

# Flexirigid, a novel two phase flexible gripper

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**Abstract**—This paper introduces a novel grasping mechanism that combines caging and force closure approaches in order to grasp an object. The main advantage of the gripper is its adaptability to various object shapes and sizes with low DOF. The two DOF gripper takes advantage of two tendon driven trunks. Inspired from the continuum manipulator concept, the trunks do not include discrete joints and rather an elastomer plays the role of the joints. The tendon driven trunks in the first phase of grasping act as rigid links and in the second phase act as flexible mechanisms. Two prototype of the gripper are developed, tested and evaluated. The under-actuated prototypes showed a very good adaptability to different object shapes and sizes.

## I. INTRODUCTION

Force closure and form closure are among the methods applied in grasping. Form closure in mechanism theory is referred to partial or complete immobilization of an object by  $n$  contact points, if the contact is self sufficient without reference to applied forces. However in spite of some theoretical and computational studies on form closure grasping (see for instance [1], [2]) no record of a form closure gripper for robotics and industrial applications was found. The main reason is that in form closure, the gripper should adapt to the form of the object and in most applications gripper should grasp a wide variety of objects with different forms and sizes. However it is not possible to change the form of the gripper to adapt to all different shapes and sizes except with a high DOF complicated system. Therefore form closure is mostly used in design of jigs and fixtures for industrial applications, where the shape and size of the workpiece is always fix.

Caging is also discussed in the literature for grasping applications. In 1990, Kuperberg formulated the caging problem as:

*“Let  $P$  be a polygon in the plane, and let  $C$  be a set of  $k$  points which lies in the complement of the interior of  $P$ . The points capture  $P$  if  $P$  cannot be moved arbitrarily far from its original position without at least one point of  $C$  penetrating the interior of  $P$ . Design an algorithm for finding a set of capturing points for  $P$ ”*[3].

Since then some research was performed to address this problem for 2D and 3D cases. Even though that there are several theoretical studies about caging grasps [4], [5], to the best of the authors’ knowledge, no practical usage of caging in grasping was presented. A cage synthesis algorithm and survey of recent results in caging can be found in Vahedi and Van der Stappen [5]. Rimon and Blake [6] viewed caging as

an intermediate step to immobilizing an object and computed caging sets that would lead to a pre-specified immobilization grasp. They suggested a practical definition of caging [6]: *“we wish to surround an object  $B$  by a multi fingered hand such that  $B$  has some freedom to move, but still cannot escape the “cage” formed by the fingers”*. This definition clarifies the difference between caging and form closure. In caging there are some freedom to move, but not to escape. Considering caging as an intermediate step grasping can be executed in two successive phases. First: Rapid and relatively low precision movement of the arm until reaching the vicinity of the object and then slow and high accuracy movement until the gripper performs the actual grasp. *“Pre-opening the fingers into a caging formation would allow the robot to place the fingers in the largest possible area around the object, while still allowing it to perform the grasping phase with little or no direct visual information”*[6].

This paper introduces a novel gripper, and to the best of the authors’ knowledge, the first gripper, which uses caging as an intermediate step to immobilize an object. Design of the Flexirigid involves some other novelties, e.g. the low DOF trunk mechanism with adjustable flexibility and a magnetic locking mechanism. The proposed gripper is a 2 phase gripper which in the first step cages an object in 2D and in the second phase immobilize it using force closure. Another advantage of the gripper is its flexibility to adapt to different shapes. In the first phase the gripper is rigid until it surrounds the object, but in the second phase it becomes flexible to adapt itself to the object shape.

According to P. Gorce et. al. [7], cylindrical workpieces have been identified as predominant in manufacturing industries followed by those with prismatic shapes. Most of the grippers used in industry (around 98% in 1994 [7]) had two fingers. Even though the Flexirigid gripper is designed mainly for cylindrical objects, it has the flexibility to grasp other shapes. Adaptability to different shapes and sizes is an important advantage for a gripper. In this paper, caging will refer to 2D caging. As an object is usually laid on a horizontal surface and due to the gravity, the object can not move on or against the gravity direction. Therefore, the proposed gripper cages the object in a plane in the first phase (2D phase) and in the second phase it immobilizes it in all directions by force closure.

## II. FELXIRIGID GRIPPER

### A. Inspiration

The idea of a belt pushing gripping mechanisms was firstly introduced in [8] as a concept to be used in pole climbing robots (Figure 1). It was inspired by humans encircling their

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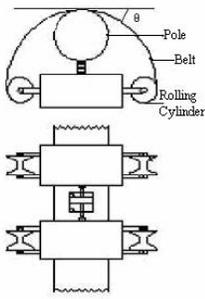


Fig. 1. The belt pushing climbing mechanism firstly introduced in [8].

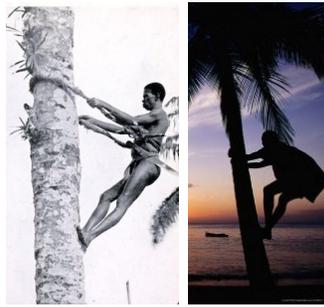


Fig. 2. Farmers encircle their hands around the tree and use a support belt in order to climb trees.

hands around the tree or using a belt to climb palm or coconut trees in order to pick fruits (Figure 2). The concept initiated in the context of designing pole climbing robots for 3D human made structures. Due to existence of T-junctions grippers designed for such robots can not make a close form which blocks passage from T-junctions [9], [10], [11], [12]. In this context, this concept has some important advantages over other grasping mechanisms. It can deal with a wide range of structure sizes and shapes which is still a problem in pole climbing robots. The other advantage is its relatively low weight for very large industrial structures and pipelines. These advantages are well discussed in a comparison study in [13].

However, the mechanism proposed in [8] (Figure 1), has a main disadvantage of not being able to pass T-junctions in industrial pipelines due to its closed structure. The current proposed design addresses this issue, making this gripper appropriate not only for pipeline inspection application, but also as a general purpose gripper.

### B. Conceptual Design

Figure 3 shows the gripper's model. It consists of two trunks, each of them containing several small links (teeth) that are fixed to an elastomer belt. Each tooth has a through hole, through which a steel wire tendon is passed. The wire rotates around a wire pulley and the rubber belt rotates around a belt pulley. One servo motor is allocated for driving the wire pulleys and a more powerful servo motor is assigned to the belt pulleys. As there exist two trunks, two wire pulleys and two belt pulleys are applied. But since the motion is symmetric, timing belts are used (not shown in the model) to drive both pulleys with the same motor.

### C. Working Principle

As partially demonstrated in figure 4, the working principle of the Flexirigid gripper consists of the following stages.

**Stage 1- 2D Caging (Surrounding):** a. The tendons of the trunks are pulled until the endpoint of the trunks approach each other. Yet due to the flexibility of the belt, endpoints can not be exactly matched. Therefore a magnetic locking mechanism with a latching system is applied at endpoints of the trunk. b. When the trunks approximate each other, magnetic locking mechanism connects the endpoints and

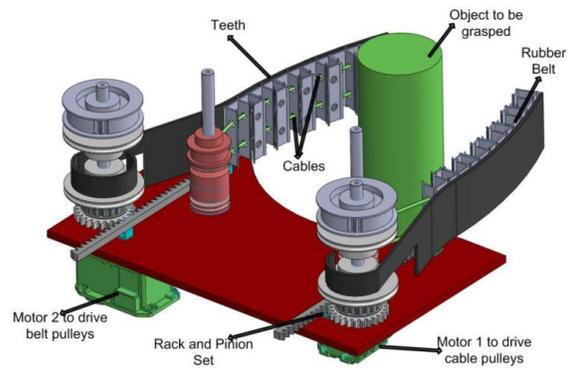


Fig. 3. Model of the Flexirigid gripper.

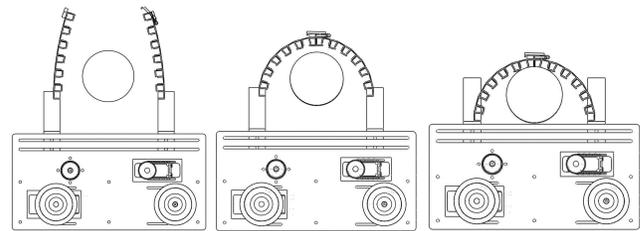


Fig. 4. The working principle of the Flexirigid gripper.

automatically locks the mechanism. c. In this stage the object is surrounded by the flexible belt. Since the wires are pulled, at the end of this stage the gripper trunks are in a rigid status.

**Stage 2- Transition stage and flexibility adjustment:** The teeth of the gripper are rigid modules which are connected to each other by an elastomer (figure 3). The elastomer plays the role of the joint between the teeth. Retraction of the tendons adjusts the distance between teeth. When this distance is less than the normal distance between the teeth, the trunk is on the rigid status. After the trunks are locked, tendons are released for a certain length. Higher released length allows for more joint flexibility, as the length of the tendon between the teeth limits the maximum motion allowance between each couple of teeth. In the transition stage, by allowing a controlled amount of the flexibility, a better adaptability to different object shapes and sizes is possible i.e. more contact points might be established.

**Stage 3- Force Closure:** In this stage the bigger motor drives the belt pulleys, so that the object is squeezed between the gripper body and the trunks (force closure).

**Stage 4-Releasing the object:** The latching mechanism of the magnetic lock is released by a memory alloy actuator. Due to the pulling forces on both sides of the elastomer, the belts unlock and the object releases.

### D. Trunks

The tendon driven trunks are composed of several teeth connected together through an elastomer belt and is driven by a tendon. Even though the working principle of each trunk has similarities with the previously developed trunks, e.g. in [14], [15], there are fundamental differences. A tendon driven trunk mechanism may consist of several independent

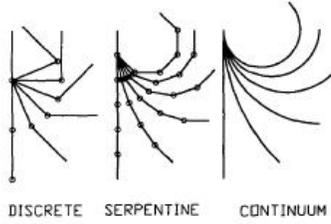


Fig. 5. Discrete, continuum and serpentine robots [17]

active DOF, e.g. 8 DOF in [14], [15], or 7 DOF in [16]. With the higher number of DOF a better maneuverability and adaptation to different shapes would be possible. But at the same time the weight, the size, the complexity and the cost of the system increases. In the current design our purpose is to minimize the number of active DOF. Furthermore the already developed multi-DOF trunk mechanisms are not effectively being used in robotics and industrial applications due to their complexity.

Moreover as can be seen in figure 5, serpentine and continuum trunks differ in their configuration; that is serpentine robots use short rigid links and discrete joints but continuum robots do not contain rigid links and identifiable rotational joints. Instead the structures bend continuously along their length via elastic deformation[17]. The trunks of Flexirigid gripper pose short links(teeth), but do not include discrete joints and the flexible belt plays the role of the joint. This leads to a simpler, lighter and a smaller trunk. But in the same time the pose of the trunk can not be controlled precisely. To clarify this we should describe the kinematics of the trunk.

### E. Kinematics of the trunks

Figure 6 shows 3 different status of the trunk mechanism. In all cases  $m$ , length of the flexible part and  $l$  the length of the rigid part, are constant, but the length of the tendon between the rigid links ( $n$ ) varies. In the first case, the tendons are not retracted, and thus the trunk is in an undetermined shape. Retracting the tendon until satisfying the condition  $n = m$  leads to a straight trunk. Further retraction leads to the condition  $n < m$ . The kinematics of the mechanism is a function of the kinematics of each module as shown in figure 6. In the first stage of the gripper operation, the end of the trunks are free, and thus the belt is not stretched i.e. the length of the belt ( $m$ ) is fix. But there are two unknown variables  $\theta$  and the curvature of the belt. Consequently the geometrical analysis of the system in order to calculate  $\theta$  leads to an indeterminate equation. The real value of  $\theta$  can not be retrieved until the curvature of the belt is known. While the tendons are pulled the curvature of the belt is a function of the applied force by the tendon as well as size and material properties of the elastomer. But if  $m$  is very small, the curvature of the belt can be estimated as linear and in this case the kinematics of the module can be extracted as:  $\phi + \omega = \arccos\left(\frac{\rho^2 + \eta^2 - m_1^2}{2\rho\eta}\right) - \arccos\left(\frac{\rho^2 + \eta^2 - m_2^2}{2\rho\eta}\right)$  Where  $\phi + \omega$  is the angle between the rigid links.

The alternative design of the trunk with a very small  $m$  is

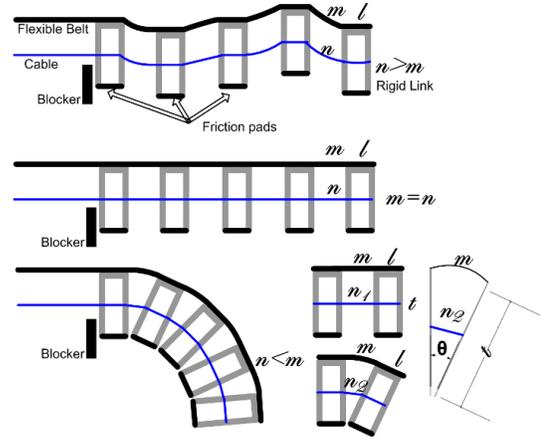


Fig. 6. Schematics and kinematics of the trunk mechanism

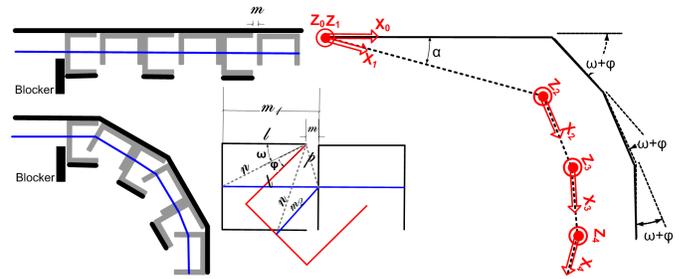


Fig. 7. Left: An alternative trunk design with lower flexibility-schematics and kinematics. Right: The Denavit-Hartenberg representation of the trunk

shown in Figure 7, which is applied in the second prototype.

The complete kinematics of each trunk should take into account the initial angle of the belts; that is the rotation angle of the belt pulley. In Figure 7-right the dashed line demonstrates the trunk kinematics including the rotation of belt pulleys. Figure 7-right shows the frame of references of the trunk in Denavit-Hartenberg convention from which the kinematics of the trunk can be easily obtained. Due to simplicity, here we avoid presenting the matrices transformation of the D-H parameters.

## III. PROTOTYPES

### A. First Prototype

Figure 9 shows the first prototype of the gripper which was built according to the trunk configuration shown in figure 6. A Dynamixel AX-12 servo actuator (12V- 900mA- 1.2Nm) is used for retraction and release of the tendons. A



Fig. 8. Grasping stages of a cylindrical object with a diameter of 50mm

Dynamixel RX-64 servo actuator (18 V- 1200 mA-6.4N.m) is used for wrapping the elastomer belt around its pulley in order to make the force closure action. Figure 8 shows the three grasping stages of a cylindrical object with a diameter of 50mm. The left image demonstrates the gripper's normal status. The middle image shows the gripper after locking of the trunks and caging of the object and the right image shows the force closure of the object. A soft pad is used in order to support longer objects. Figure 9 shows the gripper grasping various objects with different shapes and dimensions. Considering cylindrical parts, the first prototype can seize cylinders with a range of diameters from 40mm to 160mm. The weight of the gripper model is 1970 gr.

One of the difficulties associated with this design is that due to the lack of discrete joints, the trunks tend to incline toward the gravity direction, specially in case of bigger unsupported belt length that is bigger  $m$  in figure 6. To solve this problem we considered the following two measures in the second prototype.

- 1) In the second prototype we changed the trunk configuration to the second configuration, which is presented in figure 7. Reducing the distance between the teeth could successfully address the trunk inclination problem.
- 2) . We changed the design of the gripper to decrease the length of the elastomer, without decreasing the effective grasping length of the belt. Therefore we substituted the end part of the belt with a rigid link and used a rack and pinion system rather than wrapping the belt around the pulley.

Another problem which was revealed from the first prototype was small height of the trunks and adaptability to objects with different profiles at their height. To resolve this, in the second prototype we integrated two belts at each trunk. Both belts include teeth and tendons based on the configuration in figure 7. Therefore they act similarly in their rigid status, but after locking both trunks and releasing the tendons, each belt can adapt to a different profile size or shape of the object.

### B. The second prototype

Figure 10 shows the 3D model and dimensions of the second prototype and figure 11 shows the second prototype. The second prototype can grasp cylindrical objects with a diameter of up to 190mm. It is bigger in height compared to the first prototype in order to support long objects profiles. It weighs 2610gr and can hold objects up to 4000gr.. The length of the trunks is 250mm. Table I shows the characteristics of the second prototype. In addition to the modifications which were described in the last section, following changes were also made.

- 1) Body of the robot was redesigned for a better adaptability to longer objects.
- 2) To reduce the weight of the system, the body of the gripper and custom designed parts were 3D printed (in the first prototype it was from aluminum).
- 3) Rather than one Dynamixel AX-12 servo actuator for both trunks, each trunk is equipped with one actuator.

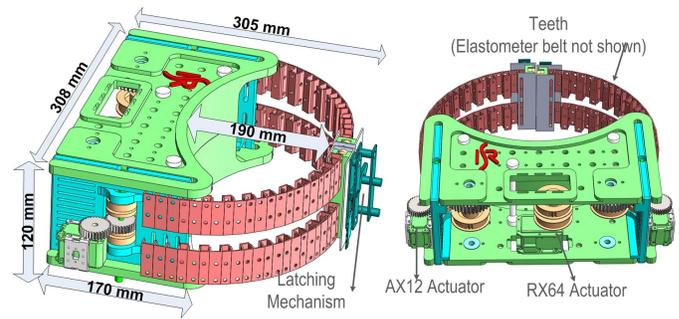


Fig. 10. The 3d model and dimensions of the second prototype of the gripper

Dimensions	308X120X305mm
Weight	2610gr
Maximum support weight	4000gr
Maximum object diameter which can be grasped	190mm
Length of the trunks	250mm
Actuation	Two AX-12 rotary actuators & one RX-64 actuator

TABLE I

THE MAIN CHARACTERISTICS OF THE SECOND PROTOTYPE

Adding one actuator enables the possibility of separate control over each trunk, and reduces the design complexity by reduction of two timing pulleys and one timing belt.

1) *Locking and unlocking:* The locking mechanism is one of the robot's novelties in design framework. Due to flexibility of the trunks, it is not possible to control the trunks precisely enough to guarantee their endpoints reach each other. Therefore we left the last tooth of the trunk free from tendon to allow it some additional flexibility. At the end point a series of magnets were placed figure 12. The magnets are placed by alternating polarity, so that the endpoints meet each other on the exact position. Such exact positioning is needed for the latching mechanism. We need a latching mechanism for a secure locking and for a controlled unlocking. Magnets are selected so that the magnetic force between them at a distance of 40mm is enough to join the end points of the trunks(40mm is the maximum mismatching between the endpoints of the trunks). But after the magnets meet each other, the attraction force is less than the maximum force which is applied by the RX-64 actuator to the belt, so that later it can be unlocked. Therefore a normal close latching mechanism is added which locks the system. As can be seen in figure 12, the latching mechanism is loaded by a spring from one side, and a memory alloy actuator on the other side for unlocking. For unlocking, the memory alloy opens the latch mechanism, while the belts are pulled from both side by RX-64. As the pulling force overcomes the magnetic force, trunks will be unlocked.

2) *Experiments with the second prototype:* We tested the Flexirigid gripper against many different objects and profiles. As explained in the kinematics of the trunks, as we are

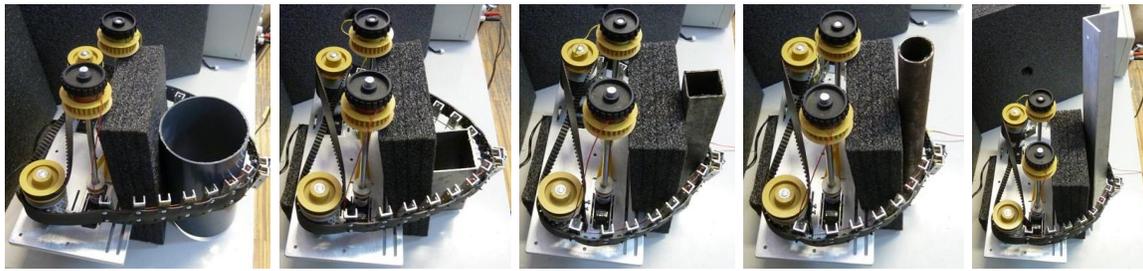


Fig. 9. The first prototype of the gripper can grasp cylindrical objects with different sizes and non cylindrical objects with different profile shapes.

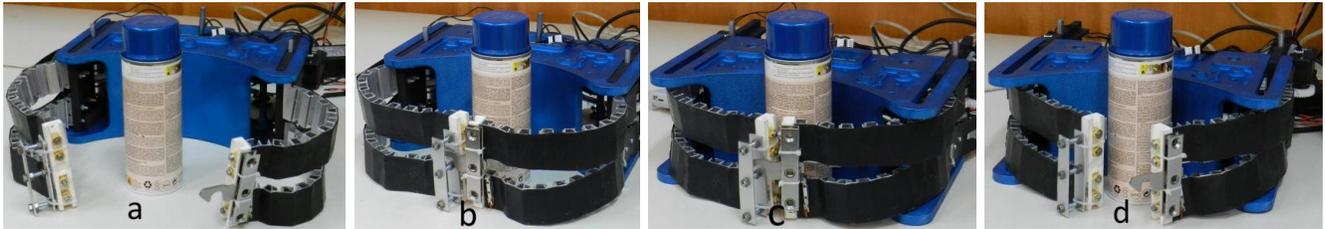


Fig. 13. Grasping a circular profile by flexirigid gripper. a: Before grasping b: Tendons are pulled around the pulley and trunks are locked. After locking, tendons are released, so that the trunks gain their flexibility again. c: Retraction of trunks by RX64 actuator and grasping d:Unlocking



Fig. 14. Flexirigid gripper could adapt to a variety of object profiles due to its flexibility and could successfully grasp them. Images show the status of the gripper before and after retraction of the trunks.

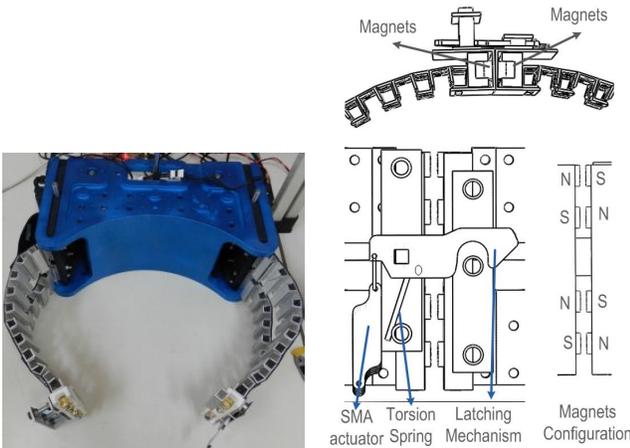


Fig. 11. The actual implementation of the Flexirigid gripper.

Fig. 12. The locking mechanism consist of a configuration of magnets and a latching mechanism, and a SMA actuator for unlocking.



Fig. 15. Adaptation to and grasping of several objects.

using the configuration shown in figure 7 in the second prototype, the belt curvature and the pose of the trunks' endpoints can be estimated. Therefore the kinematics of the trunk was modified for the second prototype according to the configuration shown in figure 7 and the initial revolute joint in figure 7 was substituted by a linear joint. We can

remotely control the gripper both trough a GUI in a PC and also by a joystick. Figure 13 shows the process of grasping a circular profile. Figure 14 shows how Flexirigid trunks adapt to different profiles. It can be seen that the shape of the trunk is changed according to the profile of the object. We also experimented the gripper for grasping of multiple objects. Several objects were placed in arbitrary positions within the reachable space for the trunks and grasped it as can be seen in figure 15. Another concept which is not yet well explored in this research is control of the trunks in order to actively adapt to the object profile. An experiment was performed for the proof of the concept, as can be seen in figure 16, which shows the normal grasping approach (middle picture), versus the active control of the trunks before the trunk retraction (right picture).



Fig. 16. Two different approaches for grasping two objects. The second approach (right picture) is by active control of each trunk to form it close to the object's profile.

#### IV. CONCLUSION

The main advantages of this gripper can be summarized as:

- 1) Simplicity and Low DOF
- 2) Good adaptability to different shapes and sizes
- 3) Adaptable to very large objects
- 4) Adjustable flexibility
- 5) Grasping can be performed by manipulators with low positioning accuracy
- 6) The manipulator which holds this gripper can approach the object more rapidly comparing with a manipulator with conventional grippers.

The two latterly mentioned advantages, is due to the fact that in the first phase, the gripper surrounds the object without requiring a good positioning accuracy (2D caging). Placing the manipulator in a precise grasping pose is a well known problem in Robotics applications, where usually manipulators should move with a lower speed in order to fulfill the required positioning accuracy. In case of integrating the Flexirigid gripper on a robotic arm, the arm can approach the object rapidly with relatively low precision until the gripping mechanism reaches the vicinity of the object which decreases the overall grasping time.

The first prototype of Flexirigid was developed with configuration shown in figure 6, which allows more flexibility compared to the configuration shown in figure 7, but the maximum length of the trunks is limited because of problems such as inclination toward the gravity direction. The second prototype, built according to the configuration shown in figure 7, showed a good adaptability to many different object profiles and its inclination toward the gravity direction is very low.

One of the advantages of this gripper is that for very large but light objects, e.g. plastic tubes, one should only increase the length of the trunks, which makes this gripper very light weighted for such applications. The only limitation is the inclination problem. That's why the inclination problem is particularly important, since it limits the maximum length of the trunks. To resolve this problem we are developing a custom design belt which is optimized for the trunk applications. Taking advantage of a nonuniform profile, the thickness of the new belt will decrease along its length and the rigid links will be embedded into the belt.

#### VIDEO ATTACHMENT

This article is accompanied by a video attachment showing several experiments of single and multiobject grasping with flexirigid gripper.

#### NOTIFICATION

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