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DESIGN OF A BIO-INSPIRED SOFT ROBOT FOR BREAK BULK MANIPULATION IN TRANSPORT ENGINEERING

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ABSTRACT
This research explores the possibility of upscaling bio-inspired designed soft robots in transport engineering application with the focus on grabbing and manipulating break bulk such as windmill blades or rolls of steel. Upscaling current state soft robotic systems includes challenges regarding the structural strength of the robot. Also certain actuation methods could be affected by upscaling the actuators as well. The design of the proposed bio-inspired soft robot is determined by analysing the functions and constraints of the design as well as evaluating different types of gripping solutions based on the different types of shapes of the object. In this research the claw gripping is selected to be applied in break bulk manipulation. This gripping solution could potentially be combined with the vacuum gripping solution to be able to manipulate more types of objects. The three fingers of the claw are designed based on the trunk of an elephant as the trunk of an elephant can lift heavy loads and can therefore be seen as a good starting point to design a high load capacity gripper.

Keywords: bio-inspired design, soft robotics, gripping mechanism, scaling, break bulk, smart materials, transport engineering

1. INTRODUCTION

The living organisms that can be seen today are derived from organisms that lived here 3.5 billion years ago. The structure and mechanics of these living organisms were evolved and optimized based on the idea of adapting to survive. Bio-inspired designed systems draw inspiration from these organisms in order to solve a specific mechanical or structural problem. In contrast to conventional systems, bio-inspired systems often use soft materials and soft actuators in order to perform flexible movements or to perform specific tasks similar to the way living organisms move and perform [1]. This method of designing is currently widely being used to design small size soft robots in medical and product handling applications [2,3]. The bio-inspired design could provide solutions to complex problems such as maneuvering within the human body or the handling of different types of products in automated warehouses. Most applications of bio-inspired soft robots focus on a small size scale and just a few research on a larger size scale [4,5]. So applying bio-inspired design in larger size scale applications such as transport engineering could provide an interesting view. This research will explore the possibility of upscaling bio-inspired designed soft robots in transport engineering application with the focus on grabbing and manipulating break bulk.

One characteristic of soft robotics is the use of soft materials which makes these robots operate more flexible and also more safely around humans [3]. Because of the use of soft materials, these types of robots can move in different degrees of freedom making these robots able to move around objects while rigid robots are constrained by its rigid structure. The drawbacks of these robots are that these robots often perform slower, less precisely and that soft robots often can not lift heavy loads compared to the rigid robots that are currently being used in many industrial applications. Using bio-inspired design as a design methodology for designing a large size soft robot could provide interesting insights on the challenges and solutions to this problem.

Break bulk is the type of cargo in transport engineering applications that should be transported individually from one place to another because of its large size, irregular shape or heavy mass. Examples of break bulk are for instance project cargo such as turbine blades for a windmill or rolls of steel for manufacturing vehicles. Objects that fit in containers or dry and liquid bulk have their own specific and well established transport systems. Improvements could be made to systems that manipulate these types of objects but systems for break bulk manipulation could really benefit by the technology and quick development of soft robotics. These types of objects should be handled with care and because of the complexity of the process there are often many people involved in this process of handling these objects [6]. These people not only operate the transport systems such as the crane or trucks but they also work close to the grab and object itself. Attaching the break bulk object to the transport system is currently being done manually using hooks, cables or ropes which can result in a dangerous situation. Also the type and amount of equipment necessary to transport break bulk depends on the shape, mass and size of the break bulk. Some objects such as large windmill components require multiple cranes whereas objects such as bags can be picked up by forklifts or other smaller transport systems. In large terminals such as the Port of Rotterdam, the amount of break bulk being handled is significantly smaller compared to the other types of goods such as dry bulk and containers [7]. However because of the complex process of transporting break bulk and the increase of the amount of break bulk objects that are being transported, it is interesting to focus on these types of objects especially with the flexible characteristics of soft robotics.

The next section of this research explores the limitations of size scaling mechanical soft robotic systems. Using this information, the mechanics of the bio-inspired designed soft robot can be researched. In this section of the research, the focus will be on the design process and the type of gripping mechanics of the bio-inspired soft robot. The last section of this research presents the initial design as well as the conclusion of this research.

2. SIZE SCALING

Soft robotics is currently being used in many applications related to small size object manipulation such as medical grippers and pick and place robots in automated warehouses. If a mechanical system is scaled up in a large size scale for transport engineering applications for instance, certain parameters are not scaled linearly with size which can result in structural failure of the upscaled design. The challenges and limitations of upscaling soft robotics will be addressed in this section.

Upscaling the dimensions of a robot can be done by upscaling all dimensions equally with the length L as the scaling variable. If the length of the object is scaled with a factor L, the area scales with a factor of L^2 and the volume of this object scales with a factor of L^3. Figure 1 shows the robotic gripper with a claw design. The fingers of this claw gripper can be scaled up according to the length of the finger starting with a robotic finger of length L = 10 cm. Next to this normal sized robotic finger, an upscaled finger of factor 1.5 where L = 15 cm and another upscaled finger of factor 2 and 4 of L = 20 cm and L = 40 cm respectively can be found. In this figure the geometry in the other directions are scaled equally with the length.

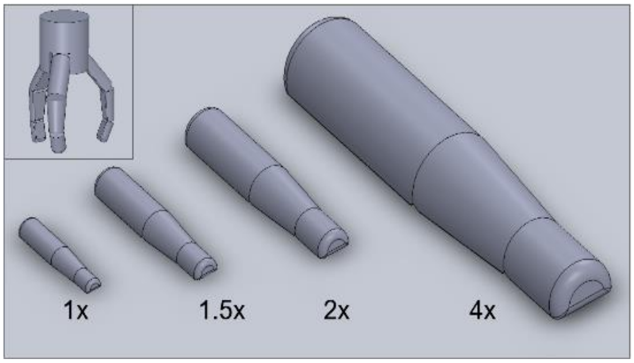

FIGURE 1: UNIFORM SCALING OF ROBOTIC FINGER OF ORIGINAL SIZE WITH LENGTH OF 15 CM AND UPSCALED TILL TIMES 4 THE ORIGINAL SIZE

The length of the fingers are scaled according to the scaling factor where the geometry in the other directions of the design scales equally with this scaling factor. However, other properties do not necessarily scale up with the same scaling factor. The graph in figure 2 presents the mass of the uniform upscaled design from an upscaled factor of 1 till 10 times the length of the finger. Mass is directly related to volume by the density of the object and if the density remains constant during upscaling, the mass will scale up with a factor of L^3 as well.

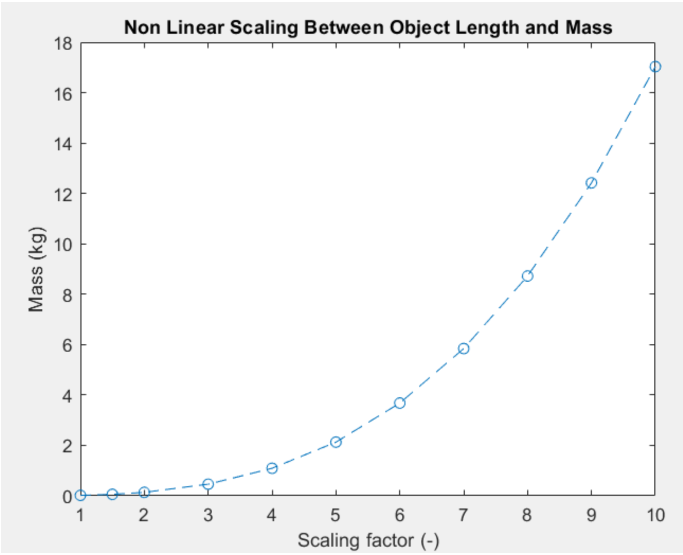

FIGURE 2: NONLINEAR SCALING OF MASS WITH THE SCALING FACTOR OF 1 TILL 10 OF THE LENGTH OF THE ROBOTIC FINGER

Upscaling a soft robotic design does have its structural consequences. When looking at the mass per unit area where mass scales with a factor of L^3 and the area scales with L^2, the mass per unit area increases linearly with the length scale. Smaller sized robots don't require much energy to operate as the weight is significantly less and the movements the robot should be able to perform are also smaller. Larger robots are significantly heavier and therefore upscaling soft robots results in larger deformation which will eventually lead to structural failure due to its own mass.

Another parameter that does not scale equally with length is for instance the heat transfer. For certain actuation methods in soft robotics, heat transfer plays a crucial role. An example of such an actuation method is shape memory alloy (SMA) where the alloy material can be deform easily and reshape back to its original shape by increasing the temperature of the material. The scaling effect of heat transfer can be looked at using area per unit volume. Because the area scales with a factor L^2 and volume scales with L^3 the upscaled designed robot will have a decrease in area per unit volume and therefore a decrease in heat transfer. Using SMA for an upscaled designed soft robot would be a great challenge as the time it takes for the soft robot to change shape by SMA increases significantly. An overview of parameters scaling factors are summarized in table 1.

Table 1: SCALING FACTOR FOR EACH PARAMETER

Parameters	**Scaling Factor**
Length (L)	L
Area (A)	L^2
Volume (V)	L^3
Mass (M)	L^3
Load bearing capacity for buckling	L^2
Friction	L^2
Heat transfer	L^{-1}
Mass/Area (M/A)	L
Area/Volume (A/V)	L^{-1}

Other scaling strategies for upscaling the soft robotic design could be scaling in one direction while the scaling factor in other directions remains the same. The length of the finger of the gripper could be extended while the diameter of this finger is fixed making the finger longer. This scaling strategy can be found in figure 3. Another scaling strategy involves the number of fingers used as seen in the same figure. Using one finger could involve a different gripping strategy compared to gripping using two or more fingers. Attaching more fingers to the gripper will result in an increase in weight of the gripper and a more complex control system but it could also increase its load capacity significantly.

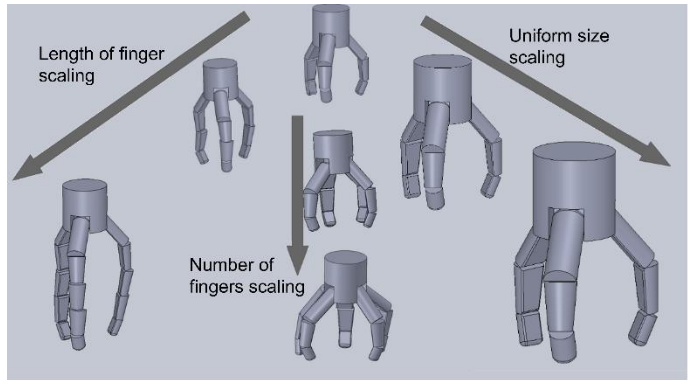

FIGURE 3: DIFFERENT SCALING STRATEGIES: SCALING LENGTH OF FINGER, NUMBER OF FINGERS AND UNIFORM SIZE SCALING

Another view to look at the design of soft robotic grippers for break bulk manipulation is by using bio-inspired design and to look at how nature is able to lift heavy and large objects. The next section explores the design methodology and bio-inspired design for a soft robot able to manipulate break bulk.

3. BIO-INSPIRED DESIGN

3.1 Functions and constraints

Bio-inspired designed soft robotic grippers are currently being used in many applications on a small size scale ranging from medical to product handling applications. For the gripper design proposed in this research, first the constraints and functions of the design have been explored as seen in figure 4. For the functions of the design, the soft robotic gripper should be able to move, grab the object, transport the object from one place to another and to release the object. The constraints of the proposed design are that it should be safe to work with around humans, the design should meet the design standards that are being applied in the field of transport engineering and it should consist of durable and sustainable materials.

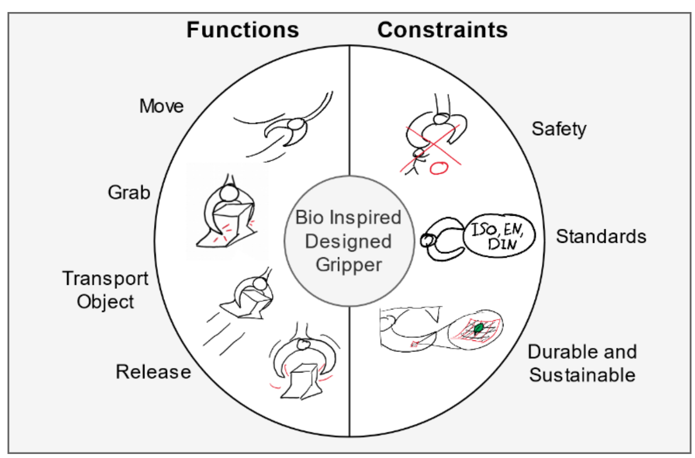

Figure 4: DIAGRAM OF THE FUNCTIONS AND CONSTRAINTS OF THE BIO-INSPIRED DESIGNED GRIPPER

3.2 Types of gripping mechanisms

From the constraints and functions, different gripping solutions have been explored and evaluated based on the gripping mechanisms and the shape of the object as seen in table 2. Many gripping designs have been evaluated based on current rigid systems and different animals such as the octopus, gecko and other animals [3,8].

Table 2: EVALUATION OF DIFFERENT GRIPPING MECHANISMS ON THE DIFFERENT SHAPE OF THE OBJECT

		Gripping Solutions					
		Friction gripping	Claw gripping	Curving	Vacuum	Jamming	Adhesion
Object Shape	Convex	+	++	+	+	+	0
	Non Convex	-	+	+	0	+	-
	Flat	+	- -	- -	++	-	+
	Deformable (bags)	-	+	-	- -	- -	- -

Friction gripping is a method of gripping an object where the gripping mechanism is holding the object on its one and opposite side. The friction between the gripping mechanism and the object alone should be sufficient to hold the object. The contact point of friction gripping is small compared to for instance the enclosed claw gripping mechanism where the gripping mechanism grasps around the object. The performance of friction gripping is therefore less compared to the enclosed gripping such as claw gripping. This method is commonly used to manipulate small sized and sensitive objects such as micro chips. Manipulating these objects requires high accuracy, precision and control to make sure these objects do not get damaged. Also the mass is very low making this gripping metc

With the enclosed claw gripper, the object is also held on by the gripping mechanisms but in this case the gripping mechanism encloses the object from different sides providing a more stable grip because of the increase of contact surface as well as the increase of normal force on the gripping mechanism. Manipulating flat objects however is more challenging compared to friction gripping because of the more complex control of claw gripping and the fact that it is more difficult to grasp around a flat object.

Curving gripping around the object is another gripping mechanism that grasps around and encloses the object from multiple sides but instead of multiple fingers from the claw gripping method, the curving mechanism uses a one-finger design. This method can be found in many bio-inspired designed grippers to provide a gripper that is able to perform flexible movements within small spaces such as tubes.

Vacuum gripping uses pressure difference in order to hold or transport the object. This pressure difference can be caused by increasing the volume of a deformable space close to the gripper or by using a driver to continuously provide a pressure difference like a vacuum machine. This method works especially great for flat and smooth objects but for any other objects with a rough surface or non flat shape, using this method is challenging.

Jamming gripping uses a soft bag filled with granular material. This bag deforms when it's pressed against the object and by increasing the stiffness of the bag by pressure difference or other techniques, the bag is able to deform around the object and provide the required gripping force to be able to hold on to the object. This design could potentially be upscaled because of the use of granular material as a stiffness component of the gripper. Because of the use of the stiffening of the gripping mechanism, this method is challenging to manipulate deformable objects such as bags or flat objects such as steel plates.

Adhesion is a gripping technique that includes molecular cohesion by Van der Waals forces or electrostatic forces to manipulate an object. These techniques can mainly be found in very small or light object manipulations as these techniques require external forces that are only significant on a small size scale. Electro magnetism is in the context of this research also included in adhesion. This technique can be found on a larger size scale but the application is limited as the objects that need to be manipulated should require magnetic properties. Adhesion as a gripping method can be useful for manipulating flat surfaces, or in the case of electro magnetisms: made out of a material that is affected by a magnetic field.

3.3 Object shapes

The different shapes of objects in table 2 are based on typical break bulk objects in transport engineering. The convex shaped object can for instance be seen in steel rolls or pipes that are too large to transport in a normal container. Another type of break bulk are project cargo such as mechanical components for bridges or wind turbine blades. These objects come in different shapes or non convex shapes and these are the objects that require specific work. Flat objects are objects that can be found in the steel industry as well. Very large and thick steel plates for projects or support are picked up using hooks on cables on a crane. The last type of shapes common in break bulk are deformable objects. These are for instance bags to transport certain types of dry bulk material or food. Because these objects are deformable, gripping these types of objects using a machine could be challenging.

As seen from table 2 there is not a specific gripping design that could be used to manipulate all the different shapes of objects. A multi purpose gripper that combines different gripping mechanisms could cover all different sizes and shapes of an object without too many functional and structural compromises. But this will increase the complexity of the design. For the proposed design in this research, the multi finger claw with fingers that could wrap around the object will be designed. Including vacuum gripping mechanisms could be optional to cover flat objects as well.

3.4 Elephant's trunk inspired gripper

Soft robotics on a large size scale are very limited but have for break bulk manipulation a great future prospective. To understand the size limit of soft robotics, research has been done in how large animals are able to manipulate large objects. For a heavy load operation, an animal that is interesting to look at is the elephant. The elephant itself weighs around 10.4 tonnes while the weight of the trunk is around 140 kg. Although the trunk of an elephant is boneless, it is able to lift objects as heavy as 300 kg. This makes the trunk of an elephant a great starting point for the design of the soft gripper. The trunk of an elephant consists of up to 40 000 different muscles while the entire human body has only around 650 muscles in comparison. This makes the trunk of the elephant very flexible and functional for interaction and manipulating objects as seen in figure 5.

Figure 5: THE MANY FUNCTIONS AND POSSIBLE POSITIONS OF THE TRUNK OF THE ELEPHANT

There are few designs already that have been created based on the trunk of the elephant. Shown in figure 6 is the Bionic Handling Assistant made by Festo [9] which is one of the designs that is inspired by the trunk of an elephant. This design uses pneumatic actuation in different bellow shaped parts of the robotic arm in order to bend in different directions. Attached to this arm is a gripper based on the fin of a fish that could mimic the sensitive grip at the end of the elephant's trunk. Using this gripper and arm this robot is able to grab and manipulate different types of small sized objects. The load capacity of this robot is however still limited because of the use of soft materials in combination with compressible fluid actuation. Also in contrast to the trunk of elephants, this robotic arm does not use its bending arm as a gripping mechanism to grasp around the object but only the fin gripper at the end of the arm.

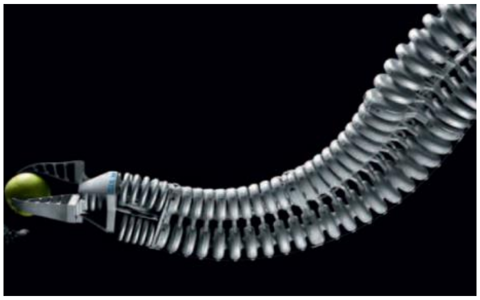

Figure 6: BIONIC HANDLING ASSISTANT FROM FESTO THAT USES THE ELEPHANT TRUNK INSPIRATION FOR THE ROBOTIC ARM [9]

One design that does use the bending structure to grasp around the object like the trunk of the elephant is the helical soft gripper shown in figure 7 [10]. This small soft robotic gripper uses variable stiffness structure (VSS) in order to increase the stiffness of the design to improve its structural strength. Using VSS with hydraulic actuation this gripper can lift up to 220 times its own mass making this design a gripper with one of the highest lift-mass ratios. This design is however very small compared to the other elephant inspired designed robots and because of the complex design involving many small components, this design would be very difficult to scale it up.

Figure 7: THE HELICAL SOFT GRIPPER WITH HYDRAULIC ACTUATION AND VARIABLE STIFFNESS STRUCTURE (VSS) [10]

More robot designs shown in figure 8 and 9 are inspired by the trunk of an elephant but are not made of soft materials and thus do not fit the soft robotics criteria. The first design shown in figure 8 is the under actuated continuum robot where the actuation takes place by a single motor [11]. Using a single electrical driver will rotate rigid links within the robot arm resulting in bending of the robotic arm. Also because of the single driver, the arm is only able to bend in one direction.

Figure 8: UNDER-ACTUATED CONTINUUM ROBOT USES RIGID LINKS AND ONE DRIVER AT THE BASE TO SIMULATE THE TRUNK OF AN ELEPHANT [11]

The elephant trunk manipulator shown in figure 9 is tendon actuated [12]. This design uses tendons and springs that could be pulled in order to move different parts of the arm. Using this method the robotic arm is able to bend in different directions. Just like the under actuated continuum robot this robot has a high load capacity because of the use of rigid structure in contrast to the first two examples of the soft robotic gripper in figure 6 and 7.

Figure 9: ELEPHANT TRUNK MANIPULATOR USES RIGID LINKS AND TENDON DRIVEN ACTUATORS TO SIMULATE THE TRUNK OF AN ELEPHANT [12]

For the initial design the soft robot should be able to grasp around the object in order to lift the object. While the robotic grippers that are being developed mostly focus on the flexible movement from one position to another. The reason for this is mainly the complex control strategy that is involved. For the initial design, other gripping solutions could potentially be integrated as wel in addition to the curving around the object gripping method.

4. INITIAL DESIGN

The proposed design is inspired by the trunk of an elephant to provide the base needed to obtain the required load capacity that is involved in break bulk manipulation. The design also includes multiple fingers that are able to move in different degrees of freedom to be compatible for different shapes of objects. Figure 10 shows the initial design of the bio-inspired soft robotic gripper. This gripper includes a skin based on the soft and sturdy material similar to the skin of an elephant. The filling of the robotic arm is made out of light and soft silicon material to provide the shape of the robotic gripper as well as providing the high deformation of the design necessary to perform flexible movements. The internal structure of the design also includes segment plates made out of electroactive polymer (EAP) that could contract the arm to improve the grip of the arm. The actuation is done by using tendon or cable driven actuators that will also act as a stiff internal and skeleton like structure that could provide the necessary axial strength of the gripper.

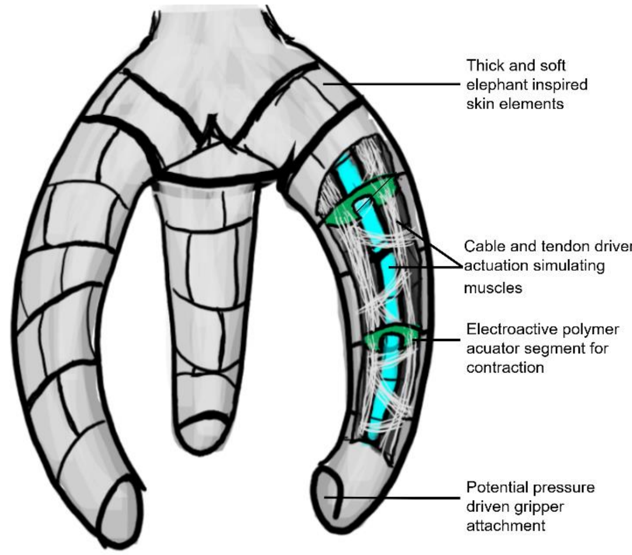

Figure 10: THE INITIAL DESIGN INCLUDING THREE GRIPPER FINGERS INSPIRED BY THE TRUNK OF AN ELEPHANT. THIS DESIGN USES SOFT SILICON MATERIAL AS FILLING AND SHAPING OF THE DESIGN. TENDONS AND ELECTROACTIVE POLYMER WILL ACTUATE THE BIO INSPIRED DESIGN.

The surface of the bio-inspired soft robot can be designed as a sturdy soft material similar to the skin of the elephant. Surface application with a softer elastomer can increase the friction between the robot and object. Certain novel actuation methods involving smart materials for soft robotics such as electroactive polymers (EAP), shape memory alloy (SMA) and shape memory polymer (SMP) as well as the more conventional actuators using vacuum, cable, tendon-driven and servo-electric actuation were explored and evaluated based on scalability and application [2,13,14,15]. For the proposed design, tendon or cable driven actuation is selected as an actuation method to mimic the functions of many muscles inside the trunk of an elephant. This actuation method can be combined with smart material such as EAP as segment plates that are able to contract the arm to increase the grip of the gripper. Including other smart material based actuators such as SMA or SMP that are able to provide a more precise control and support for the heavy load manipulation. The design of the endpoint of the gripper can potentially be attached with another gripping mechanism such as pneumatic suction cup to make this bio-inspired soft robotic gripper able to lift other types of objects such as flat sheets or plates made out of steel.

5. CONCLUSION

This research provides the bio-inspired design of the soft robotic gripper for break bulk manipulation based on the trunk of an elephant. Upscaling the current state of soft robotics in the field of medical and object handling application provides certain challenges especially in upscaling different actuation methods. Certain solutions provided by nature can be taken to solve these problems. Several gripping mechanics have been evaluated depending on the typical object shapes of break bulk resulting in the design selection of a claw gripper. Combining this with a vacuum gripper could make the gripper more compatible with other objects with irregular shapes such as flat sheets or plates of steel. To design a soft robot with the required performance of the current state break bulk transport systems, the proposed design uses actuation methods involving smart materials such as EAP, SMA or SMP in combination with conventional actuation methods such as tendon or cable driven actuators. Certain design decisions still need to be selected, evaluated and designed in more detail such as internal structure design and the actuation method. This detailed design could then be modeled and simulated in order to measure its performance. Improvements can be recommended to increase the gripping force of the gripper by including bio-inspired designed material and surface texture as a contact surface between the gripper and the object. Creating a stiff structure within the soft robot that will act as a skeleton for the soft robot could also increase the structural strength of the soft robot and therefore also the load capacity of this hybrid robot. This way a robot could be designed with the soft characteristics of soft robotics while having the benefit of fast and precise performance of rigid robots.

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