipulation abilities is developed (Figure 2.42) [19].

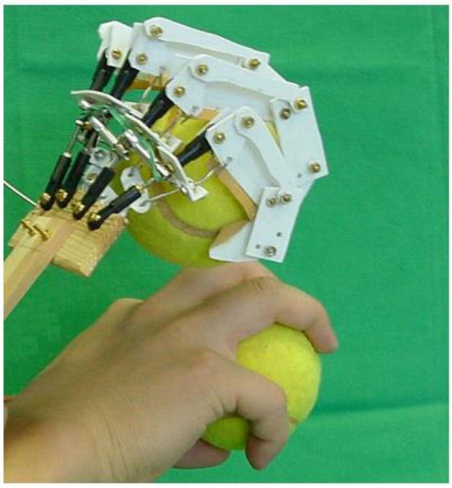


Figure 2.42 Humanoid hand

One of the main characteristics of the humanoid hand is the capability to deal with grasping objects of various geometries. The design requirements of the hand are satisfied with each finger and the palm acting together in a coordinated group, acting in a similar way to the human hand. Figure 2.43 shows how a finger link mechanism works. During the grasping process, the link-rod A pulls the link-plate D and the finger moves keeping its form. When the proximal part touches a target then link-plate D moves independently while the middle proximal part is moved by the link B. The link C attached to the proximal part pulls the distal proximal part. Finally, the finger molds around the target using the appropriate grasping force [19].

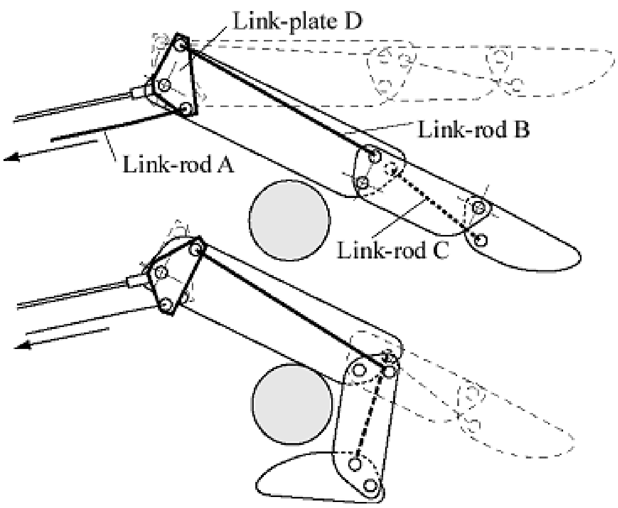


Figure 2.43 Finger's mechanism

The resemblance of the gripper to the human hand makes it a perfect option for grasping a variety of objects. In Figure 2.44 below, several grasping experiments are shown.

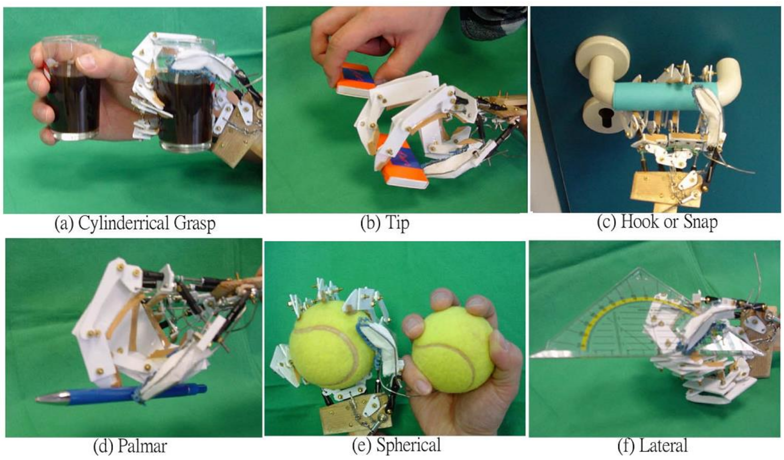


Figure 2.44 Grasping experiments of the humanoid hand

The hand presented here is able to grasp and hold objects using its fingers and palm by adapting the grip to the object's shape through a self-adjustment mechanism. The use only of one actuator simplifies the control system and the design of the hand.

2.4.10 Seabed hand

This is an idea of an adaptive three phalanges mechanism, able to pick up heavy and sensitive objects through enveloping gripping (Figure 2.45) [20].

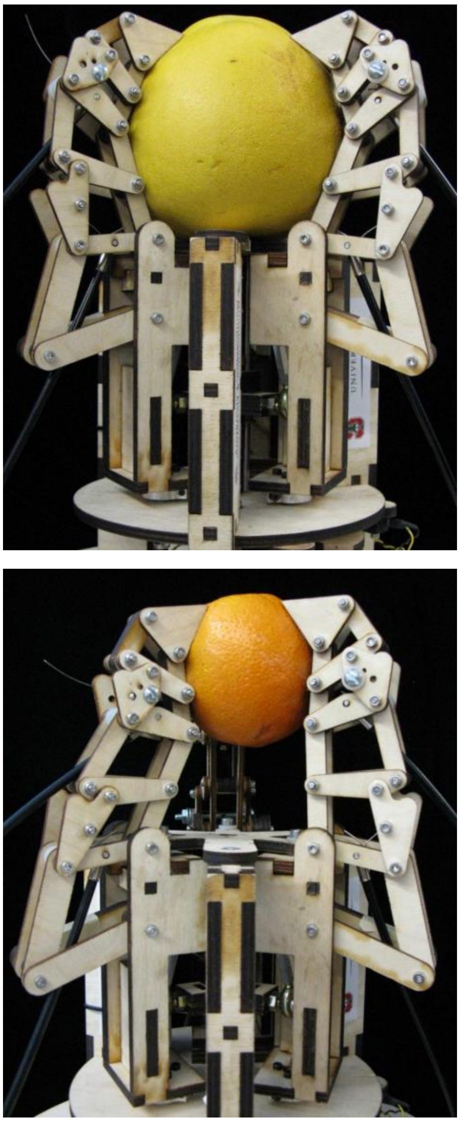


Figure 2.45 The seabed hand

The basic design of this gripper includes the use of three motors for the basic functions:

- Open/Close fingers
- Reconfigurate fingers
- Stiffen the fingers

The gripper has the ability to adapt itself to the target through the reconfiguration of its phalanxes denoting increased grasping capabilities and stability [20]. As it is indicated from Figure 2.46 below, the range of the graspable objects is wide.

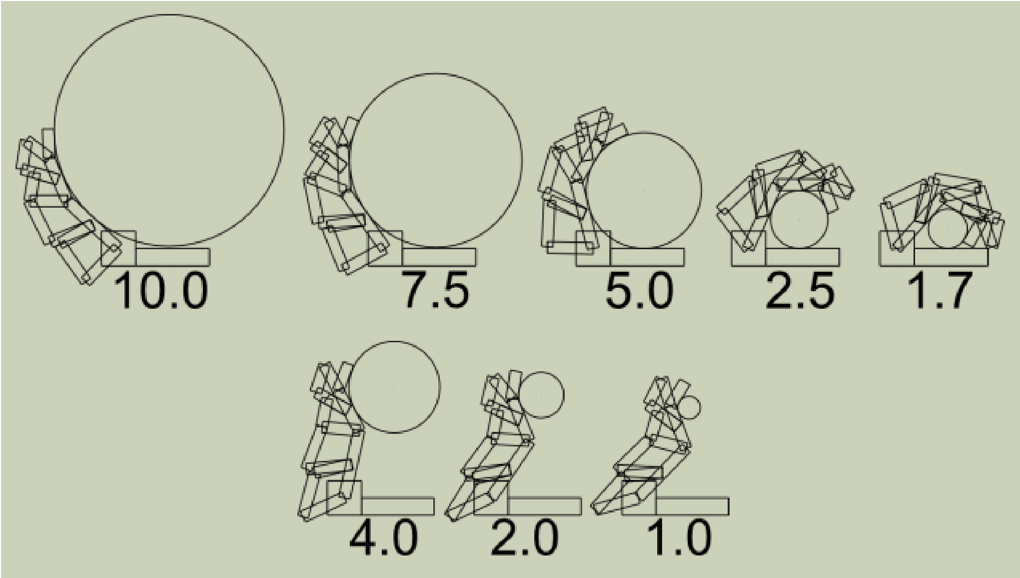


Figure 2.46 Range of graspable objects

CHAPTER 3   DESIGN METHOLOGY

There are several ways of describing the design process, of which three main categories have been identified. Though abstract and non-prescriptive, the most accurate description is the 'knowledge driven' design process. The information contents are filled in a random order and the process ends when there is sufficient information for a design recommendation. Another and frequently used description, is the divergent –convergent style process, which works along the idea of gaining, evaluating information and generating the selected alternates. However, by far the most common is the linear type design process model [21].

Creativity is an integral part of the engineering process, its presence often being the major influence on the impact of a product. Without some element of creativity in design there is no potential for innovation where new ideas are implemented and transformed into commercial value [21].

3.1 Design methology guidelines

3.1.1 Engineering design process

The formalisation of the design process is mainly splitted into two categories, the descriptive process models and the prescriptive process models. The descriptive model as described in Figure 3.1 attempts to replicate the sequence of occurrences throughout design while the prescriptive model shown in Figure 3.2 is built so as to guide the designer more efficiently through the design process [21].

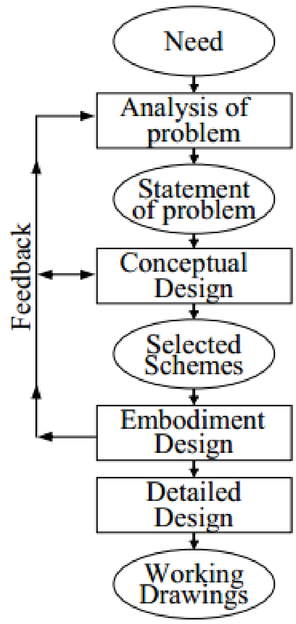


Figure 3.1 Descriptive process model

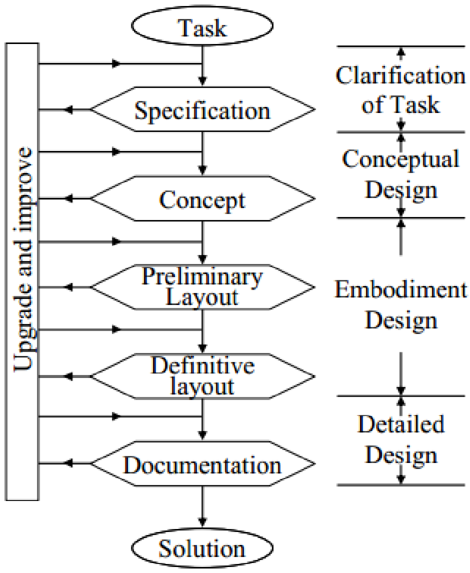


Figure 3.2 Prescriptive process model

The level of complexity of a design process model is also of great importance. Simple models generally follow a linear route with defined steps throughout the design process. During the planning phase of industrial design projects, it is common to construct other models such as gaunt-charts or timelines to map the process ahead. This can be time consuming, unless done with the use of a generic guideline. Several methods are available in the literature for this purpose. More specifically according to these, the process guides the user through a quest to reach simultaneously the desired requirements and the ideal final results [21].

<u>*3.1.2 Creative design process*</u>

Examining the creativity from the scope of its role in engineering design, three different perspectives of creativity styles dominate: situationalist, structuralist and inspirationalist [21].

Situationalists view the creativity as a social and not individual process, highlighting more importance on interaction and collaboration with other individuals and the world around. A typical function of this style is brainstorming which is a valuable way of increasing the performance of group creativity. In other words, the individual views everything in terms of information, therefore the social aspect of creativity is a dynamic stream of verbal information amongst peers [21].

Structuralism is a more systematic and methodological approach offering the advantage of a more detailed and structured route to the illumination phase. It describes an idea generation process where new designs are generated through the combination of existing ideas. This phenomenon is known as the componential approach, according to which three basic components are proposed: domain-relevant skills, creative-relevant skills and task motivation [21].

Inspirationalists focus on the individuals coming up with ideas, as a sudden change in perception giving rise to an idea from the subconscious. It is the definition of a linear process and it does not contain any feedback loops. This is the most well-known model between all the creative process models and consists of four basic stages: preparation, incubation, illumination and validation [21].

The above two design processes should fit together for the forming of an integrated descriptive process model. As a first step to the design phase is the evaluation and selection of a concept to be embodied, a phase responsible to add a physical form to the concept. This phase of the creative process is simply the evaluation of the idea generated. Following this stage, the detailed design phase which produces the appropriate inputs for manufacturing or implementation of a concept represents the engineering design process. It can be seen from the above analysis, that the creative processes could be linked into the engineering design processes with considerable benefit [21].

Therefore, the mechanical design process is a combination of engineering and creative design processes. The systematic procedure widely known for designing and constructing a component involves three stages: conceptual, configuration and parametric design.

- Conceptual Design

In the conceptual design stage, the objectives of the design are identified. Further information about how the objectives are to be achieved is collected, taking into account all physical principles as well as specifications required. Based on the above restrictions, several alternative concepts are generated as a potential solution to the design process. Evaluation of the alternatives follows using established methods. Guided by the evaluation criteria and other reasoning applicable, such as manufacturability, parts availability, simplicity etc. the design alternatives are modified and redesigned aiming to the best design solution[22].

- Configuration Design

The configuration design stage serves to the establishment of a list of attributes for the final design stage by identifying the features of the product designed. With the preliminary design generated from the first stage, the conceptual stage, any necessary re-arrangements and design improvements are determined here. As a result, list of attributes that must be given values in the parametric design stage are generated. The attributes consist of numeric (such as dimensions of features) and non-numeric (such as material or component choice) parameters [22].

- Parametric Design

The final stage is the parametric design, in which final design decisions are generated. The choice of values for a given attribute or design variable relies on the consideration of optimizing the design as a whole with respect to both function and production. Iterations on one or more of the designs variables are essential in order to analyze and determine the optimal set of parameters [22].

3.2 Design Procedure

In this section, the design procedure for the development of the smart gripper is presented. The three-stage approach described earlier, will be deployed in the context of the following chapters of this Thesis.

3.2.1 Design objectives, specifications and constraints

The current work will present the concept of a new gripper solution for industrial applications. The goal of this project is to design and analyse a smart gripper capable to deal with all types of industrial components which means axonosymmetric, prismatic and shell shaped objects. Taking into account the identification of the parts to be manipulated and their orientation in space, the gripper should change its shape in order to effectively grab the components to be handled.

In order to carry out the above objectives there are some key parameters that need to be determined defining the specifications and the constraints of the mechanism developed [23]:

- Components characteristics

They should be defined in context of their geometry, weight, material, surface quality and temperature. These are the most important characteristics from the point of view of gripping.

- Task specification

A robotised task can be specified by its type, the different components to be handled and the cycle time of operation.

- Environmental conditions

The environmental conditions of the industrial application are also of vital importance in terms of contamination and constraints.

- Robot capability

The mechanism developed should comply with the general attributes associated with a typical robot such as repeatability, accuracy, acceleration, speed, lifting capacity, payload, power source and mechanical connections.

3.2.1.1 Component characteristics

Classification of industrial components helps the development of engineering designs and accelerates product development. In this framework, the above classification is correlated with a CAD/CAM classification scheme. There are several ways to classify a geometry with the typical classification being by their shape and appearance, their functionality and their manufacturing processes [24].

- Shape and appearance - Functionality

Shape classification scheme is a natural target. Numerous research efforts in computer vision have attempted to classify products from 2D photos. Also 3D models visualization is a recent trend to computer graphics using meshes of polygons, locations of vertices and edges of triangles for representation of the model's appearance. Functional classification describes how parts are used, tying a part directly to its application. Current functional classification of CAD models is highly dependent on human labelling. Figure 3.3 below shows mechanical parts classified by their shapes and functionality [24].

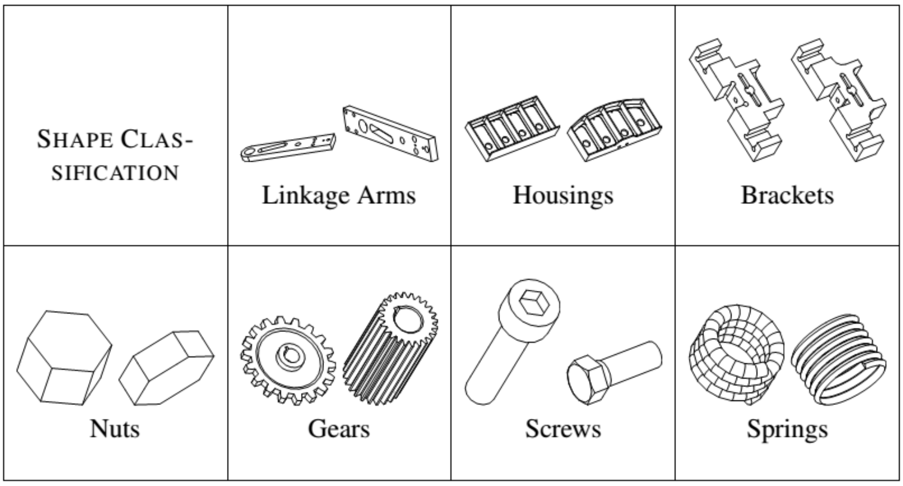


Figure 3.3 Shape and appearance classification dataset

- Manufacturing processes

Classification of CAD models according to different classes of manufacturing processes has become an important interest in the engineering community. Computer aided manufacturing (CAM) as it is widely known, automates the generation of manufacturing process plans from CAD models. Popular approaches to this problem include graph-based, volumetric decomposition and hint-based feature recognition, utilizing exact topology and geometry provided by solids. Figure 3.4 shows a sample of mechanical parts made by different manufacturing processes [24].

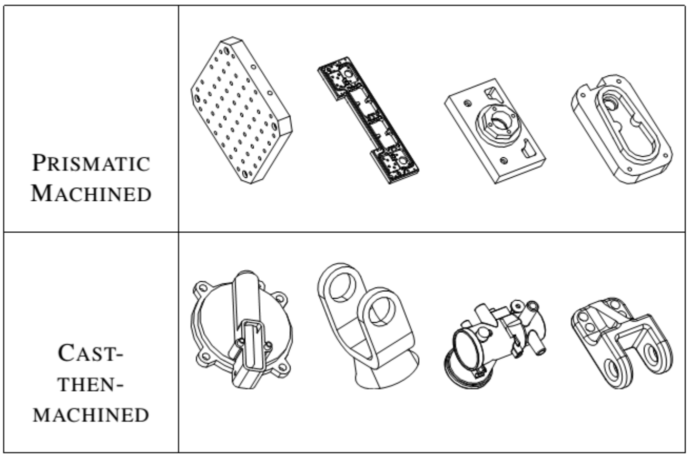


Figure 3.4 Manufacturing classification dataset

Models of actual mechanical engineering parts are provided from the publicly available National Design Repository. These models are sampled from industrial CAD data and grouped under the two classification schemes, as already described above. A sample view of the National Design Repository of CAD models is presented in Figure 3.5 [24].

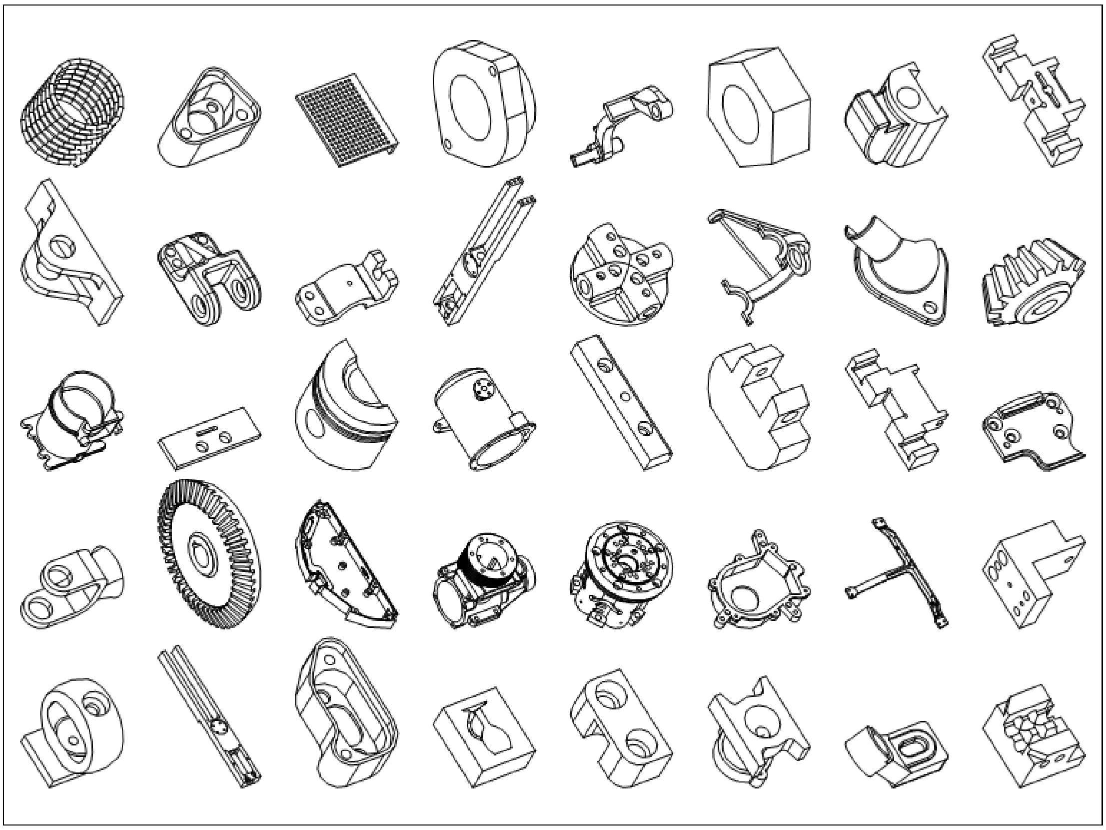


Figure 3.5 National Design Repository

However, it is well-known in engineering that product design is an iterative process and that its different aspects are independent. The form of a product or component includes shape, colour, texture, product architecture and other factors related to the structure of the product. For the engineering domain a primarily function-based classification is difficult because parts with different functions may have similar shapes. As a result, designing a function-based classification for the engineering domain is a challenge. The engineering shape benchmark (ESB) has been designed to overcome these problems. The main motivations of this projects is that parts that are similar in their form are easy to modify and reuse in new designs, may have similar manufacturing processes, provide additional insight for design analysis and can be outsourced to the same supplier [25].

Three classification classes are constructed in terms of engineering shape benchmark presented in Figure 3.6 and 3.7:

- Solids of revolution
- Rectangular-cubic prism
- Thin walled

Flat-thin wall components	# Models	Rectangular-cubic prism	# Models	Solids of revolution	# Models
Backdoors	7	Bearing blocks	7	90 degree elbows	41
Bracket like parts	18	Contoured surfaces	5	Bearling like parts	20
Clips	4	Handles	18	Bolt like parts	53
Contact switches	8	L Blocks	7	Container like parts	10
Curved housings	9	Long machine elements	15	Cylindrical parts	43
Miscellaneous	*12*	Machined blocks	9	Discs	51
Rectangular housings	14	Machined plates	49	Flange like parts	15
Slender thin plates	12	*Miscellaneous*	*21*	Gear like parts	36
Thin plates	23	Motor bodies	7	Intersecting pipes	9
		Prismatic stock	36	Long pins	58
Total	107	Rocker arms	10	*Miscellaneous*	*33*
		Slender links	13	Non-90 degree elbows	8
		Small machined blocks	12	Nuts	19
		T shaped parts	15	Oil Pans	8
		Think plates	12	Posts	11
		Thick slotted plates	20	Pulley like parts	12
		U shaped parts	25	Round change at end	21
				Simple pipes	16
		Total	281	Spoked wheels	15
				Total	479

Figure 3.6 Engineering shape benchmark (ESB)

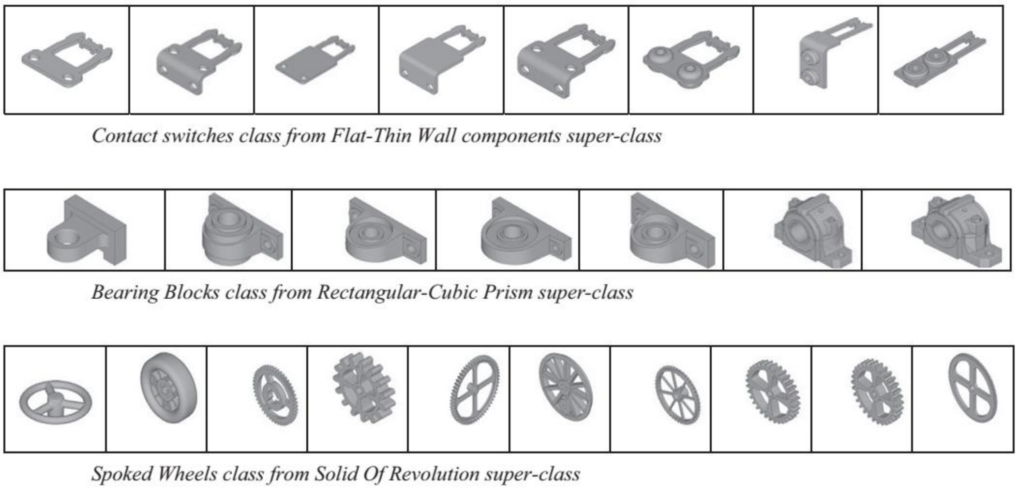
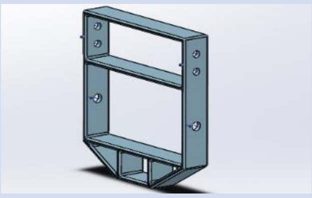
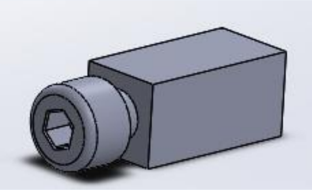
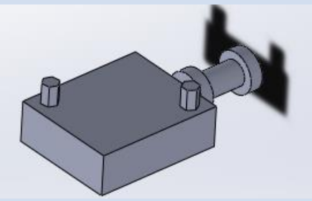
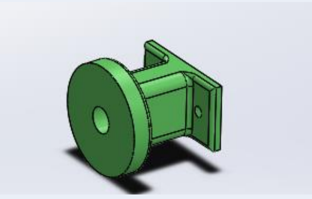
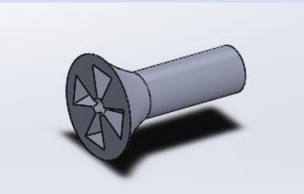
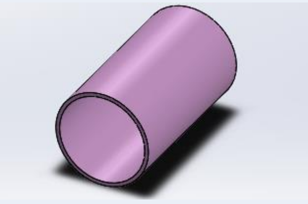
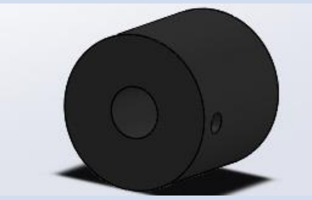
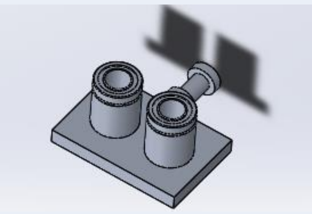
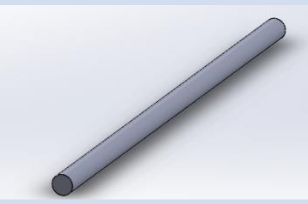


Figure 3.7 Engineering shape benchmark (ESB)

Following the literature overview presented for the classification of industrial and engineering parts, the current thesis follows the guidelines stated above. The gripped objects that will be used as sample in the current project are the components of a robotic fiber winding head developped earlier and cover a wide variety of shapes, sizes, weights and manufacturing processes [26]. In Table 3.1 that follows, there is an image of each sub-component along with its characteristics as classified above.

Objects	ESB	Material	Length (mm)	Width (mm)	Thickness (mm)	Area (mm^2)	Weight (gr)
	Flat thin wall	ABS/AISI 316 Stainless Steel Sheet(SS)	182.5	160	5	62587.74	144.52/1133.5

	Rectangular cubic prism	Alloy/AISI 316 Stainless Steel Sheet(SS)	29	10	-	1386.05	6.73/19.93
	Rectangular cubic prism	Alloy/AISI 316 Stainless Steel Sheet(SS)	35	10.0-25.0	-	3366.52	22.61/67.0
	Rectangular cubic prism	ABS/AISI 316 Stainless Steel Sheet(SS)	45	52	-	13216.21	40.75/319.59
	Solids of revolution	Carbon Steel/AISI 316 Stainless Steel Sheet(SS)	14	4.0-9.0	-	315.73	1.88/1.92
	Solids of revolution	ABS/AISI 316 Stainless Steel Sheet(SS)	90	50	4	27746.55	27.69/217.15
	Solids of revolution	ABS/AISI 316 Stainless Steel Sheet(SS)	30	30	20	5128.56	19.10/149.78
	Solids of revolution	Alloy/AISI 316 Stainless Steel Sheet(SS)	23	10.0-45.0	30	2048.8	30.72/91.01
	Solids of revolution	Alloy/AISI 316 Stainless Steel Sheet(SS)	220	10	-	7068.58	46.65/138.23

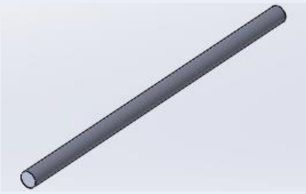
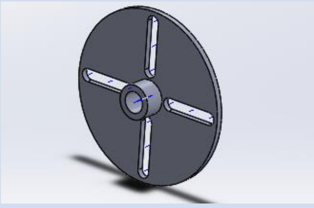
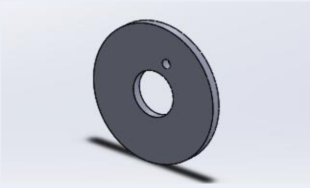
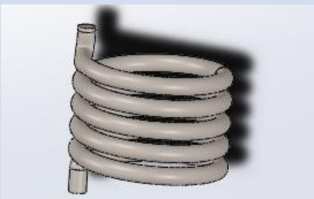
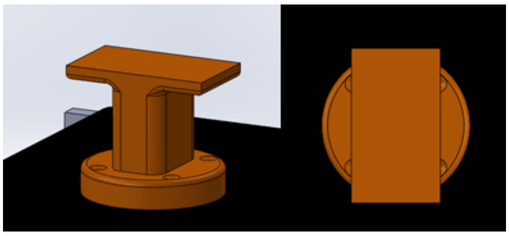
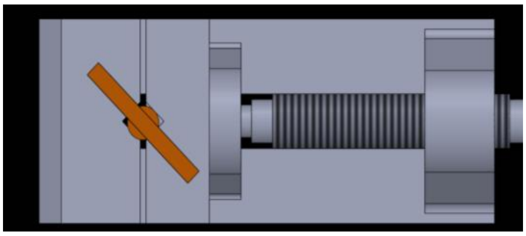
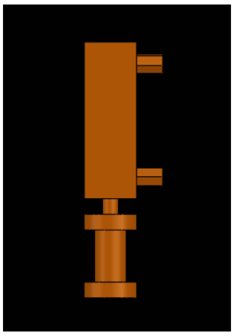
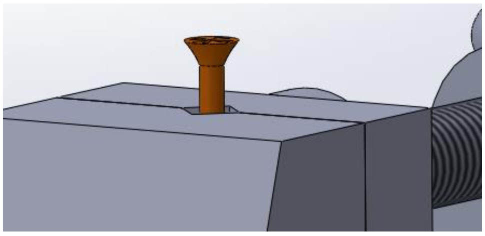
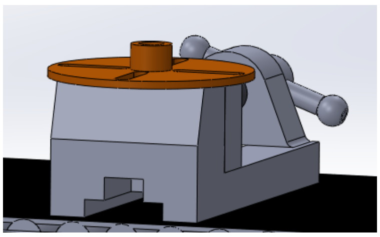
	Solids of revolution	Alloy/AISI 316 Stainless Steel Sheet(SS)	200	8	-	5127.08	27.14/80.42
	Solids of revolution	Alloy/AISI 316 Stainless Steel Sheet(SS)	13	80	3	11009.06	38.0/112.59
	Solids of revolution	Alloy/AISI 316 Stainless Steel Sheet(SS)	-	30	2	1514.25	3.38/10.0
	Solids of revolution	AISI 304	13	13	0.96	1528.86	2.44
	Solids of revolution	AISI 304	65	13	4.81	1539.56	2.46
	Solids of revolution	AISI 304 Stainless steel sheet	13	16	2.6	1624.62	6.46

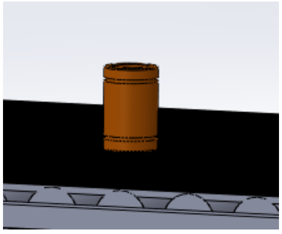
Table 3.1 Gripping components characteristics

3.2.1.2 Task specification

Three basic types of tasks can be identified, pick and place operation, machining process and mechanical assembly. In the first type, a component is simply picked up, transferred and placed at a discrete position. In the second type, a component will undergo dimensional changes and therefore the gripper should be capable of adaption to this variation. Mechanical assembly, has additionally the variant of detailed positioning which means that the gripping surfaces should be chosen so that mechanical interference is not significant during assembly [23]. In the current project a gripper that should be functional to all the above operations will be developed.

As far as the variety of components handled is concerned, all the ESB types will be handled. Consequently, they are grouped according to their gripping requirements as shown in the workplace configuration Table 3.2 below.

	Rectangular faces 30x20 mm
	Rectangular faces 10x10 mm
	Rectangular faces 45x5 mm
	Rectangular faces 10x49 mm
	Cylindrical face 4 mm
	Cylindrical faces (x2) 80 mm 16 mm

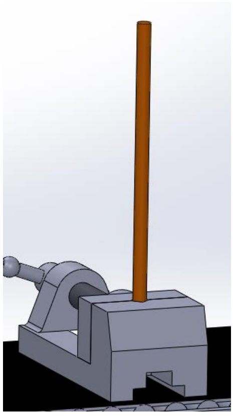


Cylindrical face

14.5 mm

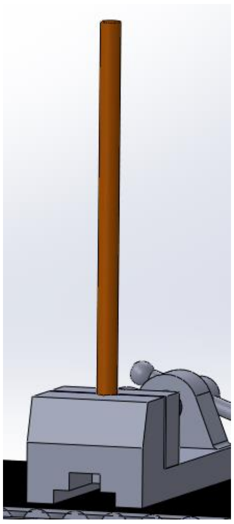
Rectangular faces

182.5x30 mm



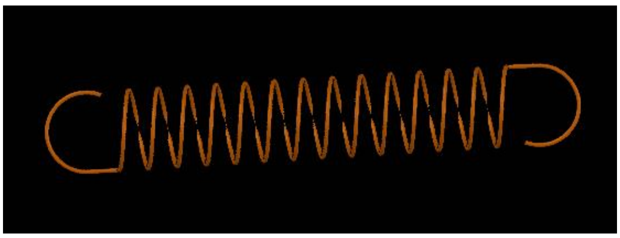
Cylindrical face

8 mm



Cylindrical face

10 mm



Rectangular faces

88x15 mm

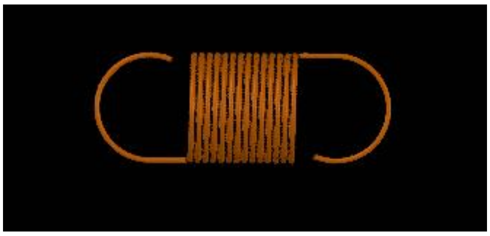
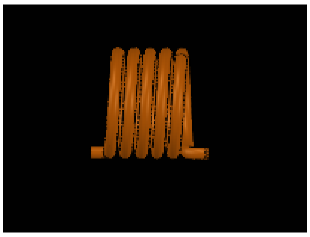
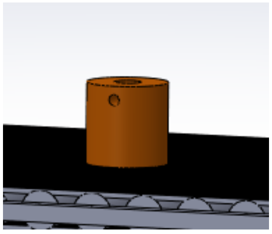
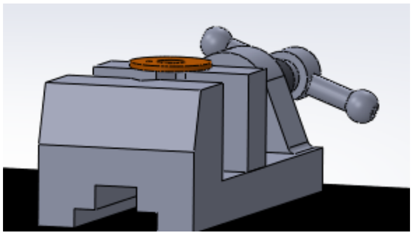
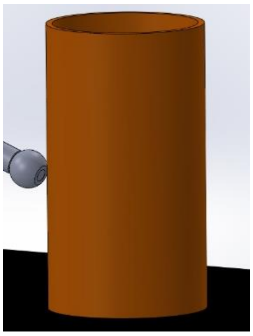
	Rectangular faces 12x14 mm
	Rectangular faces 14x17 mm
	Cylindrical face 30 mm
	Cylindrical face 30 mm
	Cylindrical face 50 mm

Table 3.2 Workplace configuration

The cycle time of a task will determine how fast the gripper has to operate. On the subject project a medium cycle time is pursued without any special time requirements. Table 3.3 presents the overall characteristics of task specification.

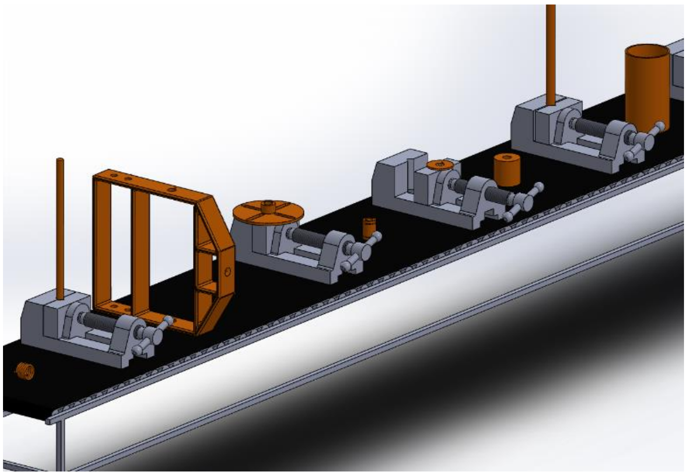
Type	Variety of components	Cycle time
Pick & place operation	Rectangular cubic prism	Medium
Machining process	Flat thin wall	
Mechanical assembly	Solids of revolution	

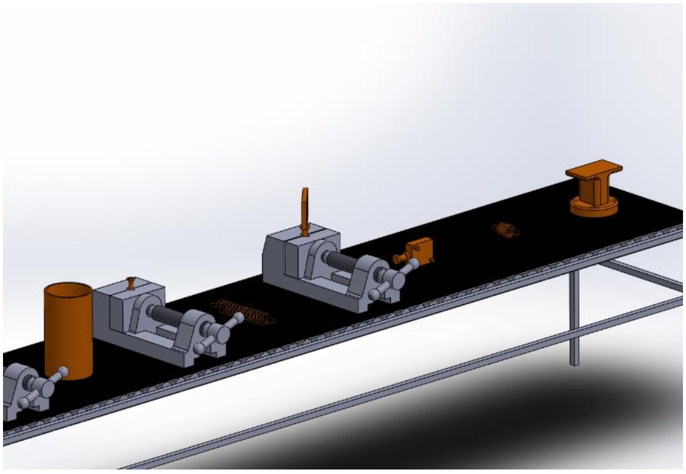
Table 3.3 Task specification characteristics

3.2.1.3 Environmental conditions

Any substances present in the environment can contaminate the surfaces of the component. This could affect the friction as well as the contact between the gripping planes of the gripper and the surfaces of the component. The operational environment here is assumed to be free of contamination.

The physical constraints of the environment can affect the accessibility of the component as a whole or partially some of its surfaces. Thus, it is necessary to ensure that any surfaces used for grasping can be reached effectively. The positional accuracy of the gripper will be of a medium level. This refers to the accuracy with which a component is available for grasping and with which it has to be placed at the destination [23]. In terms of the current project, it is assumed that the components are placed with their widest dimension available and its rectangular surfaces free for grasping. As shown in Figure 3.8, the components that cannot easily comply with the above rules are placed specially in order to be reachable under the same principles. Table 3.4 shows the positional accuracy ruling. Finally, the characteristics of environmental conditions are specified in Table 3.5.





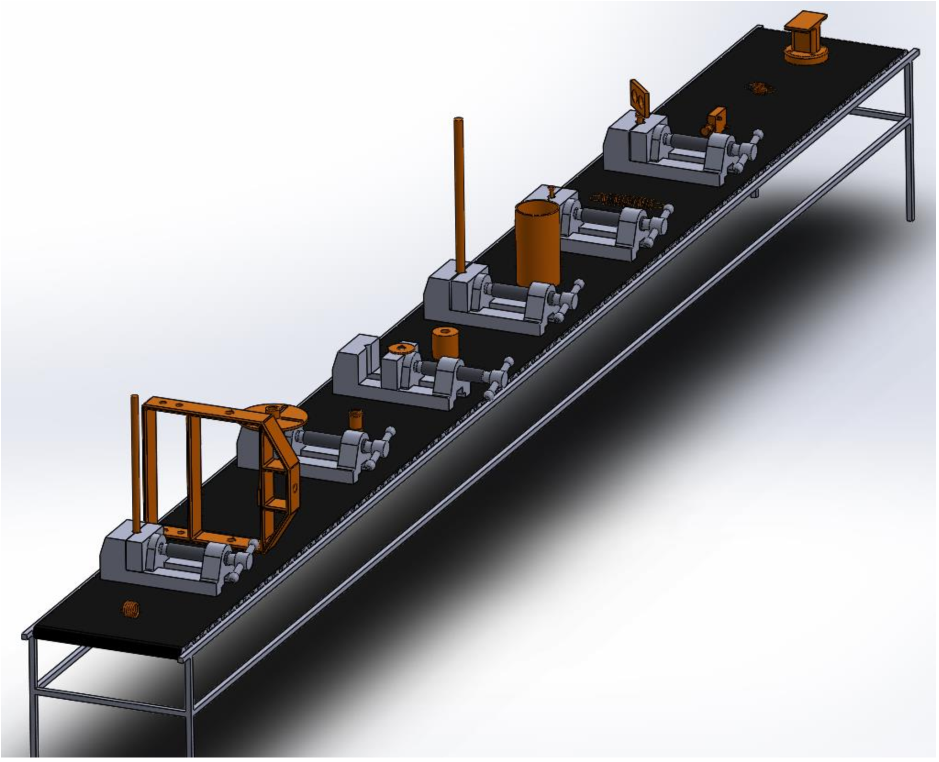


Figure 3.8 Positioning grasping rules

Variety of components	Positioning Rules for grasping		Exceptions
	Widest dimension available	Rectangular faces free	
Rectangular cubic prism	✓	✓	Additional base
Flat thin wall	✓	×	Special cases
Solids of revolution	✓	×	Springs: Free launching

Table 3.4 Positional accuracy ruling

Contamination	Constraints
No	Total clearance

Table 3.5 Environmental conditions characteristics

3.2.1.4 Robot Capabilities

The robot available for this thesis is a Staubli RX-90 robot whose characteristics are available on the below Tables (3.6 - 3.9).

Joints	1	2	3	4	5	6
Amplitude (°)	320	275	285	540	225	540
Working range (°)	±160	±137.5	±142.5	±270	15	±270
Nominal speed (°/s)	236	200	286	401	320	580
Max speed (°/s)	356	356	296	409	480	1125

Angular resolution (°)	870	870	720	1000	1170	2750

Table 3.6 Staubli DOFs

Characteristics	
DOF	6
Mass (kg)	112
Max speed (m/s)	11
Max Cartesian speed (m/s)	1.5
Min Cartesian speed (m/s)	0.25
Min spherical speed (m/s)	10% of nominal speed

Table 3.7 Staubli characteristics

Load capacity	
Nominal speed (kg)	6
Min speed (kg)	9

Table 3.8 Staubli load capacity

Environmental characteristics	
Temperature (°C)	14732
Humidity (%)	30-95
Max altitude (m)	2000

Table 3.9 Staubli environmental characteristics

3.2.2 Alternative concepts

Based on the above specifications and restrictions the need of a gripper capable of manipulating components with various geometric particularities, designated for various tasks and able to comply with special environmental conditions is obvious.

Three alternative design concepts have been developed inspired by the literature review conducted among this thesis. These ideas are trying to fill any design gap noted in terms of the objectives, specifications and restrictions of the current project.

3.2.2.1 1st Concept: Truss inspired gripper

This idea is inspired geometrically by the truss structures. In the static physics, these structures consist of two-force members organized so that the assembly as a whole behaves as a single object. The advantages of this structure can be combined, from the dynamic point of view, with an idea of form closure mechanism, which means that the several members of each gripper's finger move, adapting themselves to each particular object's shape. Below in Figure 3.9 a first sketch of this idea is presented.

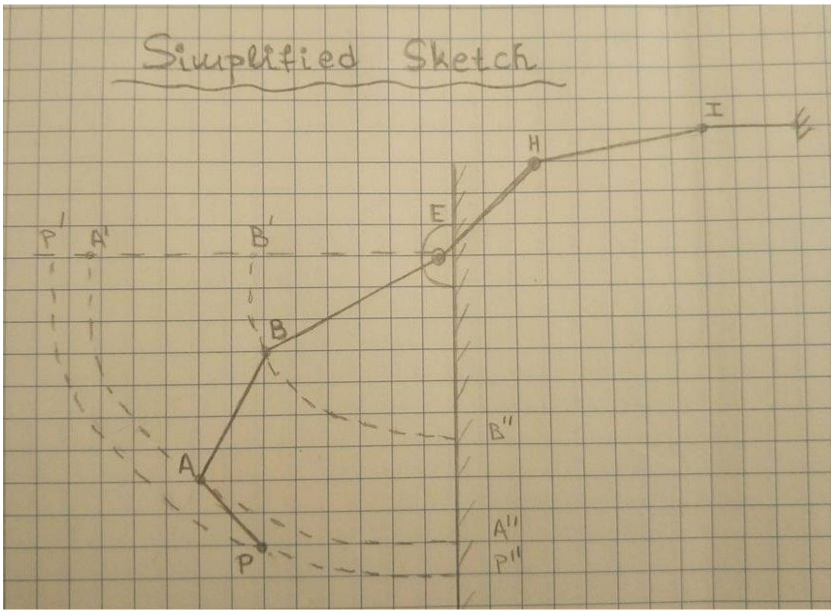
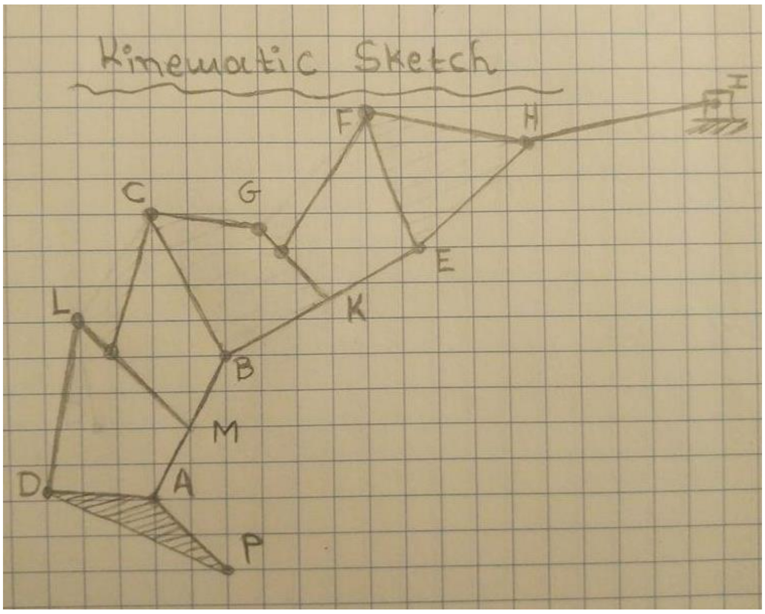


Figure 3.9 Simplified sketch of the truss inspired gripper

This mechanism is based to a reconfigurable principle, where mechanical architectures of self-adaptive robotic fingers are driven by linkages. Below in Figure 3.10, a more detailed sketch is presented taking into account the kinematic model of the mechanism.



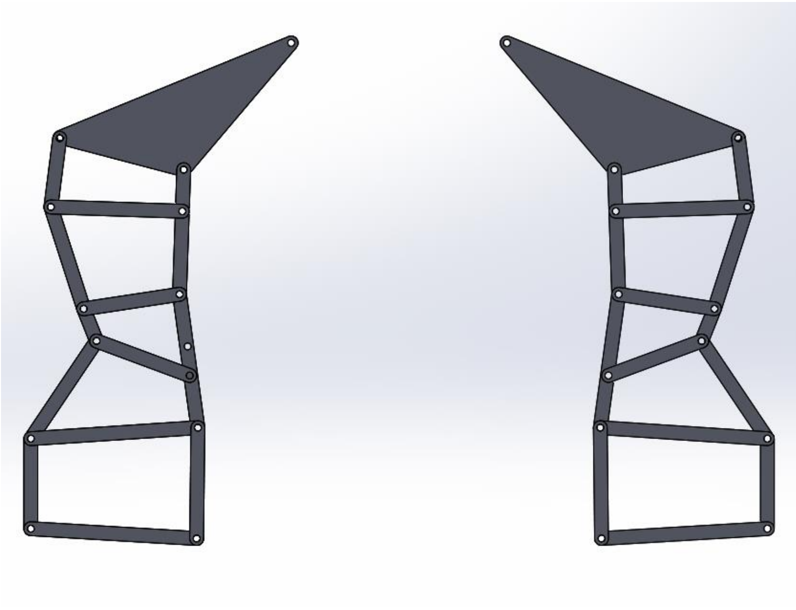
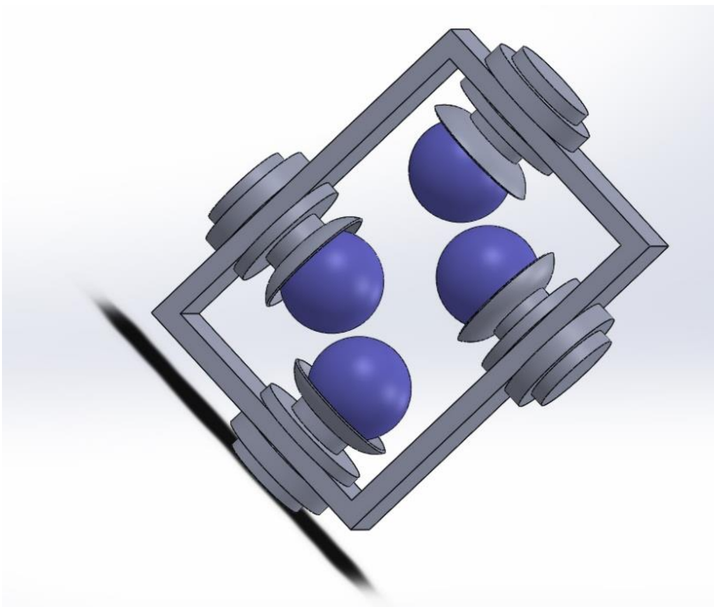


Figure 3.10 Kinematic sketch of the truss inspired gripper

3.2.2.2 2nd Concept: Balloon inspired gripper

The second idea developed is inspired by the balloon design but also combined with the flexibility that a granular material in combination with air can impose to it. The form closure is also the aim of this mechanism with the granular balloon being capable to mold around an object forming its shape. Further to the above, the developed design is aiming to handle a variety of object sizes which means that several points of contact are required. As a result, this idea is combined with a jaw-gripper principle. Figure 3.11 shows the first sketch of this balloon inspired gripper.



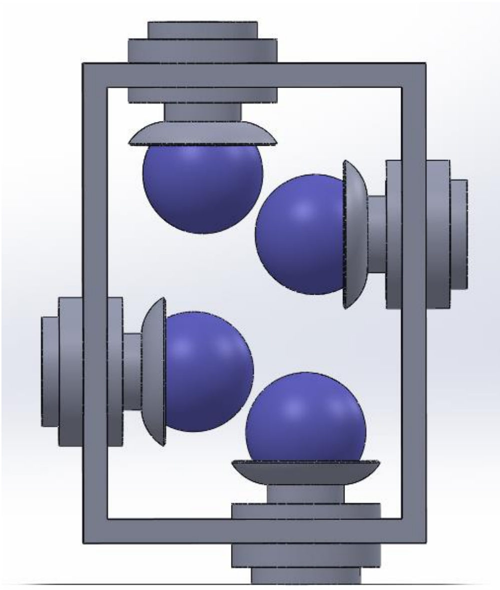


Figure 3.11 Sketch of balloon inspired gripper

3.2.2.3 3rd Concept: Belt conveyor inspired gripper

The third concept developed is inspired by an industrial assembly line. The belt is the dominant mechanical parts used in automatic conveyor systems, often used also as a gripping mean. Considering the principle of the mechanism as form closure, the belt will be used as a reconfigurable part wrapping around the subject object following its actuation by mechanical mechanisms. Figure 3.12 presents the first attempt to sketch this design idea.

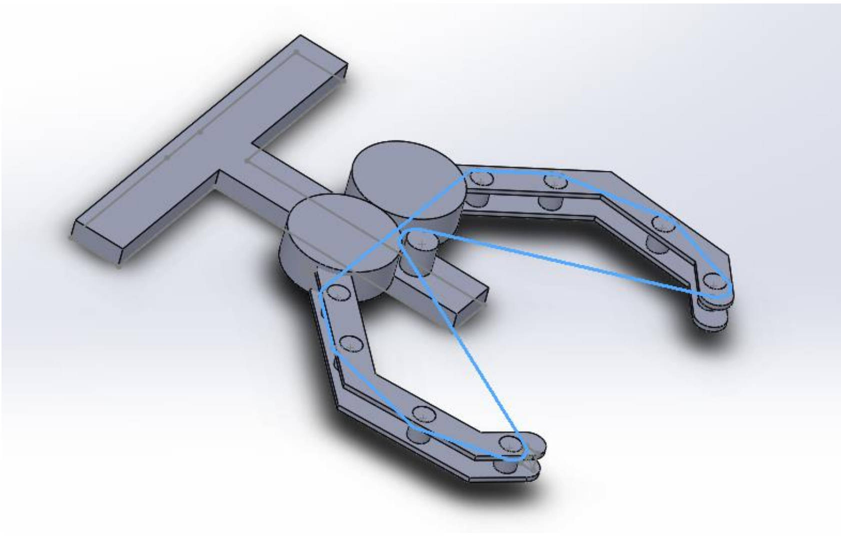


Figure 3.12 Sketch of belt conveyor inspired gripper

3.2.3 Detailed concept's design

3.2.3.1 Truss inspired gripper

This design is based on the principle of self-adaptive mechanisms used in robotic fingers, providing them with the ability to adjust themselves to the shape of the object without any dedicated control system installed. This self-adaptive behaviour is obtained by combining two elements, transmission linkage and passive elements. The general idea where self-adaption is based is that the number of actuators decreases without decreasing the number of DOFs (Degrees of Freedom).

Below in Figure 3.13 the actuation phases of a typical two-DOF finger driven by linkages is presented. The finger is actuated through the lower link and a spring with a mechanical limit is used to maintain the finger fully extended. Firstly, the finger behaves as a single rigid body in rotation about a fixed pivot. Secondly, the proximal phalanx makes contact with the object. Then, the actuation torque overcomes the preloading of the spring and the second phalanx moves away from the mechanical limit and rotates with respect to the first phalanx. Finally, both phalanges are in contact with the object and the finger has completed the shape adaption [27].

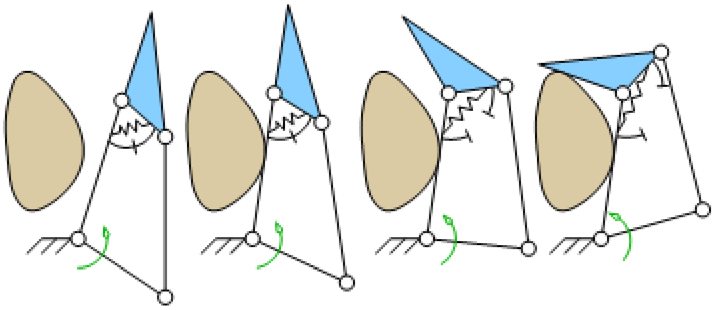


Figure 3.13 Closing sequence of a two-DOF self-adaptive finger

The first question arises at the beginning of the self-adaptive finger's design is how to design the transmission linkage and what linkages do actually achieve the desired properties. The characteristics of the linkages should satisfy a few simple hypothesis. The transmission linkage should reach the distal phalanx, should be connected to the ground and must not restrict the DOF of the finger. The first two geometrical conditions render the system a closed-loop one, while the last hypothesis ensures that the mobility of the system is not constrained by the transmission linkage [27]. With respect to the above, there are several architectures of two or three phalanx fingers with diverse positions of actuation and passive elements. These are typical geometries according to literature ensuring that the actuation torque is equally distributed to all the joints of the driven system [27]. Picture 3.14 illustrates these models.

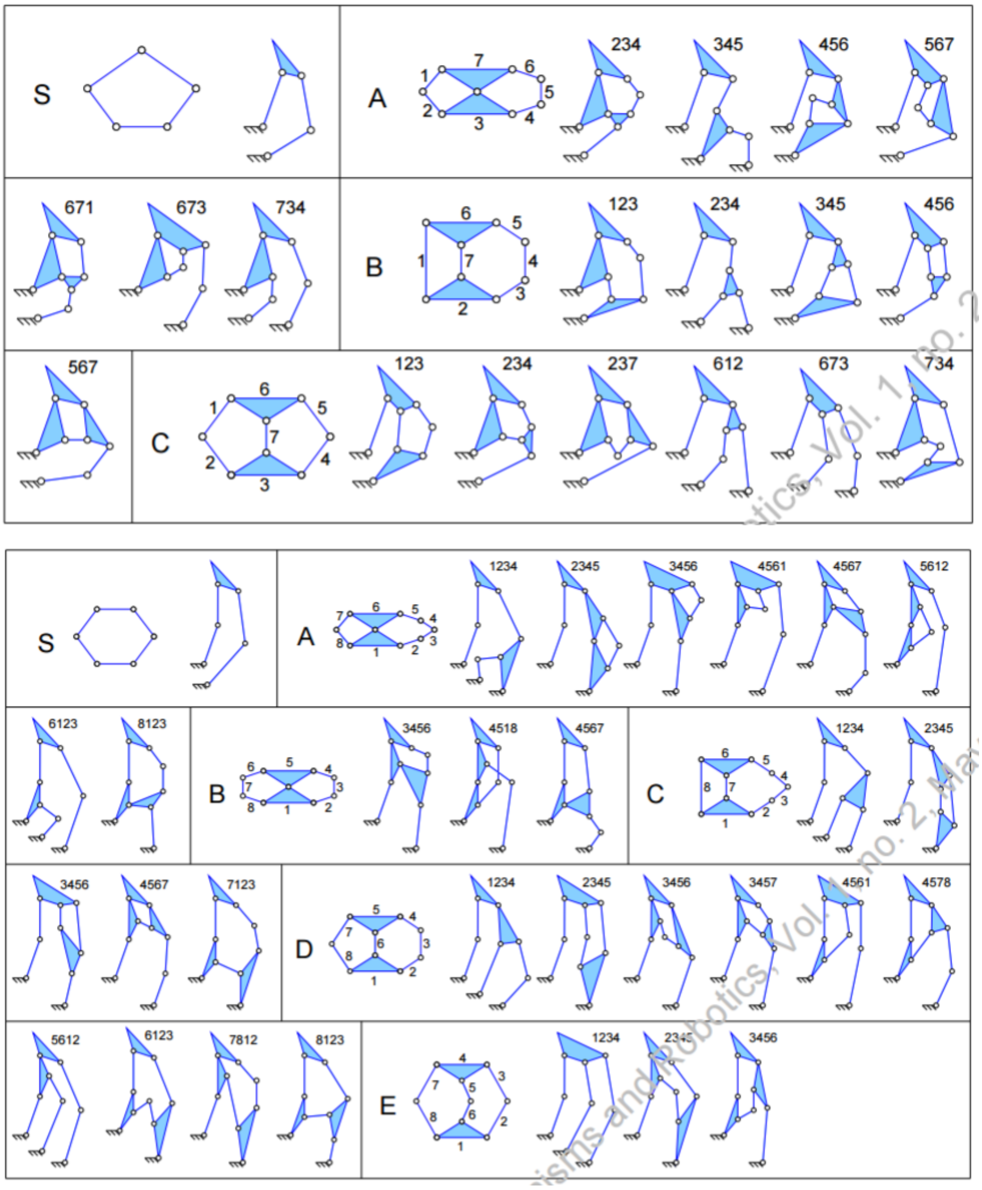


Figure 3.14 Architectures of two and three phalanx fingers

Second though during the design development procedure is the identification of passive elements. The most common of these elements, used in self-adaptive mechanisms, are illustrated in Figure 3.15 and are categorized into two families, triggered and continuous elements. Triggered elements allow motion in the joint only after a certain force or torque arises in the latter. The most common solutions to achieve this behaviour is the preloaded spring. Continuous elements exhibit a continuous motion of the associated joint with respect to the force or torque applied. Examples of continuous elements are the damper and a mass or inertial element [27].

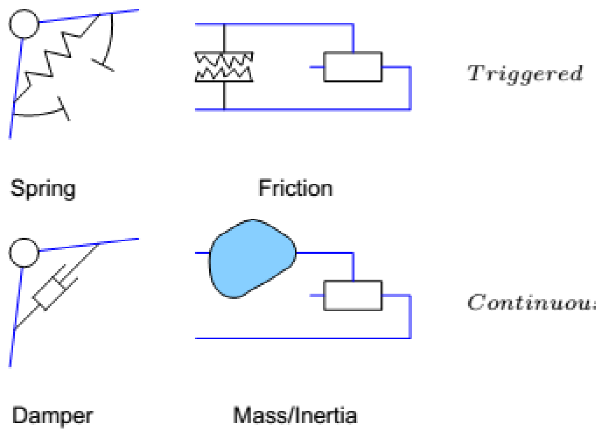


Figure 3.15 Passive elements

Then comes the actuation torque distribution, as a fundamental characteristic of self-adaptive fingers. Some of the architectures proposed above can be actuated through a joint placed between the transmission linkage and the ground, but not all of them. The joint selected for actuation should satisfy a distribution condition according to which for each joint of the driven finger there exists at least one configuration where the actuation torque is distributed to this joint. In other words, the joint torques of the driven finger must not be independent of the actuation torque [27]. Below in Figure 3.16 the actuation torque distribution in two and three phalanx fingers is presented.

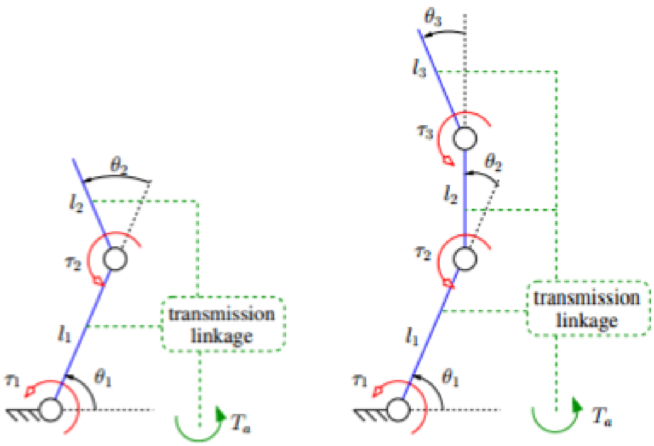


Figure 3.16 Distribution of the actuation torque in two and three phalanx

The design of the finger mechanism proposed here uses the concept of underactuation applied to mechanical hands. As a result, several parameters of the designed architecture should be determined in the pre-design phase which are described thereafter. A three-phalanx finger with revolute joints is chosen for design due to the variety of sizes of the grasped objects. The transmission linkage has only one ground attachment and the finger is actuated through the link attached to the ground. The locations of the passive elements are chosen by a kinematic constraint according to which during the pregrasping phase all the phalanges should stay aligned in order to increase the reachability of the finger. From this kinematic constraint, both passive elements are required to be springs located between the phalanges (proximal-intermediate and intermediate-distal joints). Following the above, the architecture chosen for design from Figure 3.14 is the 4567 model, presented below (Figure 3.17).

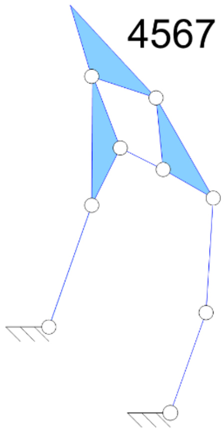


Figure 3.17 Kinematic sketch of the underactuated finger mechanism

Another important decision for the fingers' design, is the determination of the phalanges length. This is a parameter according to which the operation workspace of the finger is defined. The dimensional synthesis of the transmission linkages shown in Figure 3.17, is formulated by using the Freudenstein's equations and the transmission defect [28]. This methology is based on a loop closure equation for a four-bar linkage illustrated below in Figure 3.18.

$$\boxed{K_1 c_2 + K_2 c_4 + K_3 = \cos(\theta_2 - \theta_4)}$$

$$K_1 = \frac{r_1}{r_4}$$

$$K_2 = \frac{r_1}{r_2}$$

$$K_3 = \frac{r_3^2 - r_1^2 - r_2^2 - r_4^2}{2 r_2 r_4}$$

$$\cos\theta_i = c_i$$

$$\sin\theta_i = s_i$$

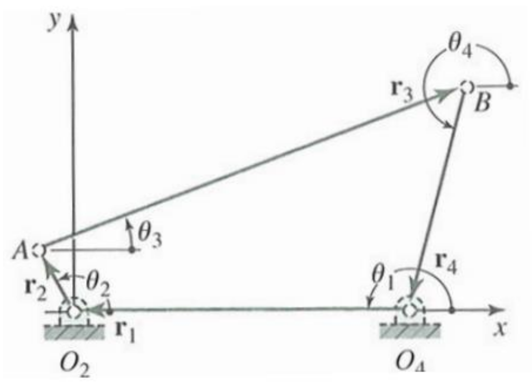


Figure 3.18 Freudenstein's Equataion fundamentals

The model construction procedure is described in the flowchart presented in Figure 3.19 and the fundamental parameters that should be defined are outlined below [28]:

- the function of the kinematic model or the dimensions of the phalanges
- the range of the independent variables or the workspace designation
- the rotation range of input and output links

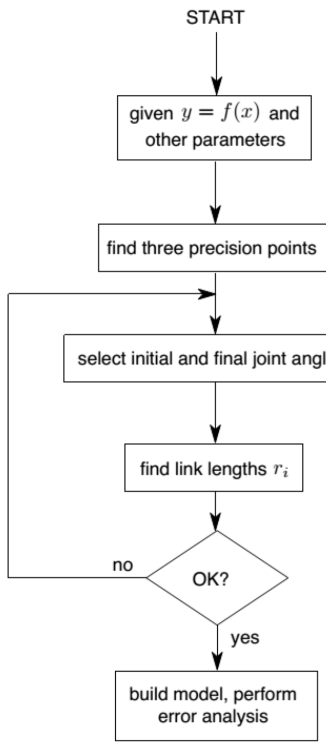


Figure 3.19 Flowchart for dimensional synthesis

Following the above, the procedure presented has been applied in the current work. The dimensions of the phalanges have been chosen according to the overall characteristics of the human finger given in Table 3.10.

Phalanx	Length	Angle
m_1	l_1 = 43 mm	θ_{1M} = 83°
m_2	l_2 = 25 mm	θ_{2M} = 105°
m_3	l_3 = 23 mm	θ_{3M} = 78°

Table 3.10 Characteristics of a human finger

The fragmentation of the finger consists of two four-bar linkages (ADKL, BCKL), two three-bar linkages (ABL, KCD) and one five-bar linkage (EFGCB) as shown in Figure 3.20. However, the kinematic synthesis according to which the actual analysis has been built consists of two four-bar linkages (ABCD, BEFG) and three rigid bodies (BGC, BLA, KCD).

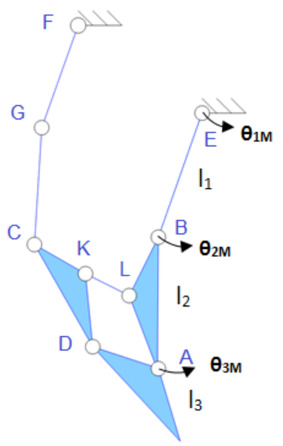


Figure 3.20 Kinematic synthesis of the underactuated finger

By considering the four-bar linkage ABCD, equations can be solved when three positions of both links BC and AD are given through a pair of angles. Some design parameters are assumed as follows and other are obtained for the starting and final configurations respectively. Then an optimization procedure in terms of force transmission has been developed by assuming as starting values the middle positions of the links. Figure 3.21 illustrates an example of a four-bar linkage starting and final positions and geometrical characteristics [29].

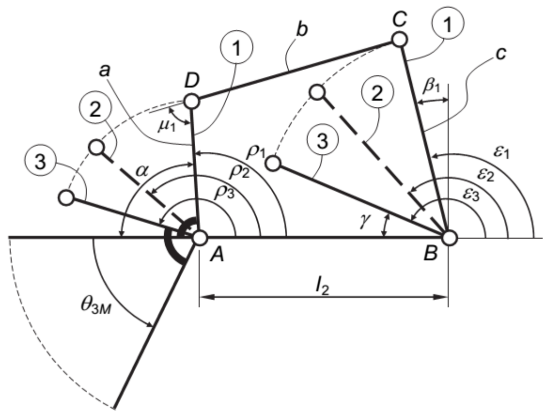


Figure 3.21 Kinematic sketch of an example four bar-linkage

The precision points assumed and optimized in the current work for ABCD linkage are presented below in Table 3.11. Table 3.12 illustrates the kinematic sketch and the geometrical characteristics resulted from the Freudenstein's equations procedure for linkage ABCD. Same procedure for linkage BEFG is given in Tables 3.13 and 3.14.

Point 1	$a = 50^o$ $\beta = 25^o$	$\varepsilon_1 = 90^o$+25^o=115^o $\rho_1 = 180^o$-50^o=130^o
Point 3	$\gamma = 40^o$ Max (θ_{2M})	$\varepsilon_3 = 180^o - 40^o$=$140^o$ $\rho_3 = 130^o + 78^o$=208^o
Point 2	**Starting point**	**Ending point**

	$\varepsilon_2 = \dfrac{\varepsilon_1 + \varepsilon_3}{2} = 128^o$ $\rho_2 = \dfrac{\rho_1 + \rho_3}{2} = 168^o$	$\varepsilon_2 = 136^o$ $\rho_2 = 194^o$

Table 3.11 Four-bar linkage ABCD precision points

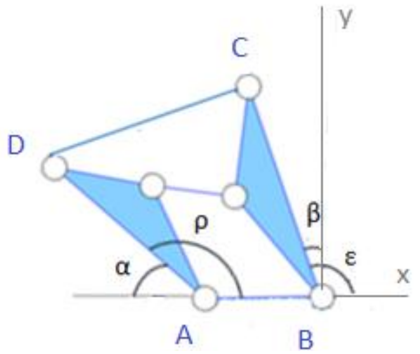
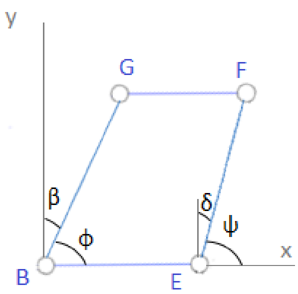
<table>
<tr>
<td>
</td>
<td>$AB = 50\ mm$
$BC = 33.5\ mm$
$CD = 74\ mm$
$DA = 42\ mm$</td>
</tr>
</table>

Table 3.12 Four-bar linkage ABCD geometrical characteristcs

Point 1	$\delta = 0^o$ $\beta = 30^o$	$\psi_1 = 90^o$-0^o=90^o $\varphi_1 = 90^o$-30^o=60^o
Point 3	$\gamma = 40^o$ Max >(θ_{2M})	$\psi_3 = 180^o - 40^o$=140^o $\varphi_3 = 60^o + 135^o$=195^o
Point 2	**Starting point** $\psi_2 = \dfrac{\psi_1 + \psi_3}{2} = 115^o$, $\varphi_2 = \dfrac{\varphi_1 + \varphi_3}{2} = 128^o$	**Ending point** $\psi_2 = 119^o$ $\varphi_2 = 137^o$

Table 3.13 Four-bar linkage BEFG precision points

<table>
<tr>
<td>
</td>
<td>$EB = 43\ mm$
$EF = 70.5\ mm$
$FG = 50\ mm$
$GB = 39.5\ mm$</td>
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</table>

Table 3.14 Four-bar linkage BEFG geometrical characteristcs

Table 3.15 below shows the geometrical characteristics of all phalanges and linkages as calculated above, while Figure 3.22 illustrates a 2D design of the finger in its initial and final position.

l_1(mm)	43
l_2(mm)	50
l_3(mm)	75
AB(mm)	50
BC(mm)	33.5
CD(mm)	74
DA(mm)	42
BE(mm)	43
EF(mm)	70.5
FG(mm)	50
GB(mm)	39.5

CDK, ABL	Isosceles triangles
KL(mm)	27.5
CG(mm)	45

Table 3.15 Geometrical characteristics of underactuated hand

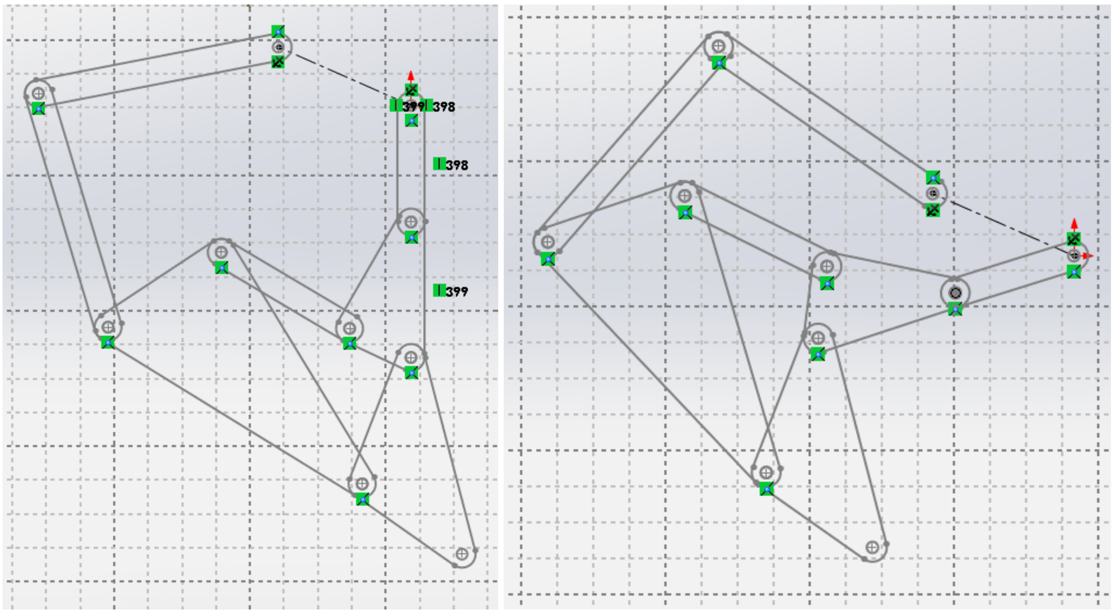
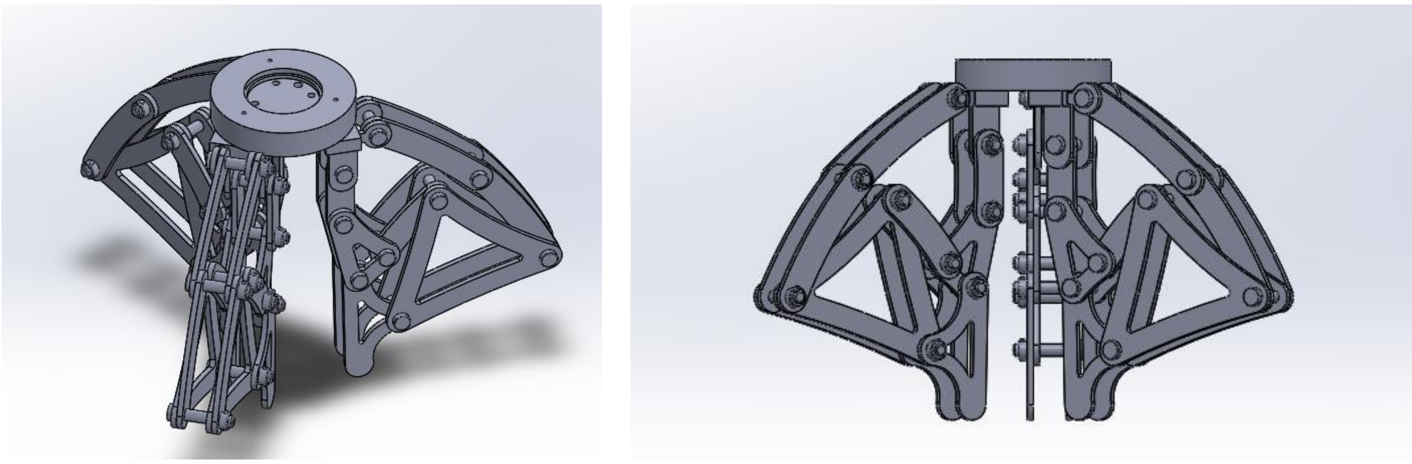
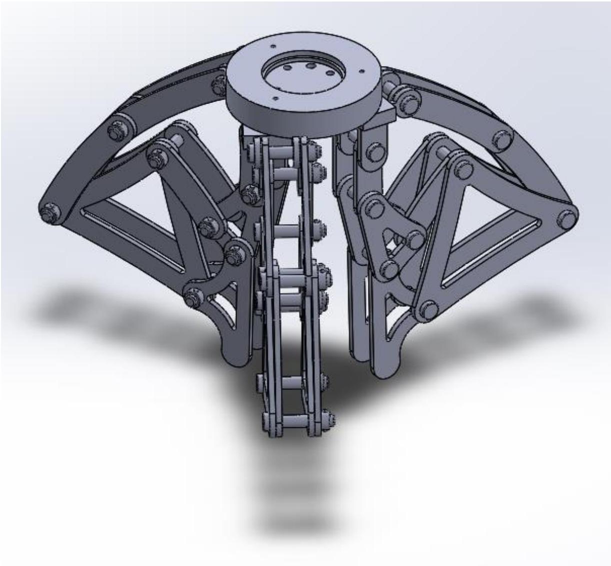
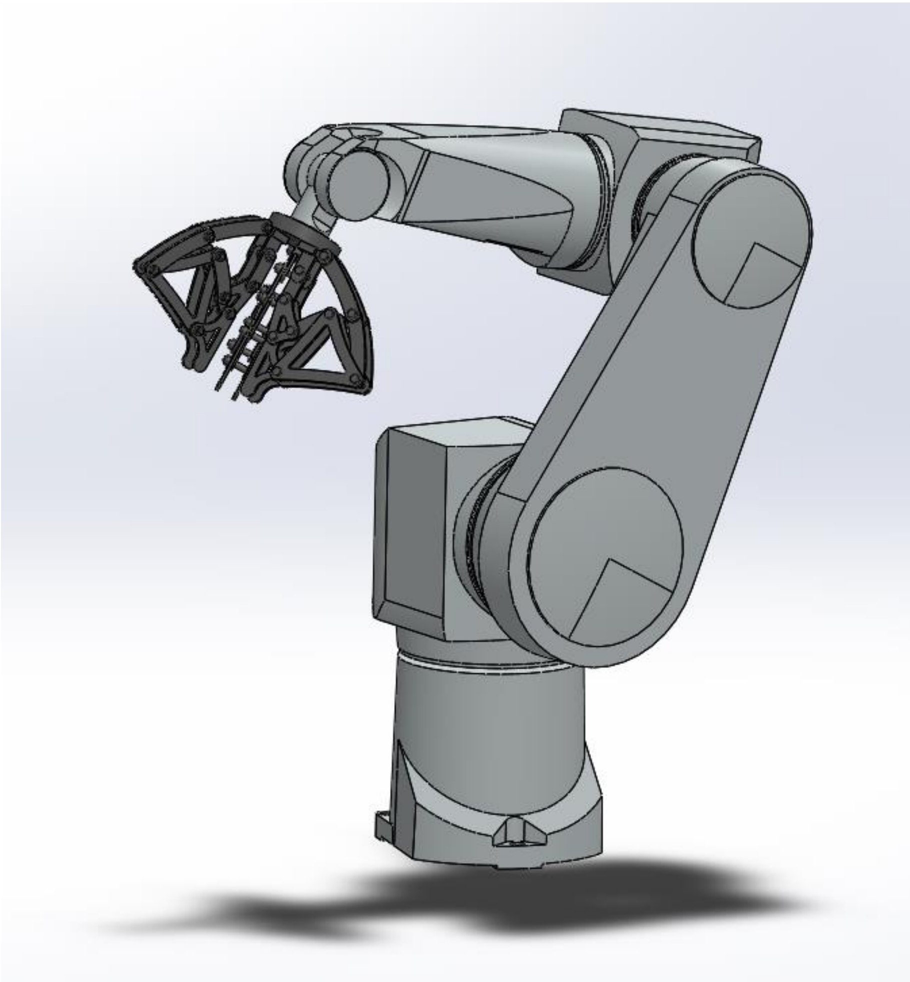


Figure 3.22 2D design of underactuated finger – Initial and final position

Based on the above, the 3D design of underactuated gripper is developed using three fingers mounted on a base which attach itself on the robot. Figure 3.23 below shows different perspectives of the mechanism constructed.







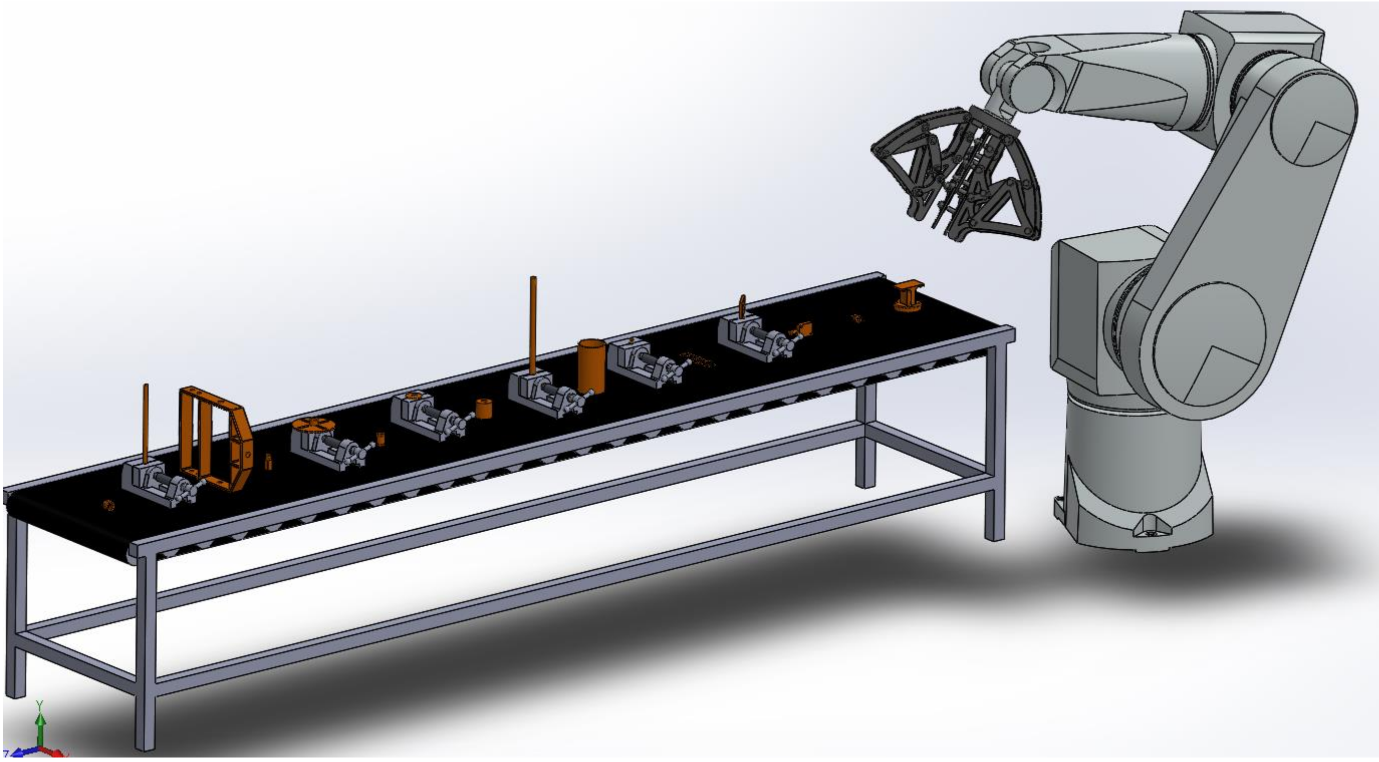


Figure 3.23 Truss inspired gripper

3.2.3.2 Balloon inspired gripper

This design demonstrates a different approach to a universal gripper. Individual fingers are replaced by a single mass of granular material that, when passed onto a target object, flows around it and conforms to its shape. Upon application of a vacuum, granular material contacts and hardens quickly to pinch and hold the object without requiring sensory feedback [30]. Most often using a combination of positive and negative pressure, the gripper can rapidly grip and release a wide range of objects. Otherwise, a manual gripper reset is also possible. The gripping process (Figure 3.24) of typical granular material grippers consists of [18]:

- Passive conformity to the shape of the object
- Vacuum hardening for gripping
- Positive pressure for transition reverse (release and deformation)

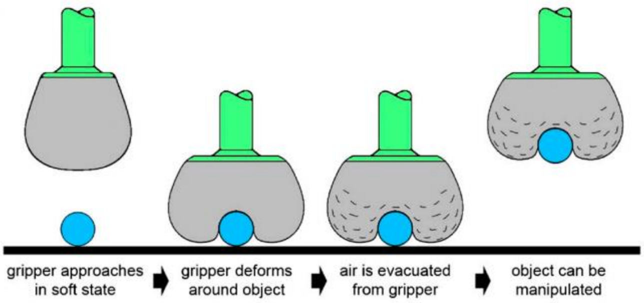


Figure 3.24 Schematic of operation

Some of the most competitive characteristics of this design concept are related to its operation. The operational principle is based on the transition between an unjammed, deformable state and a jammed state with solid-like rigidity. Reliability of gripping is also achieved because of the several operational modes that such a gripper leverages, effective for various objects' shapes (Figure 3.25) [18]:

- Static friction from normal stresses at contact
- Geometric constraints from capture of the object by interlocking
- Vacuum suction with airtight seal

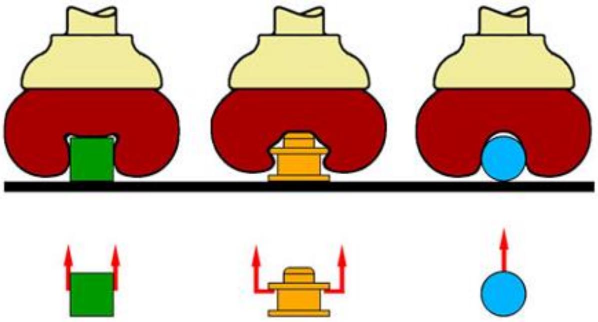


Figure 3.25 Gripper's gripping modes

On the process of defining the appropriate gripping mode of the subject gripper, objects' shape and size, orientation and surface texture should be taken into account. These constraints are already defined earlier on this Thesis. As far as the dimensioning of the design is concerned, some additional parameters should be defined. A critical parameter is the maximum force applied to an object as the gripper is deformed around it, securing the deformation of the object. The maximum contact angle at which gripper and object touch each other is determined to be 90°, while the object location should be in line with the axis of the gripper. Figure 3.26 shows a schematic of the above assumptions. The holding force of the gripping mechanism is directly related to the strength of the granular material in its jammed state. However, the key control parameter for the gripping strength is the confining pressure P_{jam} [18].

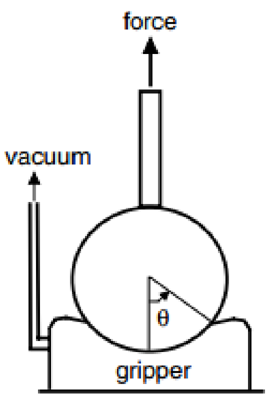


Figure 3.26 Gripper's contact with an object

Based on the above analysis, the mechanism developed in this project follows a jaw-finger approach which means that multiple 'balloon' grippers are combined in one. According to the characteristics of the objects to be grasped, there is a possibility of different jaw configurations taking advantage of all the three gripping modes described above. Balloon jaws has the ability to move in order to change the workspace for different requirements. Mutual contribution of jaws has been incorporated through symmetrical gripping and in line positioning to the objects. Finally, actuation through a central control system is developed for operational reasons.

The architecture of the gripper developed consists of the following components:

- A rigid frame where the balloon jaws are mounted
- Four balloon jaws with one-DOF each, giving the possibility of elongation which means that the vertical movement is free

Table 3.16 shows the quantitative model of the workplace designation, according to which the geometrical characteristics of the jaws are defined.

Dimension	X-axis (mm)	Y-axis(mm)
Min	4	4
Max	182.5	49

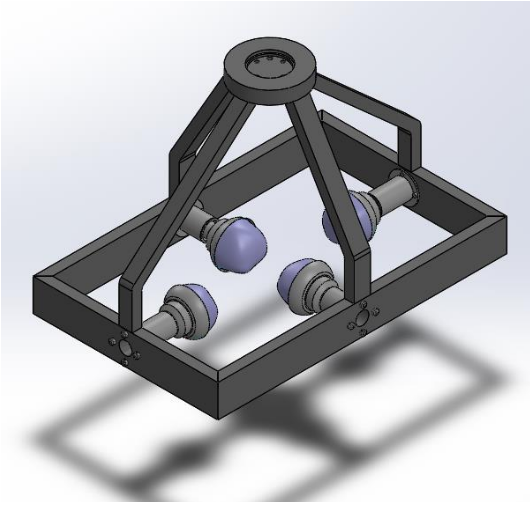
Table 3.16 Workpspace designation

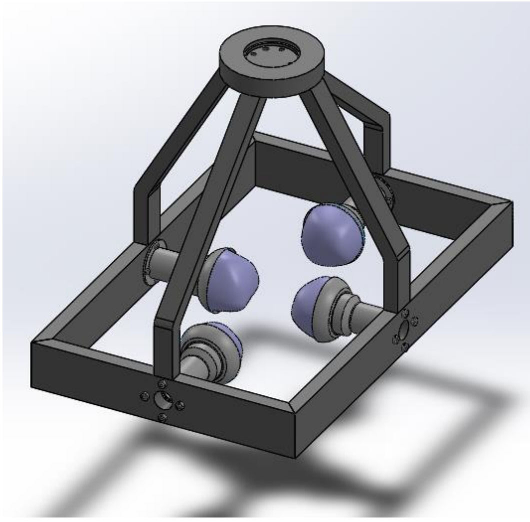
The balloon jaws positioning and the grasping principle of each one depends on the shape of the objects to be grasped. Table 3.17 shows a classification principle for different shapes of objects, which defines the spatial positioning of them as well as the size of the frame.

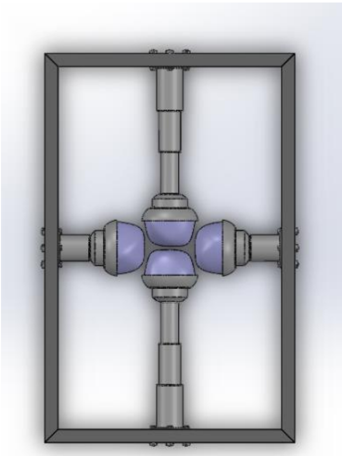
Variety of components	Grasping
Rectangular cubic prism	4 faces 2 faces on overlapping geometrical conditions
Flat thin wall	4 faces
Solids of revolution	4 faces 2 faces on overlapping geometrical conditions

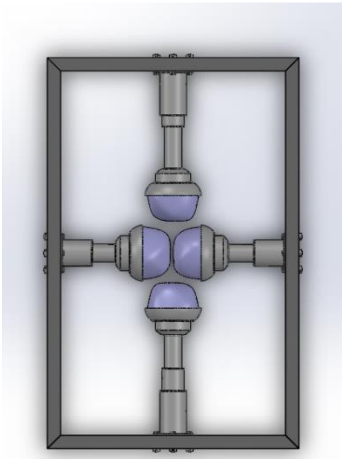
Table 3.17 Grasping principles according to object shape

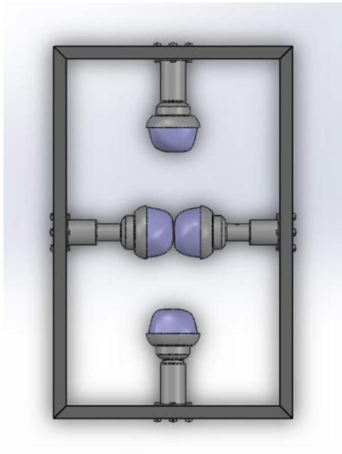
Combining the above defined characteristics, a 3D model of the granular gripper is constructed. Figure 3.27 shows several perspectives of the design and its reconfigurable characteristics.

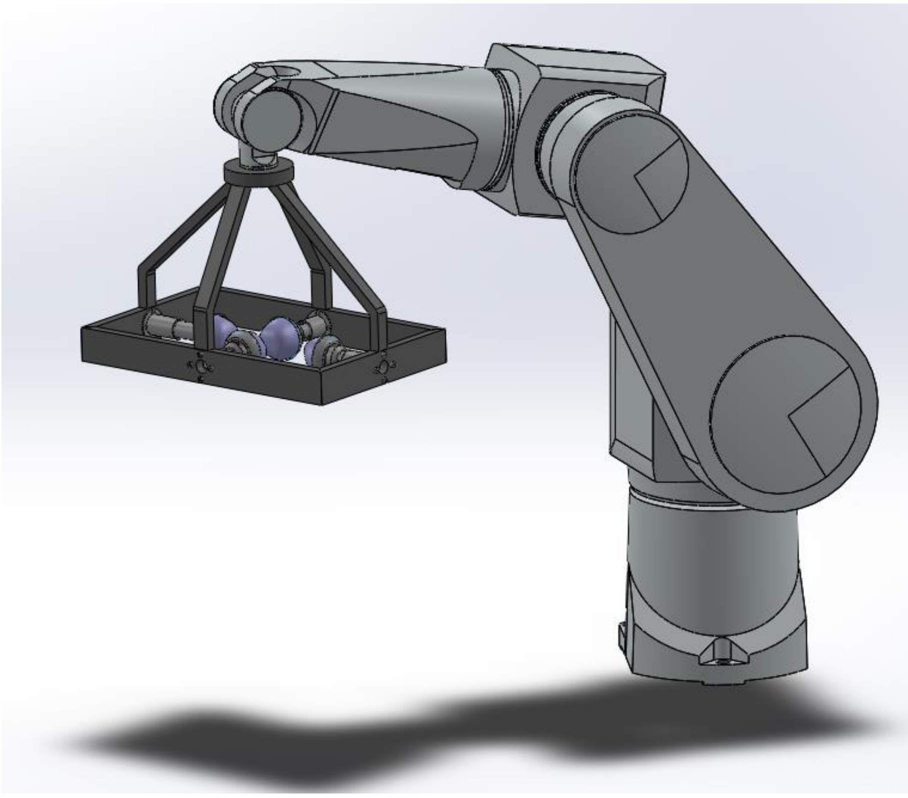












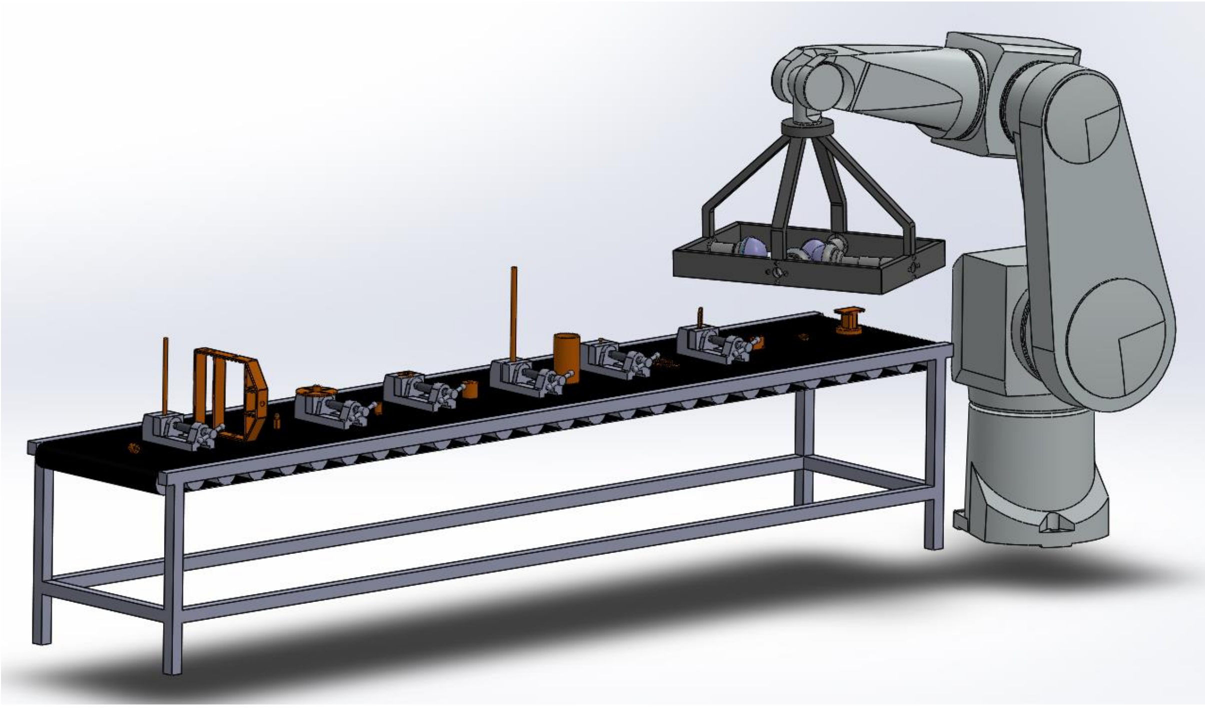


Figure 3.27 Balloon inspired gripper

3.2.3.3 Belt conveyor inspired gripper

This design is based on the use of chain components taking advantage of its geometrical and operational characteristics. These elements are used into production and manufacturing systems combined with belts and have several applications. Into this field, chains can be found in two different systems. The first one is the movement transmission which is achieved through a chain drive, as illustrated in Figure 3.28.

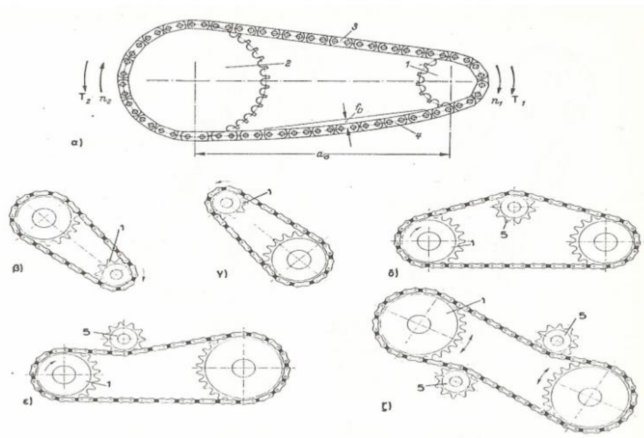


Figure 3.28 Chain drive systems

The second one is the conveyor system where chains are used as the actuation mechanism that transfers the motion (Figure 3.29).

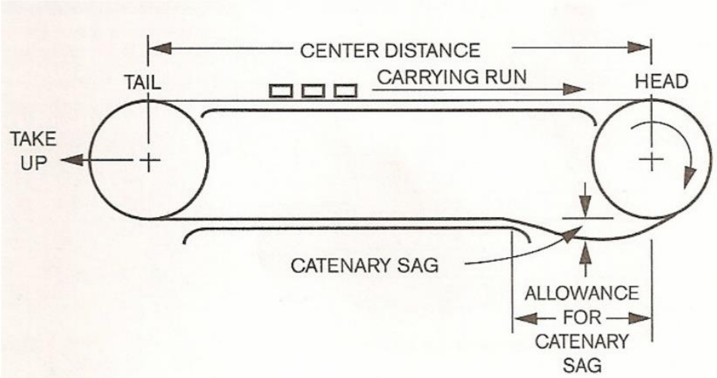


Figure 3.29 Chain conveyor systems

Combining these two main applications where chains are the dominant components, the idea of a chain conveyor system emerged. According to this, the chain is used in order to achieve movement transmission of some mounted components as well as extensive grasping capabilities through chain’s reformation. More specifically, the design consists of two main structures. The first one is the chain and the second one is the mounted plastic inserts that come in contact with the objects to be grasped. These inserts are mounted to the chain and are individual parts in a way that each chain’s movement will result to independent move of each insert. Additionally, these inserts are usually fabricated by a rubber material in order to have a high friction coefficient. Figure 3.30 shows some typical inserts that are met into the market and used in industrial conveyor systems, while Figure 3.31 illustrates a mechanical sketch of these components.

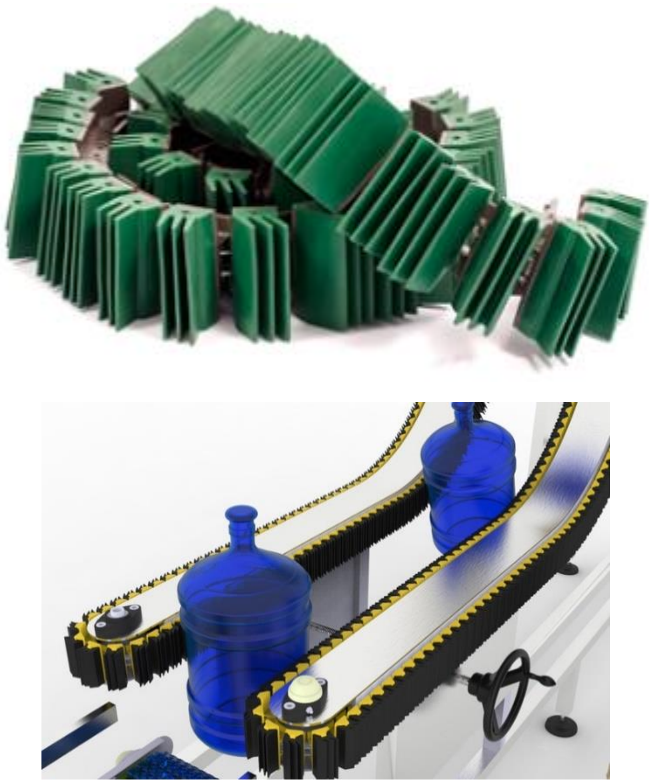


Figure 3.30 Rubber mounted inserts

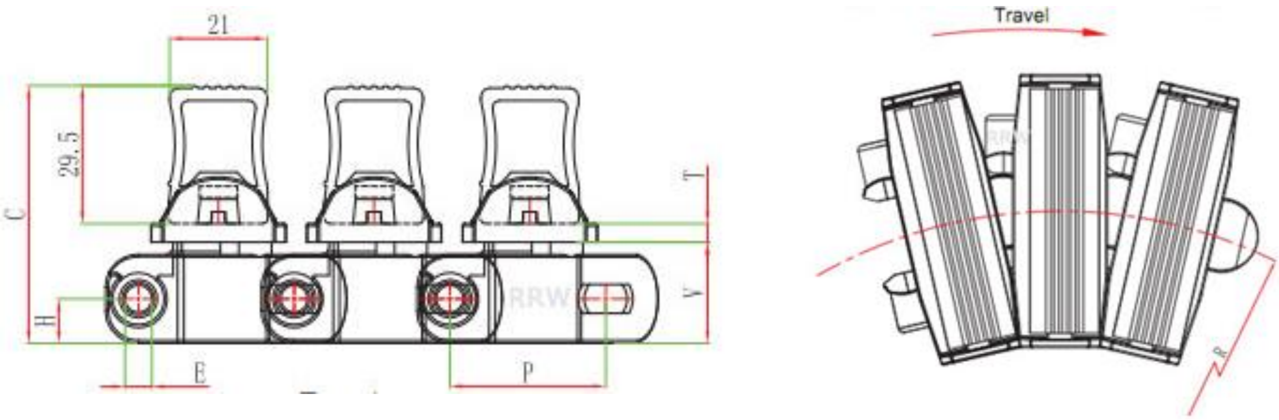
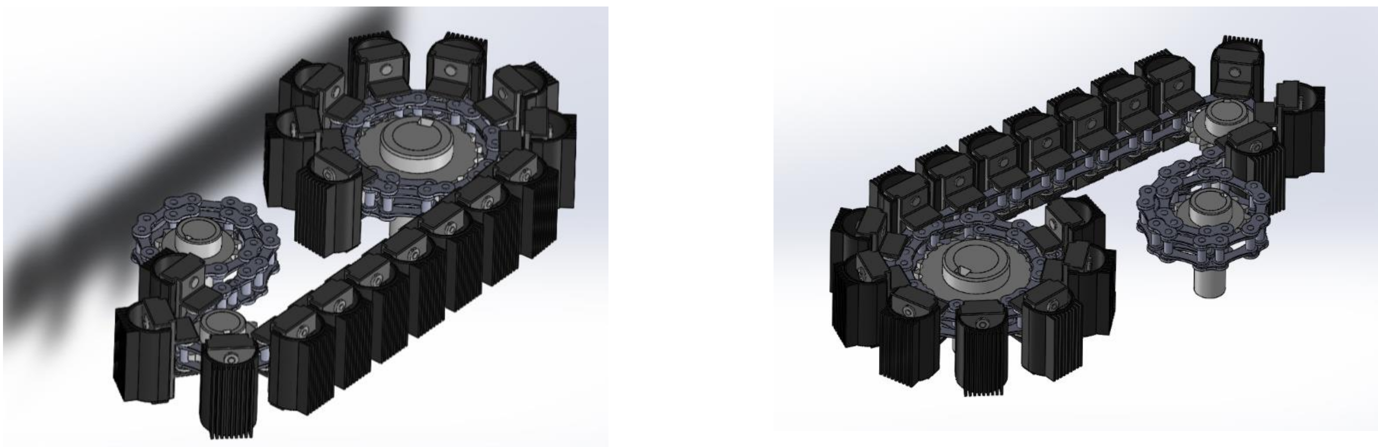
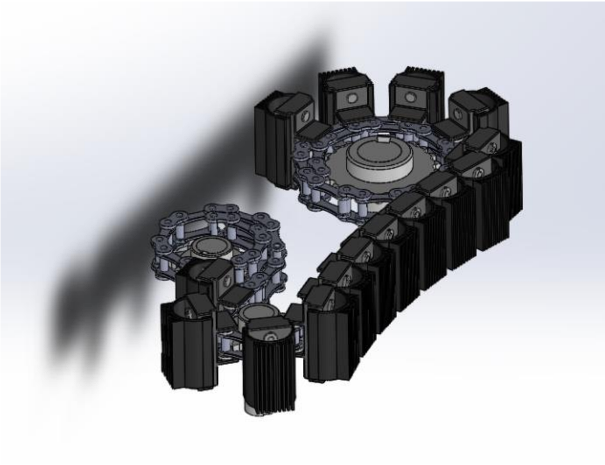


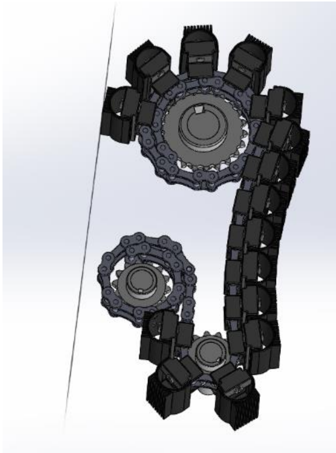
Figure 3.31 Mechanical sketch of rubber mounted inserts

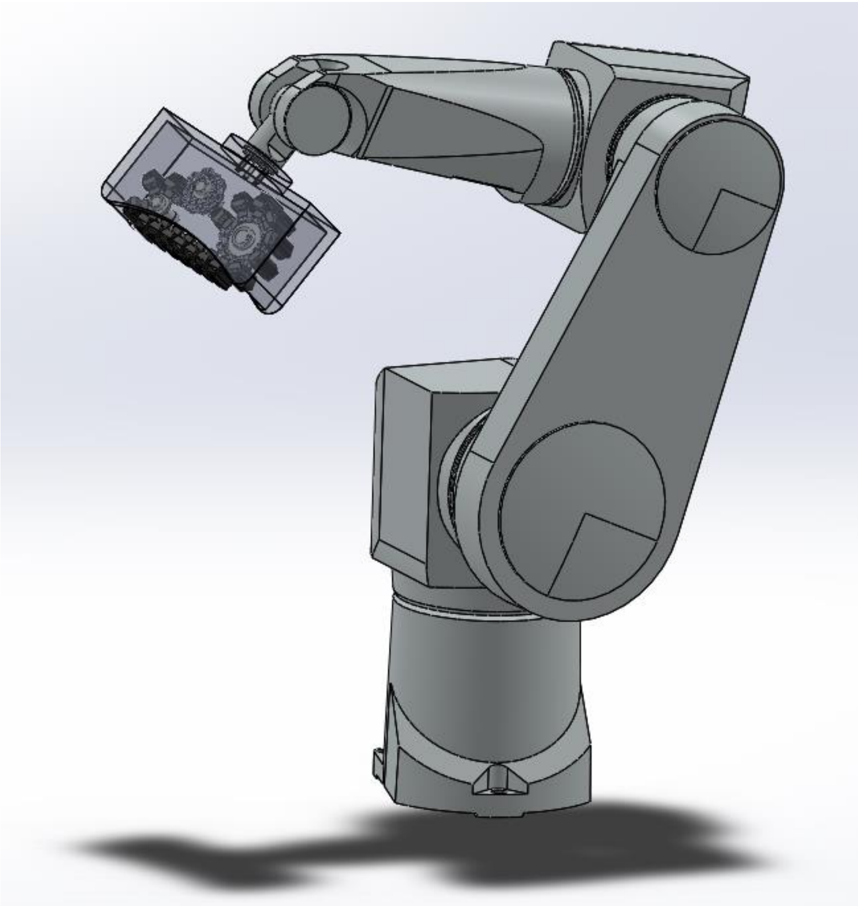
The parameters of architecture that should be defined for the design of such a mechanism, are related to two different subsystems, chain drive and chain conveyor systems. For the first system, the chain drive, the chain’s length and chain’s wheel position, geometrical characteristics and transmission ratio should be defined. These values occur by the constraints and specifications imposed earlier in this Thesis. For the second one, the chain conveyor system, the chain’s driving, mass, traction and fracture load as well as speed of operation are important factors. These factors though are not essential on the first step of mechanism’s design.

Following the above, it is assumed that vertical object conveying will be operated through this gripper. The chain is mounted to two rotational chain wheels, one of which is used for positioning purposes. The chain’s length is subject to the objects to be grasped which means that there should be adequate chain available for mold grasping. Releasing free chain means that various mold shapes can be achieved. This design will be also based on the jaw grasping approach but it is enriched with the use of alternative and flexible materials. Figure 3.32 below illustrates the 3D model constructed for this last alternative concept.









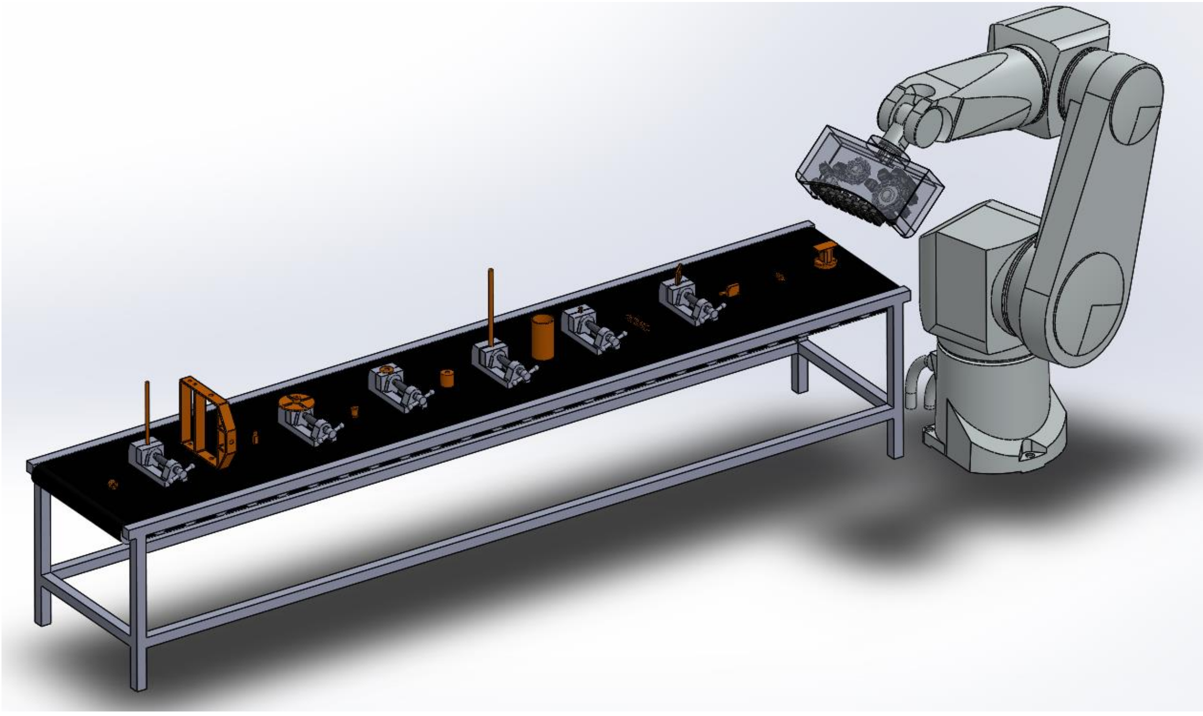


Figure 3.32 Belt conveyor inspired gripper

CHAPTER 4 DESIGN EVALUATION

Three design alternatives have been developed in the frame of this work, which have been extensively described in the previous Chapter. These designs are basically based on the specifications and restrictions imposed at the beginning of the current work. This means that the design concepts have been developed based on the Voice of the Customer (VoC). However, to design a product well, it is important to know the customer desires coupled with the integration of corporate functional groups. It is important that the customer desires will be translated into design characteristics during the product development [31].

In order to achieve this, several tools have been introduced that help on the translation of the Voice of the Customer into new, functional products that truly satisfy their needs. The most well-known technique is Quality Function Deployment method (QFD) which is used to translate customer requirements to engineering specifications. It is a link between customers – design engineers – competitors – manufacturing. It provides an insight into the whole design and manufacturing operation from concept to manufacture and it can dramatically improve the efficiency, as production problems are resolved early in the design phase [32].

On this chapter, the alternative design solutions presented earlier will be evaluated through QFD theory and the final, most powerful design concept will be selected as the dominant design solution. This concept will be furtherly analysed and improved according to the results that will arise from the application of the method.

4.1 Quality function deployment (QFD)

Quality function deployment is a systematic approach to product development. Its goal is to translate subjective quality criteria into objective ones that can be quantified and measured. It is a complimentary method for determining how and where priorities are to be assigned during product design. Its application aims at the prioritization of spoken and unspoken customer needs, the translation of these needs into technical characteristics and the development of a quality product or service by focusing toward customer satisfaction. Since its introduction, Quality function deployment has helped to the following aspects [31]:

- Planning of new products
- Design of product requirements
- Determination of process characteristics
- Control of the manufacturing process
- Documentation of existing product specifications

Quality function deployment achieves these results by breaking down customer requirements into segments and identifying the appropriate means for achieving each segment. The first phase in the implementation of Quality function deployment process involves putting together a 'House of Quality' matrix, shown in Figure 4.1. There are several steps for the construction of this matrix, the completion of which will lead to the optional design solution.

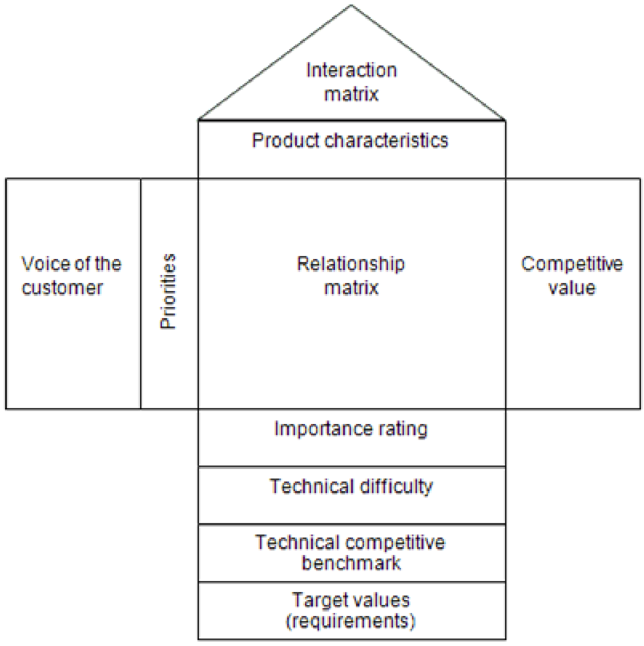


Figure 4.1 The House of Quality

The steps of the Quality function deployment will be analyzed below in parallel with the application of the method on the subject project. This will lead to a more comprehensive way of describing the structure of House of Quality. As already outlined, the aim of the application of Quality function deployment in this project is to evaluate the three alternative designs that have been developed for a smart gripper and the goal is to conclude to the most interesting design concept.

4.1.1 Steps to the House of Quality

Step 1: Demanded quality – Customer requirements/Whats

The first step is to determine which are the specifications and the requirements of the product according to the end user. This data is organized and evaluated taking into account all the aspects of the product design. Then, on a scale from 1 to 9 with 3 as a step, the importance of each requirement regarding the final product is rated. Figure 4.2 below shows the requirements of the design from the market's and customer's point of view. These are the requirements on which the design concept should comply.

Row#	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality ("Customer Requirements"/"Whats") 1
1	9	3.6	3.0	Gripping dexterity
2	3	10.7	9.0	Lifting Capacity
3	9	10.7	9.0	Gripping of various shapes
4	9	10.7	9.0	Gripping of various sizes
5	9	10.7	9.0	Reliability
6	9	3.6	3.0	Design simplicity
7	9	10.7	9.0	Gripping accuracy
8	9	10.7	9.0	Stability
9	9	3.6	3.0	Overall weight
10	3	1.2	1.0	Gripper size
11	9	3.6	3.0	Control simplicity
12	9	1.2	1.0	Force control capability
13	9	3.6	3.0	Cycle time
14	9	3.6	3.0	Cost
15	9	3.6	3.0	Maintenance
16	9	3.6	3.0	Repair
17	9	3.6	3.0	Vulnerability
18	9	1.2	1.0	Simple operation

Figure 4.2 The House of Quality – Step 1: Requirements

Step 2: Competitive Analysis

This section includes the rating of the competition. In the current work the three alternative designs are considered the competitive concepts, so they are rated according to their compliance with the imposed requirements. A scale from 1 to 5 is used for this evaluation and a graphical display is also generated illustrating the results. Figure 4.3 shows the rating of each concept and the graphical allocation of each one.

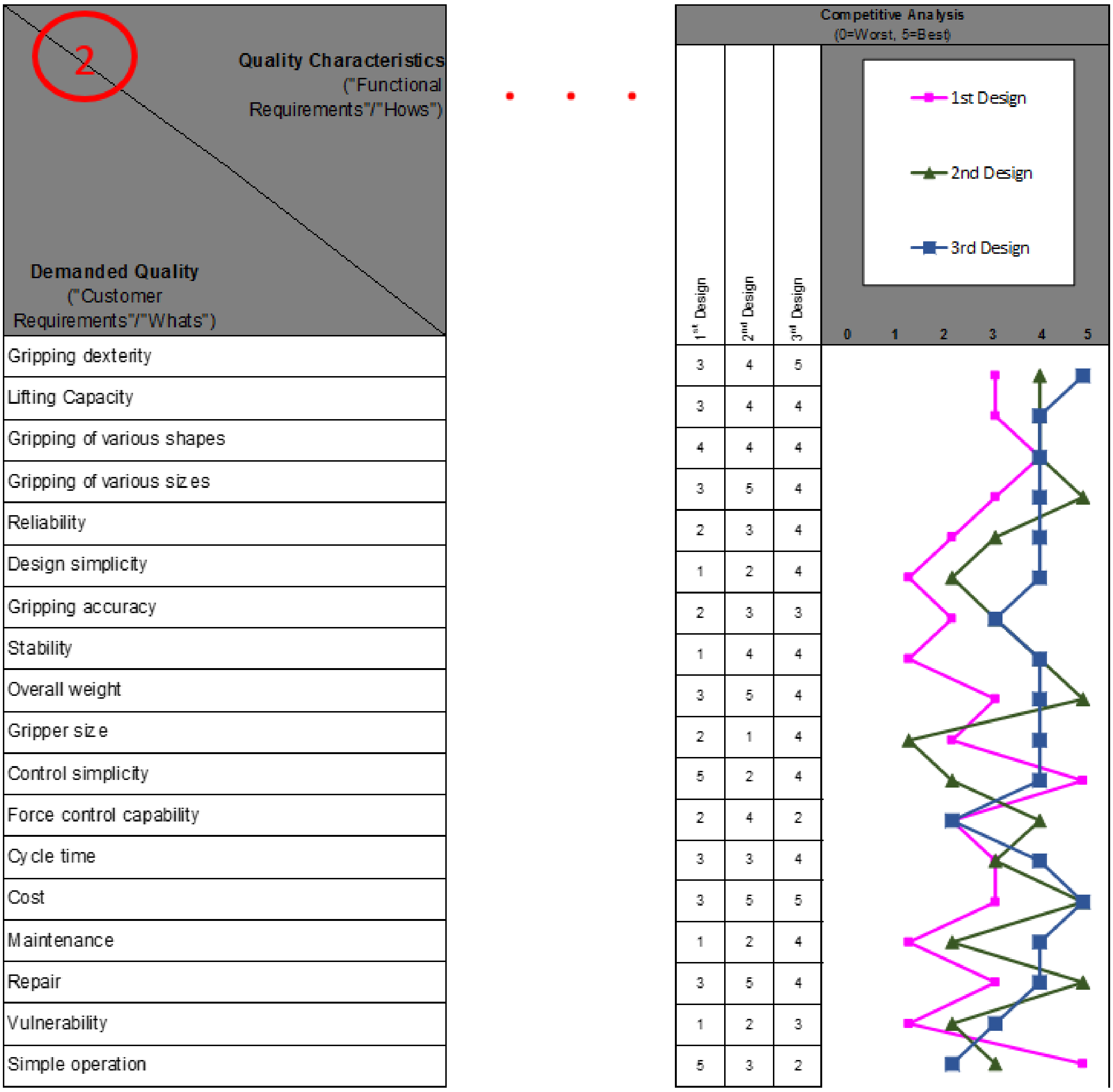


Figure 4.3 The House of Quality – Step 2: Competitive concepts

Step 3: Quality characteristics – Functional requirements/Hows

In this step the technical descriptors of the design requirements are issued into the House of Quality. These are attributes about the product that can be measured against the competition. These characteristics are determined to ensure compliance with product specifications imposed. Figure 4.4 presents the engineering characteristics in which the requirements have been translated.

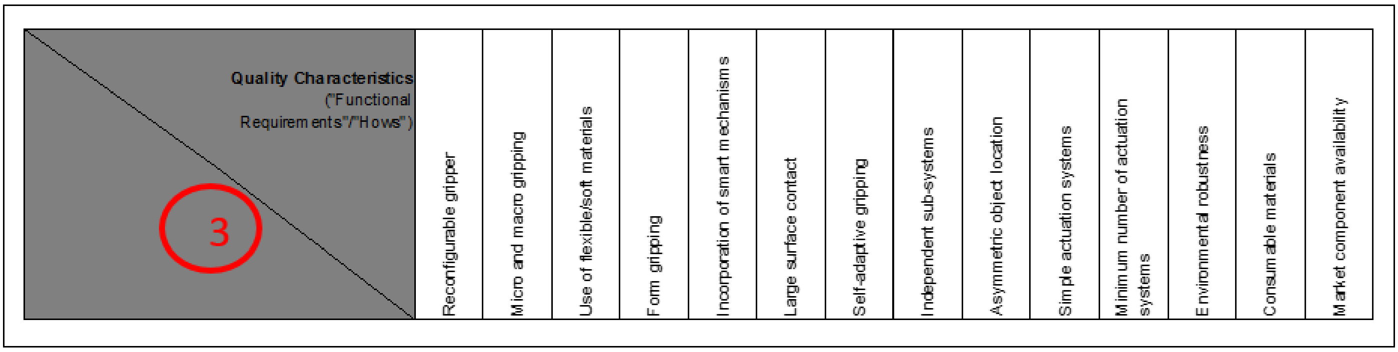


Figure 4.4 House of Quality – Step 3: Technical characteristics

Step 4: Relationship Matrix

This step describes the relationship between design requirements and technical characteristics'' ability to meet those needs. The question of how strong is the relationship between technical descriptors and design specifications is answered here. Relationships can either be weak, moderate or strong, carrying a numeric value of 1, 3 or 9. Figure 4.5 shows the symbols of the numerical values used for the relationships' determination and the relationships occurring after evaluation.

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1

4

Quality Characteristics ("Functional Requirements"/"Hows")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability
Gripping dexterity	Θ	Θ	Θ		O		O		Θ			Θ		
Lifting Capacity	O		O			O						O		
Gripping of various shapes	Θ	Θ	O	Θ	Θ				O					
Gripping of various sizes	Θ	Θ		O	Θ									
Reliability	O	O	O	Θ	Θ	Θ	▲	O		O		Θ		
Design simplicity	▲	Θ		▲	O		▲	Θ	▲	Θ				Θ
Gripping accuracy		O		O	Θ	O			Θ					
Stability		O	▲	Θ		Θ			▲			O		
Overall weight		▲	Θ								Θ		Θ	
Gripper size		O				▲								
Control simplicity	▲	▲					Θ			Θ	O			
Force control capability						Θ	Θ	Θ			▲			
Cycle time	▲			▲			Θ	O		Θ	Θ			
Cost			Θ		▲		▲				Θ		Θ	
Maintenance			O				O	Θ			Θ	Θ	Θ	O
Repair			O			O		Θ				Θ	Θ	Θ
Vulnerability			Θ		O		O	▲				Θ	Θ	
Simple operation	▲	▲					Θ							

Figure 4.5 House of Quality – Step 4: Relationship Matrix

Step 5: Accomplishment Difficulty

The technical specifications are rated in this step in terms of accomplishment difficulties. It is very possible that some attributes are in direct conflict, so the accomplishment difficulty of each one will facilitate the process of evaluation. With a range from 0=easy to accomplish to 10=extremely difficult to accomplish, this section of the matrix is filled. Figure 4.6 shows the difficulty rating of the technical attributes.

5

Quality Characteristics ("Functional Requirements"/"Hows")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability
•														
•														
•														
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	7	1	10	7	6	10	3	9	3	4	8	1	4
Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance	301.2	365.5	257.1	360.7	421.4	279.8	135.7	153.6	175.0	128.6	140.5	289.3	160.7	75.0
Relative Weight	9.3	11.3	7.9	11.1	13.0	8.6	4.2	4.7	5.4	4.0	4.3	8.9	5.0	2.3

Figure 4.6 House of Quality – Step 5: Accomplishment difficlty

Step 6: Technical analysis of competitor products

Similar to the comparison of competitive concepts regarding the design requirements, a comparison is conducted from the technical descriptors' aspect. This process involves reverse engineering competitor products to determine specific values for technical specifications. Figure 4.7 illustrates the results of this comparison.

Quality Characteristics ("Functional Requirements"/"Hows") / Demanded Quality ("Customer Requirements"/"Whats")		Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)		8	7	1	10	7	6	10	3	9	3	4	8	1	4
Max Relationship Value in Column		9	9	9	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance		301.2	365.5	257.1	360.7	421.4	279.8	135.7	153.6	175.0	128.6	140.5	289.3	160.7	75.0
Relative Weight		9.3	11.3	7.9	11.1	13.0	8.6	4.2	4.7	5.4	4.0	4.3	8.9	5.0	2.3
6 Technical Competitive Analysis (0=Worst, 5=Best)	1st Design	3	2	1	1	2	3	5	5	3	5	5	1	1	3
	2nd Design	4	5	5	4	3	5	2	2	1	2	2	2	4	4
	3rd Design	4	4	4	5	3	3	4	2	4	2	2	3	4	5

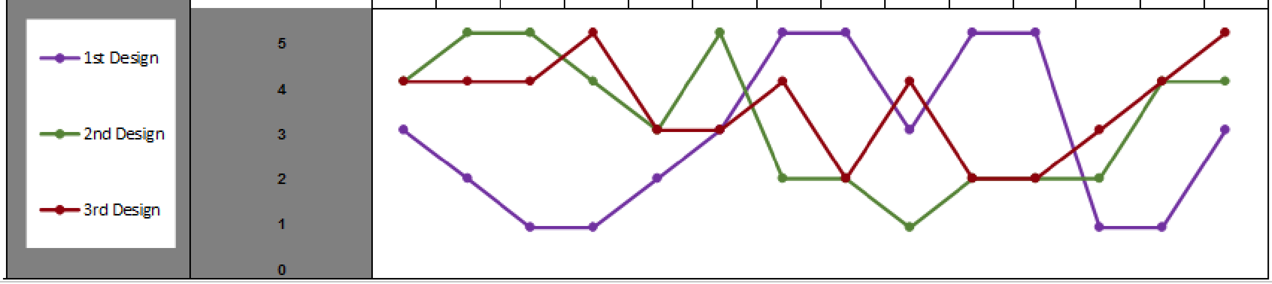


Figure 4.7 House of Quality – Step 6: Technical competitor analysis

Step 7: Correlation Matrix

This room in the matrix is where the term House of Quality comes from because it makes the matrix look like a house with roof. The correlation matrix is the room that helps most the design engineers for the final stages of Quality function deployment. According to this, it is obvious how each of the technical descriptors impact each other. Strong positive to strong negative relationship can be documented. Then, according to the evaluation of the results the section direction of improvement is filled, taking into account the relationships and the design specifications that should be met. Figure 4.8 presents the symbols of the current evaluation and the correlation matrix results.

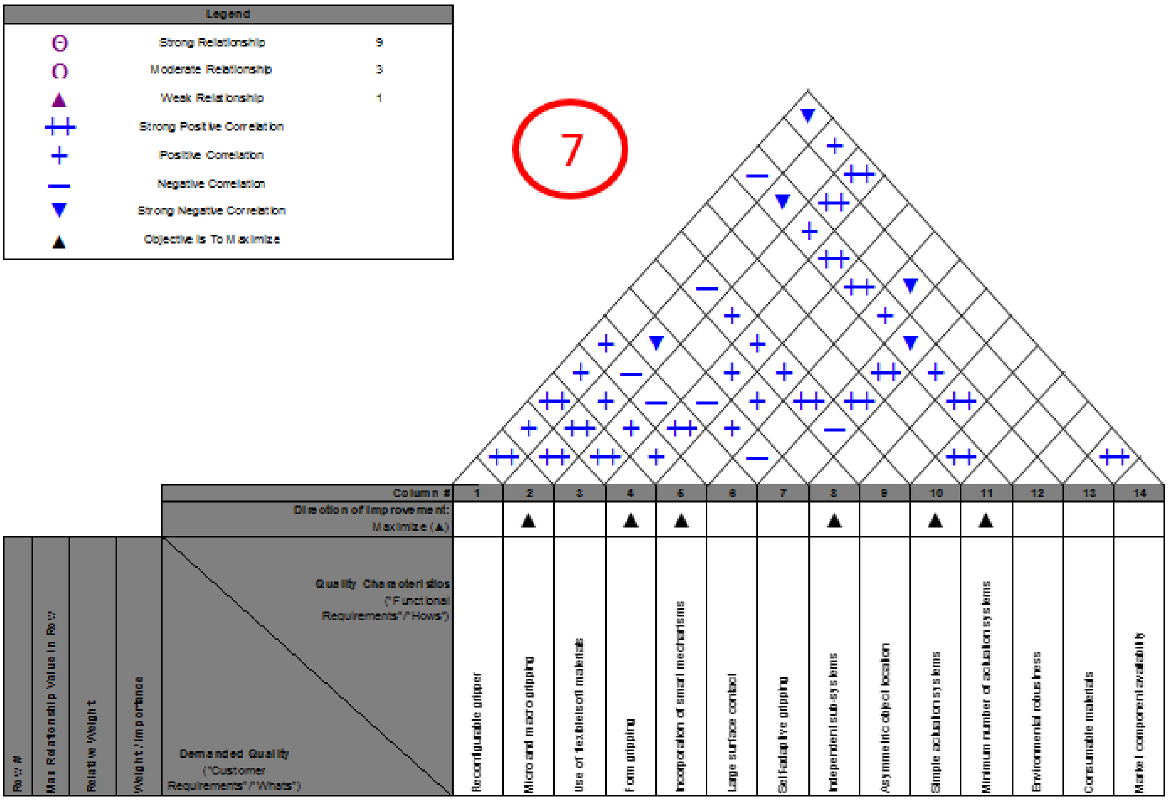


Figure 4.8 House of Quality – Step 7: Correlation Matrix

Finally, the House of Quality is presented in Figure 4.9 in its full version, including steps 1-7. The evaluation of the alternative designs follows and all the criteria according to which the optional design concept has been selected.

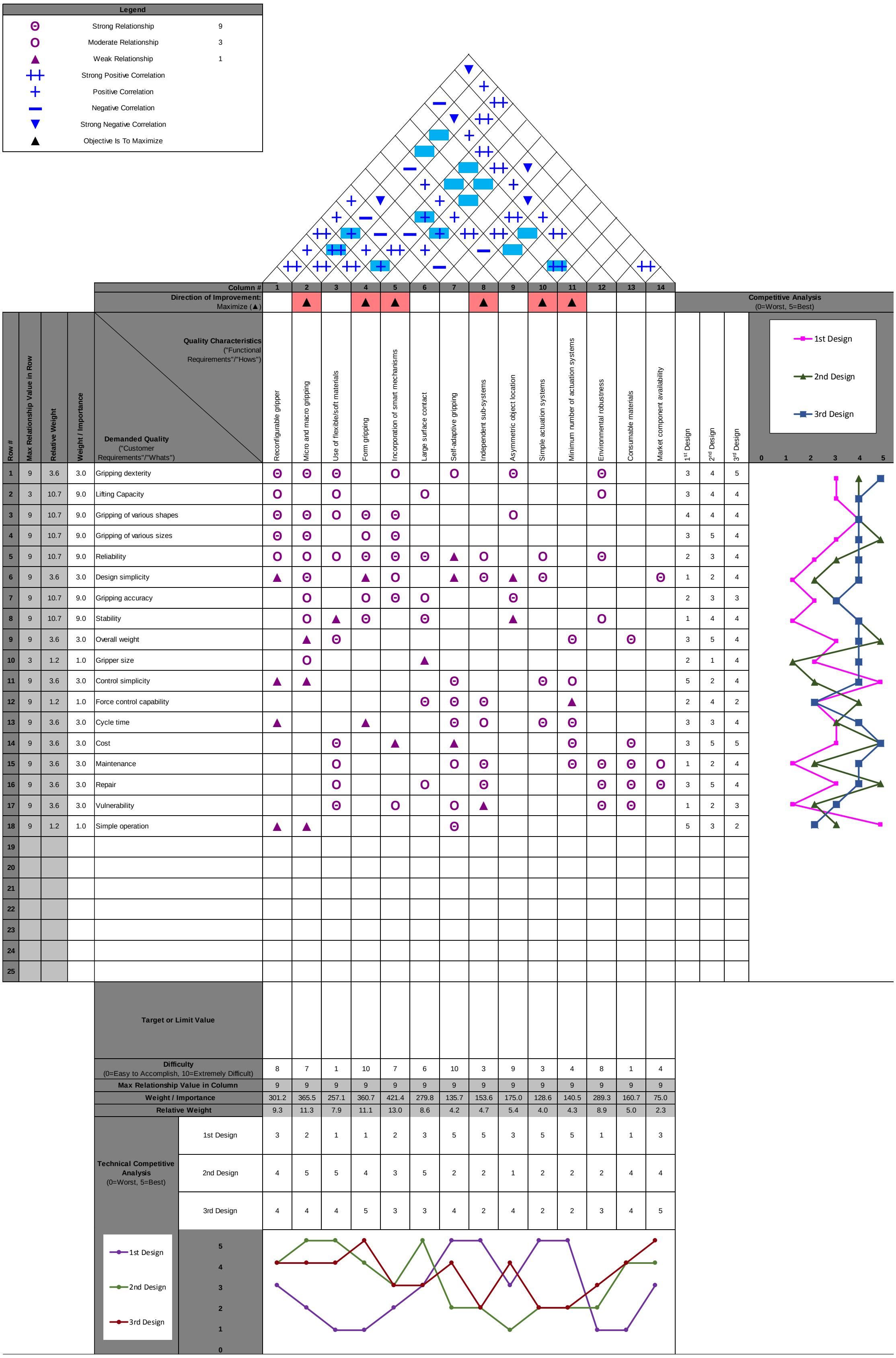


Figure 4.9 House of Quality – Full Matrix

4.1.2 Evaluation of House of Quality

As the Quality function deployment chart has been completed, the data that has been accumulated and organised must be analysed and the target values should be finalised. The analysis of the chart will identify several key areas:

- Areas in which each design holds the lead
- Areas where each design concept can gain a competitive advantage
- Areas where each design concept lags behind

The analysis procedure that will take place in the current work consists of three steps. The first one, considers as the most important attribute the highest ranked demanded quality. For these items, the highest ranked quality characteristics are identified from their relationship point of view. Then, for the lower accomplishment difficulties of quality characteristics, the technical competitive analysis is evaluated. Taking into account the performance of each design concept on the customer's needs and the technical specifications, a rank between the three alternative designs is formed. As a second step, the same procedure is followed but now the medium ranked quality characteristics are identified for the highest ranked demanded quality. Finally, on step three the medium ranked demanded quality items are identified and for these, the highest ranked quality characteristics are analysed furtherly. Figure 4.10 below shows a schematic of the described evaluation procedure is presented.

Figure 4.10 QFD evaluation prodecure

Beginning from the first step of the analysis procedure, the highest ranked demanded quality items are identified. According to the scale defined earlier, the highest ranking is 9. Figure 4.11 shows these items highlighted. For these customer requirements, a sum value has been calculated for each design concept, forming a first ranking idea.

Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics ("Functional Requirements"/"Hows") / Demanded Quality ("Customer Requirements"/"Whats")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability	1st Design	2nd Design	3rd Design
9	3.6	3.0	Gripping dexterity	Θ	Θ	Θ		O		O		Θ			Θ			3	4	5
3	10.7	9.0	Lifting Capacity	O		O			O						O			3	4	4
9	10.7	9.0	Gripping of various shapes	Θ	Θ	O	Θ	Θ				O						4	4	4
9	10.7	9.0	Gripping of various sizes	Θ	Θ		O	Θ										3	5	4
9	10.7	9.0	Reliability	O	O	O	Θ	Θ	Θ	▲	O		O		Θ			2	3	4
9	3.6	3.0	Design simplicity	▲	Θ		▲	O		▲	Θ	▲	Θ				Θ	1	2	4
9	10.7	9.0	Gripping accuracy		O		O	Θ	O			Θ						2	3	3
9	10.7	9.0	Stability		O	▲	Θ		Θ			▲			O			1	4	4
9	3.6	3.0	Overall weight		▲	Θ								Θ		Θ		3	5	4
3	1.2	1.0	Gripper size		O				▲									2	1	4
9	3.6	3.0	Control simplicity	▲	▲					Θ			Θ	O				5	2	4
9	1.2	1.0	Force control capability						Θ	Θ	Θ			▲				2	4	2
9	3.6	3.0	Cycle time	▲			▲			Θ	O		Θ	Θ				3	3	4
9	3.6	3.0	Cost			Θ		▲		▲				Θ		Θ		3	5	5
9	3.6	3.0	Maintenance			O				O	Θ			Θ	Θ	Θ	O	1	2	4
9	3.6	3.0	Repair			O			O		Θ				Θ	Θ	Θ	3	5	4
9	3.6	3.0	Vulnerability			Θ		O		O	▲				Θ	Θ		1	2	3
9	1.2	1.0	Simple operation	▲	▲					Θ								5	3	2

Figure 4.11 Highest ranked demanded quality items

	1st Design	2nd Design	3rd Design
Sum	15	23	23

Table 4.1 Design concepts ranking for the highest ranked demanded quality items

According to these first results, it seems that 1st design concept lags behind for the highest ranked demanded quality items, while 2nd and 3rd design concepts have equal rating. This is a first indication that 1st design concept does not fulfil as expected the most important product's requirements. Afterwards, the highest ranked quality characteristics are identified as shown in Figure 4.12. For these items, the accomplishment difficulty rating is reviewed and the parameters of difficulty lower than 7 are distinguished (Figure 4.13). It is assumed that a rating of 7 leaves room for improvement for the designs. The sum of technical competitive analysis is calculated again for each design and is presented in Table 4.2.

Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics ("Functional Requirements"/"Hows") / Demanded Quality ("Customer Requirements"/"Whats")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability	1st Design	2nd Design	3rd Design
9	3.6	3.0	Gripping dexterity	Θ	Θ	Θ		O		O		Θ			Θ			3	4	5
3	10.7	9.0	Lifting Capacity	O		O			O						O			3	4	4
9	10.7	9.0	Gripping of various shapes	Θ	Θ	O	Θ	Θ				O						4	4	4
9	10.7	9.0	Gripping of various sizes	Θ	Θ		O	Θ										3	5	4
9	10.7	9.0	Reliability	O	O	O	Θ	Θ	Θ	▲	O		O		Θ			2	3	4
9	3.6	3.0	Design simplicity	▲	Θ		▲	O		▲	Θ	▲	Θ				Θ	1	2	4
9	10.7	9.0	Gripping accuracy		O		O	Θ	O			Θ						2	3	3
9	10.7	9.0	Stability		O	▲	Θ		Θ			▲			O			1	4	4
9	3.6	3.0	Overall weight		▲	Θ								Θ		Θ		3	5	4
3	1.2	1.0	Gripper size		O				▲									2	1	4
9	3.6	3.0	Control simplicity	▲	▲					Θ			Θ	O				5	2	4
9	1.2	1.0	Force control capability						Θ	Θ	Θ			▲				2	4	2
9	3.6	3.0	Cycle time	▲			▲			Θ	O		Θ	Θ				3	3	4
9	3.6	3.0	Cost			Θ		▲		▲				Θ		Θ		3	5	5
9	3.6	3.0	Maintenance			O				O	Θ			Θ	Θ	Θ	O	1	2	4
9	3.6	3.0	Repair			O			O		Θ				Θ	Θ	Θ	3	5	4
9	3.6	3.0	Vulnerability			Θ		O		O	▲				Θ	Θ		1	2	3
9	1.2	1.0	Simple operation	▲	▲					Θ								5	3	2

Figure 4.12 Highest ranked quality characteristics – Step 1

Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)		8	7	1	10	7	6	10	3	9	3	4	8	1	4
Max Relationship Value in Column		9	9	9	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance		301.2	365.5	257.1	360.7	421.4	279.8	135.7	153.6	175.0	128.6	140.5	289.3	160.7	75.0
Relative Weight		9.3	11.3	7.9	11.1	13.0	8.6	4.2	4.7	5.4	4.0	4.3	8.9	5.0	2.3
Technical Competitive Analysis (0=Worst, 5=Best)	1st Design	3	2	1	1	2	3	5	5	3	5	5	1	1	3
	2nd Design	4	5	5	4	3	5	2	2	1	2	2	2	4	4
	3rd Design	4	4	4	5	3	3	4	2	4	2	2	3	4	5

Figure 4.13 Items of low accomplishment difficulty

	1st Design	2nd Design	3rd Design
Sum	15	13	10

Table 4.2 Design concepts ranking for the lower accomplishment difficulty quality characteristics – Step 1

Reviewing these results, it seems that 1st and 2nd design concepts lag behind, while 3rd design concept has a high potential of improvement.

Following the same procedure for the second step of evaluation, where the medium ranked quality characteristics are evaluated, the results are presented in Figure 4.14 and Table 4.3. According to these, 1st and 2nd design concepts still lag behind, while 3rd design concept can get more easily improved.

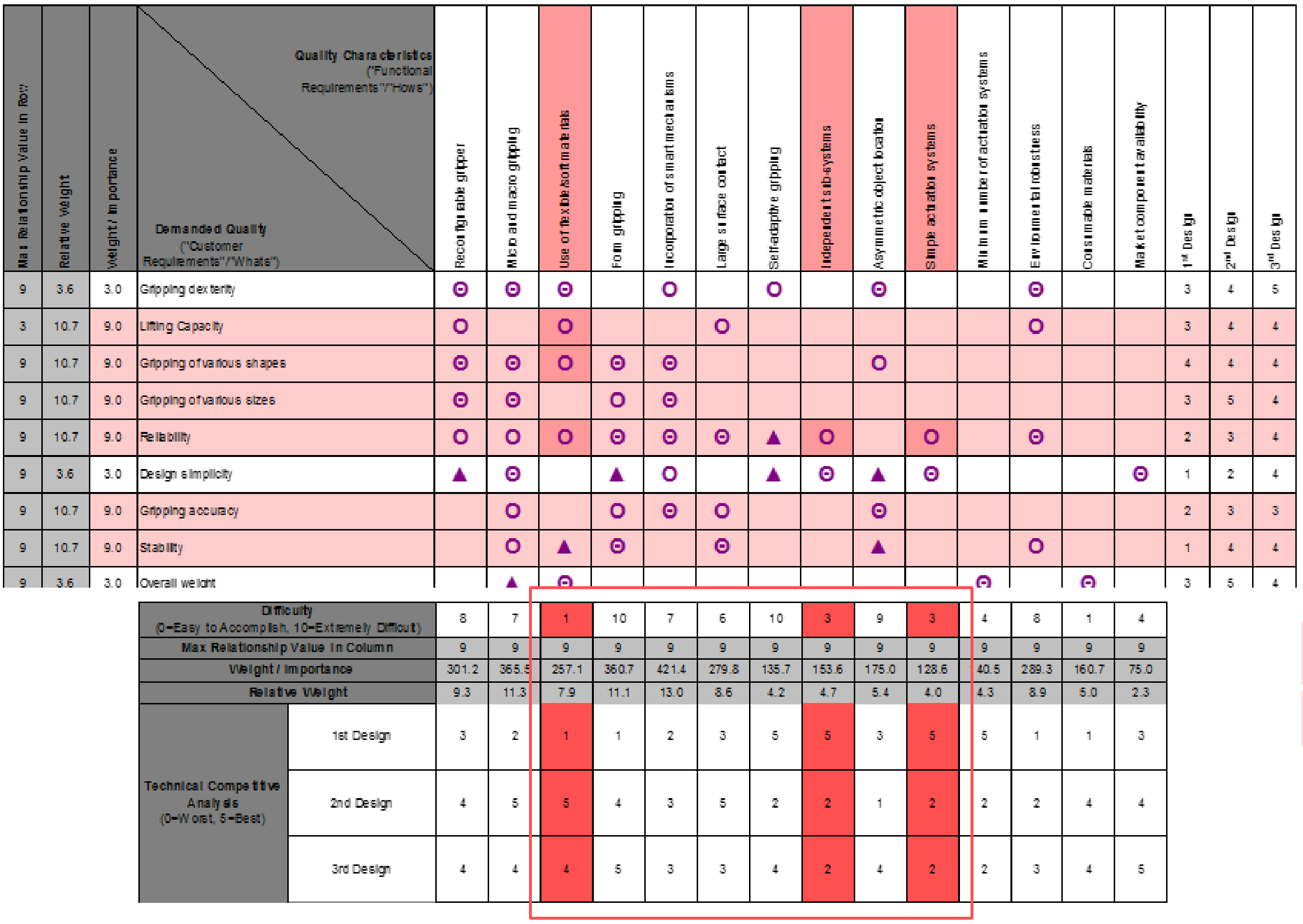


Figure 4.14 Results of 2nd step of evaluation procedure

	1st Design	2nd Design	3rd Design
Sum	11	9	8

Table 4.3 Design concepts ranking for the lower accomplishment difficulty quality characteristics - Step 2

Proceeding to the third step of evaluation where medium ranked demanded quality items are identified, the rating of concept designs regarding product's characteristics still indicates the superiority of the 3rd design concept (Figure 4.5 and Table 4.4).

Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics ("Functional Requirements"/"Hows") / Demanded Quality ("Customer Requirements"/"Whats")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability	1st Design	2nd Design	3rd Design
9	3.6	3.0	Gripping dexterity	Θ	Θ	Θ		O		O		Θ			Θ			3	4	5
3	10.7	9.0	Lifting Capacity	O		O			O						O			3	4	4
9	10.7	9.0	Gripping of various shapes	Θ	Θ	O	Θ	Θ				O						4	4	4
9	10.7	9.0	Gripping of various sizes	Θ	Θ		O	Θ										3	5	4
9	10.7	9.0	Reliability	O	O	O	Θ	Θ	Θ	▲	O		O		Θ			2	3	4
9	3.6	3.0	Design simplicity	▲	Θ		▲	O		▲	Θ	▲	Θ				Θ	1	2	4
9	10.7	9.0	Gripping accuracy		O		O	Θ	O			Θ						2	3	3
9	10.7	9.0	Stability		O	▲	Θ		Θ			▲			O			1	4	4
9	3.6	3.0	Overall weight		▲	Θ								Θ		Θ		3	5	4
3	1.2	1.0	Gripper size		O				▲									2	1	4
9	3.6	3.0	Control simplicity	▲	▲					Θ			Θ	O				5	2	4
9	1.2	1.0	Force control capability						Θ	Θ	Θ			▲				2	4	2
9	3.6	3.0	Cycle time	▲			▲			Θ	O		Θ	Θ				3	3	4
9	3.6	3.0	Cost			Θ		▲		▲				Θ		Θ		3	5	5
9	3.6	3.0	Maintenance			O				O	Θ			Θ	Θ	Θ	O	1	2	4
9	3.6	3.0	Repair			O			O		Θ				Θ	Θ	Θ	3	5	4
9	3.6	3.0	Vulnerability			Θ		O		O	▲				Θ	Θ		1	2	3
9	1.2	1.0	Simple operation	▲	▲					Θ								5	3	2

Figure 4.15 Medium ranked demanded quality items

	1st Design	2nd Design	3rd Design
Sum	23	30	37

Table 4.4 Design concepts ranking for the medium ranked demanded quality items

Then, the highest ranked quality characteristics are identified for the above requirements as shown in Figure 4.16. As far as the accomplishment difficulty is concerned, parameters of difficulty lower than 4 are considered to have room for further improvements. Following the same procedure, 3rd design concept still holds the lead at this final step (Table 4.5).

Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics ("Functional Requirements"/"Hows") / Demanded Quality ("Customer Requirements"/"Whats")	Reconfigurable gripper	Micro and macro gripping	Use of flexible/soft materials	Form gripping	Incorporation of smart mechanisms	Large surface contact	Self-adaptive gripping	Independent sub-systems	Asymmetric object location	Simple actuation systems	Minimum number of actuation systems	Environmental robustness	Consumable materials	Market component availability	1st Design	2nd Design	3rd Design
9	3.6	3.0	Gripping dexterity	Θ	Θ	Θ		O		O		Θ			Θ			3	4	5
3	10.7	9.0	Lifting Capacity	O		O			O						O			3	4	4
9	10.7	9.0	Gripping of various shapes	Θ	Θ	O	Θ	Θ				O						4	4	4
9	10.7	9.0	Gripping of various sizes	Θ	Θ		O	Θ										3	5	4
9	10.7	9.0	Reliability	O	O	O	Θ	Θ	Θ	▲	O		O		Θ			2	3	4
9	3.6	3.0	Design simplicity	▲	Θ		▲	O		▲	Θ	▲	Θ				Θ	1	2	4
9	10.7	9.0	Gripping accuracy		O		O	Θ	O			Θ						2	3	3
9	10.7	9.0	Stability		O	▲	Θ		Θ			▲			O			1	4	4
9	3.6	3.0	Overall weight		▲	Θ								Θ		Θ		3	5	4
3	1.2	1.0	Gripper size		O				▲									2	1	4
9	3.6	3.0	Control simplicity	▲	▲					Θ			Θ	O				5	2	4
9	1.2	1.0	Force control capability						Θ	Θ	Θ			▲				2	4	2
9	3.6	3.0	Cycle time	▲			▲			Θ	O		Θ	Θ				3	3	4
9	3.6	3.0	Cost			Θ		▲		▲				Θ		Θ		3	5	5
9	3.6	3.0	Maintenance			O				O	Θ			Θ	Θ	Θ	O	1	2	4
9	3.6	3.0	Repair			O			O		Θ				Θ	Θ	Θ	3	5	4
9	3.6	3.0	Vulnerability			Θ		O		O	▲				Θ	Θ		1	2	3
9	1.2	1.0	Simple operation	▲	▲					Θ								5	3	2

Figure 4.16 Highest ranked quality characteristics - Step 3

	1st Design	2nd Design	3rd Design
Sum	25	21	19

Table 4.5 Design concepts ranking for the lower accomplishment difficulty quality characteristics - Step 3

According to the Quality function deployment analysis performed for the evaluation of alternative design concepts, the belt conveyor inspired gripper concept has proved to be the most powerful design. This concept stood out, not only because it satisfies effectively the highest marked product requirements but also because of the room available for further design improvements.

More specifically, the quality characteristics of the highest and medium ranked requirements are considered to be vital for the final design. However, some of these characteristics are considered to be of lower importance from the technical point of view, as a result some of them are eliminated. Afterwards, the accomplishment difficulty of each one characteristic is taking into account and the remaining technical aspects that can be improved are even less. At the end of this procedure, the quality characteristics that can be improved in order to ameliorate the gripper's performance are occurred. At the diagram below in Figure 4.17, the quantitative model of the above reasoning is presented.

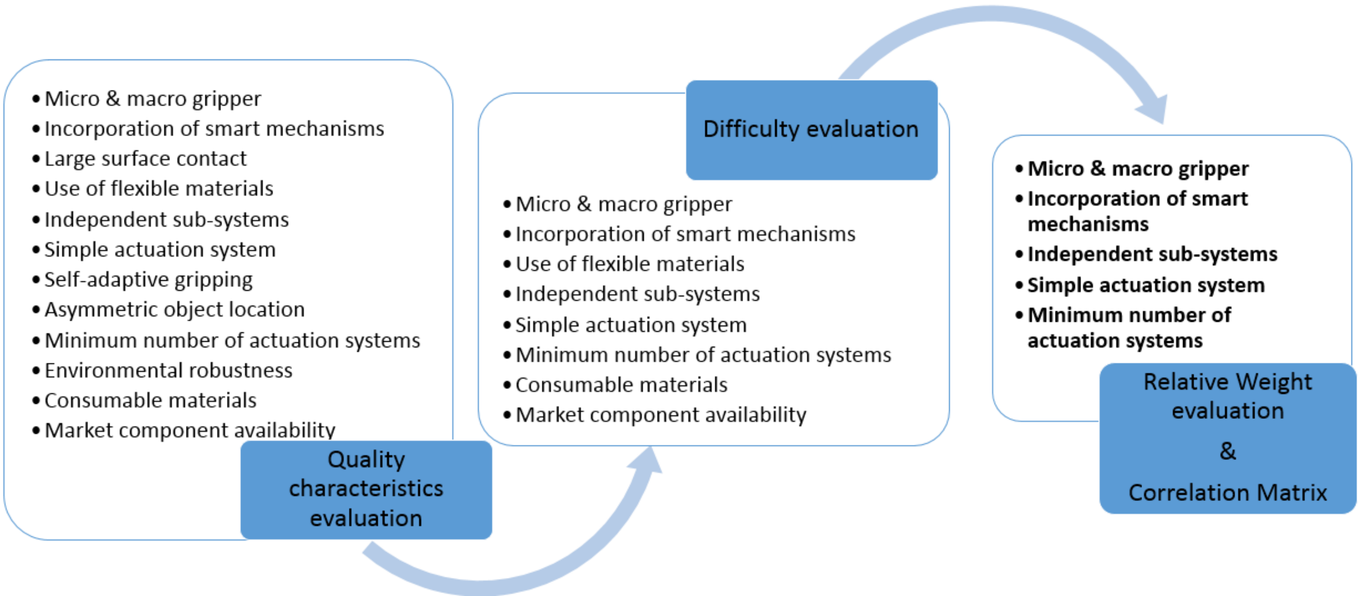


Figure 4.17 Design improvements of 3rd design

4.2 Failure Mode Effect Analysis (FMEA)

As outlined above the application of Quality function deployment method lead to the best design solution for the project's specifications and restrictions. According to this analysis, the design proposed for the belt inspired gripper proved to have room for improvements. However, the way that any changes can be valuable for a new gripper design, is a task of significant importance.

For this reason the Failure mode effect analysis (FMEA) will be conducted. A Failure mode effect analysis (FMEA) is typically used as a problem prevention tool, to improve or consolidate the basic requirements, especially at the later stages of design, to support phase two of Quality function deployment (QFD) method. The most influential use of this technique is the opportunity to use it at a concept level as the most effective proof that Quality function deployment (QFD) has delivered the main targets to production process and manufacturing controls. The Failure mode effect analysis (FMEA) transforms the voice of the customer into the voice of the engineer, focusing on functions and characteristics unseen during the first design step [33].

Quality function deployment (QFD) outlined that there are several parameters that could change and result to a more effective gripper design with the characteristics summarized below. The identification of these requirements is the first step of the Failure mode effect analysis (FMEA).

- ✓ Micro & macro gripper
- ✓ Incorporation of smart mechanisms
- ✓ Independent sub-systems
- ✓ Simple actuation system

✓ Minimum number of actuation systems

These functions can be fulfilled in various ways, however the design developed has some specific characteristics that could change effectively in terms of the above improvement requirements. These characteristics are presented below in Figure 4.18 where it is also illustrated which change affects each one requirement.

Process Step/Input	Potential Failure Mode
What is the process step or feature under investigation?	In what ways could the step or feature go wrong?
Chain length > effective chain length	1. Incorporation of smart mechanisms
> Rubber inserts size	1. Incorporation of smart mechanisms 2. Micro and macro gripping
> Rubber inserts number	1. Incorporation of smart mechanisms 2. Micro and macro gripping
Chain wheel drive	1. Simple actuation system 2. Minimum number of actuation systems
Number of chain wheels	1. Independent sub-systems 2. Simple actuation system 3. Minimum number of actuation systems

Figure 4.18 Improvement specifications' satisfaction – FMEA step 2

Summarizing the above, the combination of micro and macro gripping can be achieved by the use of more and smaller rubber inserts. These changes combined with the use of an effective and not excessive chain length can result to a smarter mechanism. This last change of the chain's length must also be accompanied by a different actuation system. More specifically, a change on the drive mechanism or on the number of chain wheels can also result to a simpler system with independent and fewer sub-systems.

As the next step of the analysis, comes the identification of potential failure effects, potential causes and current controls together with their rating for each feature. Figure 4.19 shows in detail these information.

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)
What is the process step or feature under investigation?	In what ways could the step or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?	
Chain length > effective chain length	1. Incorporation of smart mechanisms	Heavy mechanism	6	Excessive material needed	5	No alternative way of reducing the material needed	10
		High cost	6	Excessive material needed	1	No alternative way of reducing the material needed	10
		Vibrations	8	Reel wrapping (chain interaction)	8	Low operation speed	8
> Rubber inserts size	1. Incorporation of smart mechanisms 2. Micro and macro gripping	Limitations on form gripping	8	Intersection of adjacent parts	10	Form griping to the permissible limits	9
		Limitations on component sizes	8	Slot existence	10	Form griping to the permissible limits	9
> Rubber inserts number	1. Incorporation of smart mechanisms 2. Micro and macro gripping	Heavy mechanism	5	More inserts than needed	4	Minimum use of excessive inserts	6
		High cost	6	Cost for minimun use of inserts	4	Minimum use of excessive inserts	6
Chain wheel drive	1. Simple actuation system 2. Minimum number of actuation systems	Risk of chain slip	10	Chain wheel rotation	9	Low operation speed	7
Number of chain wheels	1. Independent sub-systems 2. Simple actuation system 3. Minimum number of actuation systems	Heavy mechanism	8	3 chain wheels and 3 spindles	7	Use of excessive support	8
		High power requirements	9	Use of multiple actuation systems (2 motors)	8	No alternative way of actuation	9
		Spindle alignment problem	10	Vertical posistion of spindle	10	No alternative way of actuation	9

Figure 4.19 Evaluation of potential design changes – FMEA step 3

The main failure effects that need to be taken into account for the effectiveness of the proposed changes are the heavy maintenance of the parts, the high repair cost that may occur, several limitations on the gripping process such as size and shape, as well as several operation effects such as vibration during gripping, power consumption requirements, mechanism stability such as the risk of chain slip or spindle alignment problems. These parameters have a relative severity which has been determined in accordance to the below presented severity scale (Figure 4.20).

Then, the main failure causes that lead to each feature change are presented and ranked in terms of the likelihood that they will occur. These causes can be divided into geometrical, operational and economic ones. In the first category belongs characteristics such as the use of excessive chain and rubber inserts, the existence of several slots between the rubber inserts. From the operational view, chain wrapping, intersection of adjacent parts, vertical and not horizontal position of spindle and continuous chain wheel rotation are the most important aspects. Finally, the cost of the excessive equipment needed and the cost of the operation and maintenance of this complicated actuation system are aspects that belong to the economic causes' category. The occurrence ranking of these effects has been incorporated according to Figure 4.21 below.

Finally, the current tools or mechanisms used to prevent the above failure effects are presented and evaluated. As it is obvious from Figure 4.19, given the actuation system, there is no alternative way to control the failure effects occurred than complying to the permissible limits of geometry, operational speed and costs. The detection ranking has been performed in accordance to Figure 4.22.

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	May expose client to loss, harm or major disruption - failure will occur **without** warning	10
Hazardous - With Warning	May expose client to loss, harm or major disruption - failure will occur **with** warning	9
Very High	Major disruption of service involving client interaction, resulting in either associate re-work or inconvenience to client	8
High	Minor disruption of service involving client interaction and resulting in either associate re-work or inconvenience to clients	7
Moderate	Major disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	6
Low	Minor disruption of service not involving client interaction and resulting in either associate re-work or inconvenience to clients	5
Very Low	Minor disruption of service involving client interaction that does not result in either associate re-work or inconvenience to clients	4
Minor	Minor disruption of service not involving client interaction and does not result in either associate re-work or inconvenience to clients	3
Very Minor	No disruption of service noticed by the client in any capacity and does not result in either associate re-work or inconvenience to clients	2
None	No Effect	1

Figure 4.20 Severity scale – FMEA step 3

Probability of Failure	Time Period	Per Item Failure Rates	Ranking
Very High: Failure is almost inevitable	More than once per day	>= 1 in 2	10
	Once every 3-4 days	1 in 3	9
High: Generally associated with processes similar to previous processes that have often failed	Once every week	1 in 8	8
	Once every month	1in 20	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, but not in major proportions	Once every 3 months	1 in 80	6
	Once every 6 months	1 in 400	5
	Once a year	1 in 800	4
Low: Isolated failures associated with similar processes	Once every 1 - 3 years	1 in 1,500	3
Very Low: Only isolated failures associated with almost identical processes	Once every 3 - 6 years	1 in 3,000	2
Remote: Failure is unlikely. No failures associated with almost identical processes	Once Every 7+ Years	1 in 6000	1

Figure 4.21 Occurence scale – FMEA step 3

Detection	Criteria: Likelihood the existence of a defect will be detected by process controls before next or subsequent process, -OR- before exposure to a client	Ranking
Almost Impossible	No known controls available to detect failure mode	10
Very Remote	Very remote likelihood current controls will detect failure mode	9
Remote	Remote likelihood current controls will detect failure mode	8
Very Low	Very low likelihood current controls will detect failure mode	7
Low	Low likelihood current controls will detect failure mode	6
Moderate	Moderate likelihood current controls will detect failure mode	5
Moderately High	Moderately high likelihood current controls will detect failure mode	4
High	High likelihood current controls will detect failure mode	3
Very High	Very high likelihood current controls will detect failure mode	2
Almost Certain	Current controls almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1

Figure 4.22 Detection scale – FMEA step 3

The fourth step of the analysis is the Risk Priority Number (RPN) calculation. This is a measure used when assessing risk to help identify critical failure modes associated with a design or process. The Risk Priority Number (RPN) values range from 1 (absolute best) to 1000 (absolute worst). The factors of severity, occurrence and detection that have been determined above make up this index, calculated as the product of them. The largest this value occurs the more critical failure effects are identified. However, this absolute value must be correlated with the relative values of each one factor. Figure 4.23 presents these measurements as well as some recommended actions that aim to the reduction of failure effects and the design improvement.

This is the last step of Failure mode effect analysis (FMEA), which validates the results occurred from Quality function deployment (QFD). The recommendations are the specified necessities of the design improvement, according to which the design optimization has been conducted.

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	Action Recommended
What is the process step or feature under investigation?	In what ways could the step or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the occurrence of the cause or improving detection?
Chain length > effective chain length	1. Incorporation of smart mechanisms	Heavy mechanism	6	Excessive material needed	5	No alternative way of reducing the material needed	10	300	Design reconfiguration for effective chain length
		High cost	6	Excessive material needed	1	No alternative way of reducing the material needed	10	60	Design reconfiguration for effective chain length as there is no cheaper alternative
		Vibrations	8	Reel wrapping (chain interaction)	8	Low operation speed	8	512	Design reconfiguration for effective chain length for higher speed operations
> Rubber inserts size	1. Incorporation of smart mechanisms 2. Micro and macro gripping	Limitations on form gripping	8	Intersection of adjacent parts	10	Form griping to the permissible limits	9	720	Design reconfiguration for intersection purposes
		Limitations on component sizes	8	Slot existence	10	Form griping to the permissible limits	9	720	Design reconfiguration for manipulation of a variety of objects
> Rubber inserts number	1. Incorporation of smart mechanisms 2. Micro and macro gripping	Heavy mechanism	5	More inserts than needed	4	Minimum use of excessive inserts	6	120	Design reconfiguration for effective number of rubber inserts
		High cost	6	Cost for minimun use of inserts	4	Minimum use of excessive inserts	6	144	Design reconfiguration for effective number of rubber inserts
Chain wheel drive	1. Simple actuation system 2. Minimum number of actuation systems	Risk of chain slip	10	Chain wheel rotation	9	Low operation speed	7	630	Design reconfiguration for effective chain length for higher speed operations
Number of chain wheels	1. Independent sub-systems 2. Simple actuation system 3. Minimum number of actuation systems	Heavy mechanism	8	3 chain wheels and 3 spindles	7	Use of excessive support	8	448	Alternative way of driving
		High power requirements	9	Use of multiple actuation systems (2 motors)	8	No alternative way of actuation	9	648	Reduction of actuation systems
		Spindle alignment problem	10	Vertical posistion of spindle	10	No alternative way of actuation	9	900	Alternative way of driving

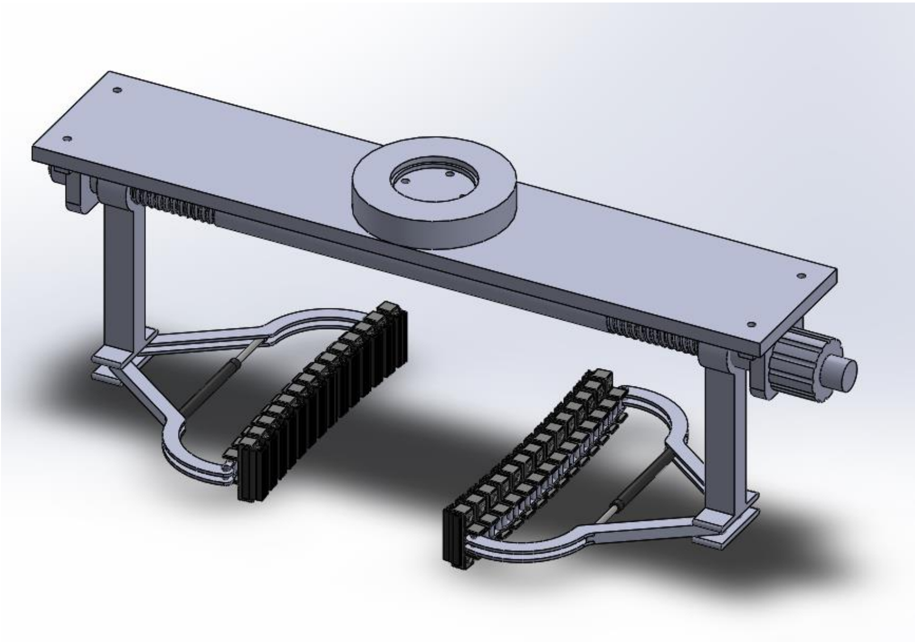
Figure 4.23 RPN and Design recommendations – FMEA step 4

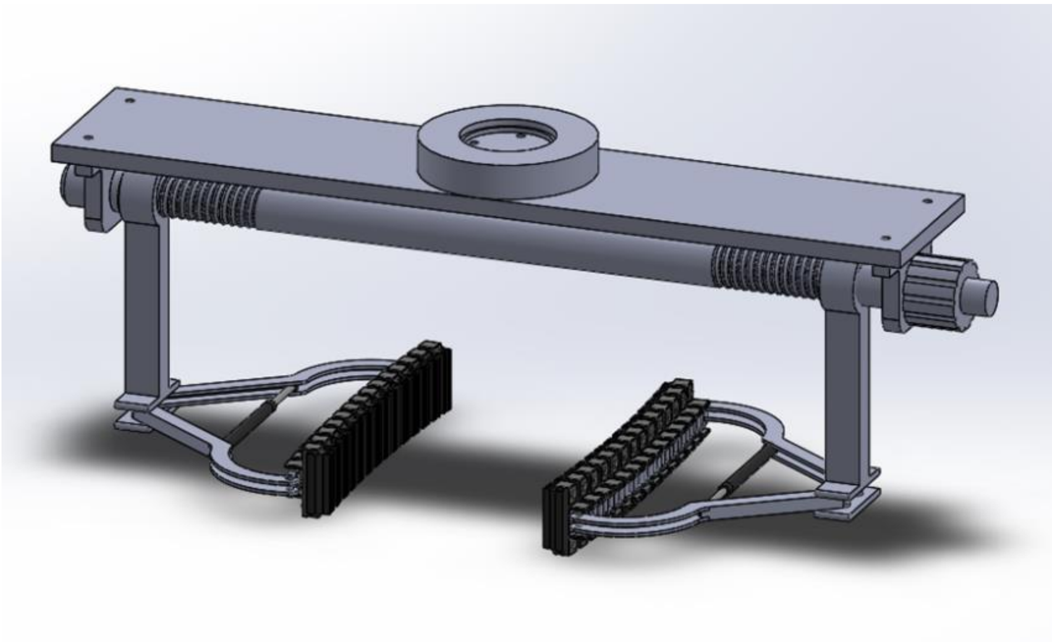
4.3 Final Design Concept

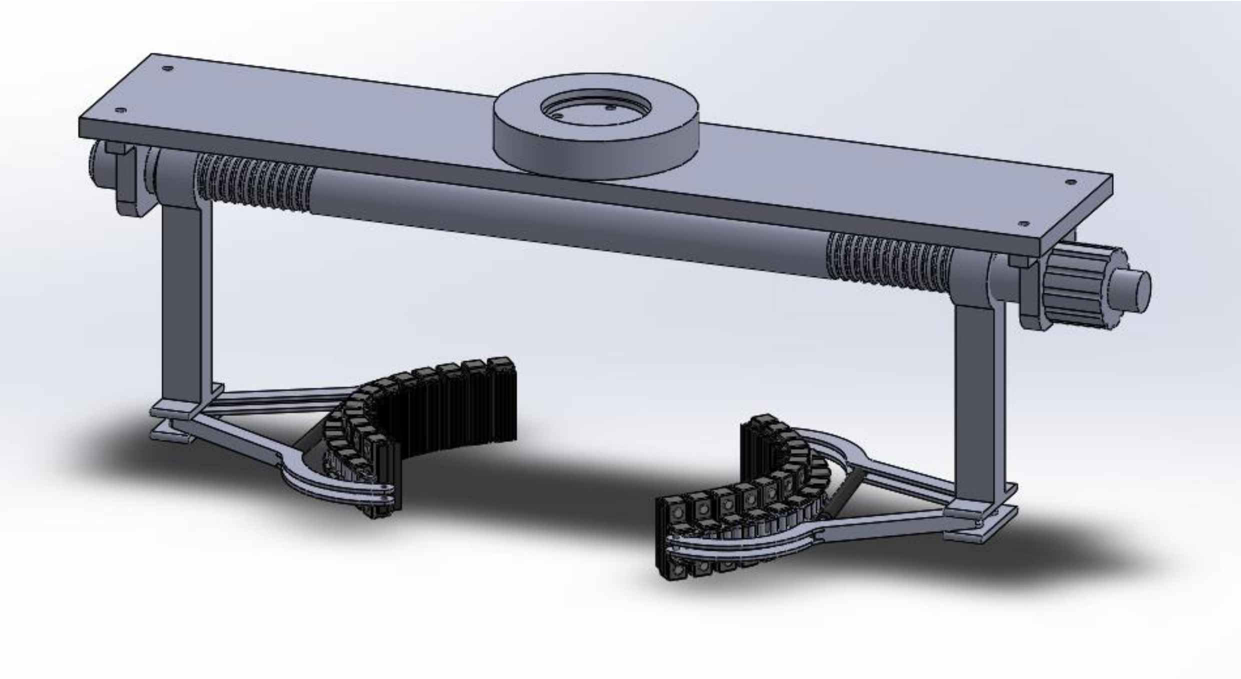
Following the application of the combination of Quality function deployment (QFD) and Failure mode effect analysis (FMEA) methods, the evaluation of the design concepts as well as the determination of the key parameters according to which the design can be improved have been conducted. At this point, the actions recommended above for the design improvement will be analysed in parallel with the final design development.

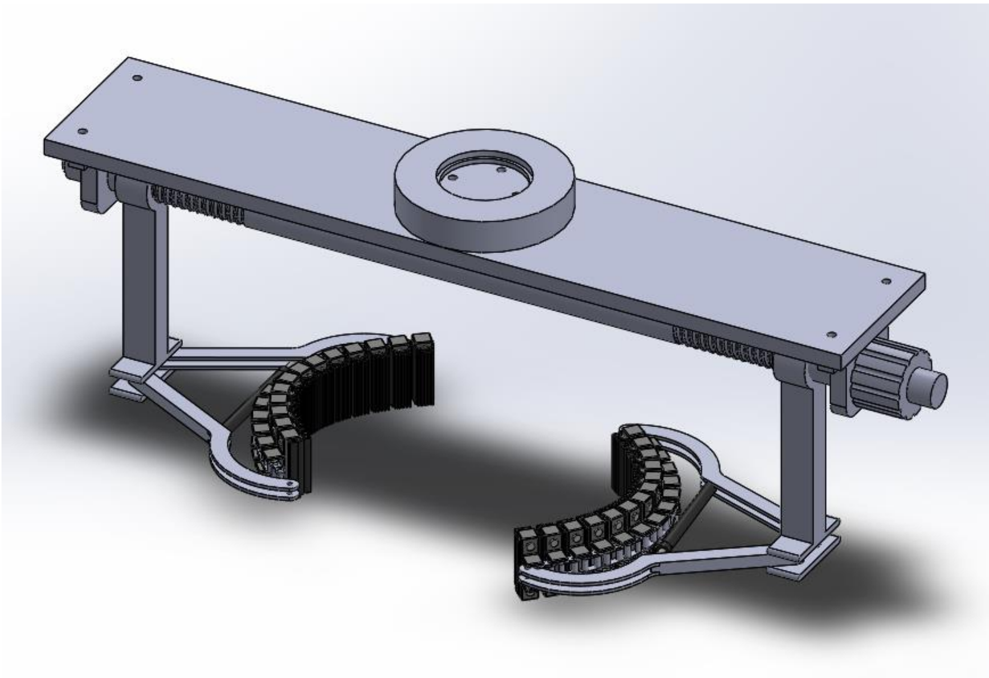
First of all, the main objective of the new design is the use of effective chain length. This means that the new configuration is meant to have the length required for gripping and not excessive material, useful only for secondary functions such as the actuation system. This development will result also to a lower-cost mechanism as well as a higher speed operation. From the geometrical point of view, the new design should be composed by an effective quantity of rubber inserts, the shape of which should ensure that no intersection may occur during the operation and that a wide variety of object's sizes can be manipulated without the risk of loss of contact. An alternative actuation system is also recommended, which will incorporate simpler and fewer actuation systems. In Figure 4.24 the final gripper design is illustrated integrated with the above analysed features.

The operating principle of this concept is significantly different from the initial developed design of this idea. More specifically, the gripping is achieved with a two-jaw reconfigurable gripper. Each finger consists of two arms linked with a chain with rubber insert attachments and a telescopic mechanism. These arms are mounted to a vertical nut-arm which is rolling on a shaft actuated by a motor. The telescopic mechanism is responsible for the reconfiguration of the gripper as its elongation and shortening result in change of the chain's shape. Consequently, depending on the shape of the available object for grasping, the telescopic mechanisms are activated and the chain with its mounted rubber inserts mold around it. The two gripper's jaws roll on the shaft in reverse. Figure 4.24 presents a general overview of the gripper reconfiguration characteristics.









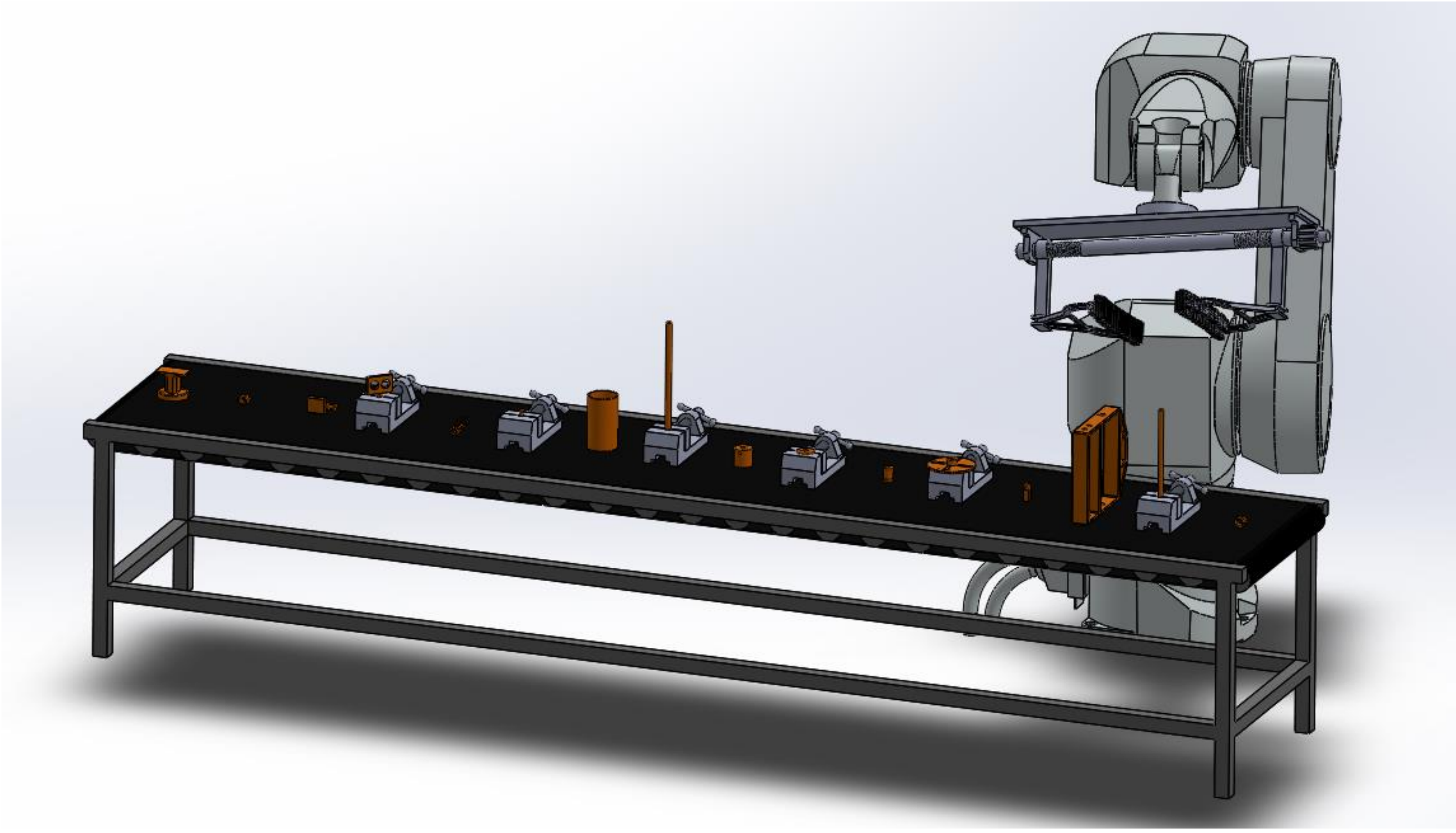


Figure 4.24 Final design concept – Reconfiguration characteristics

CHAPTER 5 DETAILED ANALYSIS

5.1 Worst case scenario selection

For object retention each gripper operates in contact with the object surface. There are several possible contact methods for the basic geometric shapes such as point contact, line contact, surface contact, circular contact and double line contact. One of the most important elements of prehension is stability of grip. Any misalignment of grasped components may result to their release. This should be ensured by the effective gripping force at the contact points or the active surfaces between object and gripper. For these reasons the structural analysis of a gripper mechanism is necessary, in order to reassure the operation functionality of the design [2].

In terms of the structural analysis of the smart gripper designed in this project, it is necessary to define the components that will be used as samples for this analysis. As outlined earlier in this Thesis, the smart gripper developed is designated to manipulate the sub-components of a robotic fiber winding head, which cover a wide variety of shapes, sizes, weights and manufacturing processes. Therefore, it is considered necessary to select the worst case scenario for the structural analysis of the gripper, in order to build a mechanism capable to handle all the designated components.

This selection is based on three basic characteristics, the active contact area, the weight and the geometry complication of the candidate components. More specifically, for the worst case scenario the smallest contact area between the gripper and the object is pursued, combined with the maximum weight and the most complicated geometry. In order to choose the component which meets the perfect combination of these conditions, a comparison between their characteristics is necessary.

First of all, the contact area between the gripper and each component should be defined. In Figure 5.1 some examples of gripping contact methods are presented as well as the current case where a two-jaw gripper has been developed using a multi-point contact principle. As explained above there are several contact types, illustrated also into Figure 5.2, according to which the classification of contact area will be conducted. For this classification, the workplace configuration determined earlier is also critical. A numerical index denoting the smaller and bigger conact area will be used, with value 1 representing surface contact, value 2 the line contact and value 3 representing the smallest contact area which is point contact.

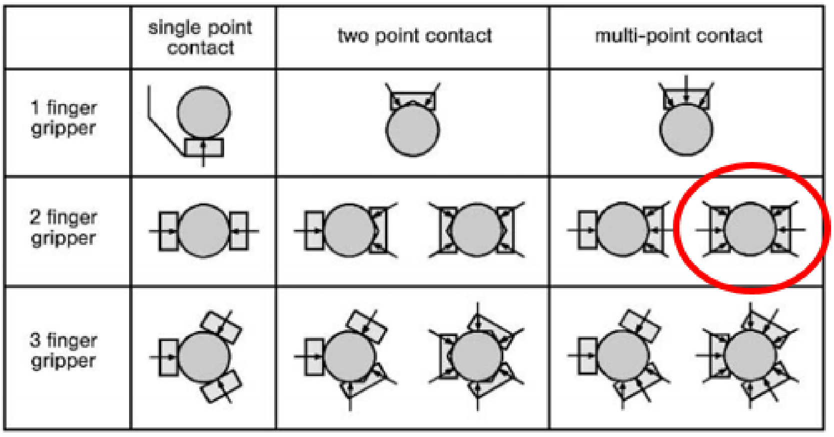


Figure 5.1 Gripping methods depending on the number of fingers and contact points

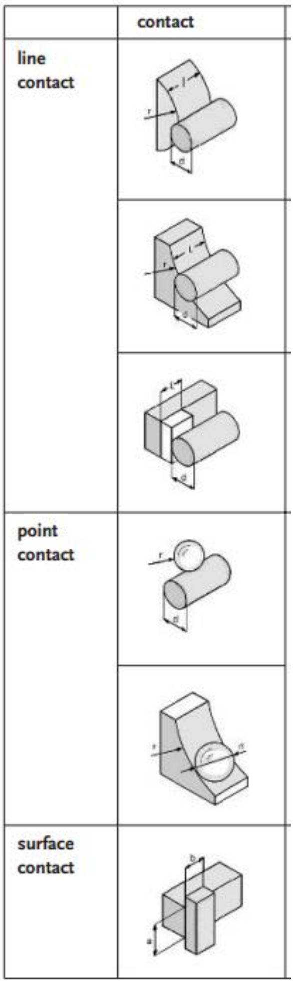
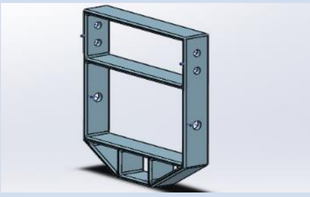
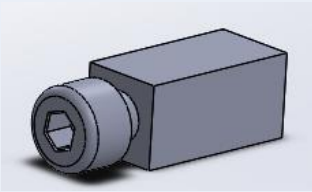
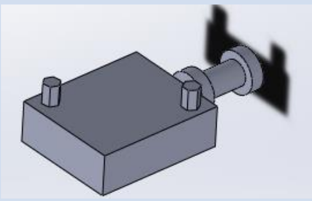
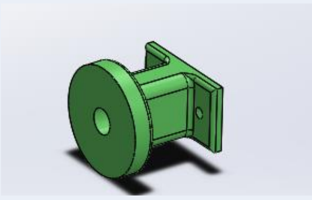
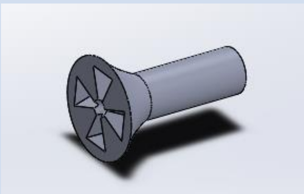
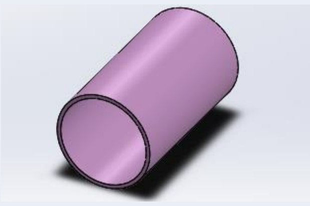
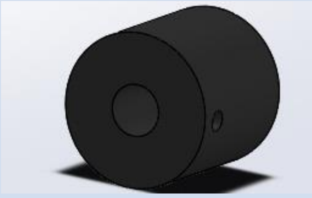
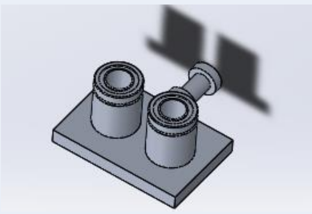
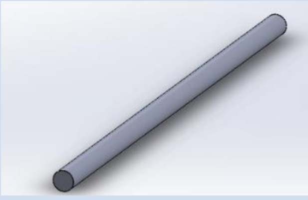
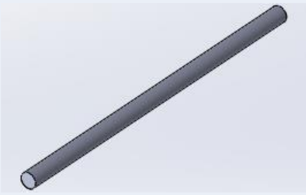
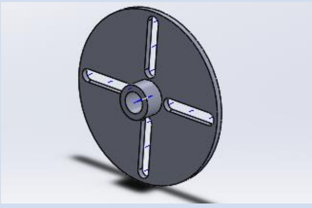


Figure 5.2 Typical contact types

The second condition that should be defined is the object's weight, a measurement which is physically defined for each component. For comparison reasons this value will be also normalised using values 1 to 3, where 1 denotes the lighter components and 3 denotes the heavier ones.

Then, the complexity of the design is a difficult aspect to define, so in this project it is assumed to be related with arbitrary shaped objects with special geometric configurations. The classification for this condition will be determined by evaluating the size of a numeric indicator with a range from 1 to 3, denoting the most simple to most complicated shape. This evaluation is taking into account the workplace configuration as already defined in the task specification section. Table 5.1 below presents the overall characteristics of all the components in terms of the three selection conditions for the worst case scenario.

	Objects	Contact Area	Weight (gr)	Shape
Part 1		Line contact -> 2	1133.5 -> 3	3
Part 2		Surface contact -> 3	19.93 -> 2	1
Part 3		Surface contact -> 3	67.0 -> 2	1
Part 4		Surface contact -> 3	319.59 -> 2	1
Part 5		Line contact -> 2	1.92 -> 1	3
Part 6		Line contact -> 2	217.15 -> 2	2

Part 7		Line contact -> 2	149.78 -> 2	2
Part 8		Surface contact -> 3	91.01 -> 2	1
Part 9		Line contact -> 2	138.23 -> 2	3
Part 10		Line contact -> 2	80.42 -> 2	3
Part 11		Surface contact -> 3	112.59 -> 2	2
Part 12		Surface contact -> 3	10.0 -> 1	2
Part 13		Line contact -> 2	2.44 -> 1	3
Part 14		Line contact -> 2	2.46 -> 1	3

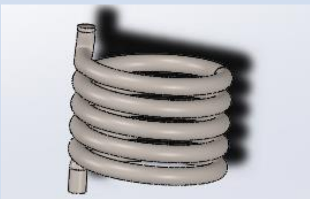
Part 15		Line contact -> 2	6.46 -> 1	3

Table 5.1 Conditions of worst case scenario

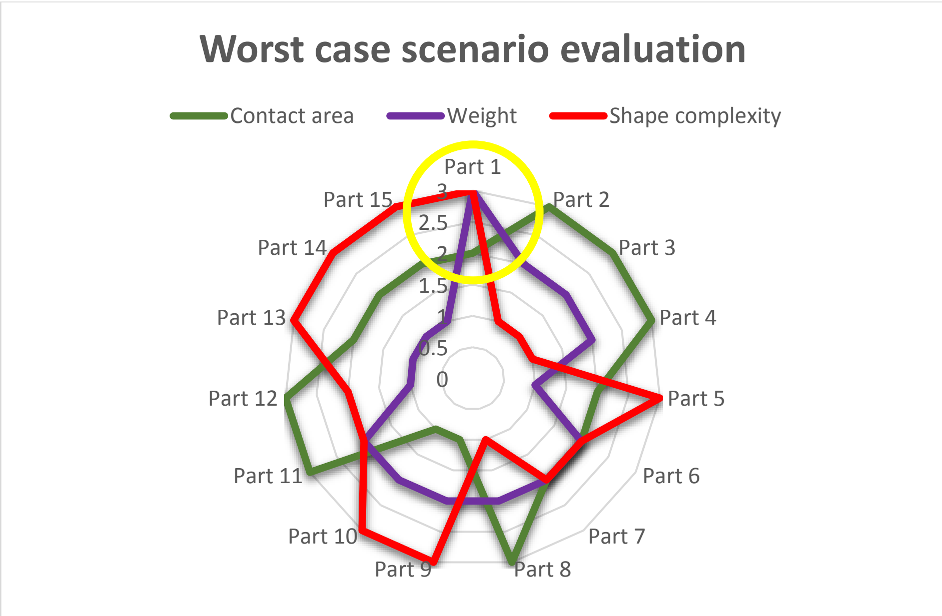
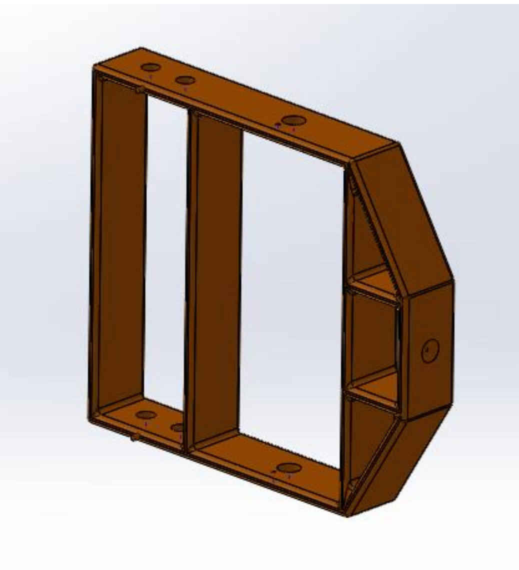


Figure 5.3 Selection of worst case scenario

According to Table 5.1 and Figure 5.3 it is obvious that the worst case scenario is the gripping of Part 1. This component is the heavier one, with the most complicated shape and the contact surfaces are the trickiest ones. As a result Figure 5.4 presents the component that will be used for the structural analysis of the mechanism.



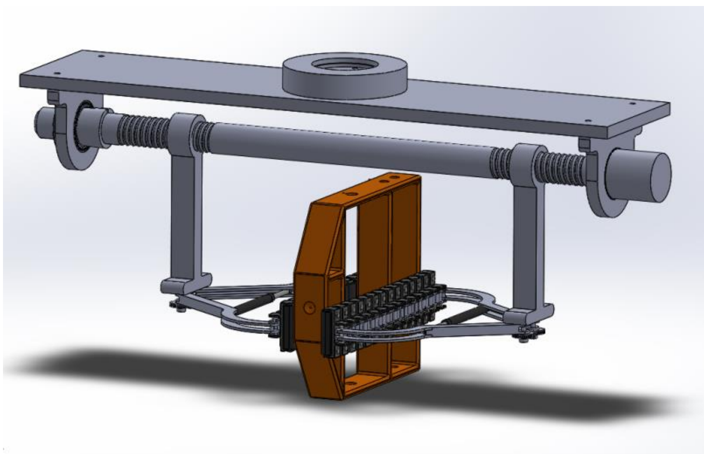


Figure 5.4 Sample part for structural analysis

5.2 Static construction analysis

The first question that arises when it comes for the analysis of a gripping mechanism is how a component with unusual shape and sensitivity to pressure is grasped. The answer on this depends on the operation used for gripping. Figure 5.5 illustrates the common types of gripping.

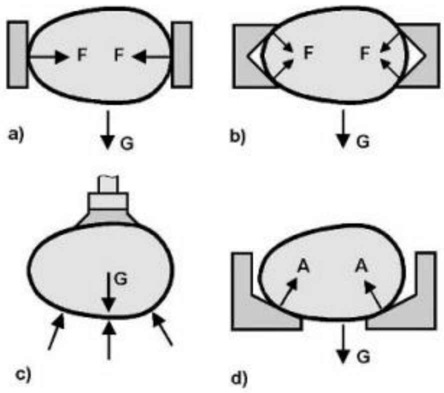


Figure 5.5 Principles of gripping

The grasping principle used in this Thesis corresponds to the second category which means form gripping. The calculation of the contact forces is critical on the development process of the mechanism for the determination of the static forces. Figure 5.6 illustrates the contact lines as well as the direction of the forces between the gripper and the sample component.

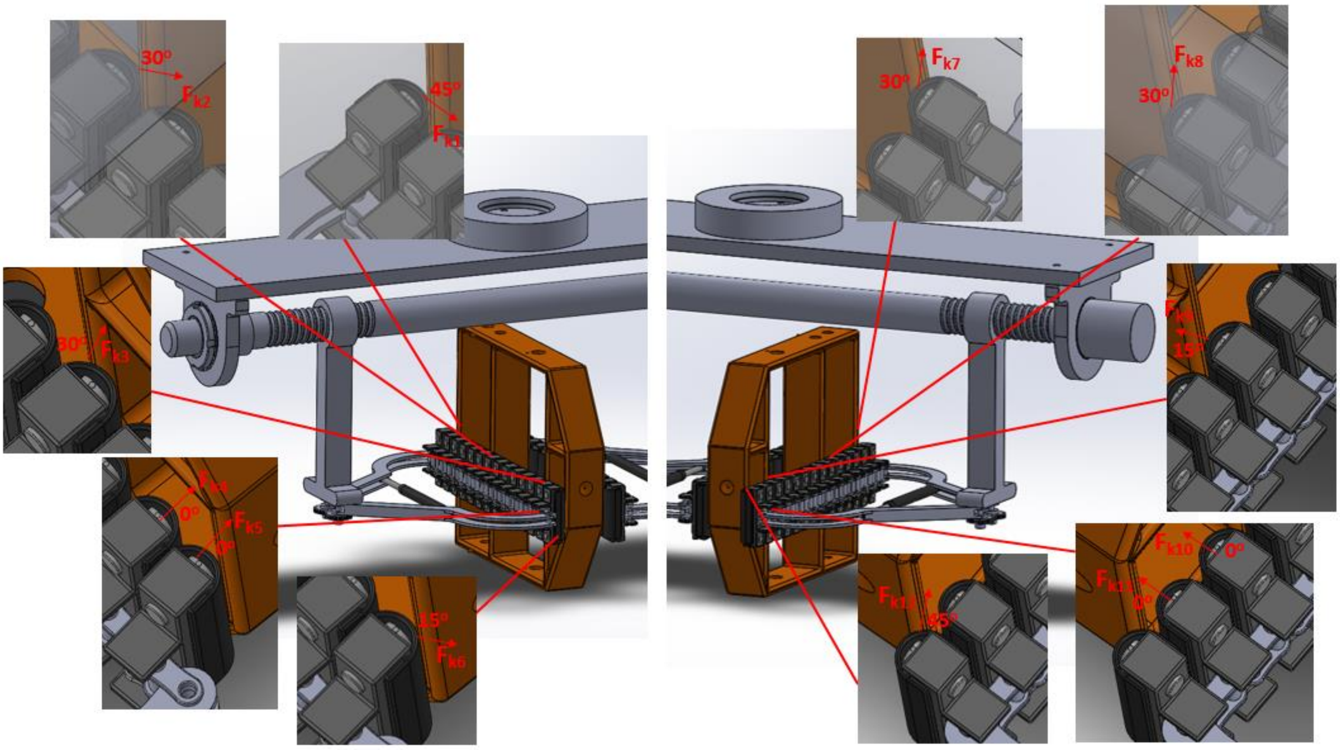


Figure 5.6 Gripper's contact forces

Contact type has already been identified as line shaped contact with two sub-categories:

- Curve to curve forces: F_{k1}, F_{k2}, F_{k3}, F_{k6}, F_{k7}, F_{k8}, F_{k9}, F_{k12}
- Plane to curve forces: F_{k4}, F_{k5}, F_{k10}, F_{k11}

It is assumed that a surface distributed pressure is exercised on the contact areas given as follows.

$$F_{kix} = F_{ki} \cos a_i \tag{1}$$

<u>Curve to curve forces</u>

$$\begin{gathered} F_{k1x} = F_{k12x} = F_k \cos 45^o \\ F_{k2x} = F_{k3x} = F_{k7x} = F_{k8x} = F_k \cos 30^o \\ F_{k6x} = F_{k9x} = F_k \cos 15^o \end{gathered} \tag{2}$$

<u>Plane to curve forces</u>

$$F_{k4x} = F_{k5x} = F_{k10x} = F_{k11x} = F_k \cos 0^o \tag{3}$$

Following the application of force balance on X, Y, Z axis, the amplitude of contact force is calculated as follows.

$$\begin{gathered} \sum F_x = 0 \\ \sum F_y = 0 \\ \sum F_z = 0 \leftrightarrow G = \sum F_{Ri} \leftrightarrow G = \sum F_{ki}\,\mu \leftrightarrow \\ mg = \mu F_k (2\cos 45^o + 4\cos 30^o + 2\cos 15^o + 4\cos 0^o) \leftrightarrow \\ F_k = \frac{1.13\times 9.81}{10.81\times 0.5} = 2.05\ N \end{gathered} \tag{4}$$

Consequently, the required gripping force for a safe grasping of the sample component is calculated as the sum of X-axis forces for two cases:

1. Zero acceleration – Minimum gripping force

$$F_{GR} = 11.08\ N \tag{5}$$

2. Acceleration a=10 m/s^2 – Maximum gripping force

$$F_{GR} = 22.44\ N \tag{6}$$

5.3 Actuation system calculation

The developed gripper has two individual actuation systems, through which the final object grasping is achieved. The first one is the actuation of telescopic mechanisms which are responsible for the finger arms motion and consequently the reconfiguration of chain and inserts. The second system is responsible for the rolling of each nut-arm on the shaft and is actuated by a servo motor.

In the previous section, the maximum and minimum forces have been calculated for the gripping of the sample component. These values specify the required power that each telescopic mechanism should have as output for an effective grasping. In this section, the required output power of the stepper motor will be calculated in terms of an effective gripping of the worst case scenario component. Figure 5.7 outlines the flow chart of a servo motor selection in terms of each output power.

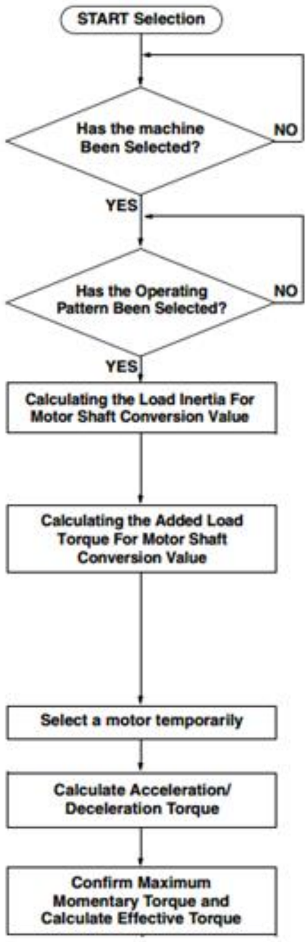


Figure 5.7 Servo motor selection flow chart

The application of the above procedure will be followed hereafter for the servo motor power determination.

1. **Machinery Selection**

First of all the size, mass, coefficient of friction, and external forces of all the moving parts of the servo motor should be determined. It is assumed that the sample component and the vertical nut-arms with their attachments are the moving parts mounted. As a result, the above parameters are defined as follows.

Load mass	$M = (0.13875 \times 2) + 1.1335 = 1.41\ kg$	(7)
Ball screw pitch	$P = 5\ mm$	(8)
Ball screw diameter	$D = 25\ mm$	(9)
Ball screw mass	$M_B = 0.29\ kg$	(10)
Ball screw friction coefficient	$\mu = 0.1$	(11)
Transmission ratio (no decelerator)	G=1	(12)
Spur gear efficiency (no decelerator)	n=0.95	(13)

2. Operating pattern

Here the selection of the operating pattern is conducted, which means the relationship between time and speed of each part that must be controlled. Then, the operating pattern of each controlled element is converted into the motor shaft operating pattern.

Speed change	1 mode	(14)
Load travel velocity	$V = 100\ {}^{mm}/_{s}$	(15)
Stroke	$L = 80\ mm$	(16)
Travel time	$t_s = 1.4\ s$	(17)
Acceleration time	$t = 0.2\ s$	(18)
Positioning accuracy	$AP = 0.01\ mm$	(19)

All the above assumptions are translated to the motor shaft operating system illustrated into Figure 5.8 below.

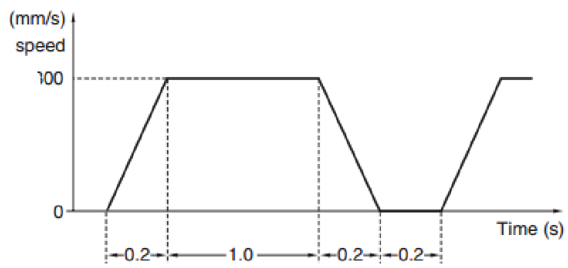


Figure 5.8 Motor operating pattern

3. Motor shaft conversion load inertia

Inertia is calculated for each element of the machine separately and then for the total mechanism

Ball screw inertia
$$J_B = \frac{M_B D^2}{8} 10^{-6} = 2.3\ 10^{-5}\ kgm^2 \quad (20)$$

Load inertia $$J_W = M \frac{P}{2\pi}^2 10^{-6} + J_B = 3.7\ 10^{-4}\ kgm^2 \quad (21)$$

$$J_L = G^2(J_2 + J_W)$$

Motor shaft conversion load inertia $$J_2 = \frac{mD^2}{8} 10^{-6} + \mathrm{mgr}_e{}^2 10^{-6} \quad (22)$$

$$J_L = 3.7\ 10^{-4}\ kgm^2$$

4. Load Torque calculation

Friction torque $$T_W = \mu Mg \frac{P}{2\pi} 10^{-3} = 1.1\ 10^{-3}\ Nm \quad (23)$$

Load torque $$T_L = \frac{G}{n} T_W = 1.16\ 10^{-3}\ Nm \quad (24)$$

5. Rotation speed

Rotation speed $$N = \frac{60V}{PG} = 1200\ {}^{rev}/_{min} \quad (25)$$

6. Motor preliminary selection

A preliminary selection of a motor is conducted based on the above calculations and the below restrictions.

$$J_M \gg \frac{J_L}{30} = 1.23\ 10^{-5} kgm^2 \quad (26)$$

$$T_M 0.8 > T_L = 1.45\ 10^{-3} kgm^2 \quad (27)$$

7. Acceleration torque

Acceleration torque $$T_A = \frac{2\pi N}{60 l_A} (J_M + \frac{J_L}{n}) = 0.25\ Nm \quad (28)$$

8. Maximum torque

$$T_1 = T_A + T_L = 0.25\ Nm \quad (29)$$

$$T_2 = T_L = 1.16\ 10^{-3}\ Nm \quad (30)$$

$$T_3 = T_L - T_A = 0.25\ Nm \quad (31)$$

$$T_{rms} = \sqrt{\frac{T_1{}^2 t_1 + T_2{}^2 t_2 + T_3{}^2 t_3}{t_1 + t_2 + t_3}} = 0.1336\ Nm \quad (32)$$

9. Results of examination

In order to evaluate the results of the above calculation procedure, the below conditions should be confirmed. As a result the final servo motor selection should be in line with the below conditions.

Load Inertia $$J_L \leq 30 J_M \quad (33)$$

Effective torque	$T_{rms} < T_M 0.8$	(34)
Maximum momentary torque	$T_1 < T_{M_{max}} 0.8$	(35)

5.4 Analytical modeling

As the last step of the analysis comes the computational evaluation of the structural characteristics of the designed gripper. This analysis has been conducted using the Solidworks Simulation program module.

The above assumptions and forces calculations are imposed as the defined parameters and the boundary conditions of the analysis. For computational analysis requirements, the gripper is divided to two simpler models imposing the appropriate fixtures and external loads to each of them. Additionally, the loads have been distributed in accordance to contact lines as presented in Figure 5.6. Figure 5.9 illustrates the first model used for the analysis as well as the fixtures and external loads imposed.

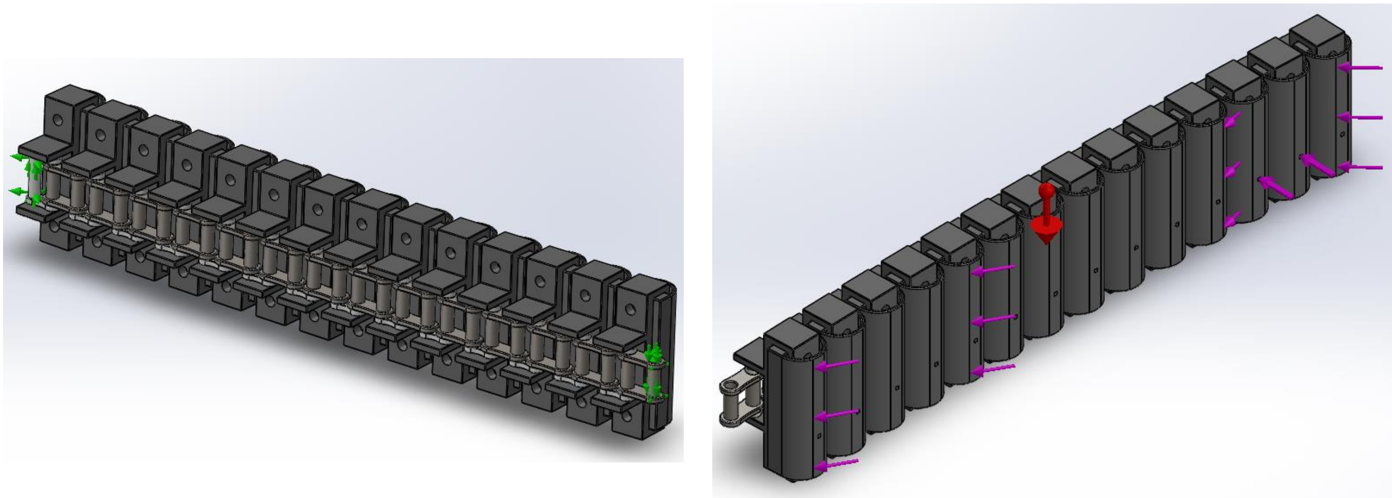


Figure 5.9 1st model gripper modeling

The forces are imposed as already calculated in the relevant section. The material of the parts has also been defined as 1035 steel for the chain, ABS for the plate inserts and polyethylene HD for the rubber mounting parts. A fine mesh has been generated for the model constructed using all the parameters described. Figure 5.10 shows the mesh as automatically generated by the program.

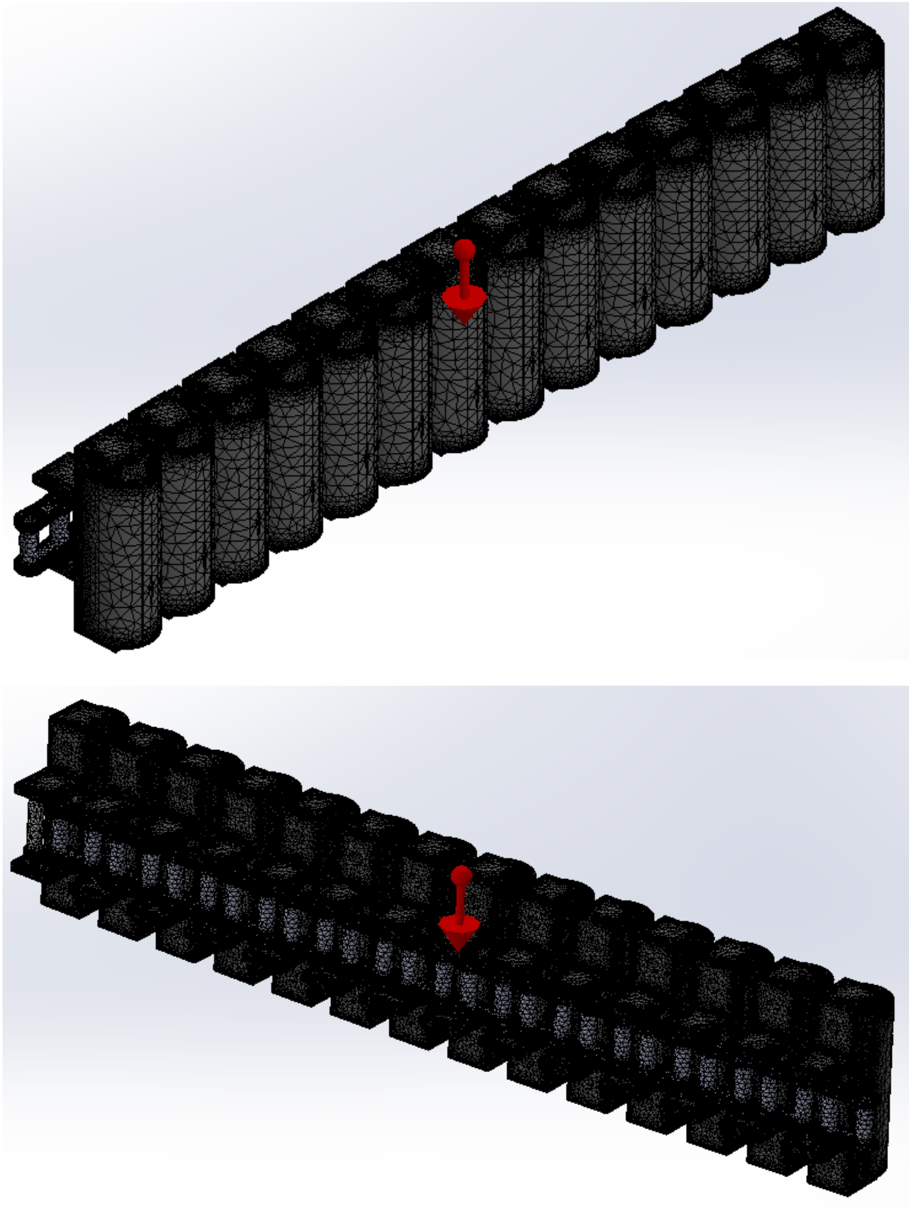


Figure 5.10 1st model mesh generation

Following the meshing of the model to be analysed a Von-Mises stress, strain and displacement computation has been conducted. The results are presented below in Figures 5.11 - 5.13.

The analysis presented here uses the maximum gripping force calculation as follows:

$$F_k = 4.15\,N \qquad (36)$$

$$a = 10\,{}^{m}/{}_{s^2} \qquad (37)$$

$$F_{GR} = 22.44\,N \qquad (38)$$

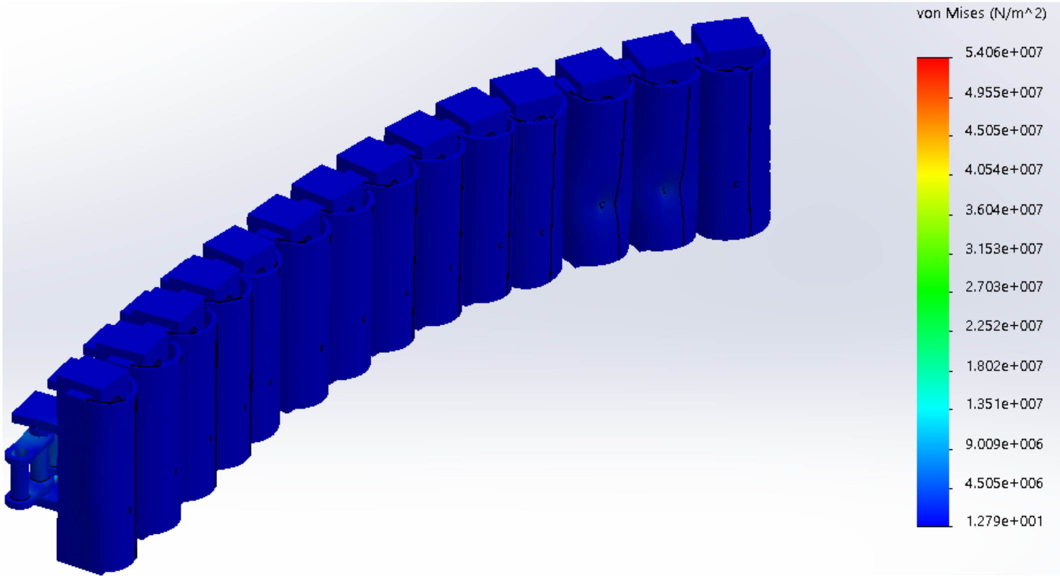


Figure 5.11 1st model Von-Mises stress results – Maximum gripping force

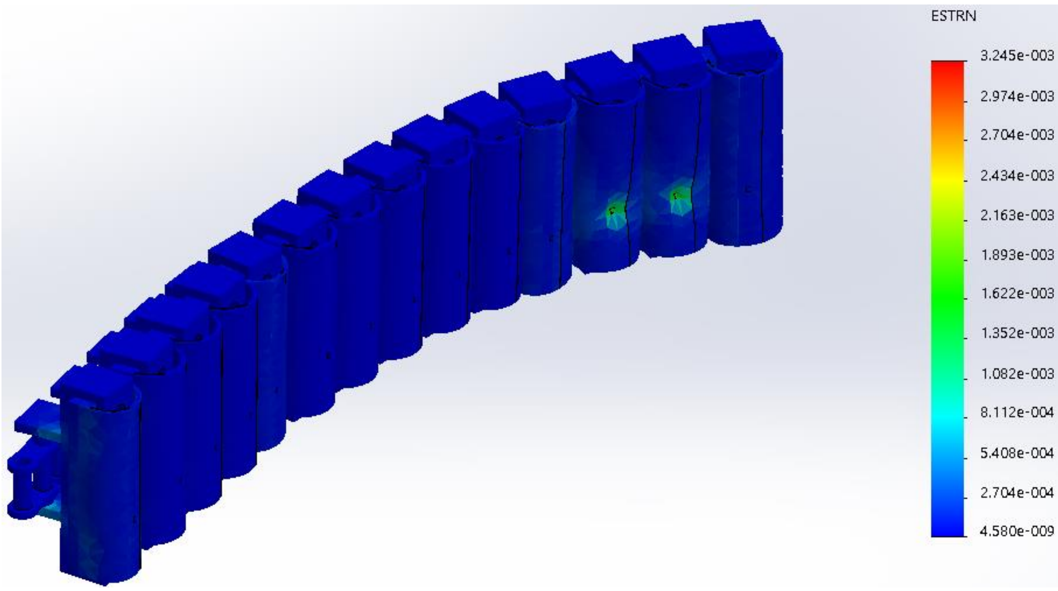


Figure 5.12 1st model strain results – Maximum gripping force

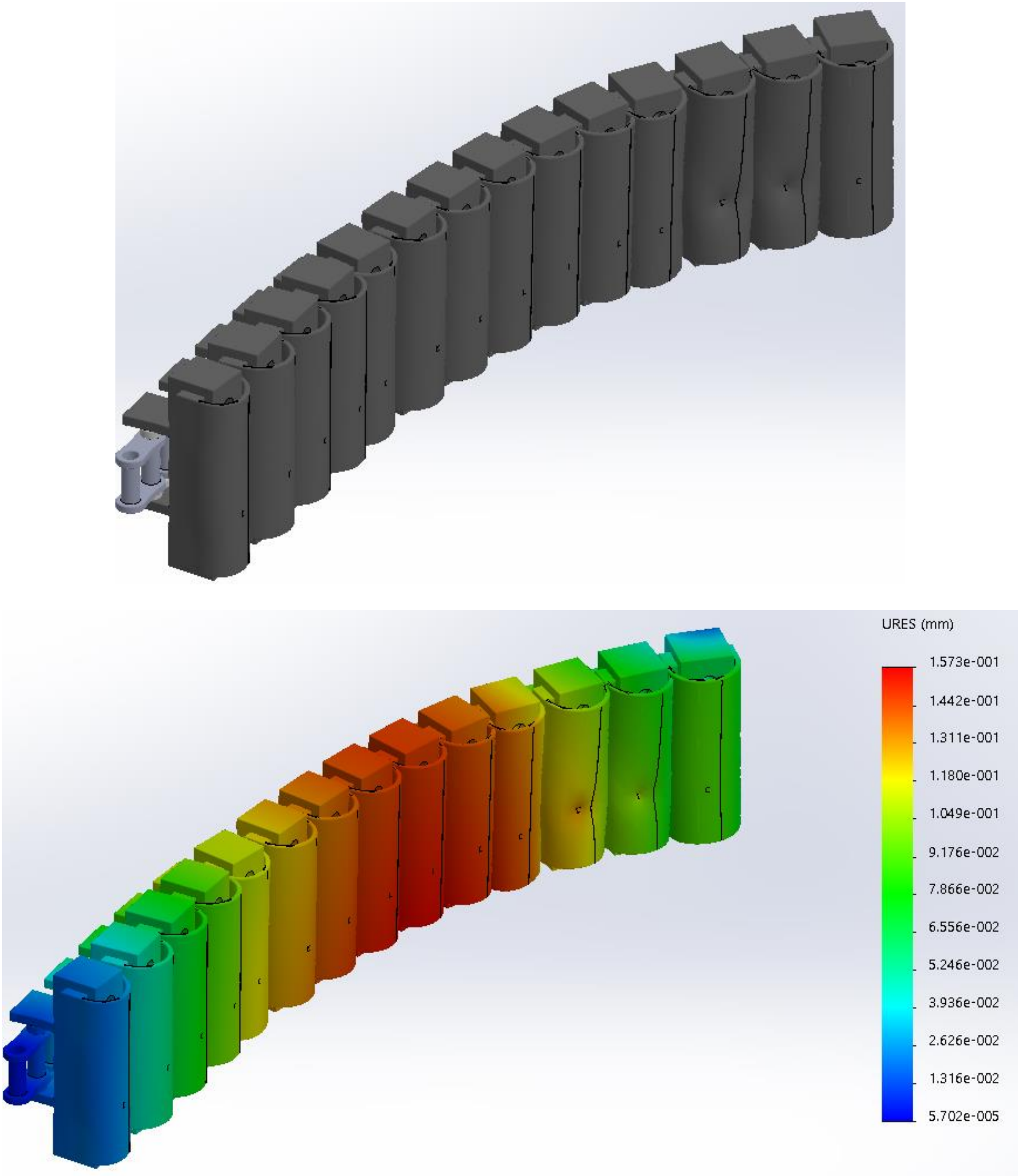


Figure 5.13 1st model displacement results – Maximum gripping force

The second model represents the remaining parts of the gripper, on which all the fixtures and loads are applied for the equivalent modelling. More specifically, the characteristics of the equivalent model are presented below according to the motor selection.

$$M = 0.9\ Nm \quad (39)$$

$$F = 6.6\ N \quad (40)$$

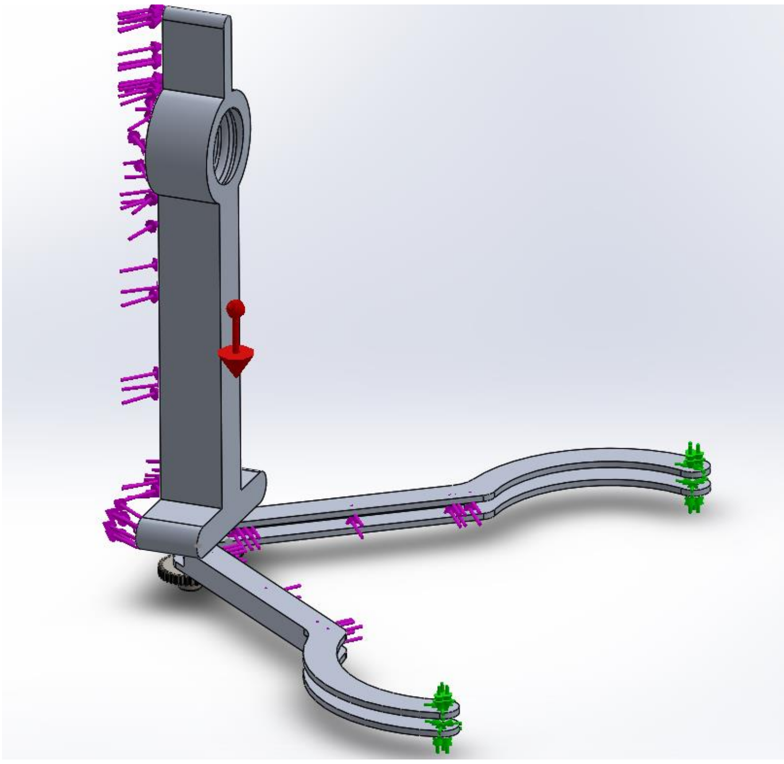


Figure 5.14 2nd model gripper modeling

Figure 5.15 2nd model mesh generation

The analysis is conducted for maximum gripping force as previously (Figures 5.16 – 5.17). The materials used for these parts are carbon steel and aluminium 7075.

Maximum gripping force case

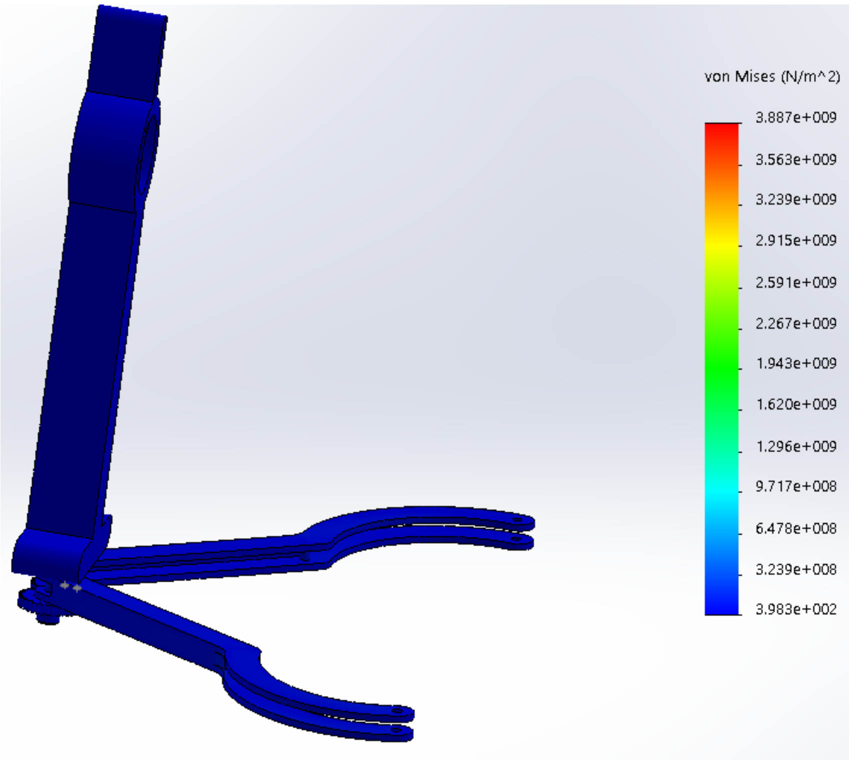


Figure 5.16 2nd model Von-Mises stress results – Maximum gripping force

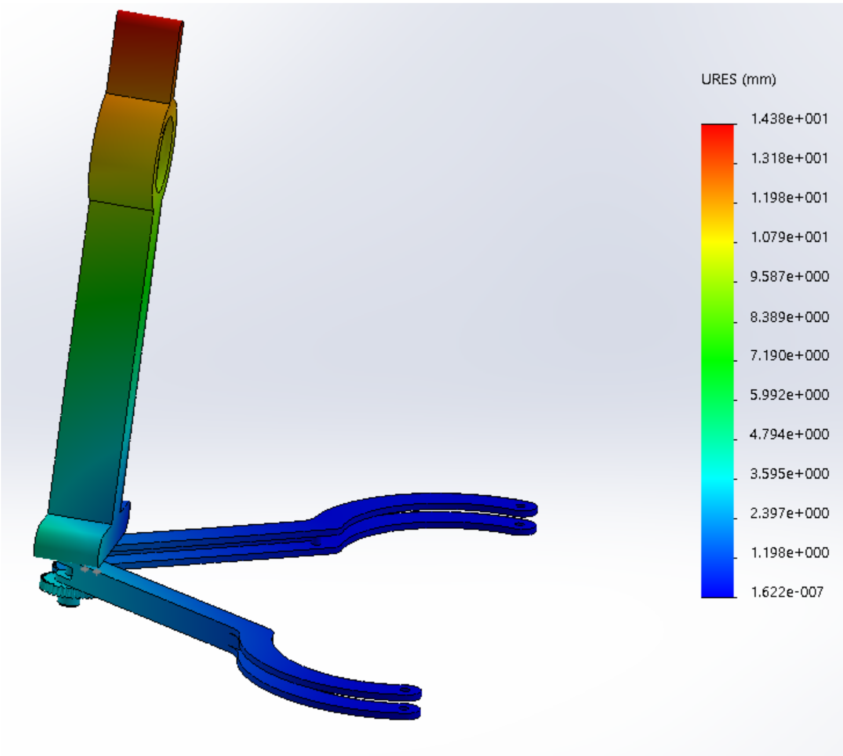


Figure 5.17 2nd model displacement results – Maximum gripping force

Reviewing the results, it is obvious that the loads imposed on both models of gripper from the object, have a normal amplitude and do not cause any abnormal or excessive deformation. It is proved that the worst case scenario does not cause any operational limitation on the gripper, on the contrary its characteristics denote that it as an acceptable component for manipulation.

CHAPTER 6 MANUFACTURING PROCESS

As a last step of a design development process, comes the manufacturing of the developed model. This stage consists of several steps necessary to be carried out before the final product development, including:

- Bill of Materials (BoM) construction for objects to be purchased or for raw materials designated to be used for in-house manufacturing
- assembly procedure of the individual components
- programming and control of the assembly system
- testing of the mechanism into a variety of applications

In the current Thesis, the manufacturing procedure performed includes the construction of a bill of materials needed for the final product as well as a preliminary manufacturing of the basic components of the end-effector, using CNC machinery.

6.1 Bill of Materials (BoM)

The bill of materials (BoM) is a list of items or parts required for finished good assembling. It presents the item code and the needed amount of every component. In addition, it can be formed with a more complex approach as a multilevel record, which represents the data of all sub-assemblies, transitional assemblies and various technical descriptions.

In the current project a detailed bill of materials has been constructed including the components that should be purchased and used on the assembly of the mechanism, but also the raw materials used for in-house manufacturing. Figure 6.1 below presents a schematic diagram with the bill of materials constructed.

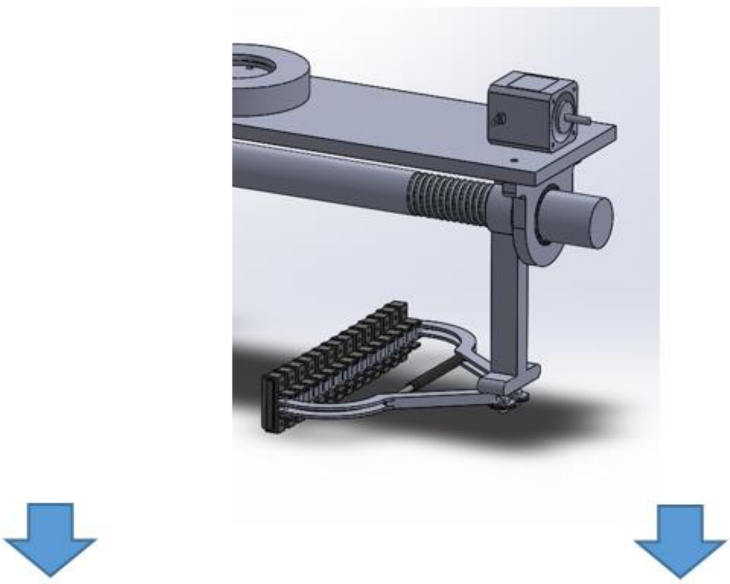


Figure 6.1 Graph of bill of material (BoM)

Following the schematic illustration of the bill of materials constructed on the current project, Table 6.1 presents in detail the components as long as the quantity needed for the final mechanism.

Part description	Quantity
Motor	1
Toothed belt pulleys	1
Shaft	Cylindrical steel block D=10 mm × 560 mm
Base	Rectangular aluminium block 520×120×10
Bearing unit	2
Chain	2000 mm
Plastic plates	28 ABS pieces
Rubber mounting chain	2000 mm
Vertical arm	2 Rectangular aluminium blocks 60×173×26
Horizontal arm	4 Rectangular aluminium blocks 30×170×12
Shoulder screw	4
Washers	16
Sprocket	4

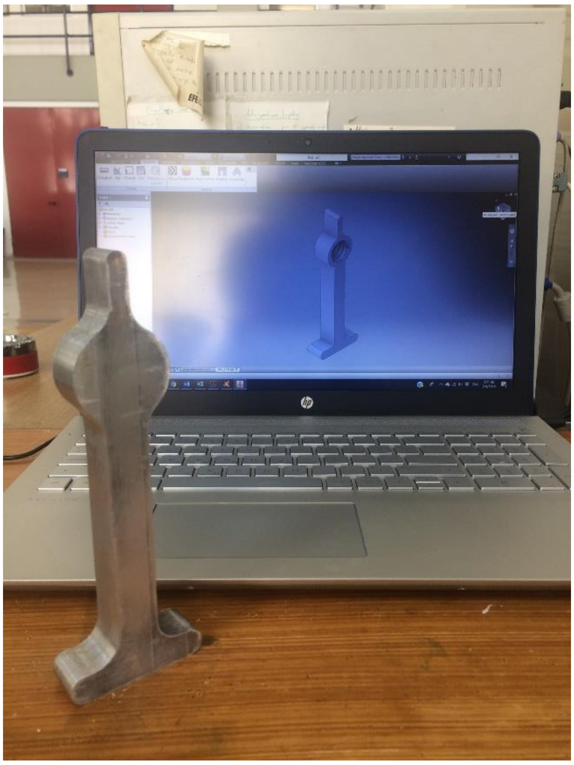
Table 6.1 Bill of Materials (BoM)

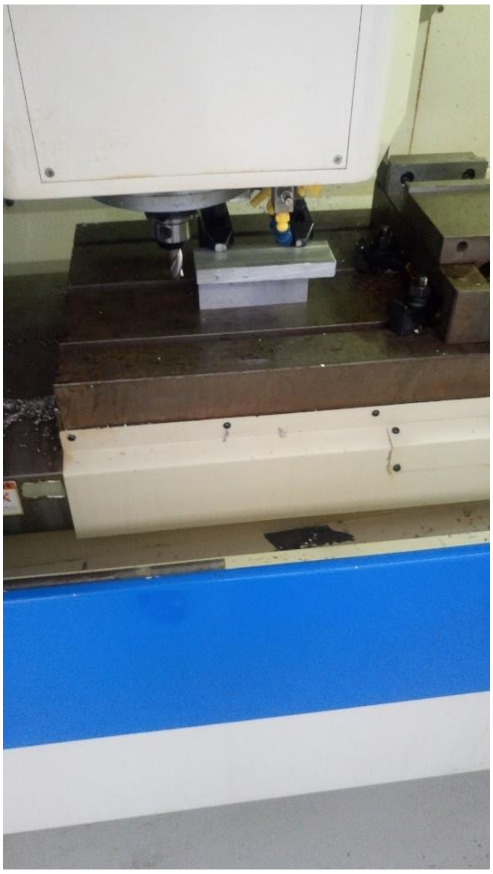
6.2 In-house manufacturing of basic components

In-house manufacturing of some basic components of the end-effector has been constructed using the sources of the laboratory of Manufacturing Systems of NTUA.

More specifically, using Computer Aided Manufacturing (CAM) software tools as well as CNC machinery available on the laboratory, the vertical and horizontal aluminium arms have been constructed. Additionally, the plastic plates mounted on the chain of each end-effector's finger have been printed with the use of a 3D printer, developed in terms of a previous Diploma Thesis, using ABS as the raw material.

The construction of the aluminium parts has been conducted with the use of G-code programmes developed into SolidCam software in respect with the design preceded (Appendix). Figure 6.2 illustrates several photos taken within the manufacturing of both components.





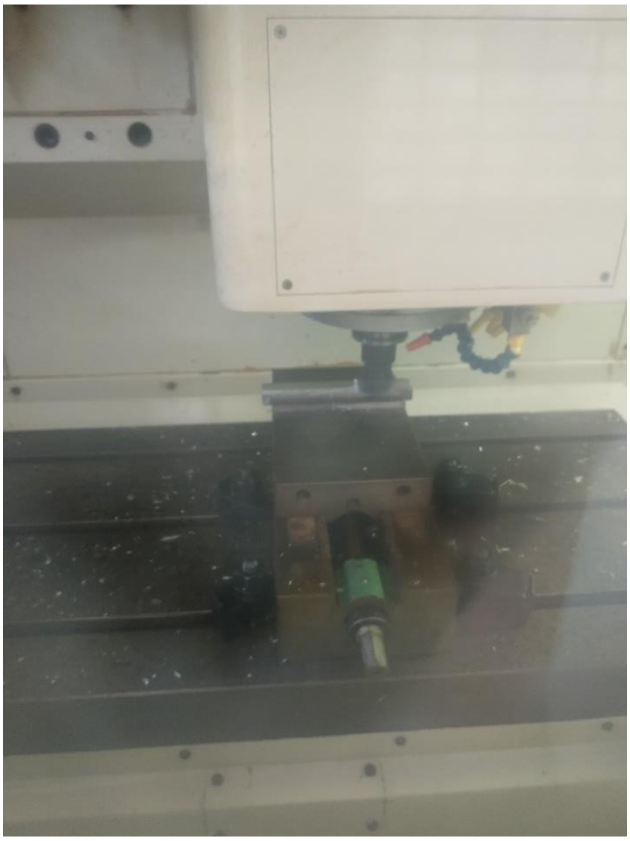
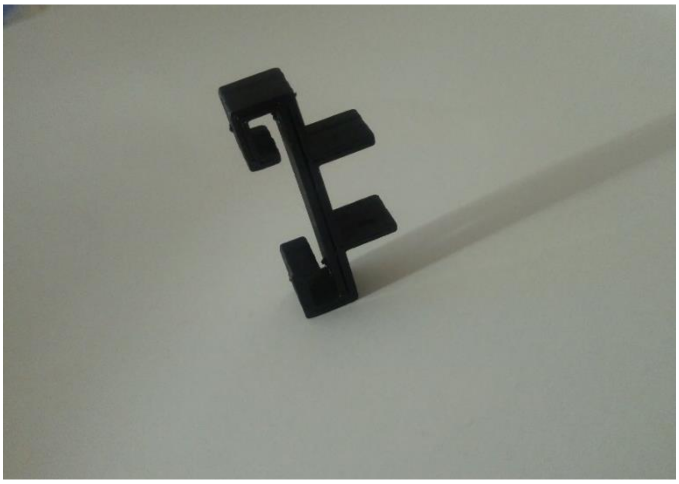



Figure 6.2 CNC manufacturing process

The construction of the plastic inserts has been conducted through 3D printing. Three components have been printed as a sample for the control and evaluation of the printing procedure. In Figure 6.3 same photos of the printed components are illustrated.



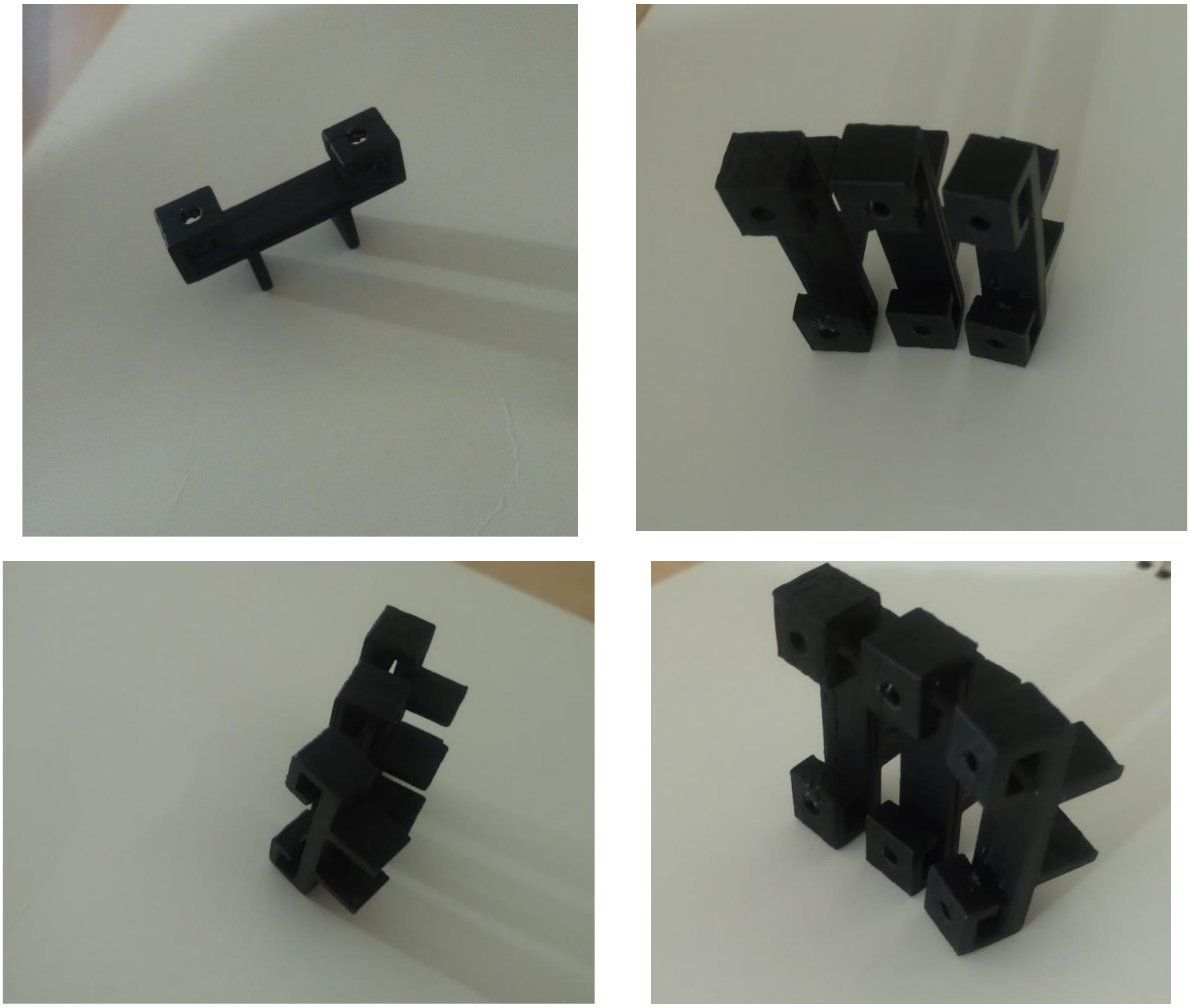



Figure 6.3 3D printing manufacturing process

CHAPTER 7 CONCLUSION - FUTURE WORK

7.1 Conclusion

In terms of this Thesis, a complete product development procedure has been taken place. Several factors such as product specifications and restrictions, market needs and customer voice have been taken into account. All these parameters have been combined with engineering and industrial rationale for an effective end product design.

More specifically, the extensive literature review conducted as a first step of the project offered an insight useful for the conceptual design stage. Emphasis was placed on the development of an end product that will stand out of the crowd and will offer unconventional functions.

Through the broadness of this research, several tools proved to be useful for the successful completion of the project. Computer Aided Design (CAD), computer aided engineering (CAE) and computer aided manufacturing (CAM) took place for the accomplishment of the project. Additionally, several intermediate tools such as Quality function deployment (QFD) and Failure Mode Effects Analysis (FMEA) analysis enriched the project with a commercial point of view.

The mechanism designed and analysed in the current work succeed to be in line with all the specifications and restrictions given as basic requirements. It is a smart mechanism that combines several operation principles, taking advantage of their positive aspects. The reconfiguration possibilities provides the advantage of various object manipulation and a sophisticated gripping.

To conclude, the product development conducted on current project seems to be successful considering its analytical results and the manufacturability of the components.

7.2 Future work

The system developed in this Thesis could be further improved and expanded in the following directions:

- Completion of mechanism assembly
- Experimental testing and operational verification
- Development of a sensored control system for object's shape and size identification
- Construction of a lighter mechanism using 3D printed components
- Design extension and re-evaluation for nano gripping

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APPENDIX

G-code programming

Arm 1st profile

```
%
O5000 (ARM_MILLING)
N100 (COMPENSATION-WEAR)
N102 (REV-0.70)
N104 (JUL-17-2018-10:39:21PM)

N106 (TOOL 10 - DIA 20.)

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N108 M06 T10 ()
N110 (F-contour-1)
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S3500 M03
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N116 Z25.
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