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DEVELOPMENT AND ADDITIVE MANUFACTURING OF A MAGNETIC "COMPLIANT MECHANISM" GRIPPING SYSTEM FOR PICKING UP SINGLE METALLIC OBJECTS

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DEVELOPMENT AND ADDITIVE MANUFACTURING OF A
MAGNETIC "COMPLIANT MECHANISM" GRIPPING SYSTEM
FOR PICKING UP SINGLE METALLIC OBJECTS

A Thesis Presented

By

Hua Minh Tuan



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Development and additive manufacturing of a magnetic "compliant mechanism"
gripping system for picking up single metallic objects



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ABSTRACT

The purpose of this bachelor's thesis is to design and additive manufacturing a magnetic "compliant mechanism" grasping system for picking up single metallic items. To begin, provide an overview and explanation of the magnetic compliance mechanism gripping system. The reasons for designing a magnetic compliant mechanism gripper and why it was chosen over another method.

Second, the state of the art in compliant mechanisms and additive manufacturing will be discussed, as well as a quick introduction to magnets. Additionally, additional patents with a similar objective that were discovered are offered as ideas for enhancing functionality.

Finally, in order to deliver the best possible, a systematic approach to the gripper's conceptual design is taken. This includes establishing the gripper's configuration, discussing the operating conditions, and addressing the disadvantages of constructing a compliant mechanism. Following that, concepts for gripper were developed utilizing existing patents as inspiration. The selection criteria are created, and logical combinations are constructed and analyzed in order to select the concept that meets the majority of the criteria. As a result, a gripper model that meets the majority of the requirements is created. These minor modifications are intended to facilitate functioning. Finally, construct the gripper and perform testing to obtain the maximum amount of optimization, as well as summarizing experience and making further improvements.

AUTHORSHIP STATEMENT

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Chapter 1 Introduction

Many centuries ago, a compliant mechanism was utilized from a daily life object to weapon. However, as industrialization progressed in the twentieth century, the dominance of other types of mechanisms such as cam and follower mechanisms, gear and gear trains overshadowed the development of compliant mechanisms. Even though the benefits of compliant mechanisms are comparable or superior to those of other mechanisms, the lack of development, design challenges, and implementation in difficult situations make compliant mechanisms less popular among engineers and technologists when it comes to high-end device design and construction. Fortunately, our knowledge has progressed over the last few decades. We've created new materials, improved our computing powers, and increased our ability to create more complex devices. Simultaneously, society has generated new requirements that are difficult to meet using existing systems. This implies that there is a greater ability to design conforming mechanisms, as well as a greater desire to do so [1]. This heralds a new era in which compliant mechanisms can realize their full potential and be used alongside a variety of other mechanisms in high-end design and implementation.

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1.1 Motivation

The majority of machine tools and mechanisms are now developed as multi-body systems. The necessary motion is achieved through the relative motion of numerous pieces joined by traditional pin-joints. Because of the kinematically decoupled structures and motions, these systems are simple to design and have been the preferred option of design engineers thus far [2]. Traditional mechanisms, while on the other hand, still have several flaws, such as relying on pin-joints for movement, requiring lubrication and maintenance, and being more difficult to repair and replace.

One of the machine tools that will be chosen for the study is a gripper, which is a pickup system that was selected as the topic of study and is seen to be a good fit for an integrated compliant mechanism. Grippers are devices that allow robots to pick up and hold objects in the manufacturing world. Grippers, when used in conjunction with a collaborative (or 'cobot') industrial robot arm, allow manufacturers to automate essential activities including inspection, assembly, pick-and-place, and machine tending. [30]

Grippers can be compared to the human hand because they are located at the end of the arm and have the ability to combine the strength of an arm with the dexterity of a hand. This combination opens up a whole new world of material handling options for cobots, from stacking massive boxes to handling small, fragile electrical components. [30]

There are many different kinds of grippers on the market. Grippers with fingers, claw-like grippers, mechanical grippers, grippers with enormous suction cups, and even grippers that resemble air-filled bags are all available. Gripper can raise objects with the help of vacuum. Pneumatic grippers use compressed air and pistons to move their "fingers," whereas hydraulic grippers use hydraulic fluids and electric grippers use electricity ... [30]. The common feature of these grippers is that they are built using an external component to operate or are made up of multiple elements that are connected together.



Figure 1.1 different type of grippers [30]

Because the goal was to create a simple gripper that was simple to use, maintain, repair, and replace, a compliant mechanism was chosen as a promising gripper construction solution.

1.2 Why using compliant mechanism?

Compliant mechanisms (CM) have risen in popularity in recent years as a viable alternative to multi-body systems for designing machine tools for small-scale applications. Unlike traditional multi-body systems, CMs are propelled by the elastic deformation of particular sections known as flexure hinges (FH). In Fig. 1.2, two medical grasping devices based on a multi-body system joined by a typical pin-joint hinge (left) and a monolithic CM (right) are compared. [2]



Figure 1.2 Medical grasping devices in comparison based on multi-body system connected by a standard pin-joint hinge (left) and based on a monolithic compliant mechanism (right) [31]

When opposed to its multi-body-based predecessors, compliant mechanism has various advantages. In terms of performance, prices, and the design process, Table 0-1 presents the most significant benefits and cons. CM are frictionless because to the absence of slippery elements in terms of performance [2]. Due to the minimal number of parts and

the lack of slipping parts, the system is completely silent. Because there are no lubricants, they are cleaner, making them ideal for applications requiring a clean environment, such as minimally invasive medical devices and micro-semiconductor manufacturing. Because there is no unpredictable and diverging bearing play, the precision is improved. In terms of expenses, CM are potentially less expensive due to the monolithic structure's minimal number of elements. Due to the small number of pieces and the typically planar structure, it is less expensive to manufacture, assemble, and maintain. [2]

Table 1.1 Comparison between conventional multi-body systems and CM in terms of performance and costs in small scale applications [2]

| | Multi-body systems | Compliant mechanism |
|-----------------------|--------------------|---------------------|
| Friction | – | + + |
| Noise | o | + + |
| Cleanliness | – | + + |
| Precision | – | + + |
| Performance | – | + |
| Number of parts | – – | + + |
| Manufacturing costs | – | + |
| Maintenance costs | – | + |
| Costs | – | + |
| Simplicity to design | + | – – |
| Influence of hinges | + + | o |
| Design process | + | – |

As a result, due to the aforementioned advantages, CM may deliver better performance while being less expensive, especially in small-scale applications.

Because of that, the development of magnetic compliant mechanism systems can be used in real-world companies and manufacturers such as:



From left to right: Semiconductor manufacturing company, E-commerce company, Technology company, Steel Ball Manufacturer.

1.3 Thesis's objective

The aim of this thesis is (1) Give a overview of compliant mechanism (2) A brief overview of magnetic and additive manufacturing of compliant mechanism (3) develop a magnetic compliant mechanism gripping system that is both more favorable and less expensive than existing systems, which to pick up metal items frequently and consistently without having a human to touch the object directly, which increases performance and preserves product quality.

1.4 Organization of the thesis

After the first part of introduction, which gives an overview of compliant mechanism, the next chapter reveal further aspects of the concept and form the main idea of the thesis. Chapter 2 focuses on the background of compliant mechanisms, magnets, additive manufacturing of compliant mechanisms, and examples of CM gripper's existence and variation.

Chapter 3 will give some conceptual design and development of different variants of magnetic compliant mechanism gripping system. Furthermore, chapter 3 will explain the process of evaluate, compare each variant and the selection of the optimal variants.

Chapter 4 will construct the preferred variant into the complete product.

Chapter 5 gives detail about the process of additive manufacturing a selected variant.

Chapter 6 show the experiment testing of the selected variant for the eligible of operation in working environment.

Chapter 7 will address the concept, its advantages and disadvantages, areas for improvement, and potential future initiatives.

Finally, references that were used for the writing of this bachelor thesis are to be listed.

Chapter 2 State of the art

2.1 What are Compliant Mechanisms and magnet?

2.1.1 What is compliant mechanism

In mechanical engineering, a **compliant mechanism** is a flexible mechanism that achieves force and motion transmission through elastic body deformation. It gains some or all of its motion from the relative flexibility of its members rather than from rigid-body joints alone. These may be monolithic or jointless structures. [1]

Whenever something bends to do what it's supposed to do, it's said to be compliant. It is a compliant mechanism if the flexibility that permits it to bend also allows it to perform something valuable. The concept of using compliant mechanisms in products is gaining traction, however when designers need a machine that moves, they typically utilize highly stiff or inflexible pieces coupled with hinges (such as a door hinge or a wheel on an axle) or sliding joints. When we look at nature, however, we see a completely different concept than rigid pieces connected at joints most moving things in nature are very flexible rather than stiff, and motion is generated by bending the flexible portions [3]. Consider your heart, which is an extraordinary compliant mechanism that began operating before you were born and will continue to operate all day, every day for the rest of your life. Consider bee wings, elephant trunks, eels, seaweed, spines, and flower blooming (Figure 2.1), which are all compliant. Even natural actions that appear to be exceptions to this bending tendency, such as bending your knee or elbow, rely on cartilage, tendons, and muscles to perform their functions. We can observe how little machines can be made in nature: a mosquito (Figure 2.1) can fly while carrying its own navigation, control, energy collecting, and reproduction systems on board. Would it be possible to improve human-designed items by applying natural lessons and focusing on flexibility to achieve movement? [4]

Some of the first man-made devices were compliant mechanisms, which is fascinating. Is it because we were more in touch with nature back then? The bow is an example of a compliant mechanism with a millennia-long history (Figure 2.2). What if we took a cue from nature and used flexibility to achieve movement? Ancient bows were fashioned of a mixture of bone, wood, and tendon, and the flexibility of their limbs was employed to

store energy that was then released to propel the arrow. It's fascinating to look at Leonardo da Vinci's designs [5] and find so many compliant systems (see Figure 2.2 for an example). Even one of engineering's greatest successes, sustained human flight, began with a compliant system when the Wright brothers (Figure 2.3) exploited wing warping to gain control of their early planes. [6]

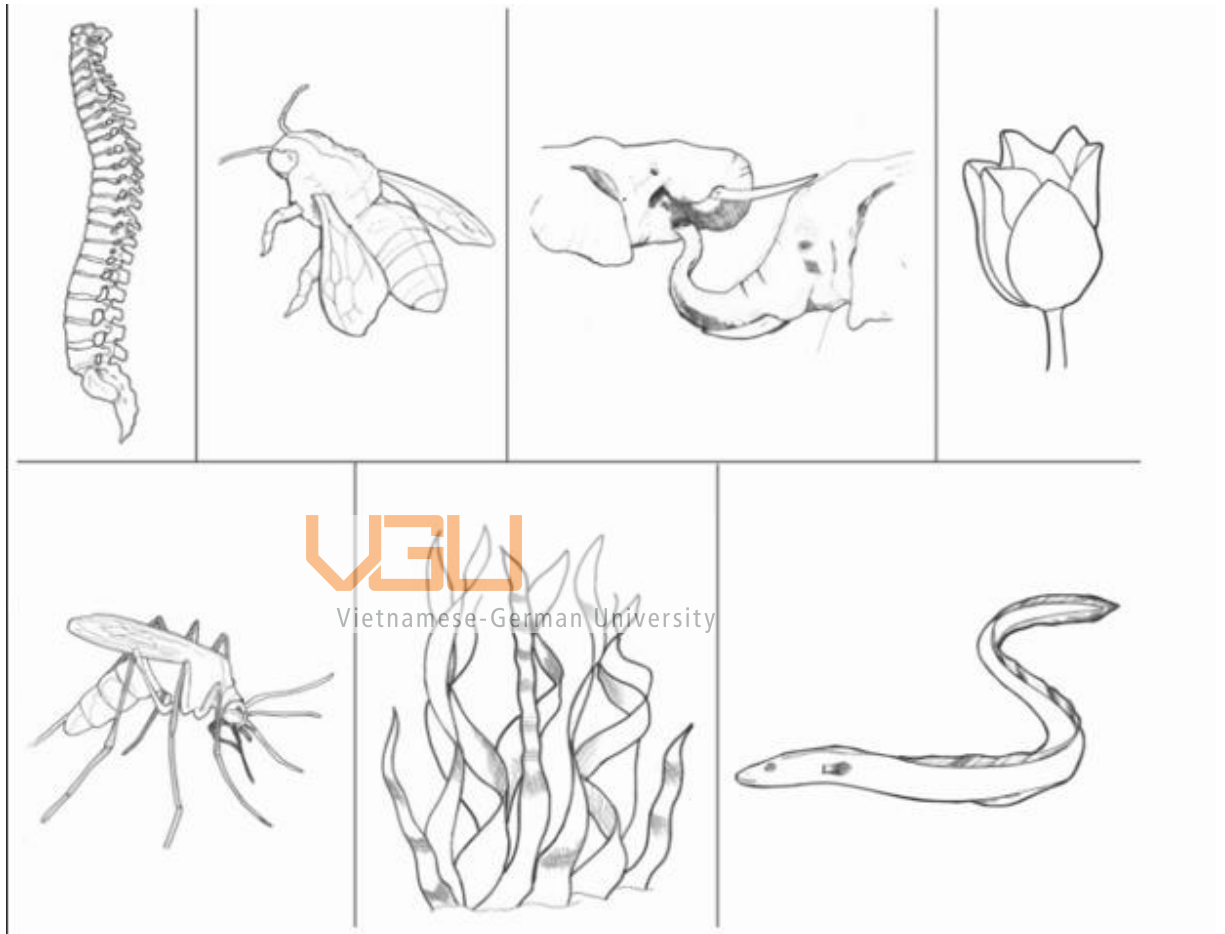


Figure 2.1 A few examples of compliance in nature: a spine, bee wings, elephant trunks, blooming flower, a mosquito, seaweed, and eels [4]

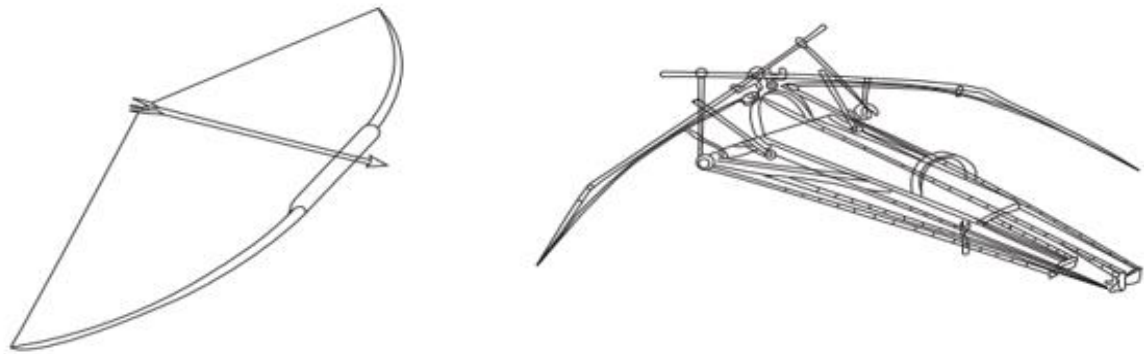


Figure 2.2 Early compliant mechanism designs include the ancient bow and many compliant mechanism designs by Leonardo da Vinci [4]



Figure 2.3 The Wright brothers used wing warping to achieve control of their aircraft for sustained human flight [4]

All of this sounds great, but designing compliant mechanisms is actually quite challenging. Nature did it, but nature did so using very different design principles than we mortals. When compliance was left to nature and we shifted to the far easier-to-design arena of rigid parts joined at hinges, great strides were made in machine design. For example, the Wright Flier's overly complex wing warping was subsequently replaced with the considerably simpler-to-use control surfaces supplied by an aileron swinging on a hinge. [4]

Traditional mechanical component design is appealing because designers may segregate different functions to be performed by different parts, and each part is allocated to perform that one function. Compliant mechanisms combine multiple functions into fewer elements, which is both a blessing and a problem. Compliant mechanisms can perform complicated tasks with a small number of parts, but they are more difficult to construct. [4]

2.1.1 How do Compliant Mechanisms work?

A compliant mechanism utilizes elastic deformation of structural parts to produce large output displacement in different direction from the input displacement. [1]

Aside from employing systematic or intuitive ways to design the CM's skeleton, a special focus is placed on the Flexure hinges (FH), which enable the necessary overall motion of the CM through a permanent deformation but become highly strained and, hence, susceptible to material failure. [2]

Flexure hinges have a critical role in the performance of the Compliant mechanism. Flexure hinges are a narrow region that, by elastic deformation, acts as a rotational pin joint. [7]

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Planar FH, rotational symmetric FH, and compliant joints that are made up of a system of FH are examples of different types of FH. Planar FH are more significant in terms of topology optimization of in-plane mechanisms, and hence are reviewed here. [2]

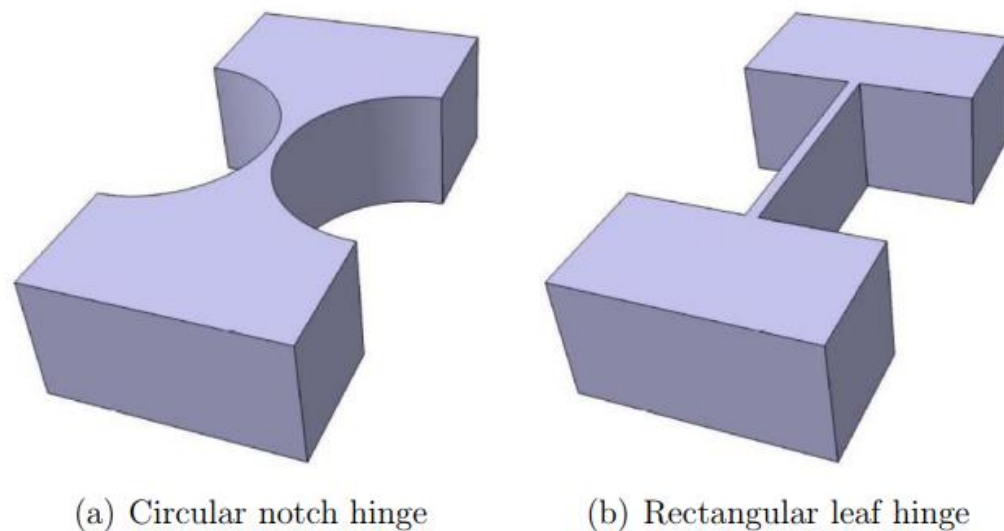


Figure 2.4 Common shapes of planar flexure hinges [9]

Several research groups have looked into various forms of FH. Because of the increasing number of CM applications in the recent decade, the design of FH has gotten more attention. A number of research groups proposed analytical, numerical, and experimental studies on circular and corner filleted, parabolic and hyperbolic, V-shaped, elliptical and conical, corner, three segment FH, and more. However, because of their manufacturability, the most popular shapes of FH used in CM are circular and rectangular FH, as shown in Fig. 2.4. [2]

Compliant mechanism's physical background is many, but in this overview will focus on some of the most importance attribute:

- Stiffness: the degree to which an object resists deformation in reaction to an applied force is known as stiffness.

The connections between stiffness, strength, and deflection are frequently misunderstood. If a minor load generates a big deflection, the part has low stiffness, but nothing about its strength is inferred. The stiffness or rigidity of a structure is related to the amount of deflection that a load will create. The material's strength is a quality that describes how much force it can withstand before failing. In other words, the stiffness of a structure dictates how much

deflection it will experience as a result of a load, but the strength determines how much stress it can withstand before failing.

A structure's stiffness is determined by both material qualities and geometry. The flexural stiffness in bending is EI , where E is Young's modulus (the modulus of elasticity), and I is the moment of inertia in cross-section. The axial stiffness for an axial load is EA , where A is the cross-sectional area. [1]

Take a look at Figure 2.5, which shows a cantilever beam. Isotropic means that the material has the same Young's modulus and strength in all directions. The moment of inertia about one axis is substantially larger than the other due to the beam shape. When a force, F_x , is applied in the x direction until the maximum stress equals the yield strength, S , the deflection in the x direction is

Equation 2.1 maximum stress in x direction [1]

$$\delta_x = \frac{2SL^2}{3Eb}$$

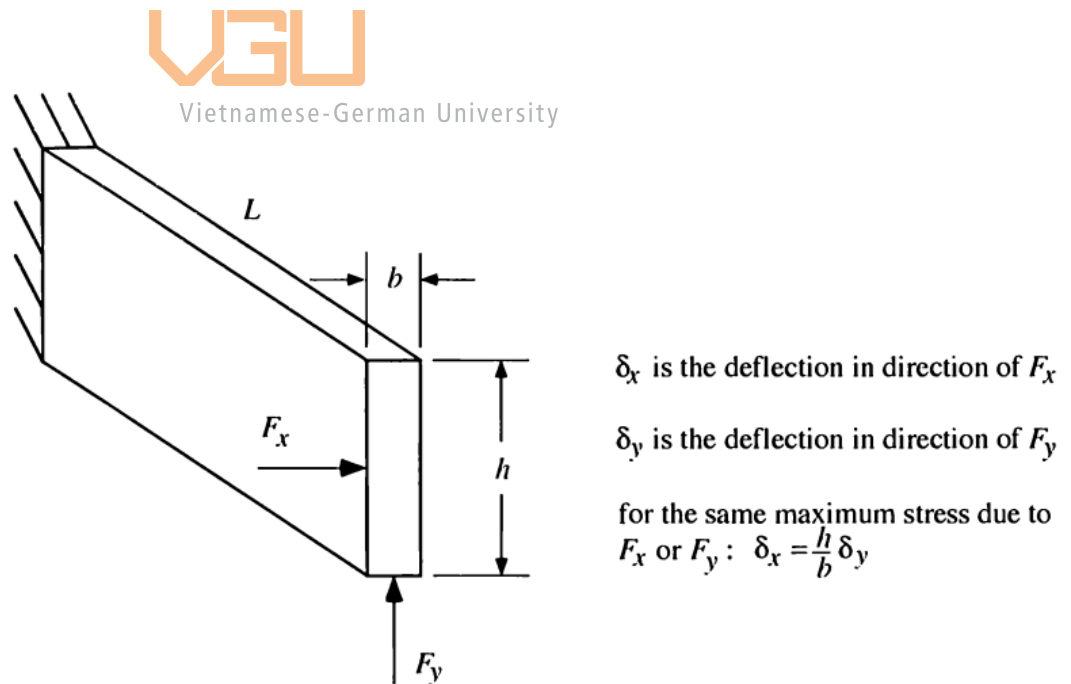


Figure 2.5 Cantilever beam equation with equal strength but different stiffnesses in the x and y directions [1]

A force in the y direction, F_y , that cause a maximum stress equal to the yield strength produces a deflection in the y direction of

Equation 2.2 maximum stress in y direction [1]

$$\delta_y = \frac{2SL^2}{3Eh}$$

The part can have a larger deflection in the x direction than in the y direction before failure, by a factor of h/b , that is,

Equation 2.3 relationship between δ_x and δ_y [1]

$$\delta_x = \frac{h}{b}\delta_y$$

The beam in this example has identical strength in both directions but significantly varied stiffness in the y and x directions. Stiffness and strength are not always related, and in some circumstances, making a member less stiff can prevent failure. When it comes to compliance mechanisms, this is frequently the case. [1]

- **Flexibility:** the ability of a material to deform elastically and return to its original shape when the applied stress is removed. The more flexible an object is, the less stiff it is. [11]

There are three main ways in which we can affect flexibility. These are: 1. material qualities (what it is made of); 2. geometry (its shape and size); and 3. boundary and loading conditions (how is it held and loaded). [4]

For most structural and mechanical systems, beam flexibility and deflections are undesired features. The flexibility of moving components, for example, creates vibrations in high-speed mechanisms, which can lead to poor mechanism performance or failure. Even though a structure's strength is more than adequate to bear the imposed loads, Deflections are minimized in most constructions to avoid the appearance of being weak. Simple linearized beam equations can also be utilized to examine the resulting deflections when the deflections are minor. For these reasons, the majority of structural and mechanical design research has focused on techniques of enhancing member rigidity to reduce deflections under load. [1]

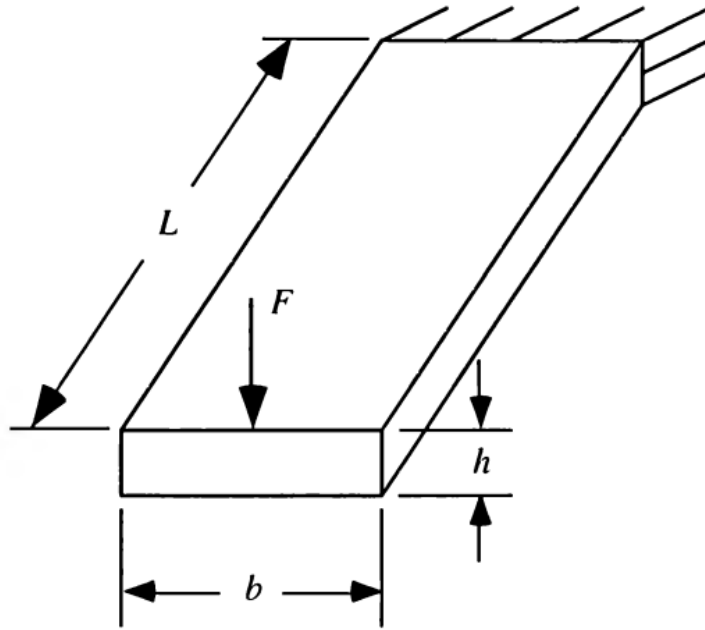


Figure 2.6 Flexible cantilever beam [1]

However, because deflection is required for compliant mechanisms to move, their components must be flexible. These deflections should be produced with as little applied load and member stress as possible. [1]

The inverse of rigidity is flexibility, which refers to a member's capacity to deflect under load. The flexibility of a beam can be altered by altering the material qualities or the geometry [1]. Figure 2.6 shows an example beam to demonstrate this. Assuming that the deflection is linear, the deflection, δ , is

Equation 2.4 [1]

$$\delta = \frac{FL^3}{3EI}$$

Where the moment of inertia is $I=bh^3/12$, so

Equation 2.5 [1]

$$\delta = 4F \frac{1}{E} \frac{L^3}{bh^3}$$

- Elastic deformation: is a self-reversible transitory deformation of a material's shape after the force or load is removed. The application of a force within a material's elastic limit causes elastic deformation, which changes the shape of the material. This physical feature guarantees that elastic materials will revert to their original dimensions if the applied load is released. Deformation is reversible and non-permanent in this case. Metals and ceramics exhibit elastic deformation at low strains, and their elastic behavior is often linear. [12]
- Energy storage: Energy is stored in the system as strain energy because compliant mechanisms have elastic parts that deflect. As a result, the energy available at the output may be significantly lower than that available at the input. This energy is not wasted; rather, it is stored and released at a later time. The stored energy is a desirable characteristic of many compliant mechanism applications and is often a reason to choose a compliant mechanism over other types of mechanisms. Examples of such applications include bistable mechanisms and mechanisms that incorporate the effects of rigid links and springs into flexible components. However, in some cases, such as with a gripper device, the amount of energy available at the output should be maximized. Whether energy storage is beneficial or undesirable in a given application, it's crucial to know what factors influence how much energy is stored. [1]

The amount of energy stored can be reduced by creating a compliant mechanism in which the limitations on a deflecting element allow it to take on a shape that requires the least amount of work to achieve. Consider a variety of various beam loadings and the work necessary to achieve up a specific deflection. Assume that each beam has a length of L , a fixed left end, and a deflection of δ at its free end. Suppose that the deflection is small enough. [1]

For a beam with a vertical force at the free end,

Equation 2.6 [1]

$$F = \frac{3EI\delta}{L^3}$$

The work required to obtain the required deflection is calculated as

Equation 2.7 [1]

$$W = \int_0^{\delta} F d\delta$$

Combining equation 2.6 and 2.7

Equation 2.8 [1]

$$W = \int_0^{\delta} \frac{3EI\delta}{L^3} d\delta = \frac{3EI\delta^2}{2L^3}$$

The work done by the moment, where M is the moment and θ is the angle at the free- end, is

Equation 2.9 [1]

$$W = \int_0^{\theta} M d\theta = \int_0^{\theta} \frac{EI\theta}{L} d\theta = \frac{EI\theta^2}{2L} = 2\frac{EI\delta^2}{L^3}$$

The energy used to deflect the beam is retained as strain energy in the beam. This is comparable to deflecting a spring, where the energy is stored in the spring as potential energy. For the same deflection, a spring that is twice as stiff as another will store twice as much energy. Knowing the loading efficiency allows users to design mechanisms that achieve the desired deflections while storing very little energy. [1]

2.1.1.2 The application of compliant mechanism

Some of the earliest applications of compliant structures extend back millennia. The bow and arrow are one of the oldest examples. Some catapult designs make use of the arm's flexibility to store and release energy, allowing the projectile to go longer distances [4]. Compliant mechanisms are being used in a number of fields, including adaptive structures and biomedical devices. Compliant mechanisms, which are often employed in robotics for gripping, can be used to develop self-adaptive systems [15]. In addition, a

compliant mechanism gripping system can be used in surgical procedures, particularly minimally invasive surgeries. [17]

One example is the flexible or resilient drive, which is frequently used to connect an electric motor to a machine (such as a pump). A rubber "spider" is wedged between two metal dogs in the drive. The motor shaft is attached to one dog, while the pump shaft is attached to the other. The rubber part's flexibility compensates for even little misalignment of the motor and pump.

Micro-electromechanical systems have compliant mechanisms. Micro-accelerometers and electro-thermal micro-actuators, for example, utilize amplifying compliant mechanisms. [16]

2.1.3 How to Design a Compliant mechanism?

Many of today's CM were developed solely on the basis of engineers' intuition and experience, rather than employing any systematic methodology. Obtaining a final CM that fulfills the specified performance requirements usually necessitates a number of trial-and-error iterations. In the last two decades, multiple research groups from various backgrounds have presented a variety of systematic design and optimization methodologies because this intuitive design process is time-consuming and results in workable – but usually non-optimal – solutions.

In the literature, there are two well-established general approaches to the systematic synthesis of CM: kinematics-based approach and structural-optimization-based approach.

The structure-optimization-based approach, no initial setup is required. It starts from a certain material (design) domain and aims to find an optimal shape, size and topology based on specified external loads and boundary conditions. [2]

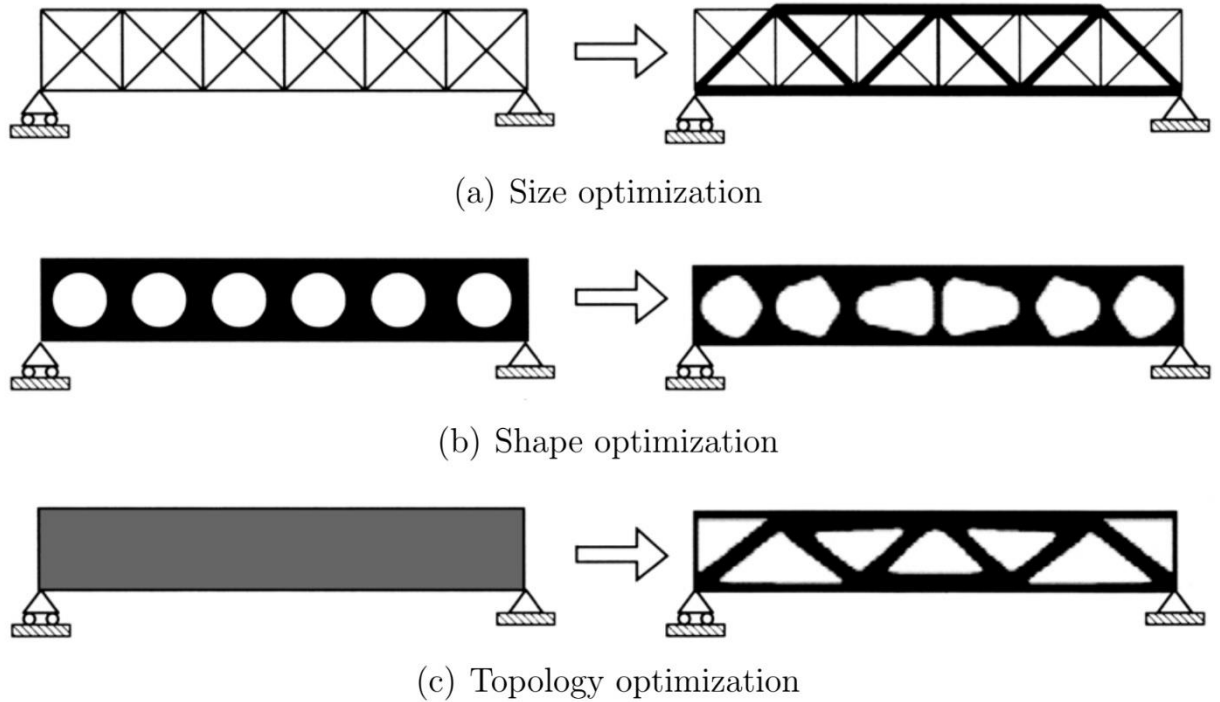


Figure 2.7 Different types of structural optimization [20]

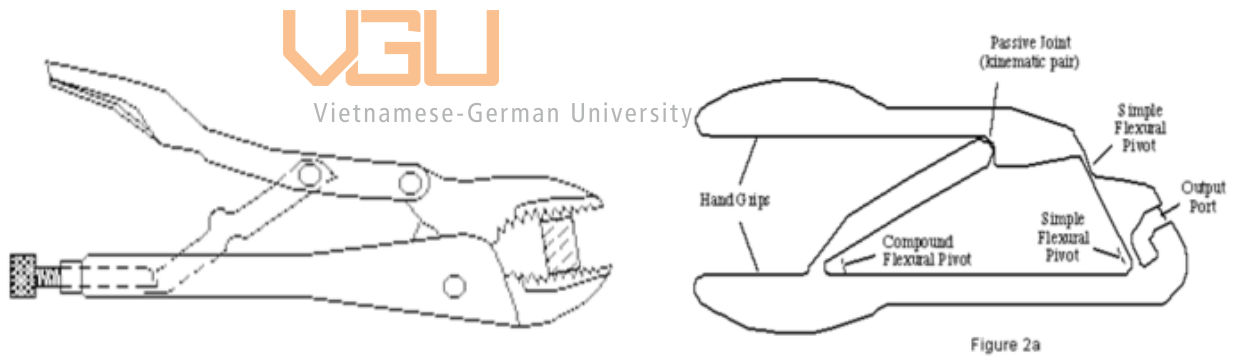


Figure 2.8 A normal crimpling mechanism (left) and an equivalent compliant mechanism (right). [27]

Kinematics approach: Kinematic analysis can be used to design a compliant mechanism by creating a pseudo-rigid-body model of the mechanism [4]. In this model, flexible segments are modelled as rigid links connected to revolute joints with torsional springs. Other structures can be modelled as a combination of rigid links, springs, and dampers. [18][19]

Figure 2.8 demonstrate the example of kinematic approach.

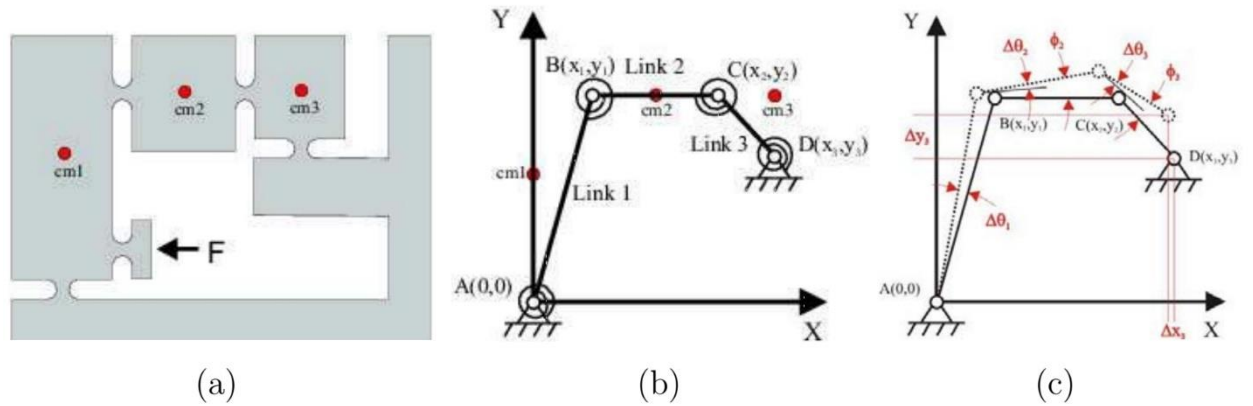


Figure 2.9 Kinematics-based approach: (a) Initial compliant mechanism, (b) corresponding pseudo-rigid-body-model and (c) deflected pseudo-rigid body-model [21]

The flexible parts of a known compliant mechanism are modeled by numerous rigid bodies coupled by pin-joints with extra torsional stiffnesses that must be tuned in the kinematics-based method. Howell pioneered the use of small-length flexure hinges in this approach. Howell and Midha developed closed-loop equations of the force-deflection behavior for other flexure members, such as flexure pivots, cantilever beams, and initially curved beams, and used them to develop commercially valuable CM, such as a parallel CM by Mattson or a micro-positioning mechanism by Handley, as shown in Fig. 2.9. Yu presented dynamic modeling for a simple parallel CM. Large, non-linear deformations are well-suited to the kinematics-based method. However, it is predicated on a known initial rigid-link mechanism, which means that the beginning configuration of a CM must be known. Because no initial setup is given, this approach is not ideal for a nonintuitive approach. [2]

2.1.4 What is magnet?

In this work will briefly introduce magnet and it's working principle.

One aspect of the combined electromagnetic force is magnetism. It refers to physical events that occur as a result of the force exerted by magnets, which are devices that generate fields that attract or repel other objects. According to Georgia State University's HyperPhysics website, the Lorentz force exerts a force on particles in a magnetic field. Magnetism is caused by the migration of electrically charged particles. The size of the charge, the velocity of the particle, and the strength of the magnetic field all affect the

force exerted on an electrically charged particle in a magnetic field. Magnetism affects all materials, although some are more magnetized than others. The strongest effects, known as ferromagnetism, are seen in permanent magnets made of materials such as iron. This is the only form of magnetism strong enough to be felt by individuals, with rare exceptions. [32]

According to online searches, no one has yet to incorporate a magnet into a compliant mechanism. However, additional research is needed to find similar concept to magnetic compliant mechanisms. 3D printing magnetic material, which can be used in compliant mechanisms, is one of the examples.

2.2 Additive manufacturing of compliant mechanism.

Overview of Additive manufacturing:

The use of 3D printing to create functional components, such as tools and end-use industrial parts, is referred to as "additive manufacturing" (AM). In contrast to "subtractive manufacturing" procedures like machining, which generate components by removing material, additive manufacturing creates geometries by "adding" feedstock like filament, wire, or powder. Despite being newer than other manufacturing processes, AM is likely the most comprehensive manufacturing category humans have. AM is now being used in a growing number of end markets, including automotive, dental, heavy equipment, oil and gas, rail, marine, and even consumer goods, although it initially gained traction for manufacturing in the aerospace and medical industries. Additive manufacturing, as opposed to subtractive procedures like milling, allows for more geometric freedom and uses less material. 3D printing, unlike other forming methods such as injection molding or composites layup, does not require the use of a mold or other tools to make a product. Although the quantities appropriate for 3D printing continue to grow, additive manufacturing has been shown to be a good option in production applications where long lead times or associated costs preclude the use of expensive tooling; complexity of geometry is advantageous; and/or low volumes are required. [33]

Type of Additive manufacturing:

- VAT photopolymerization: Stereolithography is another name for VAT photopolymerization. VAT photopolymerization gets its name from the vat of liquid photopolymer resin used in this technique of additive manufacturing. A build platform is dropped from the top of the resin, moving downward, and a laser beam creates a layer by drawing a shape in the resin. One layer's average thickness is between 0.025 and 0.5mm. After each layer of resin has been applied, it must be cured using UV radiation. Photopolymerization is a procedure that uses motorized mirrors to direct UV light across the resin surface, causing it to harden. To add layers, repeat these steps. Most equipment employs blades that travel over each layer to remove imperfections before applying and curing the next layer for greater precision and quality. The finished project produced by using a liquid has a high level of accuracy and detail, but it lacks the structural support afforded by other forms of additive manufacturing. This is remedied by constructing additional support structures. While the VAT photopolymerization process is quick, the clean-up and post-processing takes a long time. VAT From hearing aids to Nike shoes, photopolymerization is utilized to make parts and products in a variety of sectors. [34]
- Material jetting: With material jetting, the print head is elevated above the platform, and the material is deposited as droplets on the surface. Hundreds of micro-droplets are positioned using charged deflection plates, allowing for greater control and precision. After then, the droplets harden, forming a coating. This is done again and again, accumulating layers. Using the Drop-on-Demand (DOD) approach, the droplets can be distributed continuously or individually. Inkjet printers are similar to this technology. Various materials, including as polymers and waxes, can be used in material jetting. This method of additive manufacturing is precise, and it allows you to work with a variety of materials on a single project. Although precise, it is not the most efficient way because time is required re-filling the rapidly depleting reservoir. Material jetting is frequently used to make realistic prototypes or models. [34]
- Binder jetting: A binder and a powder-based substance are used in this sort of additive manufacturing. A roller applies the powder-based material to the build

platform, and the print head subsequently deposits the binder on top. The binder, which is usually liquid, holds the layers together. The product is lowered onto the platform after a layer. This is done again and again until the product is complete. You can utilize a variety of materials in this technique, including polymers, ceramics, and metals. Binder jetting is one of the fastest additive manufacturing technologies available, and it enables for customization. For example, if a consumer requires a specific quality of material, they can alter the binder-powder ratio, or they can develop a product with color fluctuation. The increase in post-processing time is one of the disadvantages of binder jetting, and it may not be the greatest solution for manufacturing structural parts. Binder jetting is utilized in a variety of applications, including industrial, dental, and medical devices, aerospace components, part casting, and luxury goods. [34]

- Material extrusion: Material extrusion is a sort of additive manufacturing process in which material is pulled through a nozzle, heated, and then deposited in a continuous stream, which is commonly employed in low-cost at-home 3D printers. The platform travels up, down, and vertically while the nozzle moves horizontally. The layers are built in this manner. The substance fuses to the prior layer because it is heated (melted) when applied. Temperature and chemical agents can also be used to influence the adhesion between layers. Although material extrusion is frequently seen in low-cost models, it has a wide range of capabilities. Polymers and plastics, which give excellent structural support, can be employed. However, there are several drawbacks to using additive manufacturing. Because of the nozzle thickness, accuracy is compromised, and material extrusion is also one of the slower kinds of additive manufacturing. Material jetting is utilized by many automobile firms to develop manufacturing equipment for assembly lines. [34]
- Powder bed fusion: A layer of powder is put to the platform for powder bed fusion additive manufacturing. Before a second layer is deposited using a roller or blade, a thermal energy source such as an electron beam or laser fuses the powder. After that, the layering process is repeated. Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), and Direct Metal Laser

Sintering (DMLS) are some of the minor variants in powder bed fusion. Regardless of the differences between these variants, all powder bed fusion is done in a pre-heated, near-vacuum chamber using inert gas. Metals and polymer powder materials, which act as a support framework, can be employed, making it a good choice for prototypes and visual representations. Although the powder bed fusion method has several drawbacks, such as the fact that it takes longer to finish projects, it is nevertheless utilized in a variety of industries, including aviation, to make parts for jet engines. [34]

- Sheet lamination: Sheet lamination is a process that binds layers using ultrasonic welding or an adhesive. There are two variations of sheet lamination: ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The difference between the two is found in the material used and the bonding process.
 - UAM uses metal that is bound together with ultrasonic welding.
 - LOM uses paper that is bound together using an adhesive.

Sheet lamination is done by placing the material on a cutting bed. Layers are applied and bonded to that material, and the shape is cut with a knife or laser. This process can bind different materials and is relatively low cost and speedy. Accuracy is sometimes lacking in sheet lamination and many projects that utilize this additive manufacturing process may require post-processing. Sheet lamination is often used for prototypes. Sheet lamination can be inaccurate at times, so projects that use this additive manufacturing technology may require post-processing. For prototypes, sheet lamination is frequently employed. [34]

- Directed energy deposition: One of the most difficult methods of additive manufacturing is Directed Energy Deposition (DED). A four- or five-axis arm will travel around a fixed object, depositing molten material. An electron beam or laser melts the material, which then solidifies. The most frequent material utilized with DED is metal powder or wires, however ceramics and polymers can also be used. Due to DED's capacity to repair and manage grain structure, you may reach a high level of precision. The finish differs depending on the type of material utilized. In the case of metal, a powder will produce a far superior finish than wire; nevertheless, wire can be post-processed to create the desired look. In

order to repair or produce parts, Direct Energy Disposition is frequently used. In conclusion, additive manufacturing is far more complicated than the phrase "3D printing" implies. Although these seven types of additive manufacturing differ in a variety of ways, they all play an important part in a variety of manufacturing processes and have the potential to revolutionize future applications. [34]

Additive manufacturing is believed to be suitable for the construction of magnetic compliant mechanism gripping system because:

- Accelerated prototyping: AM speeds up product development by allowing the manufacture of a large number of different prototypes that can be produced faster and for less money than traditional approaches. [35]
- Customization: Design innovation and creative flexibility are possible thanks to additive manufacturing, which eliminates the cost and time limits of traditional manufacturing. [35]
- Energy savings: In traditional production, auxiliary tools with higher energy requirements are frequently required by machinery and equipment. AM consumes fewer resources, necessitating less supplementary equipment and, as a result, decreasing manufacturing waste. [35]
- Part flexibility: Additive manufacturing appeals to those who want to make odd or complex components that are difficult to make with standard methods. Nearly any geometric form may be designed and created with AM, as long as it reduces the weight of the object while retaining its stability.

However, there are several disadvantages to AM that should be addressed when constructing the gripper:

- Cost of entry and production cost: with AM, individuals are still finding it difficult to afford entrance costs such as machines and equipment. Furthermore, AM materials are usually required in the form of extremely fine or small particles, which can significantly increase a project's raw material cost [35]. Despite the fact that this research is supported by university funds and facilities, the gripper construction process must be as efficient as feasible.

- Time consuming: Even though additive manufacturing technology has been known since the 1980s, it is still considered a niche process in 2021. This is partly due to the fact that AM still has sluggish build rates and does not offer a cost-effective solution to scale operations to generate huge quantities of parts. Depending on the final result, additive manufacturing could take up to 3 hours to construct a shape that would take a traditional process second to build. [35]
- Post-processing: A certain level of post-processing is required in additive manufacturing because surface finishes and dimensional accuracy can be of a lower quality compared to other manufacturing methods. Additive manufacturing's layering and various interfaces might result in product faults, necessitating post-processing to correct any quality issues. [35]

Material extrusion is the technology that is suited for creating a CM gripper based on the current state and ability to access AM of the author. Because this technique is well-known and is currently being implemented in university laboratories. As a result, constructing a prototype and obtaining university assistance is easier, and prior experience working with this technology has been established. When using this technique, some limitations such as time consumption and post-processing must be considered.

2.3 Existence and variation of a compliant mechanism grasping system.

There are a variety of grasping systems that use compliant mechanisms. This section will discuss some of the CM gripping systems that are now available or in development.



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Figure 2.10 tweezers and chopstick helper

Tweezers are a type of compliant mechanism that operates by deforming the material elastically. Tweezers are made up of two third-class levers, one of which has the pincers attached (the fulcrum point of each lever). Applying force to the two levers to allow the tweezer to grasp a small object, then removing the force causes the tweezer shape to reopen (rebound) and the small object to be released. The same principle also apply to chopstick helper.

Hair clips are another example of a compliant mechanism. To keep hair in place, hair clips use the elastic deformation of springs. When applying force to a hair clip, it will

release the object (hair), then release force to secure the hair in place, in contrast to tweezers.



Figure 2.11 Hair clip



Figure 2.12 phone holder

The functioning mechanism of a phone holder is similar to that of a hair clip. There is a spring inside the phone holder that deforms when force is applied. The phone will be held in place by the spring's elastic deformation.



Figure 2.13 Bench press clip

The bench press clip operates by utilizing the elasticity of its member. It has a monolithic and jointless construction. When users squeeze the handle, the clip loosens and returns to its original position on the bar when released, securing the weight when being lifted.

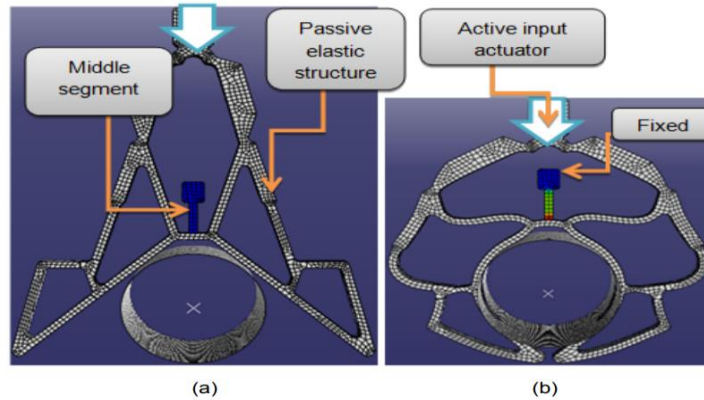


Figure 2.14 The main features of the adaptive gripper [7]

The primary gripper features are shown in Figure 2.14.

- The entire gripper structure is one passive elastic structure (Figure 2.14(a)).
- One active input actuator (Figure 2.14(b)).
- The gripper contains multi-output contact sites for one active input (Figure 2.14(b)).

Figure 2.14 depicts the gripper's adaptation to the cylindrical object (b). The gripper component is also illustrated, which is fixed while gripping and holding of a grabbed object. [7]



Figure 2.15 Verification of the gripper functions for different shapes of grasping objects [7]

The gripper's ability to tolerate a variety of various shapes of grabbing items was demonstrated (Figure 2.15) and it was shown that the gripper could handle a variety of shapes and sizes of grasping objects.

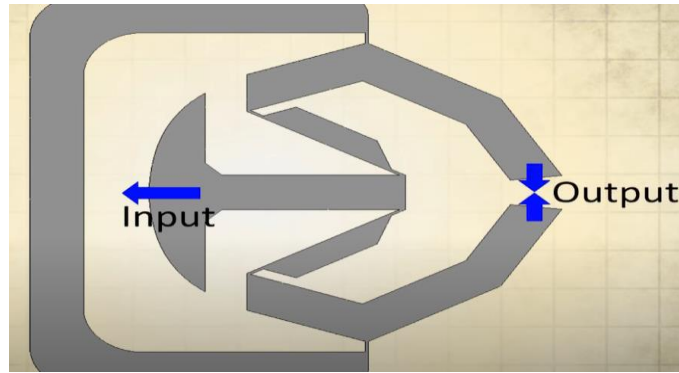


Figure 2.16 . Compliant gripper [14]

In Figure 2.16, the transmission mechanism is created by a compliant gripper that transforms one motion into other motions at different locations and in different directions. It was made in monolithic structure and jointless.

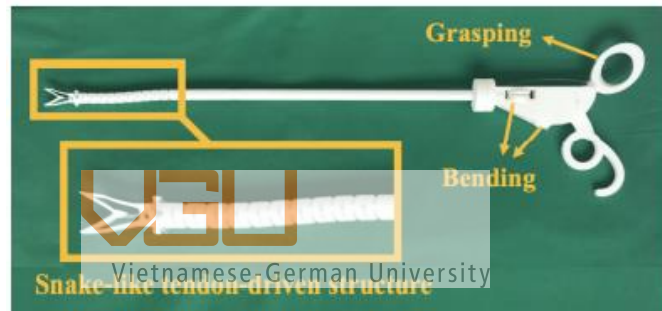


Figure 2.17 A SLS-printed continuum manipulator for robot-assisted MIS. [36]

3D printable robotic systems for minimally invasive surgery (MIS) are being developed. Because of their tremendous adaptability and practical benefits to patients, snake-like robots are used in our applications. The prototype of a selective laser sintered (SLS) continuum manipulator is shown in Figure 2.17, which includes a snake-like robotic structure for dexterous bending movements and an adaptive compliant forceps for safe handling of sensitive tissues. The adjoining flexure hinges' orientations in Fig. 2.17 are always vertical to each other, and the continuum structure is actuated by two tendons. The continuum structure can be bent in various directions in this manner [36]. This device can be used by surgeons to grab tissue. It's also made to handle sensitive abdominal tissue safely during laparoscopic surgeries. One of its key purposes is to keep intestinal tissue out of the operating area, allowing appropriate access to the surgical site. [13]



Figure 2.18 spring cord lock

Spring cord locks (Fig 2.18) work by grabbing the wire, which may be adjusted to open or lock a bag, and they also use elastic deformation of a spring as a working basis.



Figure 2.19 Compliers Fishhook Remover

The Compliers fishhook remover (Fig. 2.19), for example, is a one-piece compliant tool with flexible and rigid parts. When the handles are squeezed, the flexible segments contract, allowing the jaws to exert a grabbing force and forcing the mechanism to move, allowing the fishhook to be removed from the fish. Handles *a*, flexural pivots *b*, and jaws *c* are shown in compliers. Grasping and disgorging actions are used to remove hooks. [8]

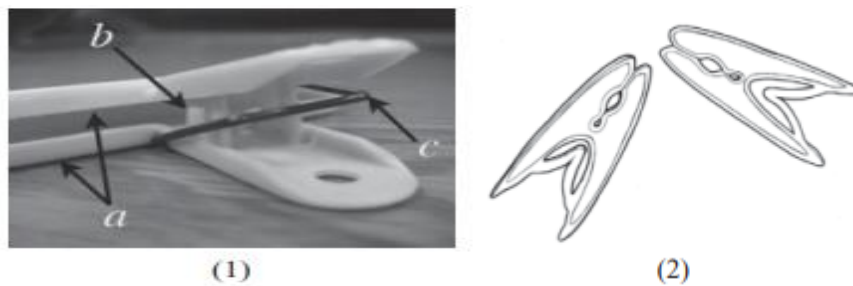


Figure 2.20 Clip [8]

Similar to hair clip, the clip (Fig 2.20) uses a bent metal wire as a spring to hold objects between plastic clamps. The clamping motion keeps food fresh by keeping open food bags closed. Other clips are monolithic, meaning the conforming member is built into the clip. (1) A rocker joint b connects two plastic parts a , which are kept together by the force exerted by the metal wire c . When the clip is opened, the metal wire deflects, causing the components to align and applying a force at the end when an object is placed between them. (2) Clips that are monolithic. [8]

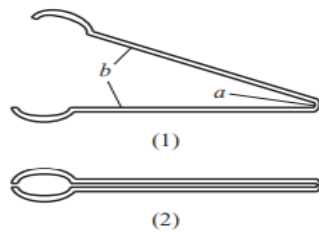


Figure 2.21 One-Piece Tong [8]

One-piece tongs (Fig 2.21) use a single plastic or metal flexible segment to allow clamping motion and provide return force. (1) The tongs are in the open position. The spring back energy storage and clamping motion are provided by flexible segment a . When gripping objects, the rigid segments b does not deflect. (2) Tongs are in the closed position. [8]

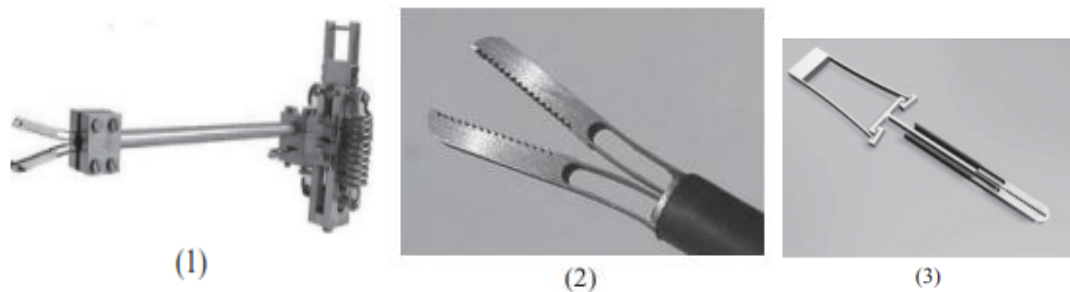


Figure 2.22 Statically Balanced Gripper [8]

A surgical gripper with a fully compliant gripper is the subject of this design. Despite the benefits of the compliant system, the stiffness caused by deformation confuses the surgeon's force feedback. A negative stiffness mechanism (balancer) was installed to cancel out the stiffness, which solved the problem. The mechanical efficiency is improved as a result, and force feedback is restored. (1) Overview of the instrument with

partly compliant balancer. (2) Close-up of the fully compliant gripper. (3) Fully compliant design. [8]

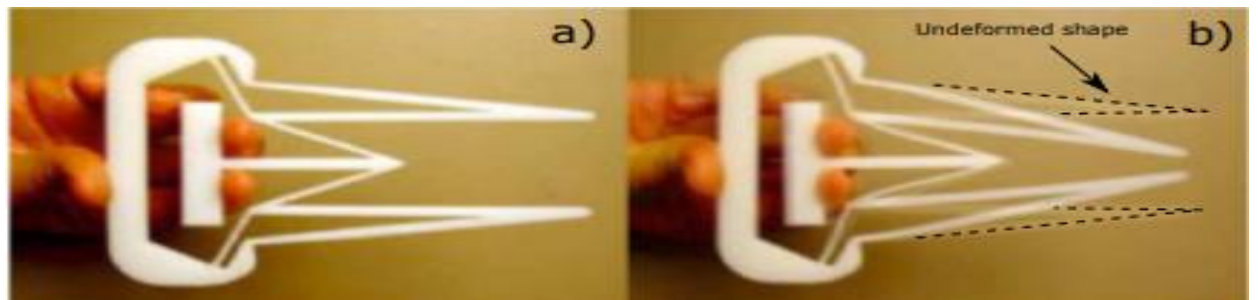


Figure 2.23 A simple compliant gripper mechanism [22]: a) Gripper position with no actuation force. b) Gripper deflection with actuation force applied

The above-mentioned compliant mechanism grippers served as inspiration for the gripping system in this thesis. In addition, this thesis proposes certain enhancements for use in the manufacturing setting. One of these is the incorporation of a magnet within the gripper, which will help secure the gripping object while also improving maneuverability in specific situations such as grasping metal. Figures 2.23 and 2.24 depict a variety of CM grippers, ranging from simple to complex, that aid in navigating the design's ideal.

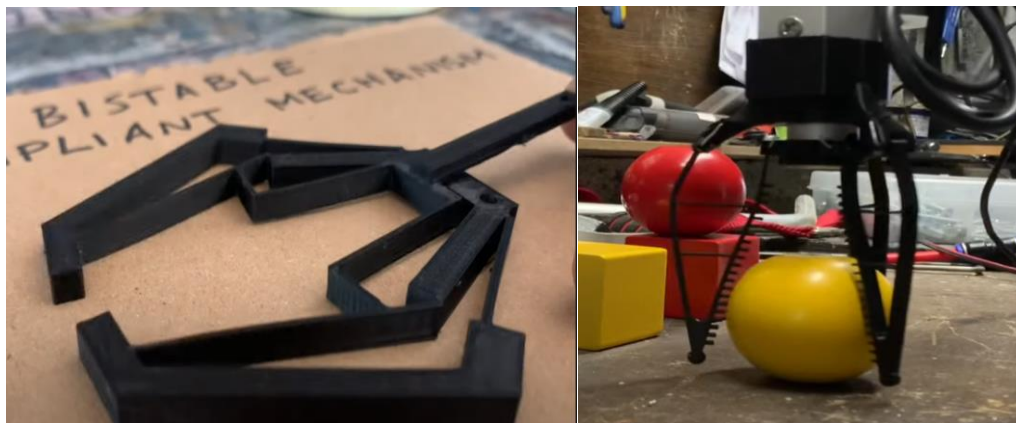


Figure 2.24 Compliant mechanism gripper (left) and Another type of compliant mechanism gripper (right) [28]

When designing CM grippers, traditional mechanism grippers (figure 2.25), which use pins and joints, are also being used as inspiration to create new concepts and have multiple perspectives.

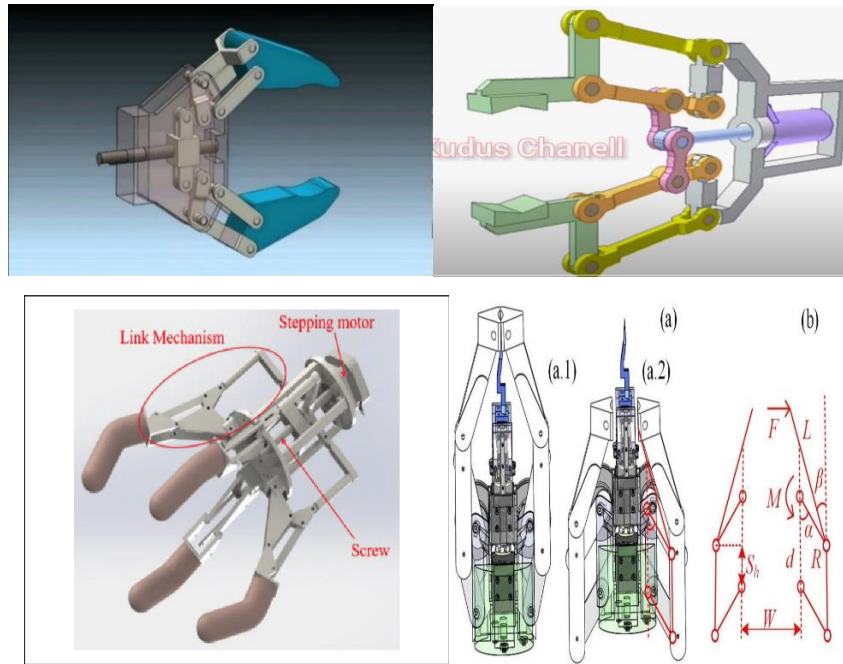


Figure 2.25 Traditional mechanism grippers as inspiration for a compliant mechanism gripper.

From left to right, up to down: [23]; [24]; [25]; [26]



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Chapter 3 Conceptual design, development of different variants and evaluation/ selection of the variants.

Introducing the aim for the CM gripper design:

This gripper will be created for a specific application. The compliant mechanism gripper will first take up a metal ball with a diameter of 5 centimeters. The ball will then be transferred to the next targeted place and released by the gripper's compliant mechanism.

When developing this gripper, one of the initial challenges was designing a compliant mechanism. Because the design process is the most significant disadvantage of compliant mechanisms. It is sometimes possible to build a simple design by following some examples from everyday life. However, a compliant mechanism might also be made up of a collection of complex systems. It is necessary to have a working knowledge of mechanism analysis methodologies and the deflection of flexible elements. Combining the two kinds of knowledge in compliance mechanisms necessitates not just a knowledge of both, but also a grasp of how they interact in a complex system. Linearized beam equations are no longer viable since numerous flexible members experience considerable deflections. Large deflections produce geometric nonlinearities, hence nonlinear equations must be utilized to account for these. Because of these challenges, numerous compliance systems have been created via trial-and-error methods in the past. Such methods are only appropriate for very simple systems that execute relatively simple tasks, and they are frequently inefficient for a wide range of potential applications. Theory has been created to make the analysis and design of compliant systems easier, and the limits are no longer as severe as they were previously. Despite these advancements, compliant mechanism analysis and design is often more challenging than rigid-body mechanism analysis and design. [29]

As a result, the development's first safety strategy is based on existing compliant mechanism design. Many universities and academics have investigated and researched a variety of designs, ranging from traditional rigid body systems to the most recent compliant mechanism designs. A suitable compliant mechanism was chosen and implemented into the gripper as a result. The gripper was designed as a result of this,

based on the precise working circumstances outlined at the beginning of this chapter. The original aim was to construct a magnet to hold a ball metal object, and then to utilize a compliant mechanism to release the object at the desired location. Another concept was to combine a magnet and a compliant mechanism in the same grasping mechanism; however, this idea would need to be tested in a real environment to evaluate how well it would work in practice, such as how easy it would be to release the object.

The gripper's excellent adaptability is due to the combination of under actuation and a compliant mechanism, and the elasticity of the silicon rubber (if used) enables a soft contact between the gripper and the gripped object. The only disadvantage of this constructed gripper is its extreme flexibility, which means it cannot hold heavy objects. [7]

Changing the gripper material, for example, to a stronger silicone rubber, is one approach for dealing with the gripper's high flexibility, but this must be done carefully because too stiff a material leads away from a compliant mechanism with distributed compliance. [7]

In addition, a magnet will be added to provide support when lifting heavy metal objects and to keep the object securely in position during the lifting operation.

PLA plastic will be utilized as the material in all of the idea designs that will be detailed later because it shares many characteristics with the plastic that will be used for 3D printing.

Many FEM simulations of gripper designs were intended to establish the ideal design of the fully compliant mechanism gripper. ABAQUS is considered to be a software tool to do the FEM analysis. Furthermore, the Inventor shape generator is also employed for FEM and optimization. Because it is simple to access and use, and because it is incorporated in Inventor alongside Inventor CAD, the process of topology optimization is made easier and more continuous.

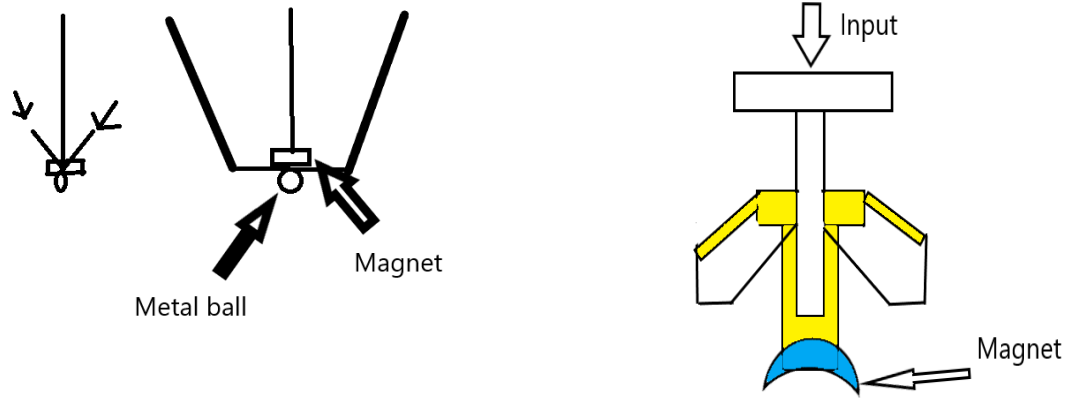


Figure 3.1 Initial ideals

These initial concepts were developed using the above-mentioned setting. However, there is a lot of space for improvement in terms of shape and utilization. FEM was still seen to be useful for improving those notions or even creating new ones. Although, because to a lack of software understanding and the difficulty of optimization, using FEM software in design poses a significant challenge.

Task clarification:



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This is the first phase in the process of designing the gripper. There are various requirements that must be met in order for the gadget to be accepted and used by customers. These include: The ability to do the work, the ease of usage, and the simplicity of construction are all important considerations.

Requirement list table:

| | | |
|---------------|----------------------|--|
| Hua Minh Tuan | Date: 31.01.2022 | Requirement list for a magnetic CM gripper |
| Changes | Demand (D)/ Wish (W) | Requirements |

| | | |
|--|---|---|
| | | <p>1. Geometry: Dimension of the prototype: Length = 15-25 cm Width = 5-10 cm Height= 2-5 cm</p> <p>2. Forces: Maximum weight of object can be carried: 0.4- 0.8 kg Elastic deformation: shape returning after force apply</p> <p>3. Energy: Manually by hand Electrical</p> <p>4. Material: Temperature range: 10 – 40 degrees Celsius Have high enough Stiffness and flexibility for CM designing</p> <p>5. Safety: Operator safety</p> <p>6. Production: Can be 3D printing No need for assembly Easy to be manufacturing</p> <p>7. Operation: Destination: Factory, outdoors Easy to operate</p> |
| | D | |
| | D | |
| | D | |
| | D | |
| | D | |
| | D | |
| | W | |
| | D | |
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| | | |
|--|---|---|
| | D | 8. Maintenance: Require barely maintenance |
|--|---|---|



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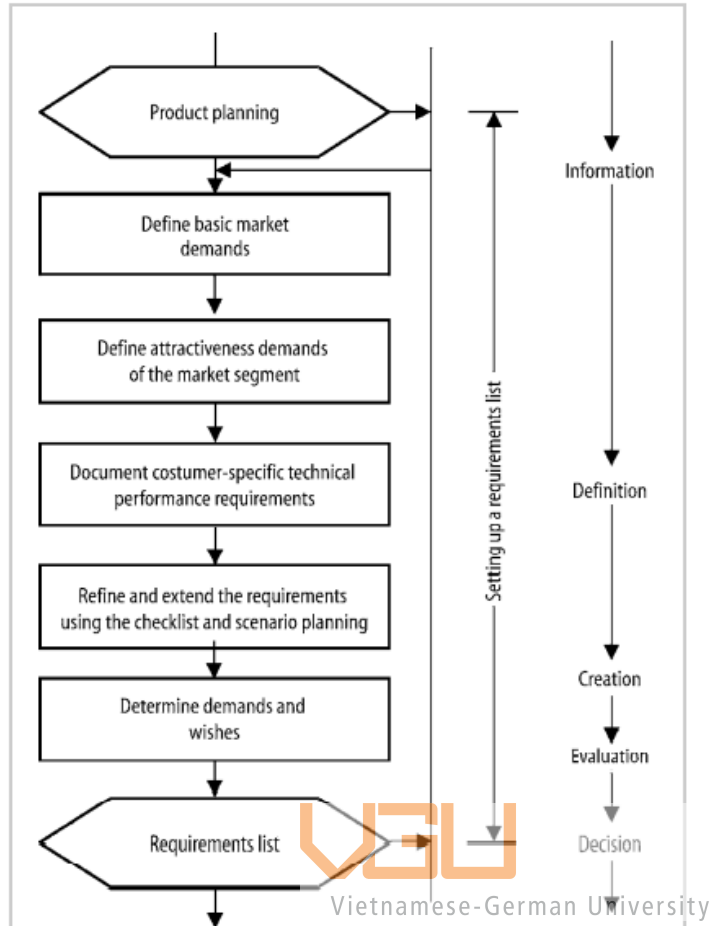


Figure 3.1.1 Main working steps required to set up a requirements list [37]

Design process: To efficiently tackle the problem of conceptualizing a device to pick up a metal ball while also meeting as many of the aforementioned criteria as feasible, a methodical approach is essential, and as such, should be employed to assess the problem before coming up with a possible solution. The thesis attempts to follow and must improvise on a systematic approach to engineering design as taught in the book "Engineering Design: A Systematic Approach" [37]. A CM gripper was developed as the thesis progressed, and some

of the steps in the systematic approach were carried out before the perfect notion of the gripper could be realized. That occurred as a result of the author's lack of prior expertise with CM, the difficulty of CM design as previously indicated, and the small scale of this thesis. Consequently, the concept and prototype were created on the basis of previously completed designs, the author's abilities, and some of the phases in the conceptual design process. Some phases in the conceptual design process may be combined with another or skipped entirely as a result of this.

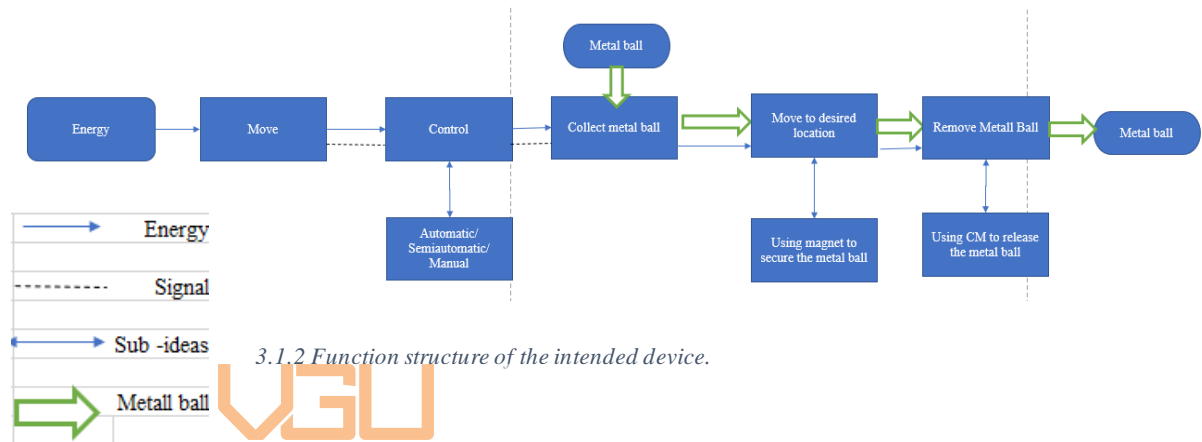
- **Abstracting to identify the essential problems**

Conceptual design begins with a generalization of the task's requirement, which is accomplished in the first phase. Consequently, fixed values and constraints are temporarily overlooked, and the spotlight becomes the primary focus of the work,

rather than the set values and limitations. As a result, the key restrictions become evident, and there is no bias toward any one solution or solution set.

According to the outcome, the project would be entitled "Development of magnetic CM gripping system for metal ball." It is nearly identical to the thesis's central idea, which was introduced at the beginning. This is due to the requirement of the thesis, which is to propose a fresh idea to deal with the difficulties without providing too many specifics in order to fulfill the requirements.

- **Establishing function structure – sub-functions**



3.1.2 Function structure of the intended device.



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A system's general function structure can be determined after a problem's crux has been identified and defined. The entire function is then broken down into sub-functions, understanding the problem from a more transparent perspective... Following that, the link between the sub-functions can be depicted using a block diagram, which depicts the movement of energy, material, and signals between the various components. This has resulted in a clear illustration of the relationship between the inputs and the outputs.

A grasping mechanism to capture a metal ball is the objective of this issue. Thus, collecting metal balls is the primary function of the device. The methods required to perform this function can be broken into discrete tasks in order to get the desired result: First and foremost, it should be held by any means necessary to do this. The device's movement should be considered, and then we should investigate how we can regulate it. Collecting, then relocating, and finally removing are the duties that remain to be completed. In order to determine sub-functions of the design, numerous questions must be answered. These questions include: What

kind of object would be chosen? What is its shape? What is the best way to go about the pick-up? What is the best way to move an object to the specified location? Is there a significant difference between the new system and the old one? An illustration of the link between sub-functions is depicted in the diagram above.

- **Mechanisms that fulfil sub-functions**

It is necessary to undertake a search for relevant operating principles and their combinations after the sub-functions have been defined and their relationships have been established. The first step is to create a table of sub-functions and solutions. Solutions are for any feasible method, approach, mechanism, or other mechanism that may be used to solve that particular sub-function, whereas sub-functions are for the ones that were brainstormed during the preceding steps. After all of the solutions to all of the sub-functions have been enumerated, it is necessary to discard approaches that are not practical. Following that, various combinations of these solutions are created. The decision must be made in such a way that the logically and physically conceivable associations of the sub-functions can be established, rather than arbitrarily selecting one solution from each sub-function as before.

Table 3.1 shows alternative techniques that might be used to perform the sub-functions that the author is familiar with or has read about. This implies that many alternative viable options may have been overlooked as a result of a variety of constraints - especially, personnel, time, and experience.

Table 3.1 Possible mechanisms to fulfil sub-functions for a magnetic CM gripper

| Options \ Subfunctions | 1 | 2 | 3 | 4 |
|------------------------|---------------------|-----------|-----------|-----|
| Energy | Elastic deformation | Hydraulic | Electric | ... |
| Movement | Human | Robot | Automatic | ... |
| Control | Manned | Un-manned | Hybrid | ... |

| | | | | |
|-----------------------|-----------------------------|---------------------|-----------------|-----------------------------|
| Collecting metal ball | Magnetic | Mechanical gripping | Vacuum gripping | Compliant mechanism gripper |
| Removing metal ball | Compliant mechanism removal | Mechanical removal | Vacuum removal | ... |

Given that this thesis is primarily concerned with building a magnetic CM gripper, the collection and removal of metal balls are the most important components, and hence the majority of time has been devoted to their design. As a result, energy, movement, and control are not given the same significance and cannot be offered the same amount of detail as other subfunctions in the design process. While this thesis will not supply all of the answers for those subfunctions, it will provide some of them as a component of the future concept.

Because of the nature of the compliant mechanism, the gripper will operate by utilizing elastic deformation and strain energy storage to accomplish its tasks. An additional option, such as hydraulic or electric, is still being studied; however, these options will necessitate the use of a typical mechanism or a non-compliant mechanism, which is not appropriate for the theme of this thesis. As a result, it is highly improbable that they will contribute to the answer.

The gripper's control system will be primarily designed for human interaction. As a result, the hand's operating space, as well as making that space pleasant for the hand, must be given top attention in the design. Aside from that, the employment of robots and autonomous moments is also taken into consideration in the solution. However, utilizing the hand is still the most important option, and other methods will be developed if the scope of this thesis grows in scope or if a future project requires it.



3.1.3 Gripper control option using robot or human to operator.

There is a plethora of alternatives available when it comes to selecting a mechanism for a grasping system. Some of the different mechanisms that are available on the market are depicted in Fig. 1.1. Some of the solutions, such as vacuum or pneumatic, stand out and appear to be promising for the thesis's application in this area. The employment of magnetic and compliant mechanisms, on the other hand, is required by the thesis topic; hence, these mechanisms will be emphasized as mandatory options for the idea. The magnetic and compliant mechanisms can be designed alone or in conjunction with one another. In chapter 2, section 2.3, there are numerous kinds and types of compliant mechanism gripper examples that can be used to demonstrate the notion of compliant mechanism gripping. The grasping system can be configured in a variety of ways to increase its efficiency and effectiveness.

For the method of metal ball release, one of the obvious choices is the compliant mechanism, which also happens to be the thesis's core focus, as previously stated. Many instances of compliant mechanism release may be found in Section 2.3 of Chapter 2. Some of the instances, such as the one in Fig. 2.24, are being considered for use as a solution. Another option is also being examined, but if they are picked, the complexity of the design will expand and the scope of the thesis would be exceeded, thus the likelihood of them being chosen is extremely slim.

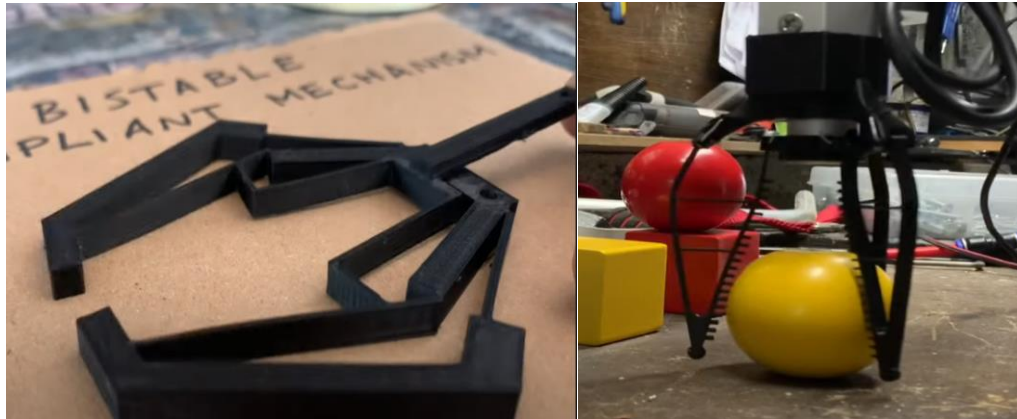


Figure 3.2 Compliant mechanism gripper (left) and Another type of compliant mechanism gripper (right) [28]

- **Combination of mechanisms - Working principle**

The next phase would be to put together a working structure based on the working principles. It is decided on a list of versions that are the most rational to construct. As previously indicated, the thesis topic is magnetic CM gripper, and the collecting and removing metal ball mechanism has magnetic and CM as the preferred candidates, as previously stated. Elastic deformation is an obvious choice for the energy of the gripper when it comes to the use of CM. In order to accommodate the thesis's scale, the design will be oriented toward human usage; as a result, the gripper's movement and control will be coordinated with the user.

The sum-ups below are written in the order: Variant number – Energy – Movement – Control – Collecting metal ball – Removing metal ball.

Variant 1 - Elastic deformation – Human – Manned – Magnetic - Compliant mechanism removal

Variant 2 - Electric – Robot – Hybrid – Magnetic - Mechanical removal

Variant 3 – Electric - Automatic - Un-manned - Compliant mechanism gripper - Compliant mechanism removal

Variant 4 – Hydraulic - Human – Hybrid - Vacuum gripping - Compliant mechanism removal

The combinations listed above are conceivable for a device concept. The first two types are straightforward, utilizing both CM and magnetic properties to their fullest extent. As a result, the evaluation will be less favorable for Variants 3 and 4, which use partially CM or magnetic technology. However, in the future, they may be able to demonstrate significant promise.

- **Evaluating principal solution variants**

Following the identification of potential variants, it is necessary to evaluate them in accordance with the criteria derived from the system requirements. First and foremost, the evaluation criteria must be specified. Second, those criteria are weighted according to how important they are to the system as a whole. Third, parameters are introduced in order to make the system's grading more clearly distinguishable. Last but not least, the versions are graded and compared to one another.

The version was graded and compared in the following table: Table 3.2. When selecting a gripper, evaluation criteria are based on both the requirements of the thesis topic as well as the requirements of the standard gripper that is used in actual situations.

CM utilize: The variations 1, 3, and 4 are all integrated with a compliant mechanism, which is a requirement for the topic of the thesis. Variant 2 does not have CM, in contrast to variant 1.

Magnetic utilize: The magnetic installation is included in the first two variants. The other varieties, on the other hand, do not have magnetic components.

Ease of operation: The four variants are not difficult to use and require only a minimal amount of training. Even if the usage of both manual and automatic at the same time in variation 4 requires more time to become acclimated to, it is still recommended.

Operation safety: In general, the four variations have demonstrated minimal harm while in use, according to the analysis. When compared to the previous two forms, the absence of magnetic made variants 3 and 4 slightly more dangerous.

Ease of production: The first variant demonstrated tremendous potential in terms of manufacturing capability. The others require more resources in order to generate.

Table 3.2 Table of evaluation

| Evaluation criteria | | | Parameters | Variant 1 | | Variant 2 | | Variant 3 | | Variant 4 | |
|---------------------|---------------------|--------|--------------------------------------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|
| No. | | Weight | | Value | Weight | Value | Weight | Value | Weight | Value | Weight |
| 1 | CM utilize | 0.2 | Integrated CM in design | 9 | 1.8 | 0 | 0 | 9 | 1.8 | 9 | 1.8 |
| 2 | Magnetic utilize | 0.2 | Integrated magnetic in design | 9 | 1.8 | 9 | 1.8 | 0 | 0 | 0 | 0 |
| 3 | Ease of operation | 0.1 | No need for skill to operate | 7 | 0.7 | 7 | 0.7 | 7 | 0.7 | 6 | 0.6 |
| 4 | Operation safety | 0.2 | Safe to use | 7 | 1.4 | 7 | 1.4 | 6 | 1.2 | 6 | 1.2 |
| 5 | Ease of production | 0.2 | Time to produce one product | 6 | 1.2 | 5 | 1 | 4 | 0.8 | 5 | 1 |
| 6 | Ease of maintainace | 0.1 | No need for assembly and lubrication | 9 | 0.9 | 4 | 0.4 | 4 | 0.4 | 4 | 0.4 |
| 0: Worst | | | | | 7.8 | | 5.3 | | 4.9 | | 5 |
| 10: Perfect | | | | | | | | | | | |

Ease of maintenance: The simpler the components, the less difficult it is to maintain them. Because of the usage of CM and magnetics, variation 1 was extremely simple to maintain. The other option makes use of mechanical or other means of gripping, and as a result, they require greater attention in terms of maintenance or lubrication.

- **Solution concept**

Essentially, a magnetic CM gripper is a device that grasps a metal ball and includes both CM and magnetic elements. It is simple to use and easy to maintain, and it is also inexpensive. The variation 1 was able to meet this requirement. As a result, the variant 1 was selected as the final solution for this thesis and will be further developed in the upcoming. The version 1 was further evolved into three further concepts, which are detailed in full depth below. Following the design of three concepts, another brief evaluation and selection process was carried out in order to arrive at the final design. The following section depicts the steps involved in developing those concepts:

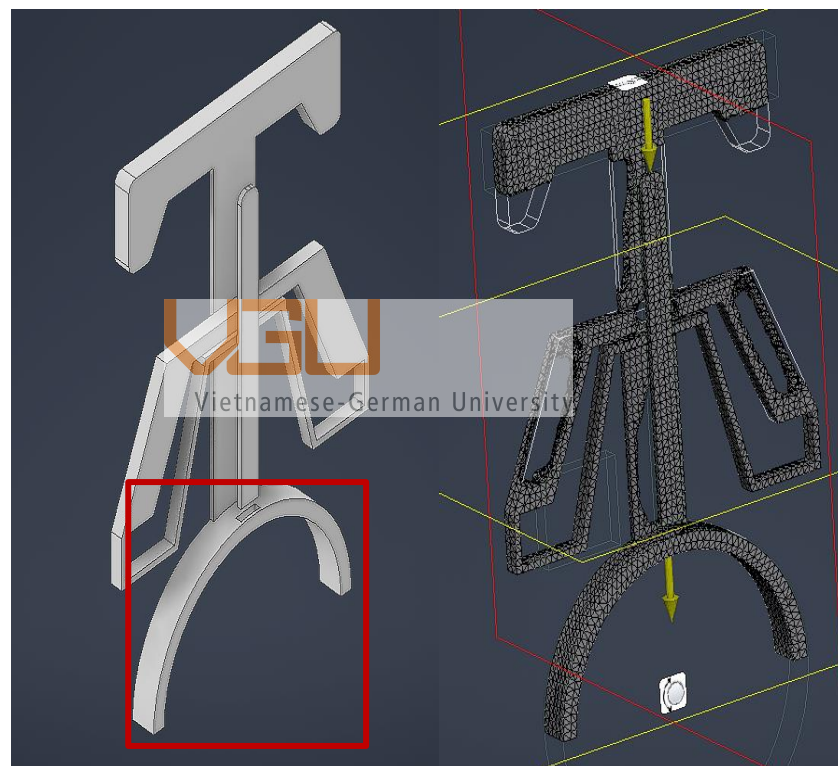


Figure 3.3: First concepts(left), optimization in Inventor software (right)

The CM gripper in Fig 2.24 (left) influenced the left idea in Fig 3.2 (a). The metal ball will be picked at the arc part of this design, which will be integrated magnet in the red rectangular shown in Fig 3.2. After then, the bar will be pressed to push the ball out of the gripper. The compliant mechanism, which is inspired by the left figure in Fig 2.24, will bounce the bar back to its original position, and the picking procedure will be repeated.

The topology optimization is performed once the original design is completed, as seen in the figure (b) in Figure 3.2. Because the design was created in Inventor, it was decided that the optimization would be done there as well. In this optimization, the metal ball's substance was chosen to be iron. Because the ball has a diameter of 5 cm, the whole weight is 0.52 kg, which is approximately 5.1 N.

The weight of the ball is represented by the bottom arrow in the right figure in Fig 3.2, and the ultimate amount of force is 10 N after adding tolerance to the optimization. The force that will be utilized to push the bar is set at 10 N, as shown by the top arrow in Fig 3.2's right figure.

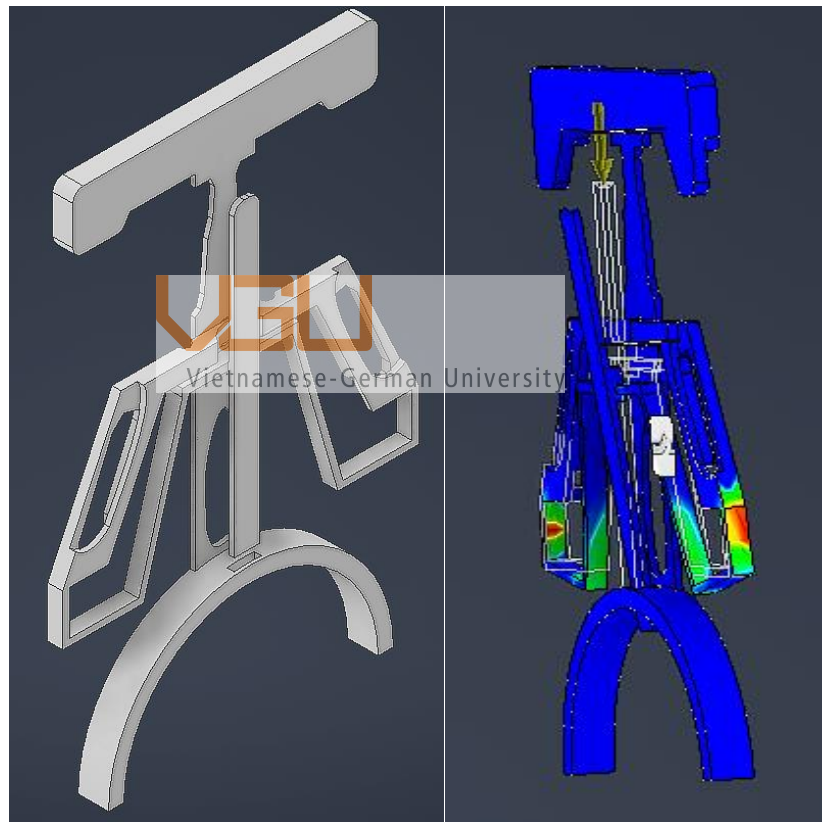


Figure 3.4 Final design after optimization (left) and stress simulation when the bar is pressed (right)

Figure 3.3 (left) depicts the optimization's ultimate outcome. In comparison to the initial weight, the new optimization has reduced the weight by approximately 22%. The stress analysis was then carried out, as illustrated in Fig 3.3 (right). Even though the result is as anticipated, the creator is not completely satisfied because the bar bends unnecessarily. This will necessitate a real-world test to confirm the design's efficacy.

Following the design of the first idea, the second is then developed. The right image in Fig 2.24 served as inspiration for the second concept. The metal ball will be selected for the bottom half of the gripper (temporarily referred to as "fingers"), as seen in Fig 3.4 by the red rectangle. The top ring of the gripper will not move throughout the picking operation in order for the gripper to work. To make the "fingers" grip or release the ball, the bottom ring will be moved up or down as demonstrated in Fig 3.5 (right).

In addition, a magnet will be attached on the tip of each "finger" to secure the metal ball when picking it up. The topological optimization was performed after the initial design was finalized, just as the first concept. The force used to pull the bottom ring this time is 20 N, while the force used to pull each of the three "fingers" is 5 N.

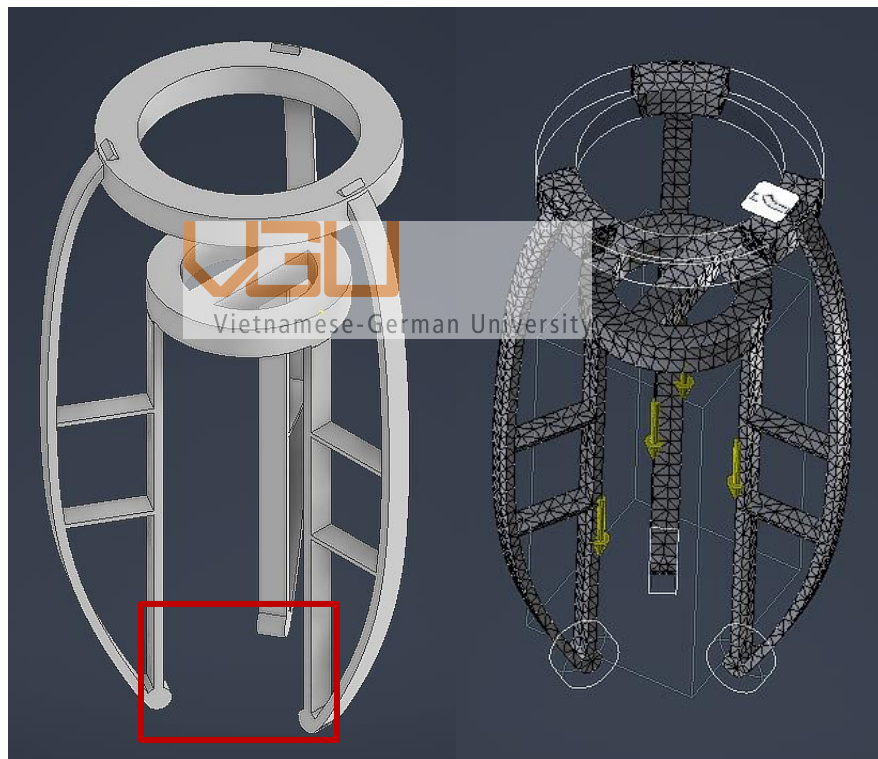


Figure 3.5 Second concept (left) and topology optimization (right)

The preservation zone used for optimization is fairly vast because the part from the bottom ring to the tip of the fingers is required for the gripper to function. As a result, the top ring of the gripper contains the majority of the optimizer. When compared to the original, the end product has a weight of less than around 23%.

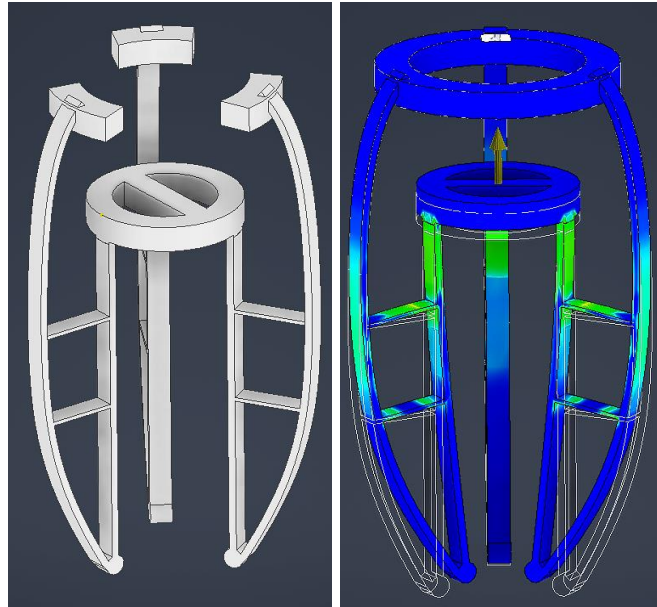


Figure 3.6 Final design after optimization (left) and the stress simulation of the gripper when grasping (right)

The third design, like the first, uses the CM in the same way as the left figure in Fig 2.24. In Fig. 3.5 (left), the magnet will be integrated into the tip of each arc component of the design, which is represented in red rectangular.

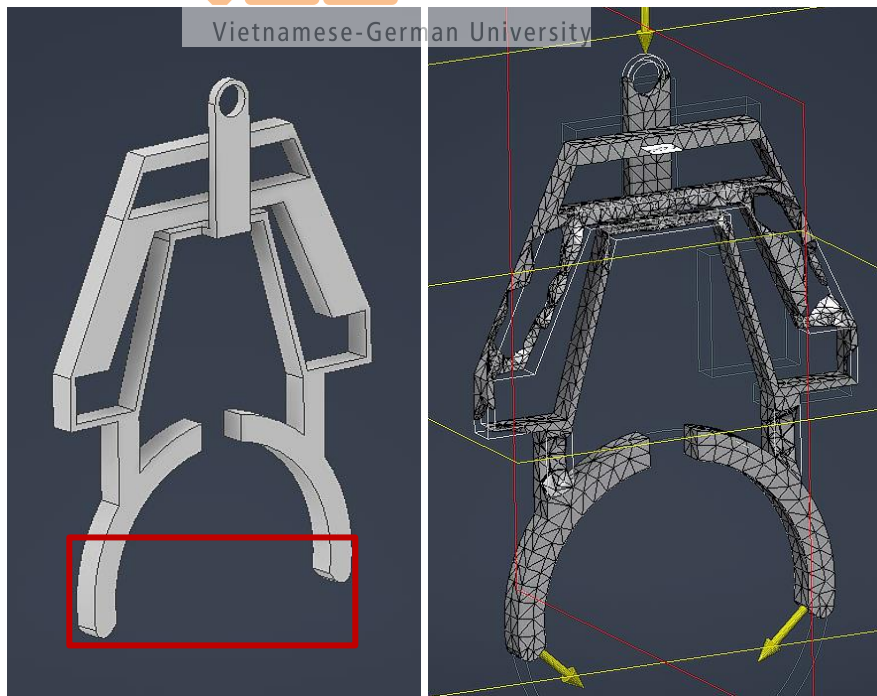


Figure 3.7 Third concept (left) and topology optimization (right)

The magnet will attract the ball to it. When the gripper releases the ball, the bar at the gripper's top is pushed down, causing the gripper to release the ball. The gripper's shape when the bar is pushed is shown in Figure 3.7 (right). The most concerning aspect of this design is that even after the ball has been released from the gripper, the magnet can remain adhere to it, making it difficult to operate. The force used for the top bar was 10 N, and the force used to pull the 2-arc component of the gripper was 5 N during the optimization process. In comparison to the original design, the optimization design has a weight of roughly 17%.

For efficient operation, the location where the hand holds the gripper will be improved if one of the concepts is selected for construction. Furthermore, the optimized design will be treated as a suggestion rather than an absolute; additional testing will be performed to establish the final design for all three concepts.

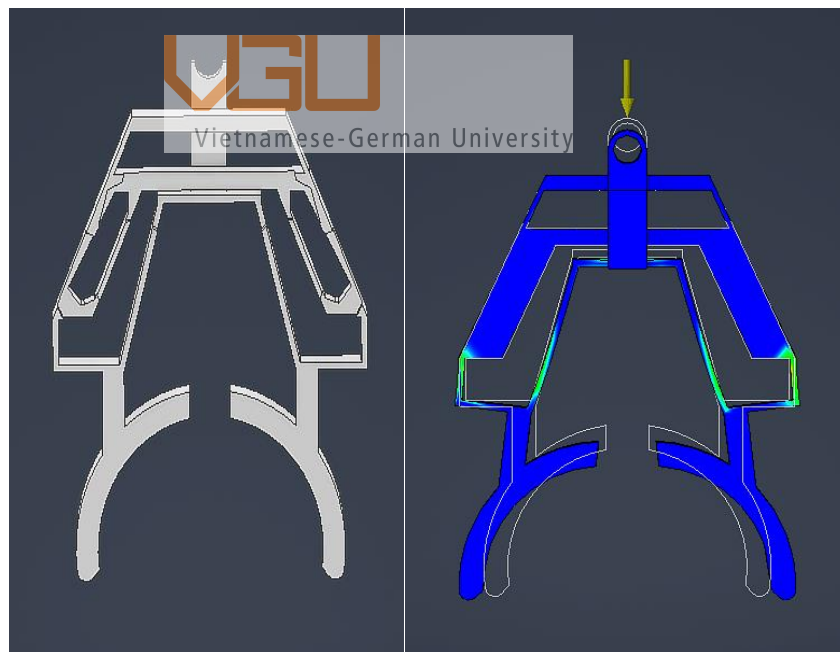


Figure 3.8 Final design after optimization and the gripper when in release position

Following the construction of three concept designs, the evaluation step is the next to be completed. The ability to fulfill the task, the simple to use, and the ease of construction are the first three criteria used to select the final concept.

The second of the three designs is by far the most complicated and difficult to manufacture of the three. The necessity for three "fingers" to operate, the fact that the second concept is larger than the other as well as the complex operation set-up make the second concept unlikely to be picked as the final design to build. As a result, the race's final clash will be a battle between the first and third concepts. They all use the same CM which is inspired on the left figure in Fig 2.24. The grabbing and releasing process is what makes them different. As previously stated, the third concept's capacity to operate constantly is a problem. On the other hand, the initial design still has a fault in the bar where the ball is released, as previously described. However, when it comes to the ability to complete a task, the first thought outperforms the second. As a result, the first concept will be chosen as the final design to be built. The third notion, on the other hand, will serve as a backup in the event that the first fails to meet the operation's requirements.



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Chapter 4 Construction of the preferred variant

As mentioned in the previous chapter, the first concept will be choice to be a final design for magnetic CM gripper.

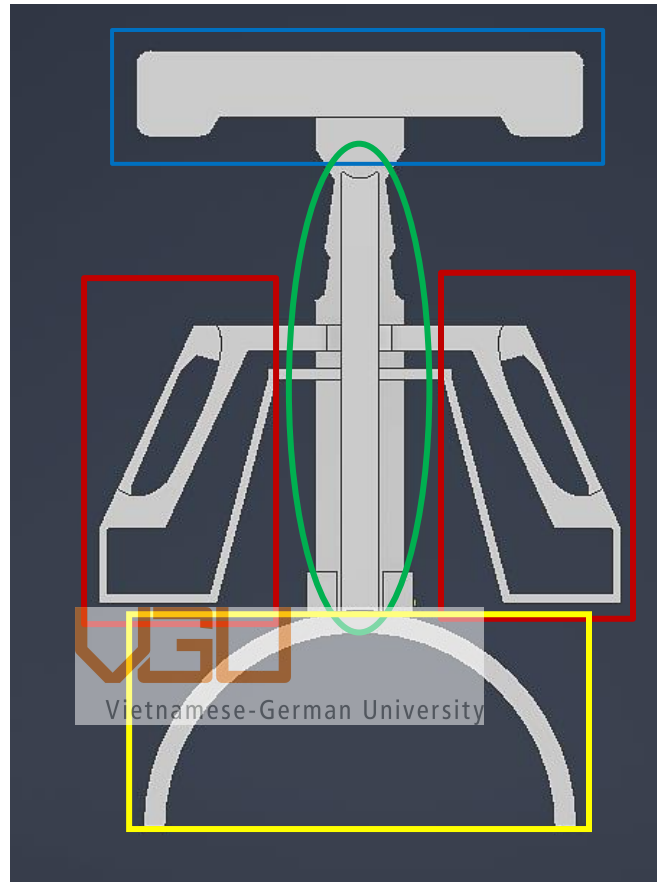


Figure 4.1 The first concept after some modification.

The initial concept is built around and based on the illustration 2.24 (left), which was discussed in Chapter 3. The gripper is composed of five major components:

- The first component is the holder, as represented by the blue rectangle in Figure 4.1. This element serves as the primary point of contact between the gripper and the operator; it is designed to allow the operator to grasp the gripper while manually operating it, especially suitable for using by hand. Fig 4.2 illustrates the dimensions of the holder in greater detail. The holder's longest side measures 56 mm in length and its shortest measures approximately 7.6 mm. The holder is 4 mm thick, which is expected to be sufficient to hold the remainder of the gripper

while also saving material. The forces acting on the holder during operation are seen in Figure 4.3. The blue arrows represent the force required to raise the gripper manually or mechanically, which is roughly 10 N, and the red arrows indicate the weight of the metal ball and the remainder of the gripper, which is also approximately 10 N.

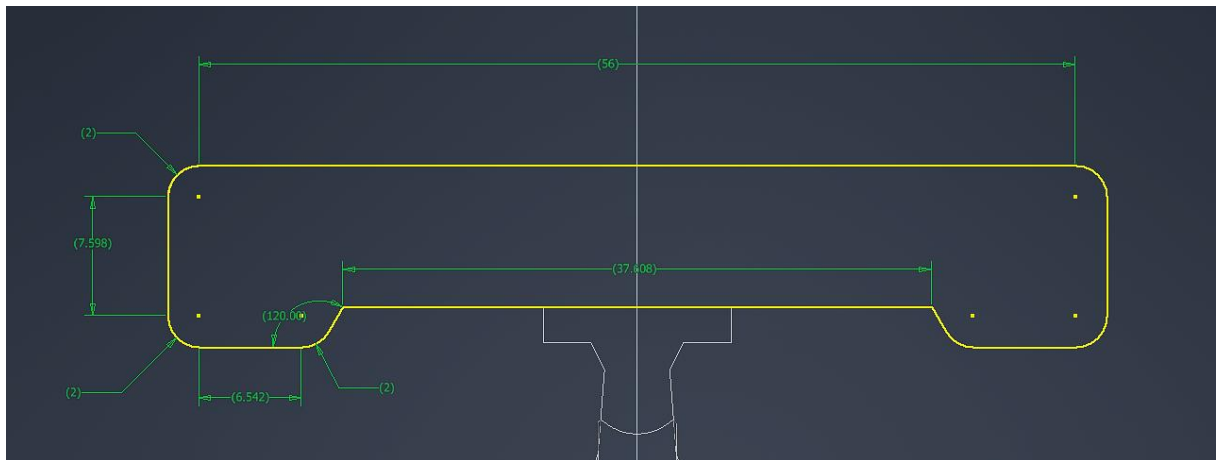


Figure 4.2 The dimension of the holder (the unit is in millimeter)

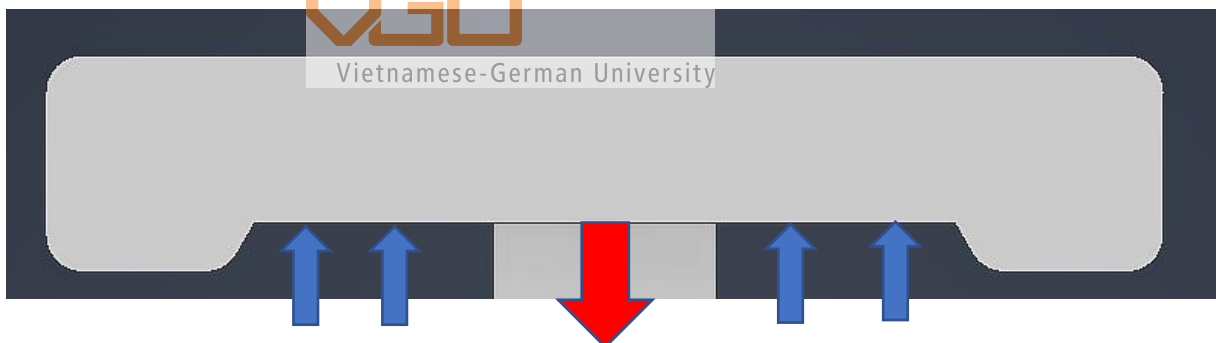


Figure 4.3 The force act on the holder

- The second component is the bar, which is shown in Figure 4.1 by the green eclipse. This section acts as the gripper's release mechanism. When the gripper secures the ball, the bar will press and push the ball down from the gripper, causing it to release. Fig 4.4 illustrates the dimensions of the bar in further detail. The bar measures 61.5 millimeters in length, 5 millimeters in width, and 1 millimeter in thickness. The curvature to the

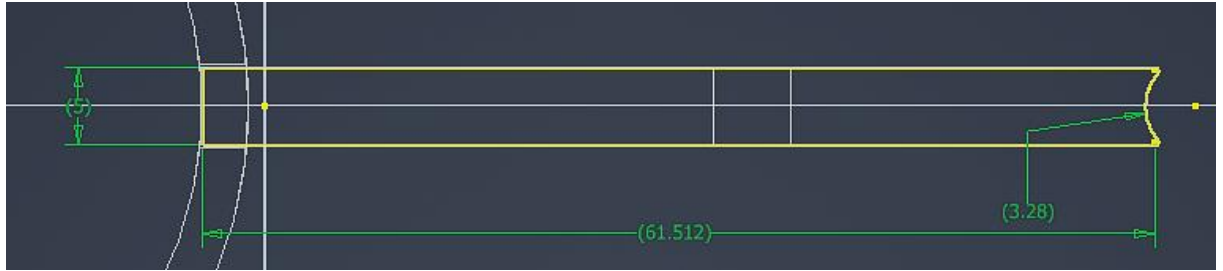


Figure 4.4 Dimension of the bar in horizontal position (the unit is in millimeter)



Figure 4.5 The force act on the bar

left of Fig 4.5 is for the tip of the finger to contact, which makes pressing the bar simpler. The blue arrow indicates the force used to press the bar, while the green arrow indicates the force used to press the bar against the metal ball to cause it to release. The green arrow indicates the attraction force exerted by the magnet on the metal ball. Thus, for the ball to be released, the blue arrow force must be greater than the green arrow force.

- The third component is the compliant mechanism, which is denoted by the red rectangles in Fig 4.1. The purpose of this element is to assist the bar in returning to its initial position after being pressed by utilizing its elastic deformation. Fig 4.6 illustrates the specific dimensions of the CM, and the thickness of the CM is 3mm, which is considered to be strong and flexible enough to operate as a good compliant mechanism.

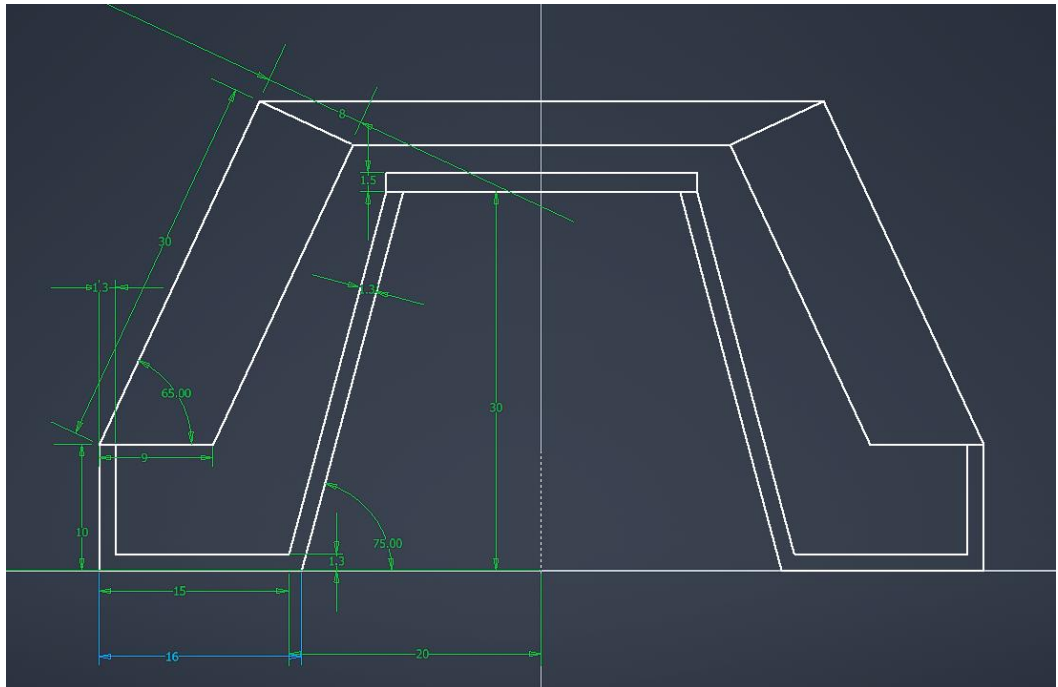


Figure 4.6 Dimension of the compliant mechanism (the unit is in millimeter)

The deformation of the compliant mechanism after the bar is pressed is seen in Fig. 4.7.

The red arrow depicts the amount of force that will be applied by the bar to the CM. In accordance with the CM's design, the bar can be pressed for a specified length in order to force a metal ball to fall off before the bar is returned to its original position. The red arrow force shown in Fig. 4.7 is approximately 5 N, which is the force used in the simulation. In addition, in Fig. 4.7, the part indicated by the blue rectangle is connected to the body and does not move, whereas the part indicated by the yellow rectangle is not connected to the body but to the bar, which has the mission to travel and has caused the bar to move up and down during the operation process. In addition, after the bar was pressed, the green to red zone in Fig 4.7 illustrates the highest stress impact zone on the CM, which corresponds to the parts that deform the most when the bar is pressed.

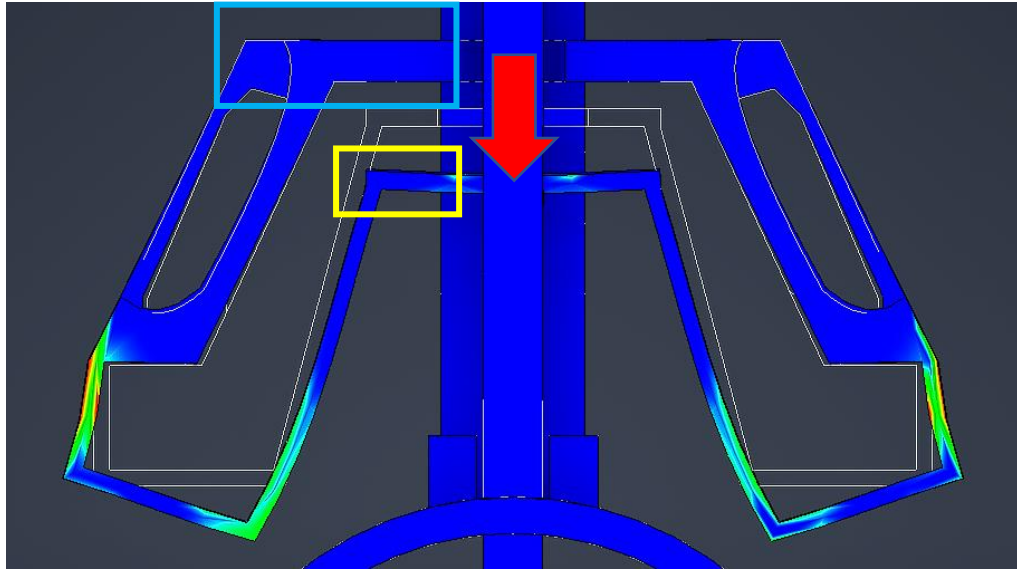


Figure 4.7 The force applies on CM and how it will shape

- Body is the fourth component, which may be thought of as the "skeleton" of the gripper as a whole and serves to connect each and every aspect of it together. Figure 4.8 shows the body's detailed dimensions in further detail (left). With a length of around 67 mm, a width of approximately 12 mm, and a thickness of 1 mm, this body is simulated and is supposed to be highly effective in maintaining the functioning state. On the body, the circle and eclipse holes are intended to reduce the amount of material used in its construction, and those holes were developed through topology optimization done on the Inventor Shape generator. Figure 4.8 (right) depicts the force that will be applied to the body as well as a simulation of how the force will affect the body's structure. A similar illustration shows the white arrow representing the force exerted by the holder on the body, while the red arrow represents the weight of the metal ball, as well as the remaining force exerted by the gripper, on the body. As illustrated in the figure, the green zone of the body, particularly the top green zone, is under the greatest amount of stress. The topology of this zone is adjusted numerous times in simulation in order to accomplish topology optimization while also ensuring that it does not break during operation. After all is said and done, the final result is depicted in Fig 4.8 (right), which, in simulation, can support the red arrow weight of 10 N.

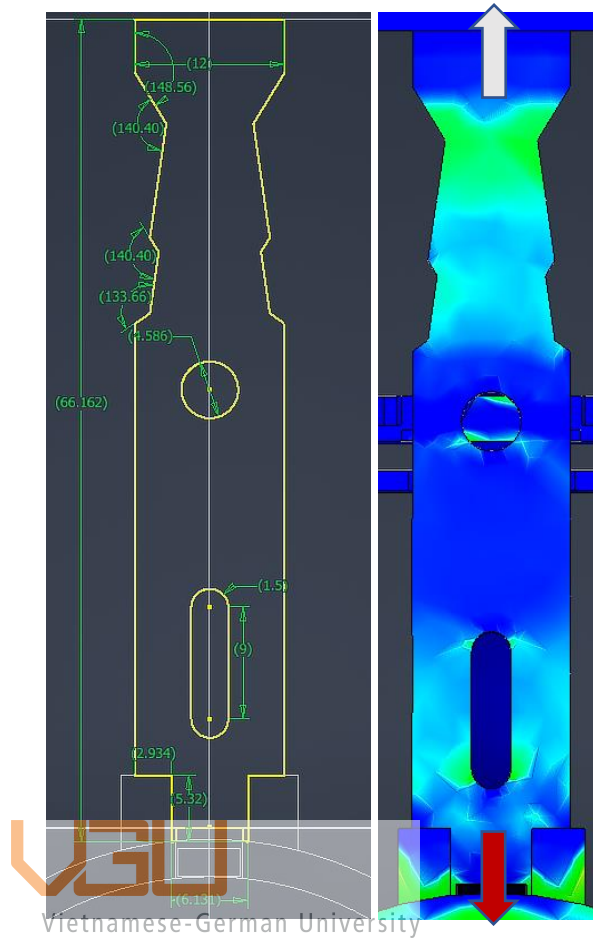


Figure 4.8 Dimension of the body (in millimeter) (left) and the force applies on the body (right)

- The final section, denoted by the yellow rectangle in Fig 4.1, is the arc component that will be utilized to pick up the metal ball. This component will have a magnet to assist the gripper in picking up and holding the ball. This portion is shaped like an arc to assist the ball in maintaining its position while being picked up as well as to facilitate the ball's release by the bar. The dimensions of the arc component are depicted in further detail in Figure 4.9. The outer arc has a radius of 29 mm, while the inner arc has a radius of 26 mm, and the thickness of the arc component is 9 mm. Despite the fact that

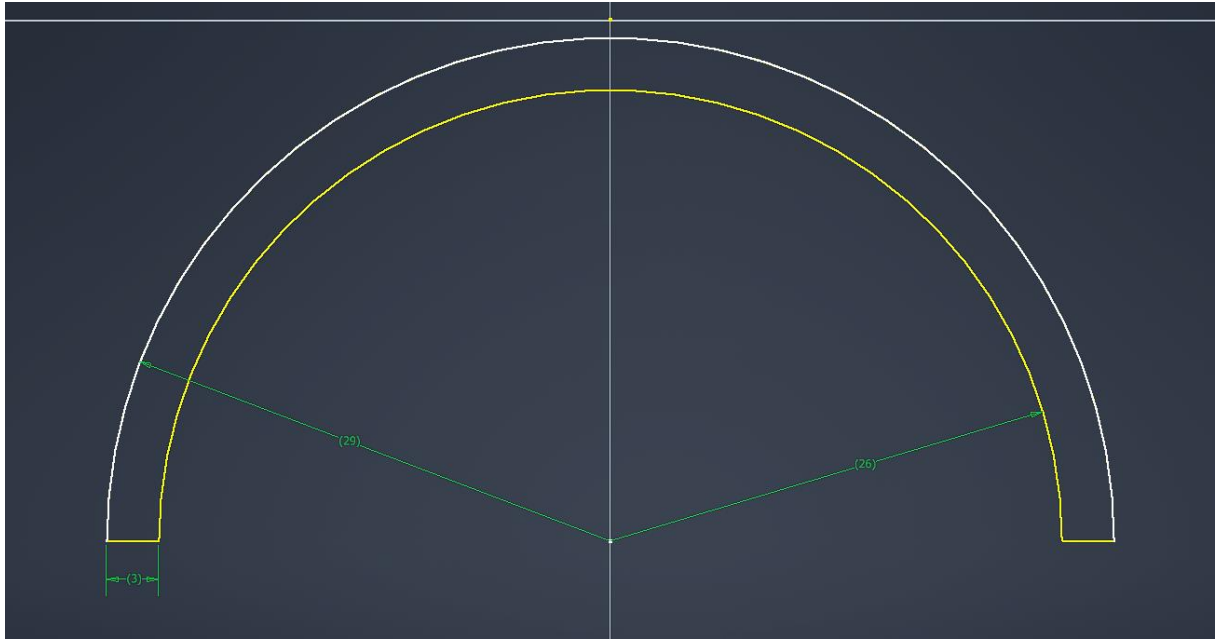


Figure 4.9 Dimension of the body (in millimeter)

the metal ball that will be used has a radius of 25 mm, the inner arc has a radius of 26 mm. This is due to the fact that the 1 mm space is required for the installation of the magnet, which has the task of attracting the metal ball in order to grab it. Figure 4.10 depicts the force acting on the component. The red arrow denotes the force exerted by the body on the arc component, which assists it in lifting up. The weight of the metal ball that impacts on the component during the pickup operation is indicated by the blue arrows.

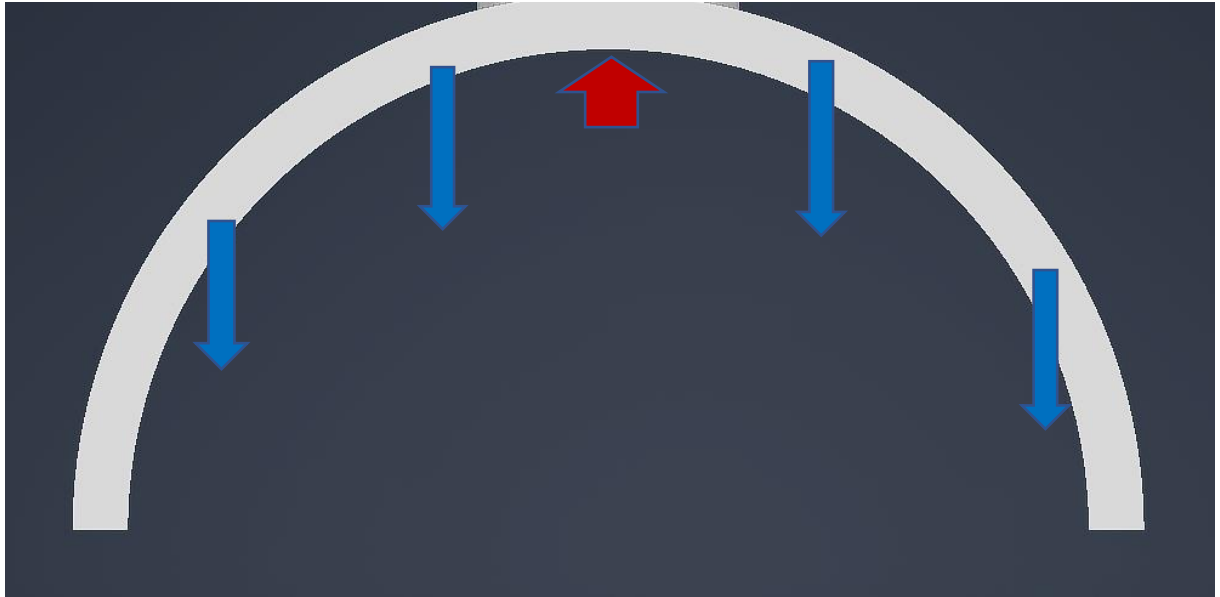


Figure 4.10 The force applies on the arc component

The concept's operating principle is as follows: initially, a metal ball is picked up at the arc portion of this design, which integrates a magnet. The bar will then be pressed to force the ball out of the gripper. The compliant mechanism returns the bar to its initial position, and the picking action is repeated.

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The next stage of the construction will be the integration of the magnet. In the market, there are two types of magnets that are considered to be chosen:



Figure 4.11 Small magnet and Magnet band

When comparing two different types of magnets in terms of gripper integration, the magnet band wins out since it is more flexible and simpler to integrate into the gripper. It may be installed concurrently with or after 3D printing.

Chapter 5 Additive manufacturing of the preferred variant

Additive manufacturing is the next stage in developing and constructing magnetic CM grippers. After completing the construction file in Autodesk Inventor, it was converted to an STL file. This file type was used by the PrusaSlicer software to export files for usage with the 3D printer. Original Prusa i3 MK3 is the name of the 3D printer that is used for 3D printing.

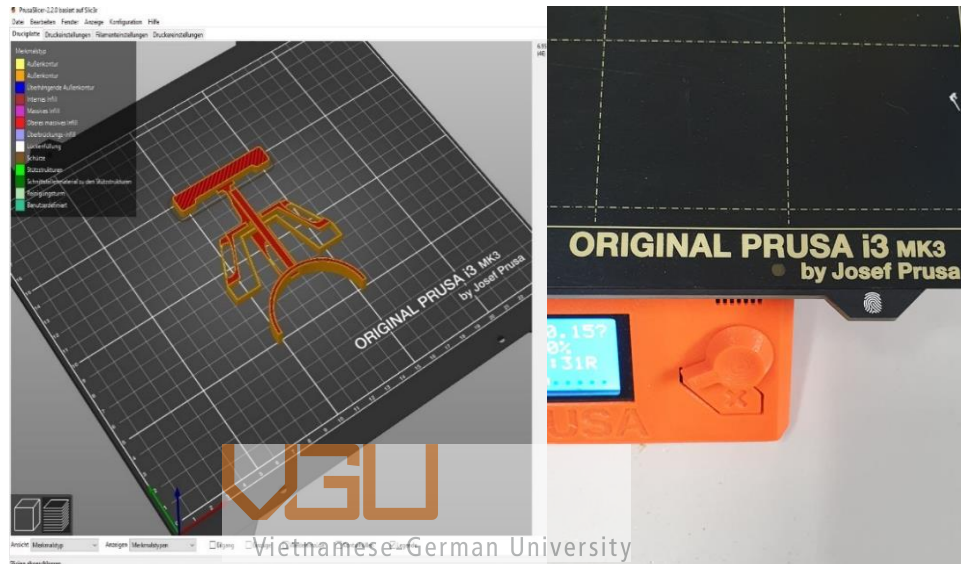


Figure 5.1 Concept 1 in PrusaSlicer software (left) and name of the 3D printer (right)

The building STL file was imported into PrusaSlicer as illustrated in Figure 5.1 (left). As with the PrusaSlicer program, several adjustments were made, such as the support arrangement. Following that, it was saved to an SD card, which was then inserted into a 3D printer, which read the file and began printing. The printing process is predicted to take approximately 1 hour and 30 minutes, which is considered fast in the world of 3D printing.

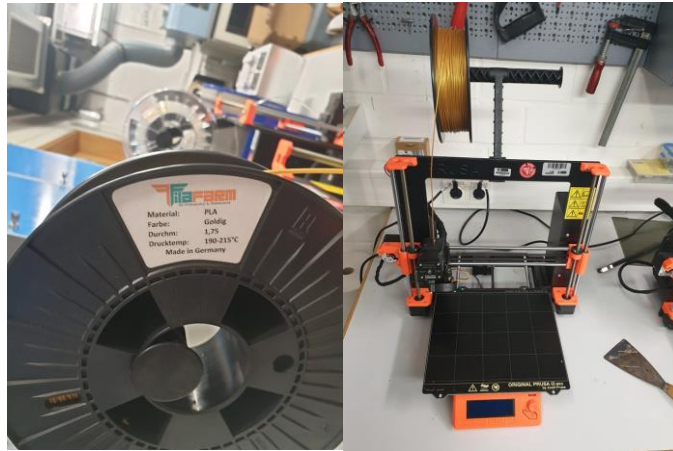


Figure 5.2 PLA plastic material (left) and the whole body of Original Prusa i3 MK3 (right)

After receiving the SD card containing the building file from PrusaSlicer, the Original Prusa i3 MK3 began the 3D printing process. The material utilized for printing in the left figure of Fig 5.2 is PLA plastic, which can also be used in simulations for the design model. The process specifications for 3D printing are provided in Figure 5.3 (left). Several of the numbers, such as 93/215° and 29/65°, refer to the nozzle and platform temperatures, respectively.

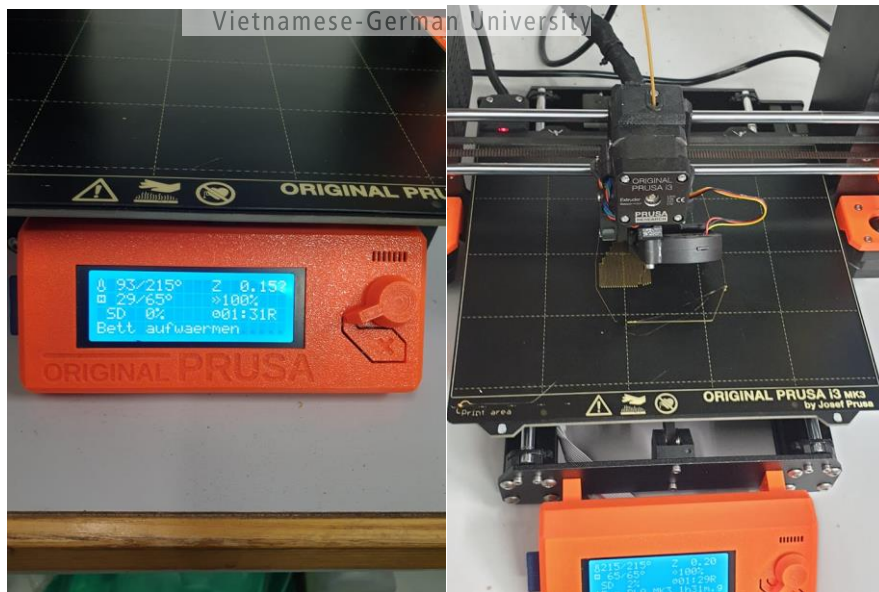


Figure 5.3 Specifications of 3D printing process (left) and the beginning of the printing (right)

After starting on the 3D printer, the printer begins calibrating the platform's surface to ensure it is even and balanced. A pressure sensor is used to determine the platform's

equilibrium at each position. The 3D printer next begins printing the gripper's support structure, which fills



Figure 5.4 Process of 3D printing, support removing and final product

the gap between each gripper component, followed by the gripper itself. The printer heats the nozzle and platform in order to facilitate the fusion of the plastic and extrude it layer by layer. Finally, as illustrated in figure 5.4, the support is removed by using tool and protective gear, and the final product is completed.

However, the first product is not up to par and was rendered impracticable. Due to an underestimation of the actual measurement during design, the final result appeared as indicated in the left figure in Fig 5.5; it was too small to use by hand in the author's situation. The holder is too small to hold, making operation more difficult. The bar has the same issue as the holder; the dimension is too narrow to push, and the curvature hurts the finger instead of supporting it. Additionally, the little tip of the bar that makes contact with the metal ball during release made it extremely difficult to release the ball from the gripper. The CM lever arm is fairly short, making it slightly more difficult to press and necessitating the use of greater force. The arc component is not thick enough to integrate the magnet band. The explanation for the diminutive size of the design might be explained by the designer's dimension illusion. While creating on a monitor, the product appears to be enormous on the screen, giving the designer an illusion of the product's true dimensions. Thus, in future projects, it is recommended to use real-world objects and measurements to approximate the true dimensions.

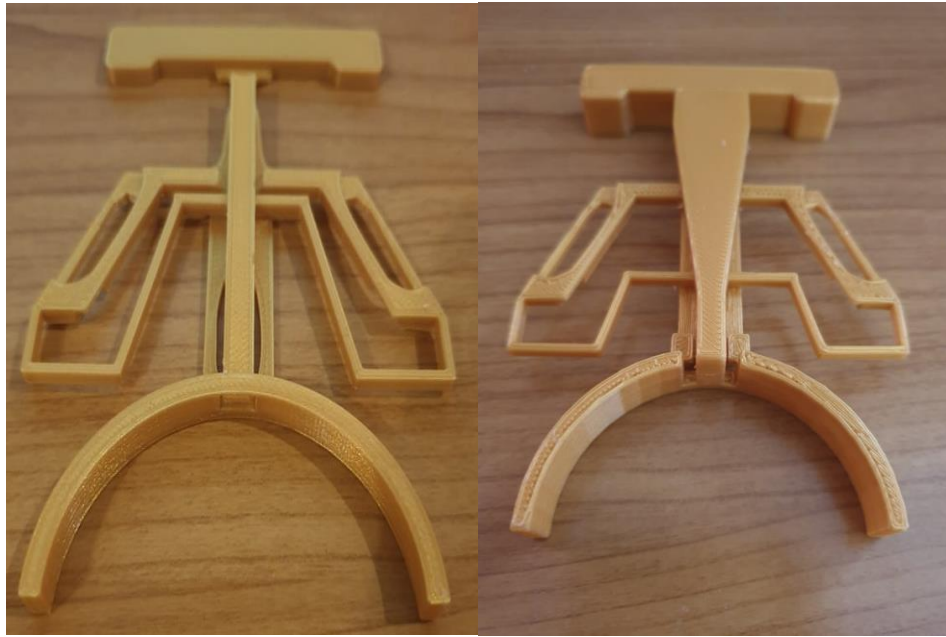


Figure 5.5 The first product (left) and the updated version (right)

Due of the fault in the original product, an immediate revision of the gripper was made. In general, the new version is thicker in three areas: the holder, the bar, and the arc component. The holder may now be held securely. The bar is simpler to press, and the tip that makes contact with the ball is wider, resulting in a bigger contact point. Finally, the arc component is thicker to accommodate the magnetic band integration. Additionally, the body is slightly thicker to support the weight of the metal ball and the remainder of the gripper. The CM lever arm was moved down to make it wider, requiring less force to press the bar. The enhanced version is depicted in Figure 5.5. (right).

Integrated Magnet and finishing product.

Finally, the gripper is merged with the magnet band. The magnet is placed in the arc component of the gripper where the contact between the gripper and metal ball happens using the glue contained in the magnet band. The finished product is shown in the Fig 5.6.



Figure 5.6 Gripper after magnet installation



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Chapter 6 Experiments testing

Following completion of construction, testing is the following step. The test will be conducted in a manner consistent with the thesis stated in Chapter 3.

Three phases comprise the test: picking, moving, and releasing. The first stage is the selection procedure. The gripper attracts the metal ball using the magnetic field. After fitting the ball into the gripper's arc component, the operator raises the entire assembly together. The ball is held and lifted securely, with no trace of wiggle or fall without the use of CM to release. The figure 6.1 illustrates the gripper's operation from initial contact with the ball on the ground to lifting it into the air.



Figure 6.1 The process of metal ball is being picked up

Following the completion of the picking process, the moving process was put to the test. Figure 6.2 depicts the gripper being moved from one position to another while still holding the metal ball in its grasp. While moving around, the body shows no signs of deterioration. The body is sturdy and can withstand the weight of the gripper itself as well as the metal ball without showing any signs of deformation or cracking. The holder is thick enough to be held and operated without causing any significant difficulties. The

metal ball in the moving process is steady and is shown to be held firmly in place so that it does not fall off accidentally.

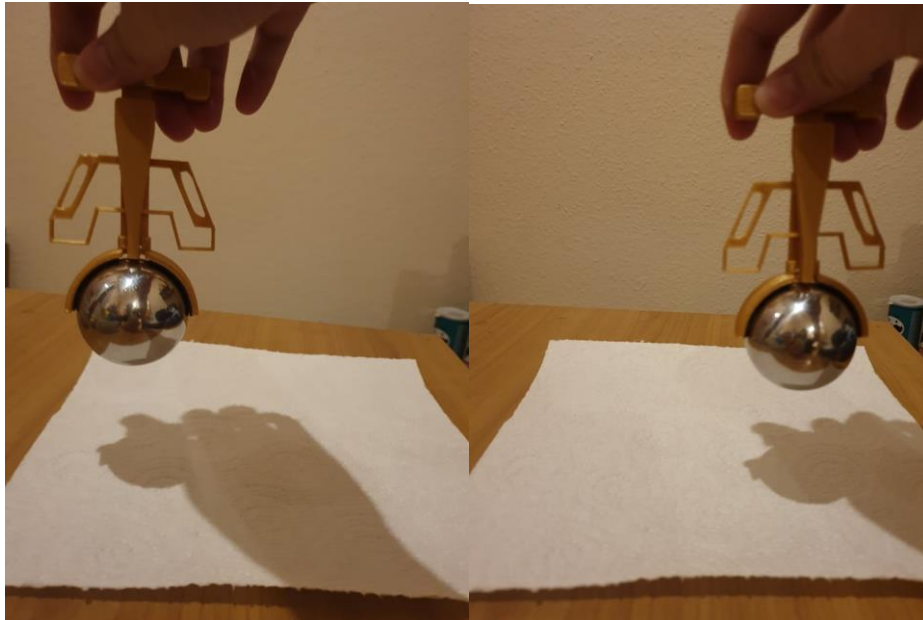


Figure 6.2 Moving the gripper with the metal ball from one point to the other

Last but not least, the gripper's release mechanism was put through its paces. The compliant mechanism plays an important function in the release mechanism in this step. As soon as when press the bar to push the metal ball off, the CM assists in keeping the bar together and returns the bar to its original position. Figure 6.3 depicts the metal ball dropping off as a result of pressing the bar. The CM portion deformed as predicted and performed as a compliant mechanism, which was exactly what was intended when it was designed.



Figure 6.3 Releasing the metal ball

The first part of this examination is the ability to grasp. When the author conducted his research, there was only a 1 mm thick magnet band with a $40\text{g}/\text{cm}^2$ strength available on the market. When the area of contact between the gripper and the metal ball is 8.66 cm^2 , the magnet can attract approximately 346 g of weight. 501g is the weight of the solid iron metal ball with a diameter of 5 cm. As a result, employing a different sort of metal ball is a viable option. In this situation, the hollow iron ball, which has a diameter of 5 cm, is hollow on the inside, and has a thickness of around 3 mm, is used to reduce the weight to only 167 g, which is a significant reduction. This metal ball is then put to use in this experiment as shown in figures 6.1, 6.2 and 6.3.

The second factor is the gripper's strength when loaded with the metal ball's weight. In addition to testing the gripper body's strength, a solution was devised to solve the problem. For this solution, a 1 kg object was hung from the gripper. The test demonstrates that the gripper is rigid, capable of holding the object securely, and free of cracks or breaks in the gripper's body.

The third part of the test is the mechanism of release, which must be compliant. In this test, the compliant mechanism operates as planned. The compliant mechanism returns the bar used to release the ball to its initial position. Without trouble, the bar can be pressed

numerous times. However, the thin nature of the compliant mechanism causes fatigue when pressed too hard, reducing the gripper's durability. Consider the amount of force applied when using. Fig 6.1 illustrates how the CM are broken by applying excessive force.



Figure 6.4 The CM broken when pressing too hard
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Additionally, some addition testing is required to perform comfortably. While the gripper is simple to operate, the bar could be thicker to accommodate operators with large thumbs.

Evaluation occurs following the result of testing.

The results of the test were in fact positive. In this case, the gripper was functioning well. Aside from that, the gripper almost completely meets all of the requirements listed in Chapter 3. The operation was completed successfully, starting with the grabbing, picking up, moving, and releasing of the metal ball.

However, several aspects of the gripper can be enhanced to make them more effective and safer. For instance, increasing the contact area of the arc component by designing it as a half sphere that covers half of the metal ball. This creates space for additional magnets and increases the force required to lift the metal ball.

Another shortcoming of this gripper is the magnet installation. While the adhesive in the magnet secures it to the gripper, the connection is not stable and may fall off while picking up a heavy object. Installing the magnet alongside the 3D printer is another option, albeit it is more complicated. Creating a containment within the arc component for the magnet is a more viable alternative. A simpler option, such as utilizing extra glue such as superglue liquid to strengthen the connection between the arc component and the magnet band, is also possible; however, this requires the addition of a further assembly step. Additionally, the use of a small magnet instead of a magnet band has the potential to improve the gripping ability of the gripper.

The bar and holder are ideal for usage by the operator in a variety of situations. But they can be formed in a variety of ways to make the process easier and more pleasurable.



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Chapter 7 Summary and outlook

Developing and additive manufacturing a magnetic compliant mechanism gripping system adds another grasping method to the manufacturing environment and daily life application. This study conducts background research on the subject. The procedure begins with an introduction to the compliant mechanism, an explanation of why it is a superior option than the traditional one, and an introduction to various products currently in development or available on the market. Providing a basic overview of magnetic and additive manufacturing. The magnetic CM gripper was then designed using a systematic approach to determine the best solution for the project. Following that, additive manufacturing was used to complete the product, which was then integrated with a magnet. Finally, a test of the final gripper product was conducted, as well as an evaluation for this product and future enhancements.

The thesis acknowledges that this work is far from comprehensive and faultless; in fact, it is far from it. The deeper one delves into a subject; the newer knowledge is discovered. The attempt was made to provide an honest opinion. Numerous things must be stated that the author does not properly understand, and hence makes only a passing reference to them or provides the best interpretations.

As with Chapter 2, the introduction of compliant mechanism was included; however, due to the subject's unfamiliarity and first-time engagement, many parts of compliant mechanism were omitted or not discussed in detail.

Chapter 3 is the design method that was taught in university, and this is the second time in the author's experience that this systematic approach was used for the design process. By outlining the work's goal via a requirement list, then abstracting to identify the fundamental problem and building a function structure, the clear path forward was identified. Finding a solution to a sub-function is not an easy process, even more so when dealing with gripping and releasing systems that involve CM and magnetic. While the procedure is arduous, it is necessary to have a holistic view of the design process and additional viewpoint information from other sources.

Chapters 4,5,6 detail the manufacture and examination of the final gripper product. Numerous errors occurred and were immediately corrected. However, inexperience with design and additive manufacturing was inevitable. Additionally, the influence of the Covid pandemic has a negative effect on the process of additive manufacturing, hindering workflow. Nonetheless, the final product created and met a most of the required list. The evaluation was discussed, as well as what may be improved.

If the work is to be developed, other concepts could be considered. Using alternative means such as vacuum instead of magnetic is possible and has the same potential for operational efficiency. Concepts 2 and 3 in Chapter 3 can also be developed further and may have greater operational promise if designed as an alternative method for grabbing and releasing metal balls.

Additional study and testing are required to perfect the concept. If the project is extended further, a more advanced version of the gripper will be required. While the finite element method is included, it is limited to topology optimization; instead, designing the gripper's shape and dimensions from the ground up using FEM is preferable but is limited by the author's competence and time. Testing in a real-world work environment, such as a factory or outdoors, is necessary to determine the gripper's suitability for real-world use.

To summarize, the development of a magnetic CM gripper is important and will have a significant influence. This bachelor thesis is only the beginning of the project. There is a lot of room for development in the quest to reintroduce pickup in a new approach.

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