Design and Performance of a Multi-Port Robotic Suction Gripper

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Abstract

This paper presents the mechanical-workings and gripping performance characteristics of a vacuum-based robotic gripper. The gripper uses multiple ports with attached commercial suction cups to grasp objects from a variety of directions using suction power. The valves remain closed until opened by a hinge-based mechanism, in order to eliminate vacuum leakage. The ability for the valves to be actuated mechanically removes the need for an actuator and active control, reducing costs and weight.

Background

Advancements in robotic hardware that can manipulate objects and the environment around them are now of greater necessity, with the advent of robotized processes, such as autonomous warehousing. Many current warehousing methods require slow and strenuous manual labor. However, a system that implements autonomous robotic technology could significantly increase the speed with which goods are transported and organized [1]. Industries such as these need cost-effective, yet versatile equipment that can keep up with the increasingly capable autonomous software technology. One example is the area of robotic gripping technology. Robotic grippers that are in environments such as a warehouse need the ability to interact with objects of varying size, shape, and weight. Many current solutions use a system with multiple motorized joints [2][3], that can perform human like grasping techniques. However, a suction gripper, if it has a proper seal and adequate suction force, can perform equally as well and occasionally better, without the use of multiple motorized limbs. The use of vacuum suction technology can provide exceptional grasping performance, while avoiding active sensing.

Introduction

The gripping device presented in this paper was specifically designed for use on a larger project - an autonomous warehousing robot that is being created to compete in the Amazon Picking Challenge. In this competition, the robot must sort through a series of shelves and pick out certain items without disturbing other items or damaging the one it is currently holding. Objects positioned on the shelves can be placed anywhere within the shelves and in any orientation. The competition robot in this project has two swiveling robot extension arms on the base of the device that incorporate the Spiral Zipper Mechanism [4] in order to extend upward. This robotic arm system is used to control the orientation of a tube housing the vacuum hose with the gripper attached at the end. When controlled by the Spiral Zipper arms, the vacuum tube, and therefore the gripper, have three translational degrees of freedom. Since the gripper cannot be rotated in any direction, the design needs multiple ports in order to be able to grasp objects from a variety of directions. However, a multi-port solution can succumb to the effects of vacuum leakage, which is why normally closed valve technology is necessary for this gripper. The suction ports need the ability to only open when in use, so that the vacuum does not leak and, therefore, reduce suction force at the engaged suction port. Preliminary designs proposed using an array of Dr. Kessen's Self-Sealing Cups [5] along a gripping device connected to a low flow vacuum pump. However, the effective grasping performance by the Self-Sealing Suction Cups required the use of multiple cups on a flexible array platform. This is due to the fact that the cups were not designed to be capable of handling moments caused by the weight of the grasped objects. Manufacturing of the flexible array, as well as the cups themselves, would have required the use of advanced, expensive 3D printing technology. This design is inconsistent with the low cost nature of the overall Amazon Picking Challenge robot. For these reasons, we decided to engineer a gripper that combined a new form of Self-Sealing [5] technology combined with inexpensive commercial suction cups that could take moments. Instead of molding cups around the selected object, our gripper prototype projects suction force in four directions using suction cups connected to gripping modules. Each module uses a valve-based system in order to passively control the airflow of the system.

Materials and Methods

The module attachment platform, as well as the modules themselves, are all made using Acrylonitrile-Butadiene-Styrene (ABS) plastic, with the exception of the axle used in the linkage, which is made of steel. All of the ABS pieces for the gripper were made using a laser cutting machine and glued together using super glue gel. The suction cups used are Silicone and have an 18mm inner channel and a 33mm outermost diameter. This suction cup was chosen due to the fact that it was a suitable size for grasping the common household objects that were used for testing. The decision to super glue laser cut parts together was made in order to minimize prototyping and manufacturing costs. It also eased the process of assembling components in the modules' interiors and making modifications. However, this method of construction sacrifices manufacturing precision and is not optimal for making an airtight design. As such, a high flow vacuum was used in this particular design in order to compensate for the fact that the device is mostly, but not completely, air tight.

Overall Module Design

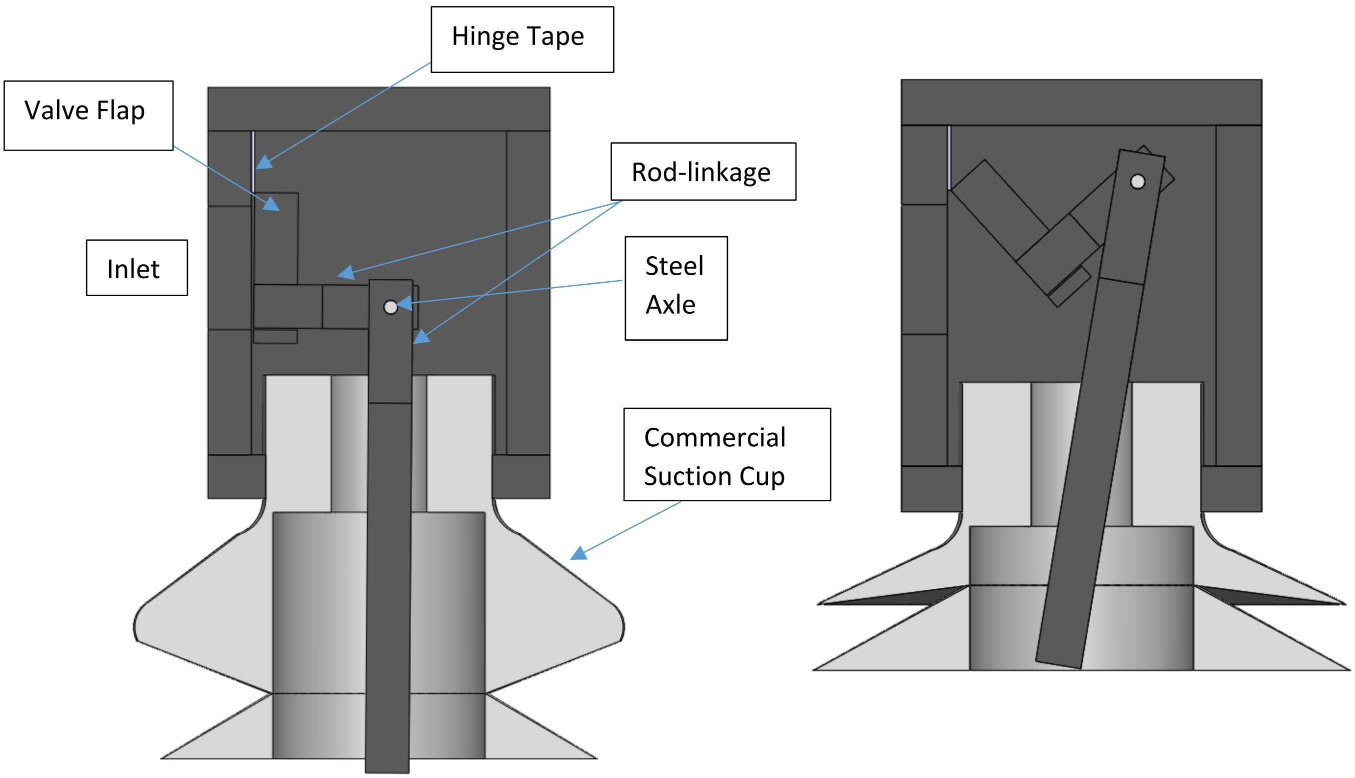

Fig. 1. Right View of Gripper Module in its closed and open states

The modules' suction ports are normally closed. Each of the modules are engaged when the suction port is opened by a hinge mechanism. The valve flap is fixed to a flexure-hinge, and is only opened when the bottom portion of the rod-linkage is pressed upward by coming into contact with the object it needs to grasp. After picking up and moving an object the vacuum is turned off so that the gripper can release the object. When the vacuum is turned back on to return to picking, the flap is closed as a result. The air molecules moving from the higher atmospheric pressure to the lower vacuum pressure push the door closed along their path. This occurrence essentially acts as a "natural" restoring force, negating the need for an additional mechanism, such as a spring.

Hinge Mechanism

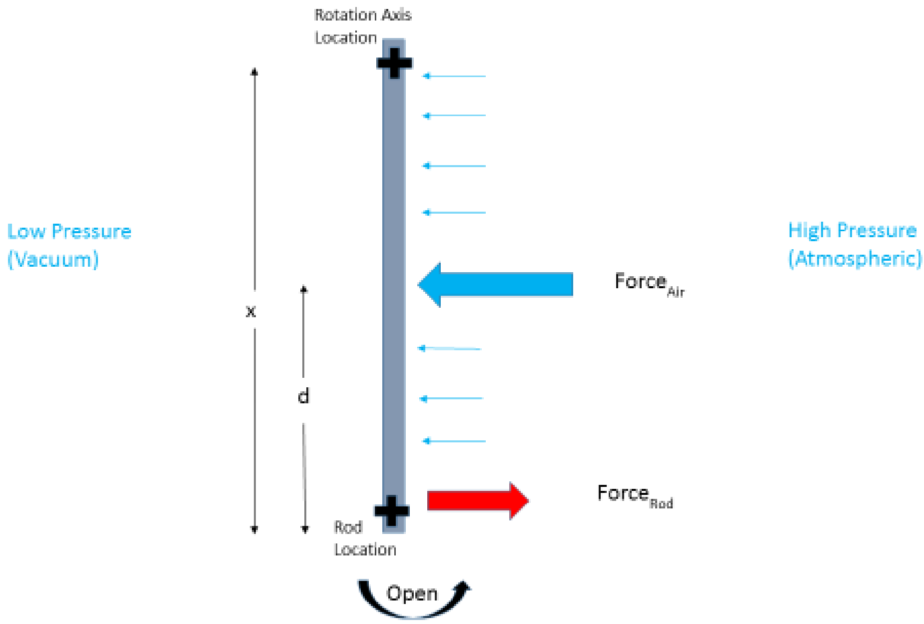

Fig. 2. Fluid Statics Representation of Valve Mechanism

One of the most critical design challenges in this gripper project was creating the rotating mechanism for the valve door to revolve about. The forces involved inside the module while the vacuum is functioning, as well as the locations of the rod and the hinge are detailed in Fig. 2. In order to open the valve door, the pulling force from the rod must achieve a minimum activation force in order to induce a moment of the valve flap about the hinge. Meeting this activation force is necessary for creating an opening moment that is greater than the moment caused by the air pressure, which is acting in the opposite (closing) direction. The two moments caused by the pulling force of the rod and the force of the air pressure can be modeled in this equation, which is in reference to Fig. 2.

$$\Sigma M_{Hinge} = F_{Rod}x - F_{Air}(x - d) = 0$$

F_{Rod} is the pulling force caused by the rod-linkage, F_{Air} is the point force of the air pressure, x is the distance between the hinge and rod locations, and d is the distance between the rod and the center of the flap. A large part in creating the opening and closing mechanisms for the valve flap required us to decide where to locate the end of the rod-linkage and the axis for the rotating mechanism, which was later determined to be a hinge. We decided to fix the location of the rod to the bottom of the flap in order to avoid a collision between the rod linkage and the valve door during the opening motion. The axis of rotation location was flexible in design, as it could be positioned anywhere on the top half of the flap. Placing it on the bottom half of the flap would cause the air pressure to generate a moment in the opening direction instead of the closing direction. The closer the hinge location is to the center of the flap, the smaller the rod-linkage's activation force has to be in order to create a moment that opens the flap. If the axis of rotation was too close to the center of the flap, then it would take a considerably large amount of force from the air pressure in order to close the flap and the activation force would be very low. The activation force cannot be too high, where it requires a tremendous amount of force to actuate the module, but it should not be too low, where the valve can be accidentally opened with ease. By locating the rotation axis at the top of the flap, we essentially made the activation force for opening the door half the size of the resultant force of the air pressure. The surface area of the valve flap is around 18 square centimeters, so the air pressure applies a relatively small force on the flap. Since the activation force, in comparison, is half this magnitude, it is not a large amount in reality. The activation force that is present is significant in the fact that it gives the gripper selectivity during the warehousing process. This force only allows the gripper to pickup items that it intentionally comes into contact with. Placing the rotation location at the top of the flap also allowed us to easily implement a hinging mechanism instead of the originally planned axle. The process of making a valve door that rotated about an axle was deemed to be unnecessarily complex. It would have required designing a plate that both fit inside the module's port and sealed this airway. Additionally, the manufacturing process would have involved drilling 1mm-diameter concentric holes in a very tight space. Instead we designed the valve flap to be larger than the area of the port, so that the flap covered the port completely when closed and blocked any leakage. We placed tape where the top end of the flap and the interior wall of the suction chamber meet, to act as the flexure hinge.

Rod-Linkage and Suction Cup

The engagement process for each of the suction modules involves the use of a rod-linkage and a suction cup. The rod-linkage is a made up of a forked rod and a thinner rod that fits in between said fork. In this position, the rods rotate about an axle that is placed between them. The cups in use are bellows cups. Since the smaller end of the rod-linkage is fixed into the valve door, as the taller portion of the rod-linkage is forced upward upon contact, the flap swings upward as well, which is show in Fig. 1. As the rod moves up and the valve is opened, the cup is compressed and makes its seal simultaneously. At this point the suction module is considered engaged. Disengagement occurs when the vacuum is powered off.

Module Attachment Base Design

The platform on which the modules are situated channel airflow in four different directions (front, right, left, and down). Each channel is designed to fit one module, which means that suction force can be directed in each of the previously mentioned directions. An attachment is fixed at the rear that allows for a vacuum hose to be connected to the platform. When the modules are assembled together on the device they create a chamber at the rear of the device where the hose attaches, which serves as the site of the vacuum.

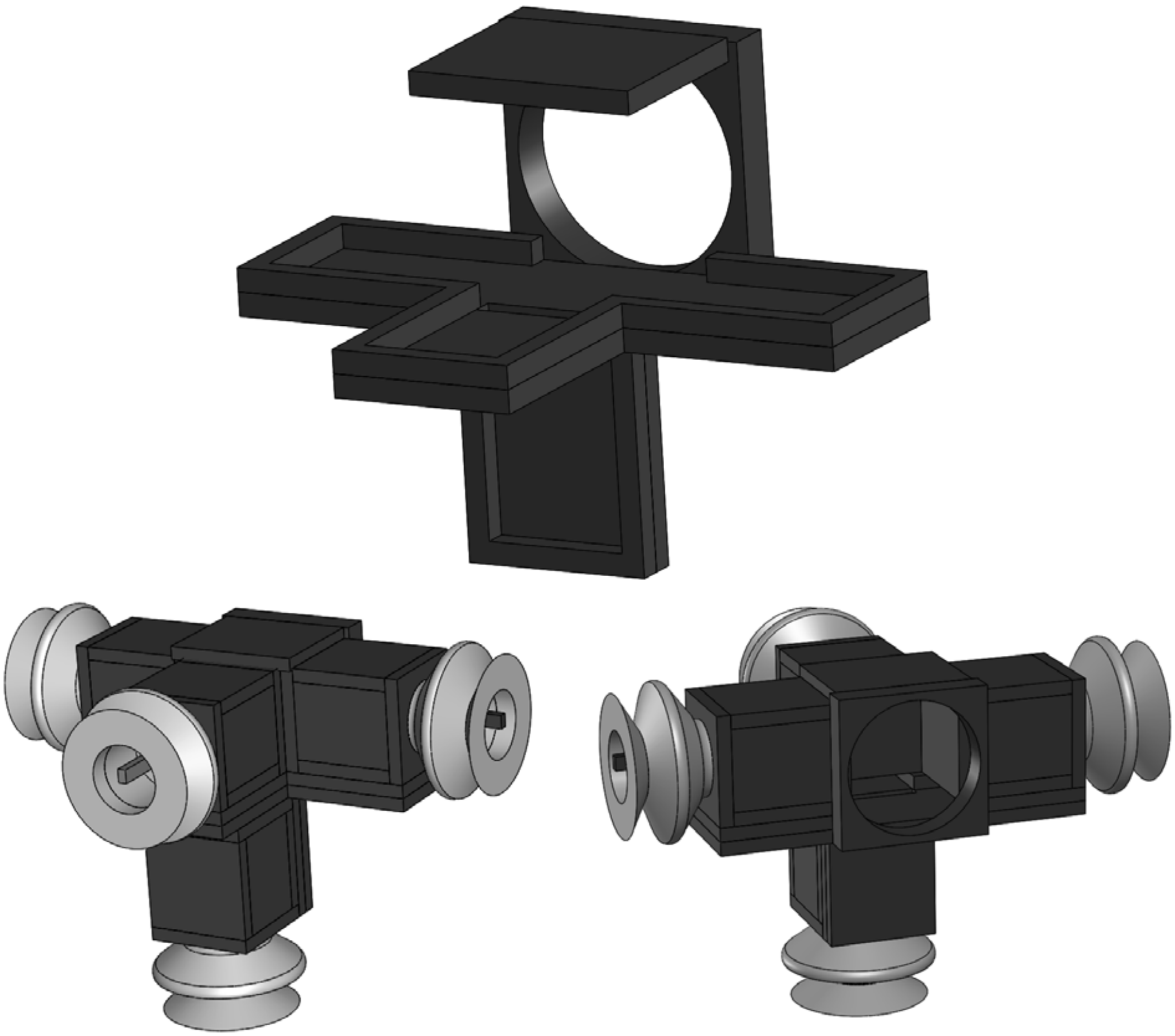

Fig. 3. Top: Attachment platform for gripper modules

Bottom: Final Gripper Design: front and back views

Results

When using a high flow vacuum (from a vacuum cleaner) with the gripper device, the worked as designed, producing minimal leakage and picking up a variety of objects. When presented with a sample of objects that might be typically be found in warehouse inventory, the gripper was able to grasp each of the items, as shown in Fig. 4.

Fig. 4. Gripper with vacuum hose picking up various articles: A water bottle, bin of coffee, plastic pack of socks, and long-sleeved shirt

The suction cup was able to create an adequate seal on all objects it encountered. This includes the curved surfaces such as the water bottle and coffee bin, as well as the light, loose and non-uniformed surfaces of the plastic packaging and the cotton shirt. In addition, the normally closed valve system blocked leakage from the ports well enough to provide a powerful suction force at the engaged ports only. The gripper was able to latch onto, pick up and move around a plastic water bottle, a plastic pack of socks, a long-sleeve shirt and a coffee container. The advantages of the valve technology can be seen by comparing the performance of the gripper to that of a gripper without a valve mechanism, as displayed in the table, Fig. 6. The gripper shown in Fig. 5 also has 4 ports of the same size using the same suction cups. It was also tested using the same high flow vacuum cleaner, however it did not incorporate the valve technology. It could make a weak seal, but it could not actually both pickup and move any of the testing objects (water bottle, coffee container, plastic sock package, or long-sleeve shirt) because of the vast amount of leakage caused by the ports always being open. This test is useful in showing the adverse effects that vacuum leakage has on suction-based grasping.

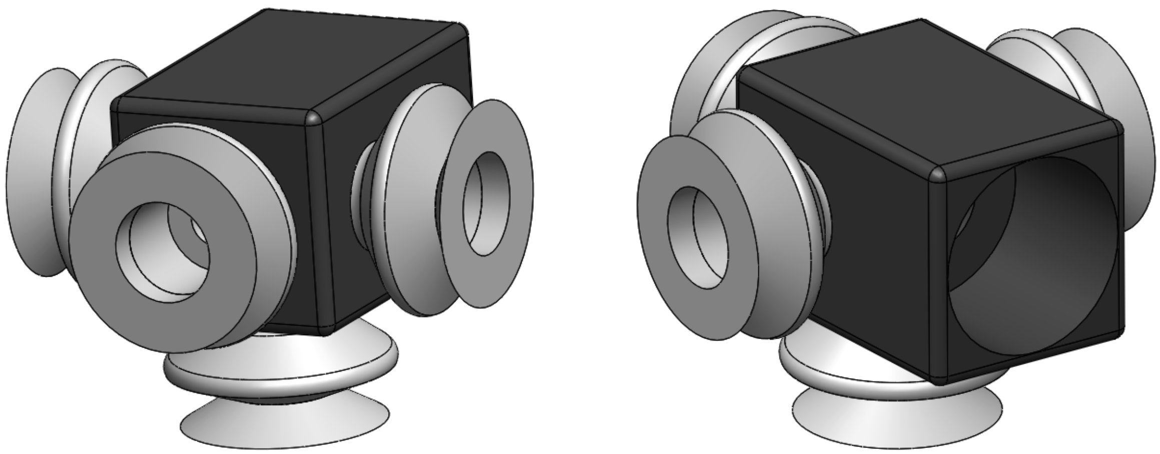

Fig. 5. Front and back views of gripper with always open suction ports

	Object			
	16.9 fl. Oz. Plastic Water Bottle	11.3 oz. Coffee Bin	Approx. 16 oz. Plastic Package of Socks	Approx. 5 oz. Child's long-sleeve shirt
Gripper Design	**Grasping Performance**			
Always Open Ports	Made seal, not strong enough to lift	Made seal, not strong enough to lift	Made partial seal, not strong enough to lift	Made partial seal, not strong enough to lift
Ports with normally-closed Valve mechanism	Made seal, able to lift and move around	Made seal, able to lift and move around	Made seal, able to lift and move around	Made seal, able to lift and move around

Fig. 6. -Grasping performance of grippers with and without leakage preventing valve mechanism

-Each of the items were grasped using one of the suction modules

We also know that the leakage was minimal with the normally-closed valves because the disengaged ports would have very little to no interaction with the objects that they hovered close to in their path. For example, when the gripper, with the vacuum activated, hovered over a stack of notebook paper, there was no actual engagement until the suction cup made significant contact with the paper. In this way, the normally closed valve system not only increases the suction force of the engaged cup, but also prevents accidental grasping on neighboring objects or walls. As this is the first fully functioning prototype that incorporates the valve system, there were some manufacturing flaws. After all the ports were used extensively, the bottom module's valve flap began to leave a very small gap in the port in the closed position. With additional prototyping and manufacturing, this problem could be resolved easily. The valve flap could have potentially been longer in length to more reliably cover the vacuum port. In addition, tape with stronger adhesive qualities could be considered in order to make the valve flap open and close with greater precision. However, despite the construction defects, the gripper still worked well with the new technology.

Conclusion

This paper proposes that normally closed valve technology based on the Self-Sealing cup technology [5] can be used with inexpensive materials and manufacturing processes to create a versatile robotic gripper. The prototype presented in this paper was able to grasp a large variety of items that might be typically found in a warehouse facility. Future research may be done on what and how different types of passive valve mechanisms perform in terms of blocking leakage and simplicity of activation. Finally, while the valve mechanism was implemented for this specific gripper design presented in this paper, we believe that it can successfully be used on other gripping designs as well.

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