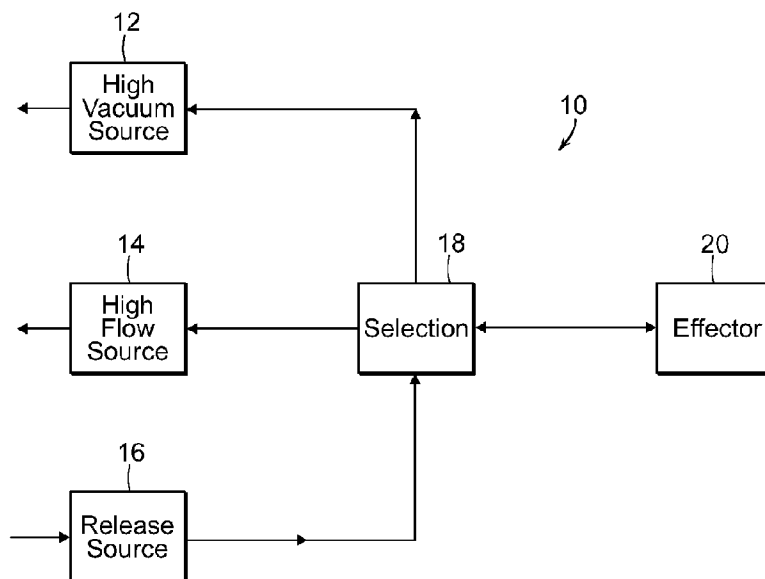




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END EFFECTOR



(57) Abrégé/Abstract:

A system is disclosed for providing dynamic vacuum control to an end effector of an articulated arm. The system includes a first vacuum source for providing a first vacuum pressure with a first maximum air flow rate, and a second vacuum source for providing a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate.

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(54) Title: SYSTEMS AND METHODS FOR PROVIDING DYNAMIC VACUUM PRESSURE IN AN ARTICULATED ARM END EFFECTOR

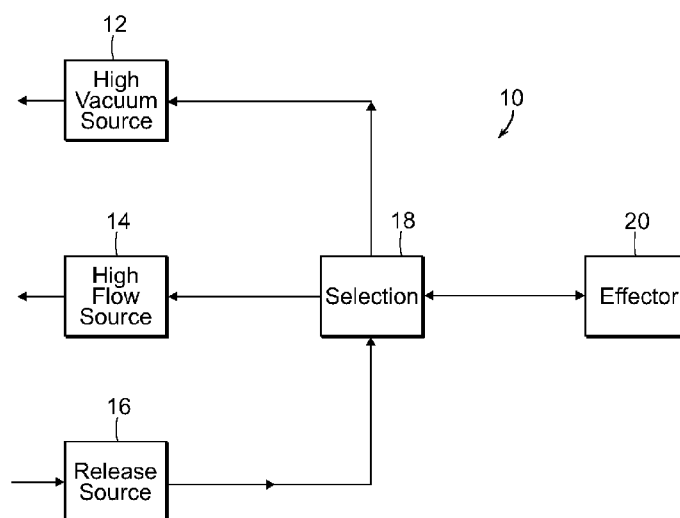


FIG. 1

(57) Abstract: A system is disclosed for providing dynamic vacuum control to an end effector of an articulated arm. The system includes a first vacuum source for providing a first vacuum pressure with a first maximum air flow rate, and a second vacuum source for providing a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate.

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SYSTEMS AND METHODS FOR PROVIDING DYNAMIC VACUUM PRESSURE IN AN
ARTICULATED ARM END EFFECTOR

BACKGROUND

The invention generally relates to robotic systems, and relates in particular to robotic systems having an articulated arm with an end effector that employs vacuum pressure to engage objects in the environment.

Most vacuum grippers employ vacuum pressures well below 50% of atmospheric pressure, and are referred to herein as *high vacuum*. A typical source for a high vacuum gripper is a Venturi ejector, which produces high vacuum but low maximum air flow. Because of the low flow, it is essential to get a good seal between a vacuum gripper and an object, and it is also important to minimize the volume to be evacuated.

Suppliers of ejectors and related system components include Vaccon Company, Inc. of Medway, MA, Festo US Corporation of Hauppauge, NY, Schmalz, Inc. of Raleigh, NC and others. In some instances where a good seal is not possible, some systems use high flow devices. Typical high flow devices are air amplifiers and blowers, which produce the desired flows, but cannot produce the high vacuum of a high vacuum source. High flow sources include the side-channel blowers supplied by Elmo Rietschle of Gardner, Denver, Inc. of Quincy, IL, Fuji Electric Corporation of America of Edison, NJ, and Schmalz, Inc. of Raleigh, NC. It is also possible to use air amplifiers as supplied by EDCO USA of Fenton, MO and EXAIR Corporation of Cincinnati, OH. Multistage ejectors are also known to be used to evacuate a large volume more quickly, wherein each stage provides higher levels of flow but lower levels of vacuum.

Despite the variety of vacuum systems, however, there remains a need for an end effector in a robotic system that is able to accommodate a wide variety of applications involving

engaging a variety of types of items. There is further a need for an end effector that is able to provide high flow vacuum using a gripper that is able to handle a wide variety of objects.

SUMMARY

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising: (i) a first air source including a compressor for providing a positive air pressure; (ii) a second air source including a blower for providing a negative air pressure; and (iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate.

In an aspect, there is provided a method of providing a dynamic vacuum source for an end effector, said method comprising the steps of: (a) coupling a first end of a multi-stage ejector to a first air source that includes a compressor such that the first end of the multi-stage ejector receives positive air pressure; (b) coupling a second opposite end of the multi-stage ejector to a second air source that includes a blower such that the second end of the multi-stage ejector receives negative air pressure; (c) providing at the end effector a first vacuum from a first vacuum source that includes the compressor, said first vacuum having first vacuum pressure and a first vacuum flow rate; and (d) switching the

dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes the blower, said second vacuum having a second vacuum pressure and a second vacuum flow rate, and second vacuum pressure being higher than the first vacuum pressure, and the second vacuum flow rate being greater than the first vacuum flow rate, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector opening of an end effector of a programmable motion device, said system comprising: (a) a first air source including compressed air for providing at the end effector opening, a first vacuum pressure with a first maximum air flow rate; (b) a second air source including a blower for providing at the end effector opening, a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate; and (c) a multi-stage ejector coupled at a first end thereof to the first air source and coupled at a second opposite end thereof to the second air source, wherein the first air source and the second air source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between providing the first vacuum pressure and the second vacuum pressure at the end effector opening responsive to a change in air pressure at an exit of the multi-stage ejector.

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising: (i) a first air source for providing a positive air pressure; (ii) a second air source for providing a negative air pressure; and (iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that

automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising: (i) a first air source for providing a positive air pressure; (ii) a second air source for providing a negative air pressure; and (iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

In an aspect, there is provided a method of providing a dynamic vacuum source for an end effector, said method comprising the steps of: (a) coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure; (b) coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure; (c) providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure

and a first vacuum flow rate; and (d) switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, said first vacuum pressure being at least about 90,000 Pascals below atmospheric, and said second vacuum pressure being no more than about 50,000 Pascals below atmospheric, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.

In an aspect, there is provided a method of providing a dynamic vacuum source for an end effector, said method comprising the steps of: (a) coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure; (b) coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure; (c) providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate; and (d) switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, said first vacuum flow rate being at most about 5 cubic feet per minute, and said second vacuum flow rate being at least about 100 cubic feet per minute, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising: a first air source for providing a positive air pressure; a second air source for providing a negative air pressure; a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second

opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve; and a covering at a contact surface of the end effector that includes a single opening that provides more air flow at a center of the contact surface than at a periphery of the contact surface.

In an aspect, there is provided a system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising: a first air source for providing a positive air pressure; a second air source for providing a negative air pressure; a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve; and a covering at a contact surface of the end effector that includes multiple openings that together provide more air flow at a center of the contact surface than at a periphery of the contact surface.

In an aspect, there is provided a method of providing a dynamic vacuum source for an end effector, said method comprising: coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure; coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector

receives negative air pressure; providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate; switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source; and providing a covering at a contact surface of the end effector that includes a single opening that provides more air flow at a center of the contact surface than at a periphery of the contact surface.

In an aspect, there is provided a method of providing a dynamic vacuum source for an end effector, said method comprising: coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure; coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure; providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate; switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, wherein the first vacuum source the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source; and providing a covering at a contact surface of the end effector that includes multiple openings that together provide more air flow at a center of the contact surface than at a periphery of the contact surface.

In accordance with a further embodiment, the invention provides a system for providing vacuum control to an end effector of an articulated arm. The system includes a vacuum source for providing a vacuum pressure at a flow rate to the end effector, and the end effector includes a cover that includes an opening that varies significantly in radius from a center of the cover.

BRIEF DESCRIPTION OF THE DRAWINGS

The following description may be further understood with reference to the accompanying drawings in which:

Figure 1 shows an illustrative block diagrammatic view of a system in accordance with an embodiment of the present invention;

Figure 2 shows an illustrative diagrammatic view of an example of a system of Figure 1;

Figure 3 shows an illustrative diagrammatic view of a system in accordance with another embodiment of the present invention;

Figure 4 shows an illustrative diagrammatic view of a system in accordance with an embodiment of the present invention employing a high vacuum source;

Figure 5 shows an illustrative diagrammatic view of a system in accordance with another embodiment of the present invention employing a high flow source;

Figure 6 shows an illustrative diagrammatic view of a detection system together with an end effector of a system of an embodiment of the present invention;

Figures 7A and 7B show an illustrative flowchart showing a process in accordance with an embodiment of the present invention;

Figures 8A and 8B show illustrative diagrammatic views of an end effector cover for use in a system of an embodiment of the present invention;

Figure 9 shows an illustrative diagrammatic view of an end effector of an embodiment of the invention engaging an object;

Figures 10A – 10D show illustrative diagrammatic views of other covers for use with end effectors of systems of further embodiments of the present invention;

Figure 11A and 11B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging a relatively light object;

Figure 12A and 12B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging a relatively heavy object; and

Figure 13A and 13B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging an object that presents an unbalanced load;

The drawings are shown for illustrative purposes only.

DETAILED DESCRIPTION

In accordance with an embodiment, the invention provides a hybrid high flow / high vacuum gripper that can grip a broader set of objects than grippers based on either high flow or high vacuum alone. Previous designs are usually designed for a particular object. When a good seal between vacuum cup and object is possible, a high vacuum device such as a Venturi ejector is typically employed. When a good seal is not possible because of object surface irregularities or porosity, a high flow device such as a regenerative blower is typically employed. The hybrid gripper of an embodiment of the invention, uses either high vacuum or high flow, selected in real time to provide the most effective grip for the object, object pose, and surrounding context.

In various embodiments, therefore, the invention provides a gripper system that combines multiple sources of vacuum, and selecting the source in real time. The invention provides, in an

embodiment, a gripper system that switches from a high flow source to a high vacuum source as the pressure drops below the level sustainable by the high flow source, and a gripper system comprising a high flow source with a multistage ejector, so that the non-return valve integrated in the multistage ejector provides a selection mechanism in accordance with further embodiments.

A general approach to a vacuum gripper design, is to characterize the object in question and select the catalog gripper, vacuum source, and other components best suited to the object. Many device suppliers and integrators offer application engineering services to assist in selection of proper components. These options are exercised at system design time however, and result in a system committed to grasp a specific object, or in some instances a few objects.

There are numerous applications for a gripping system that could handle a broad variety of objects, varying in size, weight, and surface properties. The invention provides an approach to address this need by introducing a mechanism to select between a high flow source and a high vacuum source, depending on the present situation.

Figure 1, for example, shows a system 10 in accordance with an embodiment of the present invention in which a high vacuum source 12 is provided as well as a high flow source 14 and a release source 16 that are each coupled to a selection unit 18, that is coupled to an end effector 20. The selection unit 18 selects between the high vacuum source 12, the high flow source 14 and the release source 16 for providing any of high vacuum, vacuum with high flow, or a release flow to the end effector. Figure 1 therefore shows a general form of the invention, comprising mechanisms for producing high vacuum and high flow, a release source providing either atmospheric pressure via a vent or high pressure (blow off) via a compressor or reservoir, and a mechanism for selecting the source best suited to the present situation.

In accordance with certain embodiments, therefore, the invention provides a system for providing dynamic vacuum control to an end effector of an articulated arm. The system includes a first vacuum source for providing a first vacuum pressure with a first maximum air flow rate, and a second vacuum source for providing a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate. The flow rates are characterized as maximum air flow rates because, when an object is engaged at an end effector, the flow rate may drop significantly.

In other embodiments, the invention provides a method for providing a vacuum at an end effector on an articulated arm. The method includes the steps of providing a first vacuum at the end effector at a first vacuum pressure with a first maximum air flow rate, and changing the vacuum at the end effector to a second vacuum with a second vacuum pressure and a second maximum air flow rate.

The selection mechanism may include a set of pneumatic valves driven by an estimated task state, based for example, in part, on sensor input information. The selection mechanism may also select a vent or blow-off source to release a part. In certain cases, the selection mechanism may be based in part on a non-return valve (see Figure 2), in other cases, a non-return valve integrated in a multistage ejector, with an additional valve to select a vent or blow-off source in order to release a part (see Figure 3).

In particular, Figure 2 shows a system in accordance with an embodiment of the invention that includes a compressor 30 that is coupled to an ejector 32 to provide a high vacuum source that is coupled to a solenoid valve 34. A blower 36 is also coupled to the solenoid valve 34 via a non-return valve 38, and the blower 36 provides a vacuum source with a high maximum

flow rate. A vent or blow-off source is also provided to the solenoid valve 34, the output of which is provided to an end effector 40. The system therefore, provides the ejector 32 as the high vacuum source, the regenerative blower 36 as the high flow source, the non-return valve 38 as a passive selection mechanism, and the solenoid valve 34 connecting the effector to the release source, either vent or blow-off.

The vacuum pressure provided by the ejector 32 may be, for example, at least about 90,000 Pascals below atmospheric and the vacuum pressure provided by the blower 36 may be only no more than about 25,000 Pascals below atmospheric, and no more than about 50,000 Pascals below atmospheric in further embodiments. The vacuum pressure provided by the blower 36 is therefore higher than the vacuum pressure provided by the ejector 32. The maximum air flow rate of the ejector may be, for example, no more than about 5 cubic feet per minute (e.g., 1 – 2 cubic feet per minute), and the maximum air flow rate of the blower may be, for example at least about 100 cubic feet per minute (e.g., 130 – 140 cubic feet per minute).

Figure 3, for example, shows another embodiment of the invention that includes a multi-stage ejector 50, a compressor 52 and a blower 54. The multi-stage ejector 50 provides a dynamic vacuum pressure to a solenoid valve 56 that may switch between providing an end effector 58 with either the dynamic vacuum pressure and a vent or blow-off positive air pressure source. The system uses the non-return valve of a multi-stage ejector as the selection mechanism. In particular, the multi-stage ejector includes a series of apertures of increasing size (e.g., left to right as illustrated in Figure 3). At first, the largest aperture is dominant, evacuating air quickly until the air pressure drops, then the next size aperture become dominant until air pressure drops further, and finally the smallest size aperture becomes dominant. The system of Figure 3, however, includes check valves on the larger aperture paths as well as the blower 54 to

keep the air flow path from defeating the high vacuum, smallest aperture, in the event of a good seal.

For example, with reference to Figure 4, if a good seal is formed between an end effector 60 on an articulated arm 64 (which may for example, be a tubular or conical shaped bellows) and an object 62, then the vacuum pressure provided by the smaller aperture in the multi-stage ejector 50 remains dominant because the non-return valves in the multi-stage ejector 50 prevent air flow backwards through the blower 54. This will provide that the grasp of object 62 will be maintained by the lower pressure vacuum with a lower maximum air flow rate.

With reference to Figure 5, if a good seal is not formed between an end effector 70 and an irregularly shaped object 72 on an articulated arm 74, then the blower 54 will dominate maintaining a high flow, therefore maintaining a grasp of object 72 with a higher maximum air flow rate.

With reference to Figure 6, in accordance with a further embodiment, the system may include an articulated arm 80 to which is attached an end effector 82, again, which may be a tubular or conical shaped bellows. The end effector 82 also includes a sensor that includes an attachment band 86 on the bellows, as well as a bracket 88 attached to magnetic field sensor 84, and a magnet 92 is mounted on the articulated arm 80. The bellows moves in any of three directions, e.g., toward and away from the articulated arm as shown diagrammatically at A, in directions transverse to the direction A as shown at B, and directions partially transverse to the direction A as shown at C. The magnetic field sensor 84 may communicate (e.g., wirelessly) with a controller 90, which may also communicate with a flow monitor 94 to determine whether a high flow grasp of an object is sufficient for continued grasp and transport as discussed further

below. In certain embodiments, for example, the system may return the object if the air flow is insufficient to carry the load, or may increase the air flow to safely maintain the load.

Figures 7A and 7B show the process steps of a system in accordance with an embodiment of the present invention, wherein the process begins (step 1000) by applying a high flow / low vacuum source to an end effector (step 1002). The end effector is then applied to an object to be moved (step 1004). Generally, the system begins and continues lifting the object until the end of the lifting routine (step 1006), begins and continues moving the object until the end of the moving routine (step 1008), then applies a positive air pressure force to urge the object from the end effector (step 1010) and then ends (step 1012). If the air flow at the end effector at any points falls too low, then the system may automatically switch to a high vacuum / low flow source as discussed above. In certain embodiments, sensor(s) may be employed to either confirm that such a switch is needed and / or has been made. In further embodiments, the sensor output(s) may drive a mechanical switch to change vacuum sources.

For example, Figure 7B also shows that once the end effector is applied to an object (step 1004), a subroutine is called (at A to B) that first reads the one or more sensors (step 1014). If any of the one or more sensor output(s) is outside of a threshold (step 1016), then the system may confirm that the system has switched to a high vacuum / low flow source (step 1018). As noted above, in certain embodiments, the sensor output(s) may drive a mechanical switch that changes the vacuum at the end effector to be a high vacuum / low flow source (step 1018). The system then returns to the step from which it was called. During execution of the beginning and continuing lifting until end (step 1006), the system continuously calls the subroutine (A to B) until the object is fully lifted. The system then moves to the step of beginning and continuing

moving the object until end (step 1008), and during execution of this action, the system continuously calls the subroutine (A to B) until the object is fully moved.

The system may therefore, automatically switch between high flow / low vacuum and low flow / high vacuum sources. In certain embodiments, the system may employ sensors to monitor and confirm that such switching is needed and is performed. As noted, the system may also effect the switching responsive to the one or more sensor output(s).

During low vacuum / high flow use, a specialized end effector may be used that provides improved grasping of long narrow objects. Certain grippers that are designed for high flow use to acquire and hold an object generally require large apertures in order to obtain an air flow rate that is high enough to be useful for object acquisition. One drawback of some such grippers in certain applications, is that the object to be acquired may be small, not so small that each of its dimensions is smaller than the high flow opening, but small enough that certain of an object's dimensions is smaller than the opening. For example, long narrow objects such as pens, pencils etc., do not occlude enough of the high flow opening to generate sufficient negative forces to hold the object securely.

In accordance with an embodiment, the invention provides a specialized cover for use with a high flow vacuum gripper. In particular and as shown in Figures 8A (articulated arm facing side) and 8B (object facing side), such a cover 100 may include a proximal back side 102 that does not permit air to flow through the material, and distal front side 104 for engaging objects that is formed of a foam material. Slit openings 106 in form of a star or asterisk shape are provided through the material in this example. During use, elongated objects may be received along opposing slit openings and held by the foam material.

Figure 9, for example, shows an elongated object 96 being held against the foam material 104 of a cover 100 that is coupled to the end effector 82. While the elongated object 96 covers some of the opening provided by the slits 106, other portions 108 of the opening provided by the slits 106 remain open. The pattern cut into the material allows for enough area to still obtain a relatively high flow, while providing a number or positions (or orientations) for a long, thin object to block (and thus be held by) a sufficiently high percentage of the air flow.

The compliant foam on the surface 104 contacts the object to be acquired, giving the gripper some compliance while also acting to seal the aperture around the object as the foam is compressed and the high flow vacuum is applied. The aperture cover therefore allows a high flow gripper to effectively pick up long narrow objects with an easy to attach cover that may be held in a tool changer and added or removed from the gripper autonomously during real-time operation.

In accordance with various embodiments, the cover 100 may be applied to the end effector by a human worker into a friction fitting on the end of the end effector, or in certain embodiments, the cover may be provided in a bank of available end effector attachments that the articulated arm may be programmed to engage as needed, and disengage when finished, e.g., using forced positive air pressure and /or a grasping device that secures the end effector attachment for release from the articulated arm.

A system is therefore provided in an embodiment, for providing vacuum control to an end effector of an articulated arm, where the system includes a vacuum source for providing a vacuum pressure at a high flow rate to the end effector, and the end effector includes a cover that includes an opening that varies significantly in radius from a center of the cover. The opening may include finger openings that extend radially from the center of the opening. The opening

may be generally star shaped or asterisk shaped. The cover may include compliant foam on a distal side of the cover that engages an object to be grasped, and an air flow resistant material on a proximal side of the cover. The vacuum pressure may be no more than about 50,000 Pascals below atmospheric, and the air flow rate may be at least about 100 cubic feet per minute.

Covers with other types of openings are shown in Figure 10A – 10D. Figure 10A, for example, shows a cover 120 that includes slit openings 122. Figure 10B shows a cover 130 that includes different sized square openings 132, 134. Cover 140 shown in Figure 10C includes small circular openings 142, and cover 150 shown in Figure 10D includes differently shaped openings 152 and 154. In each of the covers 100, 120, 130, 140 and 150, a compliant foam surface may face the object to be acquired, and more area of the cover is provided to be open closer to the center of the cover with respect to the outer periphery of each cover. For example, in the cover 100, the center of the asterisk shape is most open. In the cover 120, the larger slits are provided in the center. In the cover 130, the larger square openings are provided in the center. In the cover 140, the greater concentration of the circular openings is provided in the center, and in the cover 150, the larger shape 154 is provided in the center.

Systems in accordance with certain embodiments of the invention are able to monitor flow within the end effector as well as the weight and balance of an object being grasped. Figures 11A and 11B show an object 160 being lifted from a surface 162 by the end effector 82 that includes the load detection device of Figure 6. The high flow / low vacuum source is initially applied. Upon engaging the object 160, the system notes the position of the detection device and the level of flow (F_1) within the end effector as well as the vacuum pressure (P_1) and load (W_1) as shown in Figure 11A. Once the object 160 is lifted (Figure 11B), the system notes the change in the amount of flow (ΔF_1). In this example, the load provided by the object 160 is

relatively light (ΔW_1), and a small variation (ΔF_1) in flow may (when considering the load and aperture size) may be accepted, permitting the source to remain high flow / low vacuum. Figures 12A and 12B, however, show the end effector lifting a heavy object with a more flat surface.

Figures 12A and 12B show an object 170 being lifted from a surface 172 by the end effector 82 that includes the load detection device of Figure 6. The high flow / low vacuum source is initially applied. Upon engaging the object 170, the system notes the position of the detection device and the level of flow (F_2) within the end effector as well as the vacuum pressure (P_2) and load (W_2) as shown in Figure 12A. Once the object 170 is lifted (Figure 12B), the system notes the change in the amount of flow (ΔF_2). As noted above, in this example, the object 170 is heavy (ΔW_2), presenting a higher load. The system will evaluate the load in combination with the flow (F_2) and pressure (P_2) as well as the change in flow (ΔF_2) and change in pressure (ΔP_2) to assess the grasp of the object. The system may automatically switch to the high vacuum, low flow vacuum source as discussed above.

The system may also detect whether a load is not sufficiently balanced. Figures 13A and 13B show an object 180 being lifted from a surface 182 by the end effector 82 that includes the load detection device of Figure 6. The high flow / low vacuum source is initially applied. Upon engaging the object 180, the system notes the position of the detection device and the level of flow (F_3) within the end effector as well as the vacuum pressure (P_3) and load (W_3) as shown in Figure 13A. Once the object 180 is lifted (Figure 13B), the system notes the change in the amount of flow (ΔF_3). In this example, the object 180 presents a non-balanced load (ΔW_3). The system will evaluate the load in combination with the flow (F_3) and pressure (P_3) as well as the change in flow (ΔF_3) and change in pressure (ΔP_3) to assess the grasp of the object. The system may automatically switch to the high vacuum, low flow vacuum source as discussed above. In

each of the examples of Figures 11A – 13B, any of vacuum pressure sensors, flow sensors, weight and balance detections may be employed to monitor the status of the end effector and the load, and the switching may occur automatically, or by analysis of the above values.

In accordance with certain embodiments, the system may switch between a high vacuum, low flow source and a low vacuum high flow source depending on input from the sensor 84. For example, if an object is engaged such that the bellows is substantially moved in either directions B or C, then the system may elect to maintain the high vacuum, low flow source, or may elect to return the object without moving the object.

As discussed above, during low vacuum / high flow use, a specialized end effector may be used that provides improved grasping of long narrow objects. Certain grippers that are designed for high flow use to acquire and hold an object generally require large apertures in order to obtain an air flow rate that is high enough to be useful for object acquisition. One drawback of some such grippers in certain applications, is that the object to be acquired may be small, not so small that each of its dimensions is smaller than the high flow opening, but small enough that certain of an object's dimensions is smaller than the opening. For example, long narrow objects such as pens, pencils etc., do not occlude enough of the high flow opening to generate sufficient negative forces to hold the object securely.

In accordance with an embodiment, therefore, the system provides vacuum control to an end effector of an articulated arm, where the system includes a vacuum source for providing a vacuum pressure at a flow rate to the end effector, and the end effector includes a cover that includes an opening that varies significantly in radius from a center of the cover. The opening may include finger openings that extend radially from the center of the opening. The opening may be generally star shaped or asterisk shaped. The cover may include compliant foam on a

distal side of the cover that engages an object to be grasped, and an air flow resistant material on a proximal side of the cover. The vacuum pressure may be no more than about 25,000 Pascals below atmospheric, and the air flow rate may be at least about 100 cubic feet per minute to provide a high flow / low vacuum source. The cover may include an opening that varies significantly in radius from a center of the cover, and the opening may include finger openings that extend radially from the center of the opening, and for example, may be generally star shaped or asterisk shaped.

Those skilled in the art will appreciate that numerous modifications and variations may be made to the above disclosed embodiments without departing from the spirit and scope of the present invention.

CLAIMS

1. A system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising:

(i) a first air source including a compressor for providing a positive air pressure;

(ii) a second air source including a blower for providing a negative air pressure; and

(iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate.

2. The system as claimed in claim 1, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

3. The system as claimed in claim 1, wherein said first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

4. The system as claimed in claim 1, wherein the multi-stage ejector includes a non-return valve.

5. The system as claimed in claim 1, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

6. The system as claimed in claim 1, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.
7. The system as claimed in claim 1, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.
8. The system as claimed in claim 1, wherein the first vacuum pressure at the first maximum air flow rate and the second vacuum pressure at the second maximum air flow rate are selectively provided at a same end effector opening.
9. A method of providing a dynamic vacuum source for an end effector, said method comprising the steps of:
 - (a) coupling a first end of a multi-stage ejector to a first air source that includes a compressor such that the first end of the multi-stage ejector receives positive air pressure;
 - (b) coupling a second opposite end of the multi-stage ejector to a second air source that includes a blower such that the second end of the multi-stage ejector receives negative air pressure;
 - (c) providing at the end effector a first vacuum from a first vacuum source that includes the compressor, said first vacuum having first vacuum pressure and a first vacuum flow rate; and
 - (d) switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes the blower, said second vacuum having a second vacuum pressure and a second vacuum flow rate, and second vacuum pressure being higher than the first vacuum pressure, and the second vacuum flow rate being greater than the first vacuum flow rate, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.
10. The method as claimed in claim 9, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

11. The method as claimed in claim 9, wherein said first vacuum flow rate is at most about 5 cubic feet per minute, and said second vacuum flow rate is at least about 100 cubic feet per minute.
12. The method as claimed in claim 9, wherein the step of switching the dynamic vacuum source occurs automatically without any input commands.
13. The method as claimed in claim 9, wherein the method further includes the step of confirming, using an output of at least one pressure sensor, that the dynamic vacuum source has switched to the second vacuum pressure that is higher than the first vacuum pressure.
14. The method as claimed in claim 9, wherein the method further includes the step of confirming, using an output of at least one flow sensor, that the dynamic vacuum source has switched to the second vacuum flow rate that is greater than the first vacuum flow rate.
15. The method as claimed in claim 9, wherein the method occurs during application of the end effector to an object to be grasped.
16. The method as claimed in claim 9, wherein the method occurs during a process of lifting an object with the end effector.
17. The method as claimed in claim 9, wherein the method occurs during a process of moving an object with the end effector.
18. The method as claimed in claim 9, wherein the method further includes the method of providing a positive air pressure to the end effector to urge an object from the end effector.
19. The method as claimed in claim 9, wherein the first vacuum pressure at the first vacuum flow rate and the second vacuum pressure at the second vacuum flow rate are selectively provided at a same end effector opening.
20. A system for providing dynamic vacuum control to an end effector opening of an end effector of a programmable motion device, said system comprising:
 - (a) a first air source including compressed air for providing at the end effector opening, a first vacuum pressure with a first maximum air flow rate;

(b) a second air source including a blower for providing at the end effector opening, a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate; and

(c) a multi-stage ejector coupled at a first end thereof to the first air source and coupled at a second opposite end thereof to the second air source, wherein the first air source and the second air source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between providing the first vacuum pressure and the second vacuum pressure at the end effector opening responsive to a change in air pressure at an exit of the multi-stage ejector.

21. The system as claimed in claim 20, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

22. The system as claimed in claim 20, wherein said first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

23. The system as claimed in claim 20, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.

24. The system as claimed in claim 20, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

25. The system as claimed in claim 20, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.

26. A system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising:

- (i) a first air source for providing a positive air pressure;
- (ii) a second air source for providing a negative air pressure; and

(iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

27. The system as claimed in claim 26, wherein said first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

28. The system as claimed in claim 26, wherein the multi-stage ejector includes a non-return valve.

29. The system as claimed in claim 26, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

30. The system as claimed in claim 26, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.

31. The system as claimed in claim 26, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.

32. A system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising:

- (i) a first air source for providing a positive air pressure;
- (ii) a second air source for providing a negative air pressure; and

(iii) a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve, wherein the first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

33. The system as claimed in claim 32, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

34. The system as claimed in claim 32, wherein the multi-stage ejector includes a non-return valve.

35. The system as claimed in claim 32, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

36. The system as claimed in claim 32, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.

37. The system as claimed in claim 32, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.

38. A method of providing a dynamic vacuum source for an end effector, said method comprising the steps of:

- (a) coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure;

- (b) coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure;
 - (c) providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate; and
 - (d) switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, said first vacuum pressure being at least about 90,000 Pascals below atmospheric, and said second vacuum pressure being no more than about 50,000 Pascals below atmospheric, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.
39. The method as claimed in claim 38, wherein said first vacuum flow rate is at most about 5 cubic feet per minute, and said second vacuum flow rate is at least about 100 cubic feet per minute.
40. The method as claimed in claim 38, wherein the step of switching the dynamic vacuum source occurs automatically without any input commands.
41. The method as claimed in claim 38, wherein the method further includes the step of confirming, using an output of at least one pressure sensor, that the dynamic vacuum source has switched to the second vacuum pressure that is higher than the first vacuum pressure.
42. The method as claimed in claim 38, wherein the method further includes the step of confirming, using an output of at least one flow sensor, that the dynamic vacuum source has switched to the second vacuum flow rate that is greater than the first vacuum flow rate.
43. The method as claimed in claim 38, wherein the method occurs during application of the end effector to an object to be grasped.

44. The method as claimed in claim 38, wherein the method occurs during a process of lifting an object with the end effector.

45. The method as claimed in claim 38, wherein the method occurs during a process of moving an object with the end effector.

46. The method as claimed in claim 38, wherein the method further includes the step of providing a positive air pressure to the end effector to urge an object from the end effector.

47. A method of providing a dynamic vacuum source for an end effector, said method comprising the steps of:

- (a) coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure;
- (b) coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure;
- (c) providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate; and
- (d) switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, said first vacuum flow rate being at most about 5 cubic feet per minute, and said second vacuum flow rate being at least about 100 cubic feet per minute, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source.

48. The method as claimed in claim 47, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.
49. The method as claimed in claim 47, wherein the step of switching the dynamic vacuum source occurs automatically without any input commands.
50. The method as claimed in claim 47, wherein the method further includes the step of confirming, using an output of at least one pressure sensor, that the dynamic vacuum source has switched to the second vacuum pressure that is higher than the first vacuum pressure.
51. The method as claimed in claim 47, wherein the method further includes the step of confirming, using an output of at least one flow sensor, that the dynamic vacuum source has switched to the second vacuum flow rate that is greater than the first vacuum flow rate.
52. The method as claimed in claim 47, wherein the method occurs during application of the end effector to an object to be grasped.
53. The method as claimed in claim 47, wherein the method occurs during a process of lifting an object with the end effector.
54. The method as claimed in claim 47, wherein the method occurs during a process of moving an object with the end effector.
55. The method as claimed in claim 47, wherein the method further includes the step of providing a positive air pressure to the end effector to urge an object from the end effector.
56. A system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising:
- a first air source for providing a positive air pressure;
 - a second air source for providing a negative air pressure;
 - a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving

the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve; and

a covering at a contact surface of the end effector that includes a single opening that provides more air flow at a center of the contact surface than at a periphery of the contact surface.

57. The system as claimed in claim 56, wherein the covering is formed of a compliant material.

58. The system as claimed in claim 56, wherein said first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

59. The system as claimed in claim 56, wherein the multi-stage ejector includes a non-return valve.

60. The system as claimed in claim 56, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

61. The system as claimed in claim 56, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.

62. The system as claimed in claim 56, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.

63. The system as claimed in claim 56, wherein the first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric

64. A system for providing dynamic vacuum control to an end effector of an articulated arm, said system comprising:

- a first air source for providing a positive air pressure;

- a second air source for providing a negative air pressure;

- a multi-stage ejector coupled at a first end thereof to the first air source for receiving the positive air pressure and coupled at a second opposite end thereof to the second air source for receiving the negative air pressure, wherein the first air source and the second air source are thereby provided to the multi-stage ejector that automatically selects between a first vacuum source that uses the first air source to provide a first vacuum pressure with a first maximum air flow rate and a second vacuum source that uses the second air source to provide a second vacuum pressure with a second maximum air flow rate responsive to a change in air pressure at an exit of the multi-stage ejector without using an independently actuatable valve; and

- a covering at a contact surface of the end effector that includes multiple openings that together provide more air flow at a center of the contact surface than at a periphery of the contact surface.

65. The system as claimed in claim 64, wherein the covering is formed of a compliant material.

66. The system as claimed in claim 64, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

67. The system as claimed in claim 64, wherein the multi-stage ejector includes a non-return valve.

68. The system as claimed in claim 64, wherein the system further includes at least one pressure sensor for providing a pressure sensor signal representative of air pressure at the end effector.

69. The system as claimed in claim 64, wherein the system further includes at least one flow sensor for providing a flow sensor signal representative of air flow at the end effector.

70. The system as claimed in claim 64, wherein the system further includes a release source for providing positive pressure at the end effector for ejecting an object from the end effector.

71. The system as claimed in claim 64, wherein the first maximum air flow rate is at most about 5 cubic feet per minute, and said second maximum air flow rate is at least about 100 cubic feet per minute.

72. A method of providing a dynamic vacuum source for an end effector, said method comprising:
coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure;

coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure;

providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate;

switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, wherein the first vacuum source and the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source; and

providing a covering at a contact surface of the end effector that includes a single opening that provides more air flow at a center of the contact surface than at a periphery of the contact surface.

73. The system as claimed in claim 72, wherein the covering is formed of a compliant material.
74. The method as claimed in claim 72, wherein said first vacuum flow rate is at most about 5 cubic feet per minute, and said second vacuum flow rate is at least about 100 cubic feet per minute.
75. The method as claimed in claim 72, wherein the step of switching the dynamic vacuum source occurs automatically without any input commands.
76. The method as claimed in claim 72, wherein the method further includes the step of confirming, using an output of at least one pressure sensor, that the dynamic vacuum source has switched to the second vacuum pressure that is higher than the first vacuum pressure.
77. The method as claimed in claim 72, wherein the method further includes the step of confirming, using an output of at least one flow sensor, that the dynamic vacuum source has switched to the second vacuum flow rate that is greater than the first vacuum flow rate.
78. The method as claimed in claim 72, wherein the method occurs during application of the end effector to an object to be grasped.
79. The method as claimed in claim 72, wherein the method occurs during a process of lifting an object with the end effector.
80. The method as claimed in claim 72, wherein the method occurs during a process of moving an object with the end effector.
81. The method as claimed in claim 72, wherein the method further includes the step of providing a positive air pressure to the end effector to urge an object from the end effector.

82. The method as claimed in claim 72, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric

83. A method of providing a dynamic vacuum source for an end effector, said method comprising:

coupling a first end of a multi-stage ejector to a first air source such that the first end of the multi-stage ejector receives positive air pressure;

coupling a second opposite end of the multi-stage ejector to a second air source such that the second end of the multi-stage ejector receives negative air pressure;

providing at the end effector a first vacuum from a first vacuum source that includes a compressor, said first vacuum providing a first vacuum pressure and a first vacuum flow rate;

switching the dynamic vacuum source to provide at the end effector a second vacuum from a second vacuum source that includes a blower, said second vacuum providing a second vacuum pressure and a second vacuum flow rate, wherein the first vacuum source the second vacuum source are provided by the multi-stage ejector that employs a non-return valve as a selection mechanism to select between the first vacuum source and the second vacuum source; and

providing a covering at a contact surface of the end effector that includes multiple openings that together provide more air flow at a center of the contact surface than at a periphery of the contact surface.

84. The method as claimed in claim 83, wherein the covering is formed of a compliant material.

85. The method as claimed in claim 83, wherein said first vacuum pressure is at least about 90,000 Pascals below atmospheric, and said second vacuum pressure is no more than about 50,000 Pascals below atmospheric.

86. The method as claimed in claim 83, wherein the step of switching the dynamic vacuum source occurs automatically without any input commands.

87. The method as claimed in claim 83, wherein the method further includes the step of confirming, using an output of at least one pressure sensor, that the dynamic vacuum source has switched to the second vacuum pressure that is higher than the first vacuum pressure.

88. The method as claimed in claim 83, wherein the method further includes the step of confirming, using an output of at least one flow sensor, that the dynamic vacuum source has switched to the second vacuum flow rate that is greater than the first vacuum flow rate.

89. The method as claimed in claim 83, wherein the method occurs during application of the end effector to an object to be grasped.

90. The method as claimed in claim 83, wherein the method occurs during a process of lifting an object with the end effector.

91. The method as claimed in claim 84, wherein the method occurs during a process of moving an object with the end effector.

92. The method as claimed in claim 84, wherein the method further includes the step of providing a positive air pressure to the end effector to urge an object from the end effector.

93. The method as claimed in claim 84, wherein said first vacuum flow rate is at most about 5 cubic feet per minute, and said second vacuum flow rate is at least about 100 cubic feet per minute.

1/11

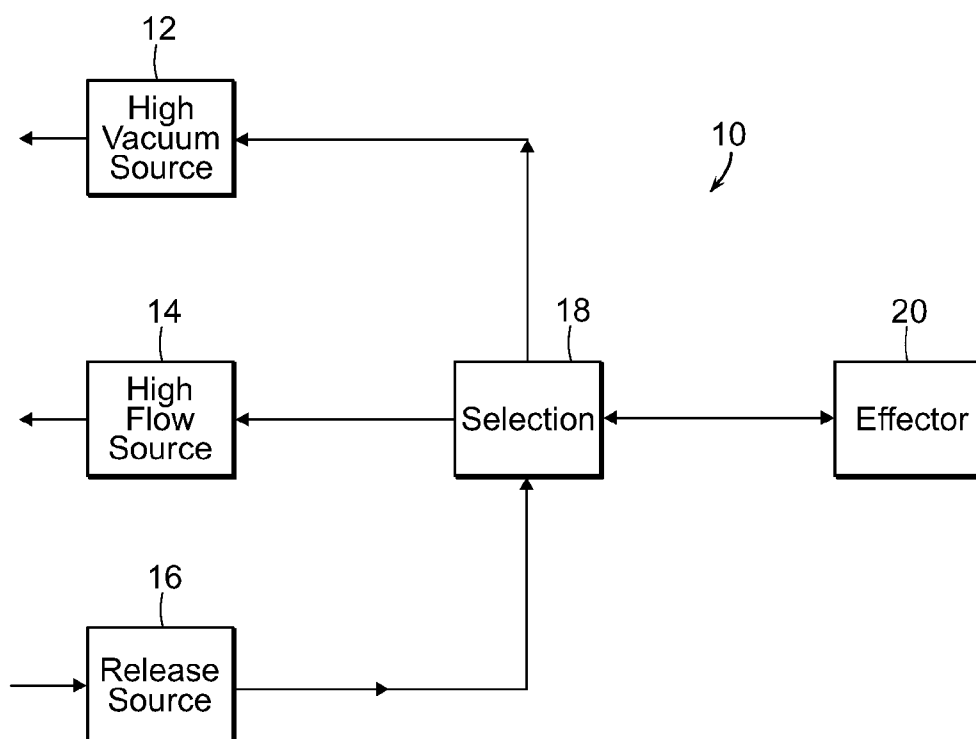


FIG. 1

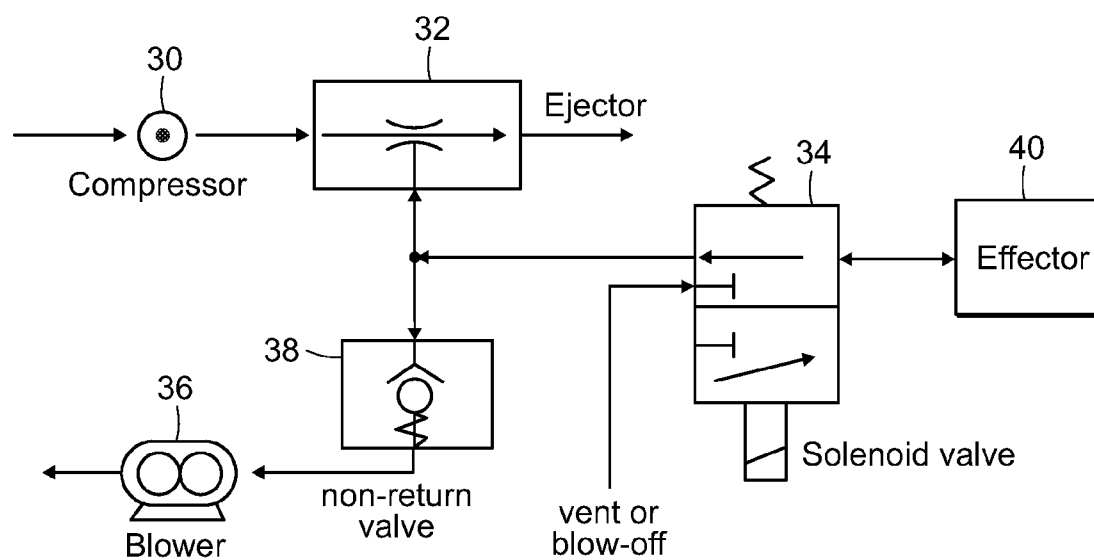


FIG. 2

2/11

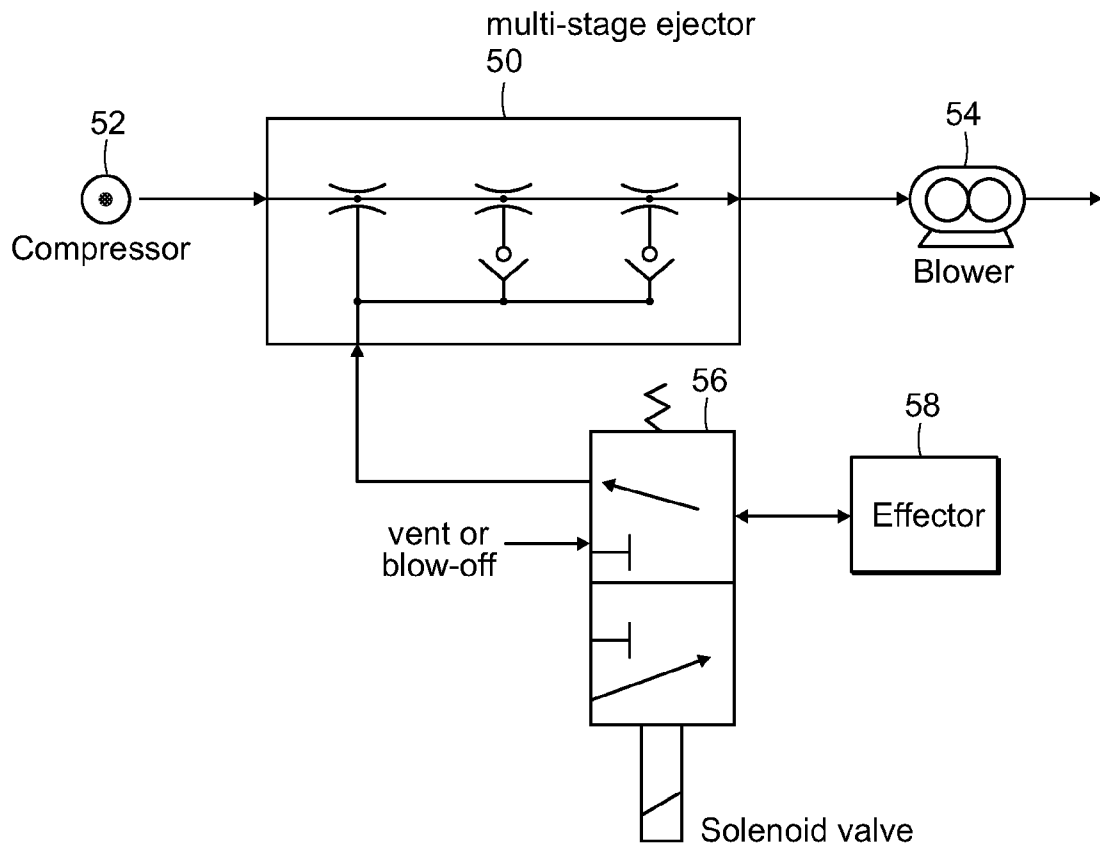


FIG. 3

3/11

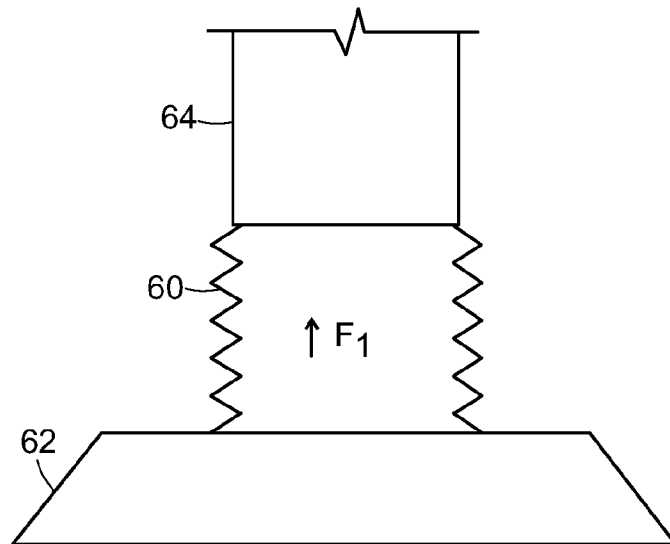


FIG. 4

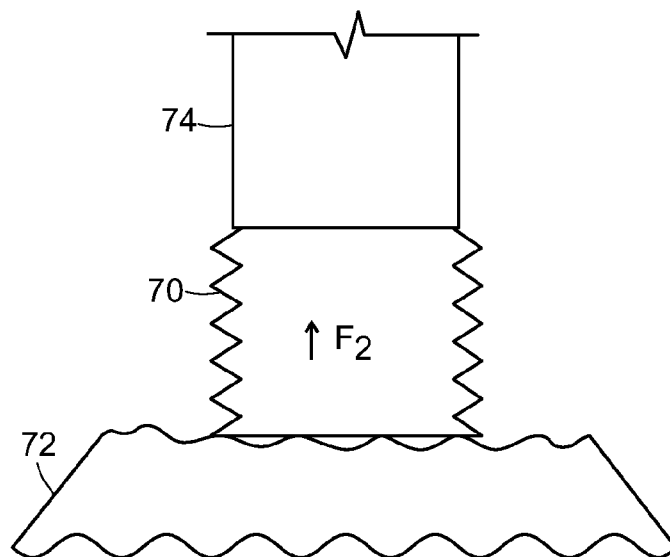


FIG. 5

4/11

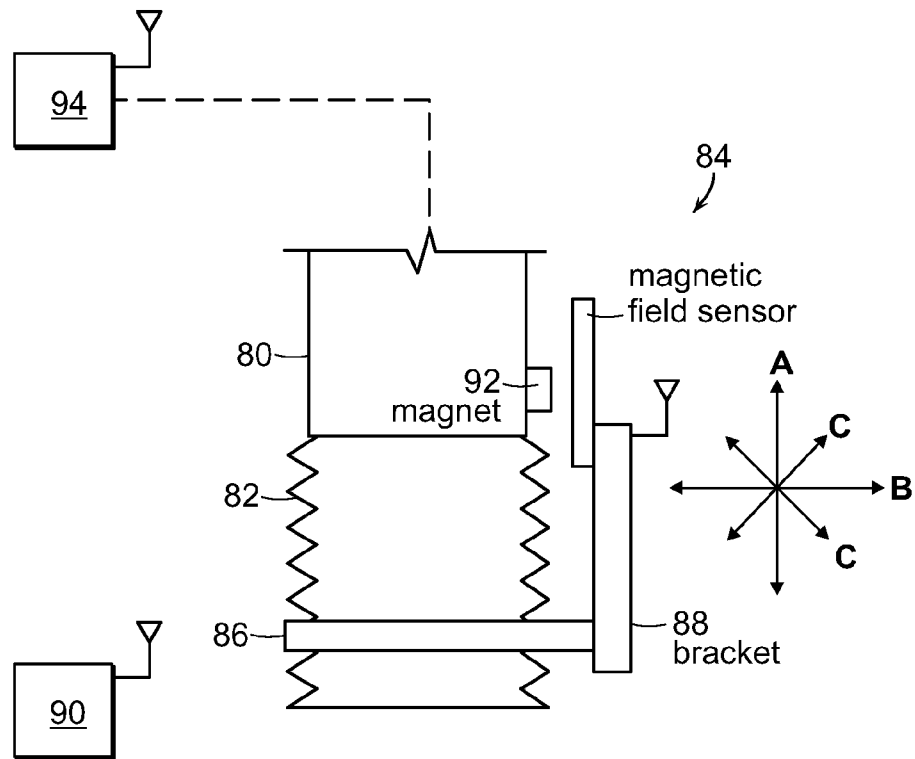


FIG. 6

5/11

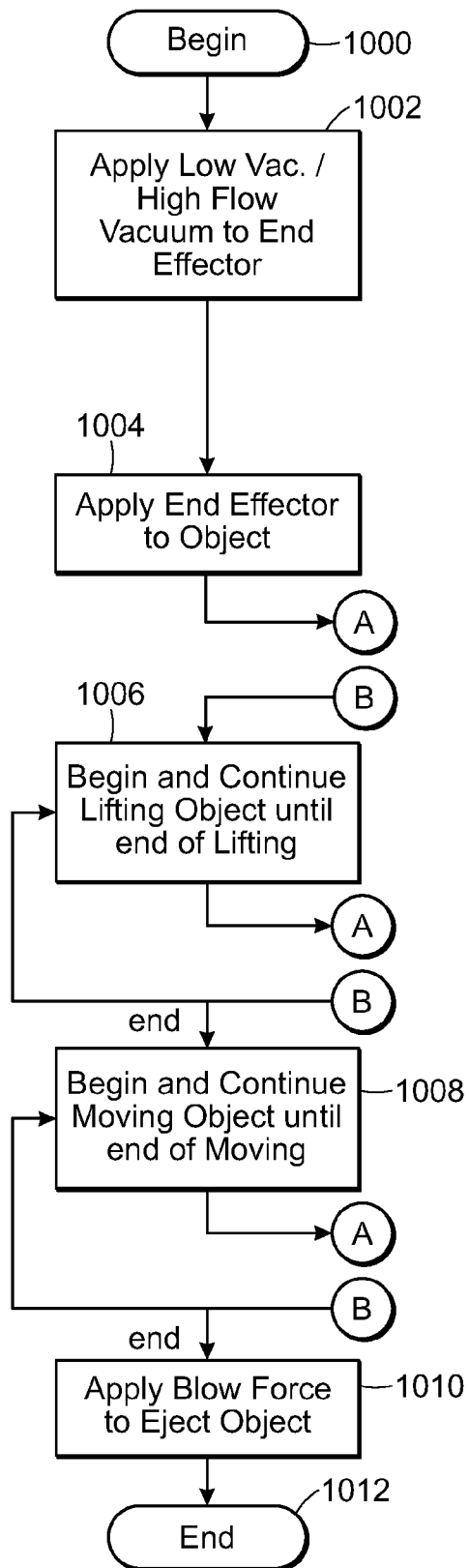


FIG. 7A

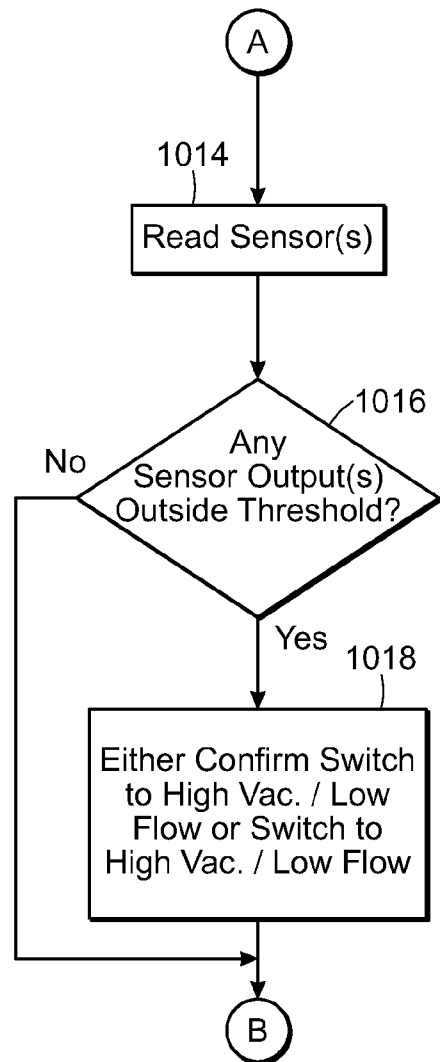


FIG. 7B

6/11

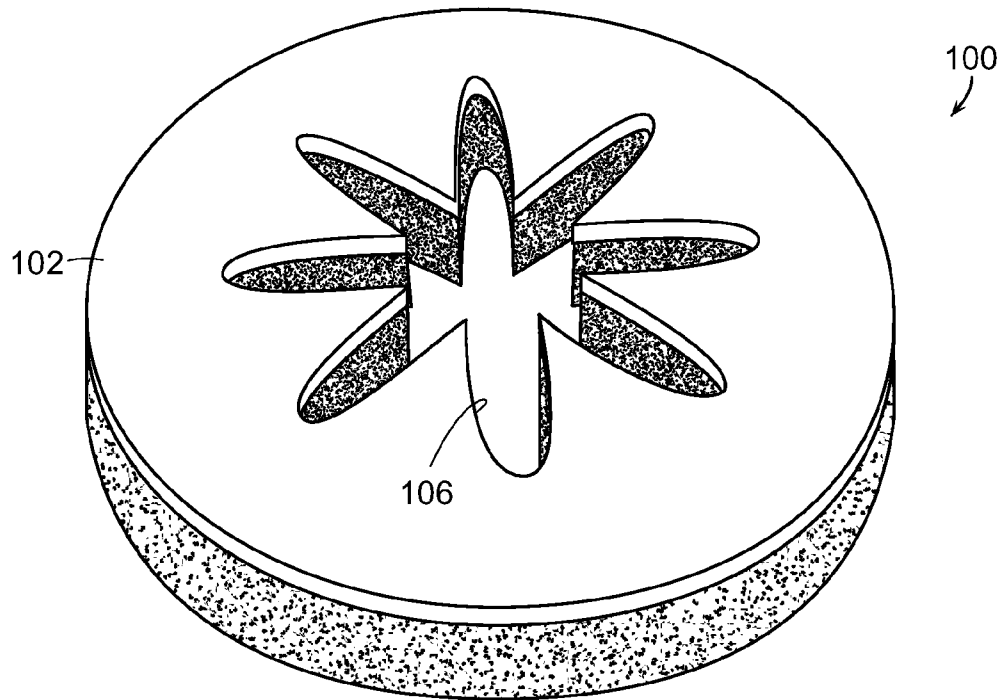


FIG. 8A

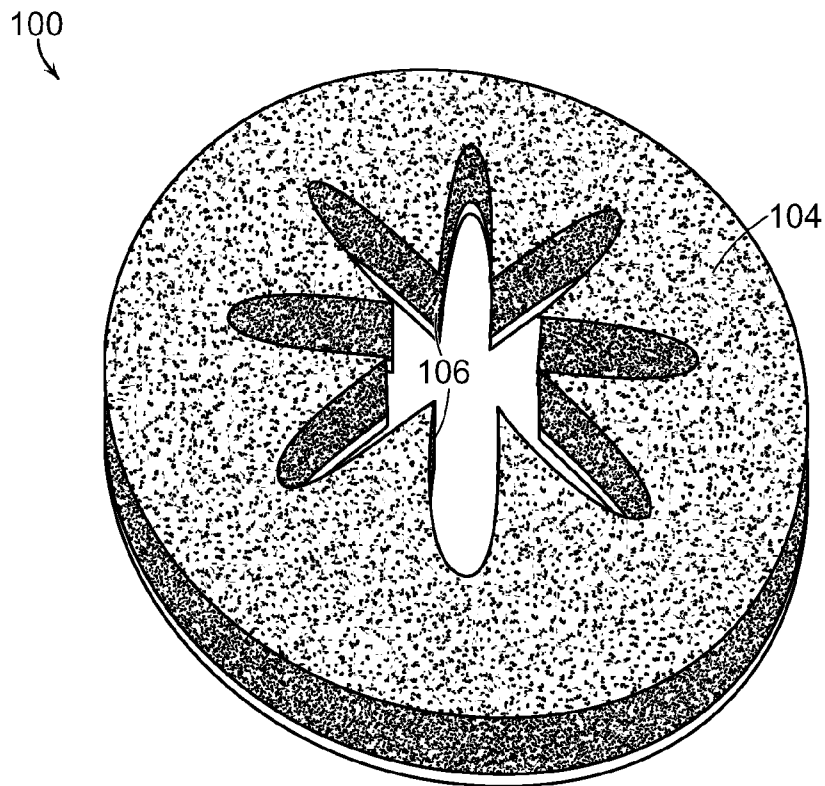


FIG. 8B

7/11

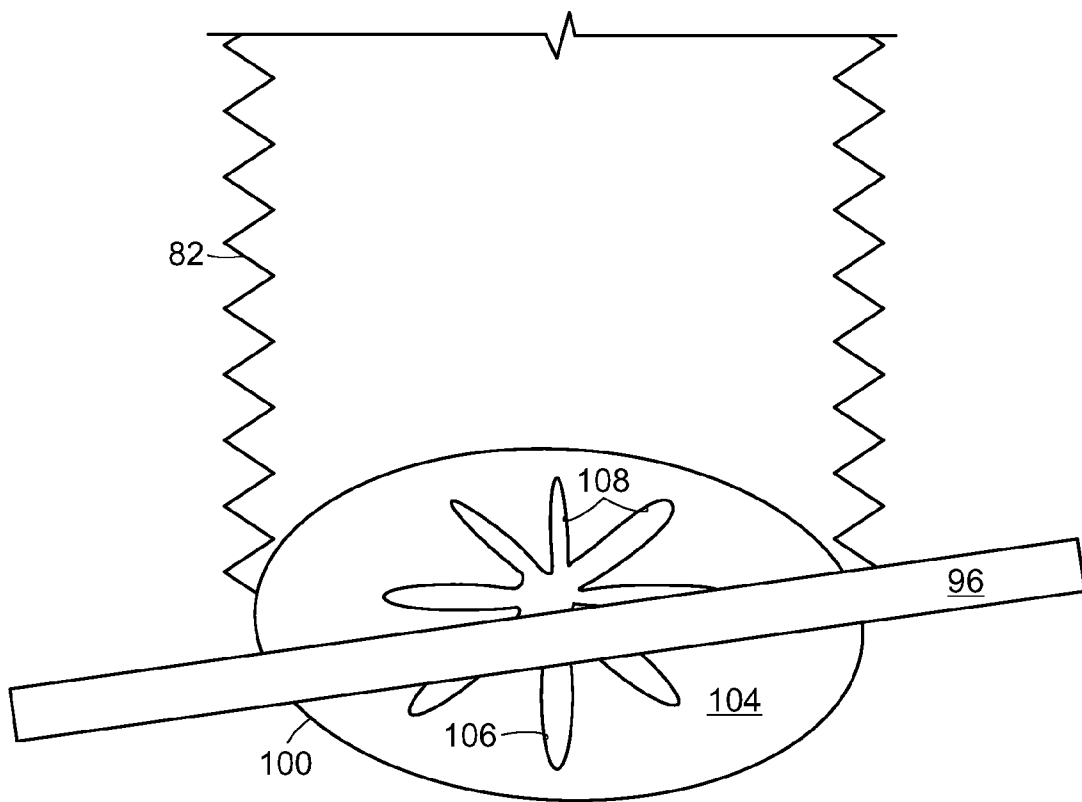


FIG. 9

8/11

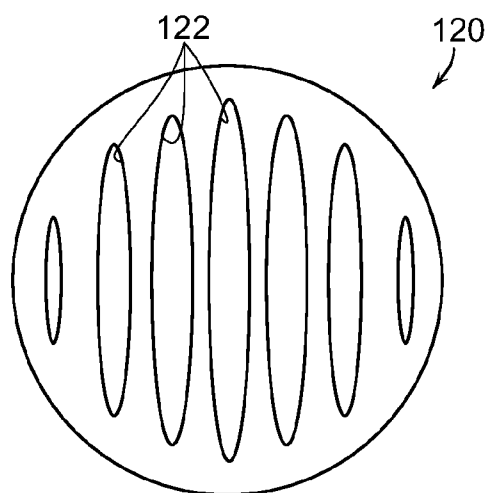


FIG. 10A

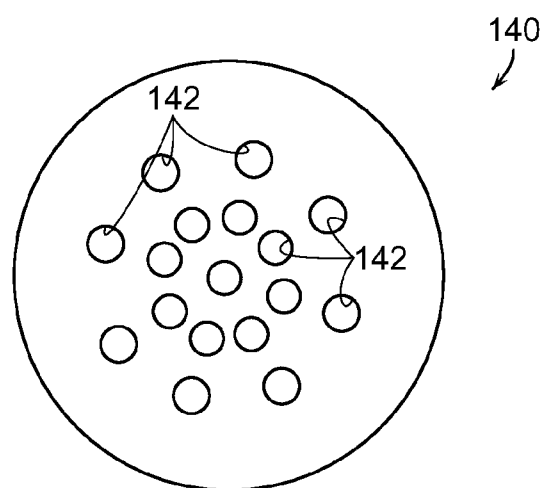


FIG. 10C

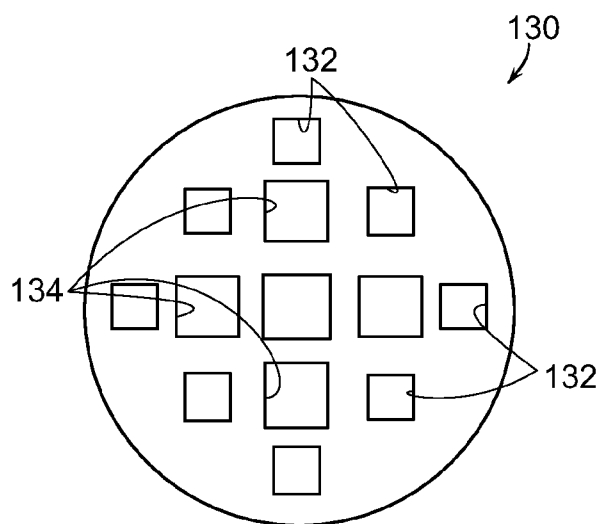


FIG. 10B

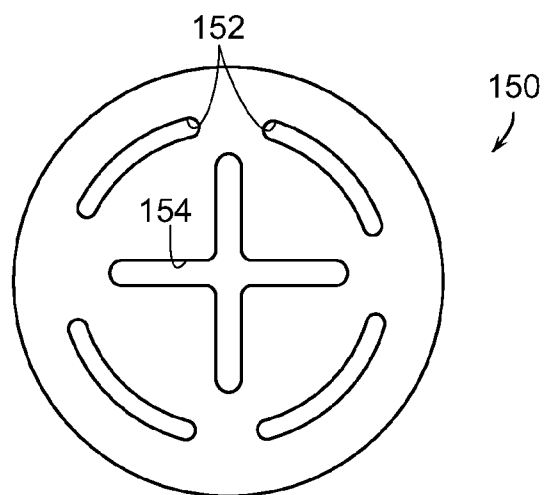


FIG. 10D

9/11

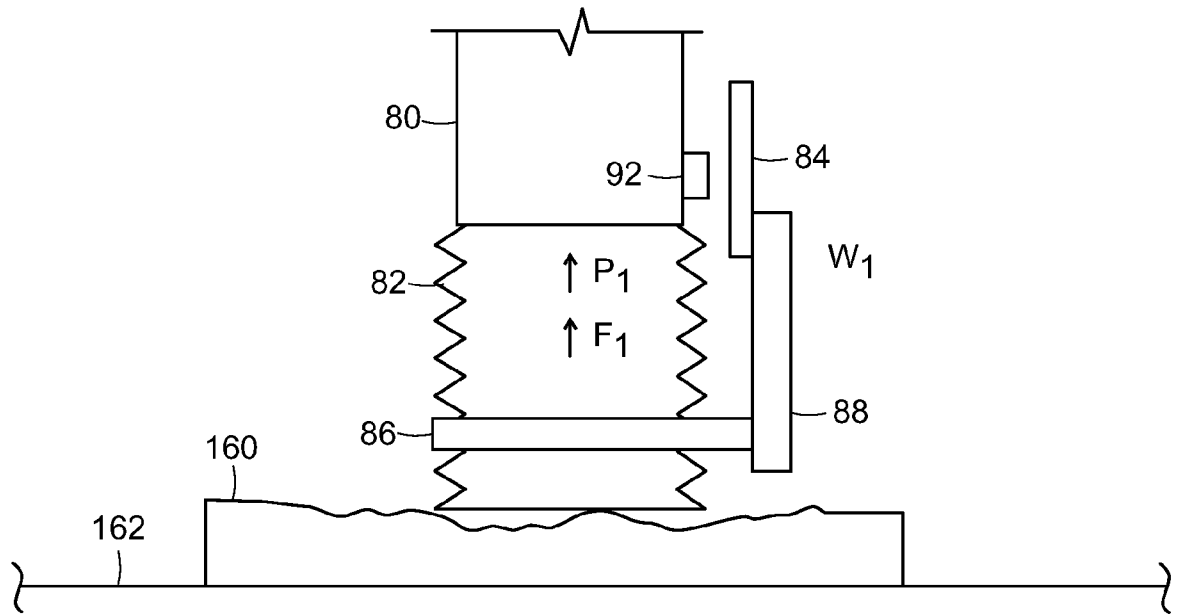


FIG. 11A

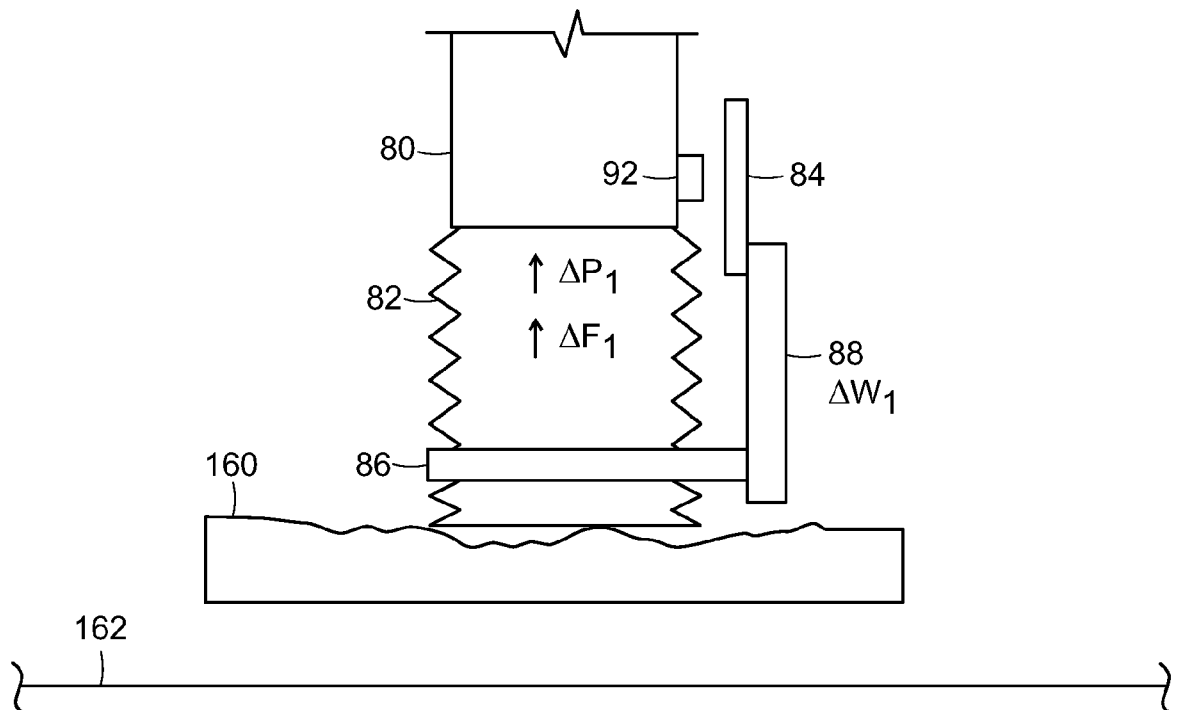


FIG. 11B

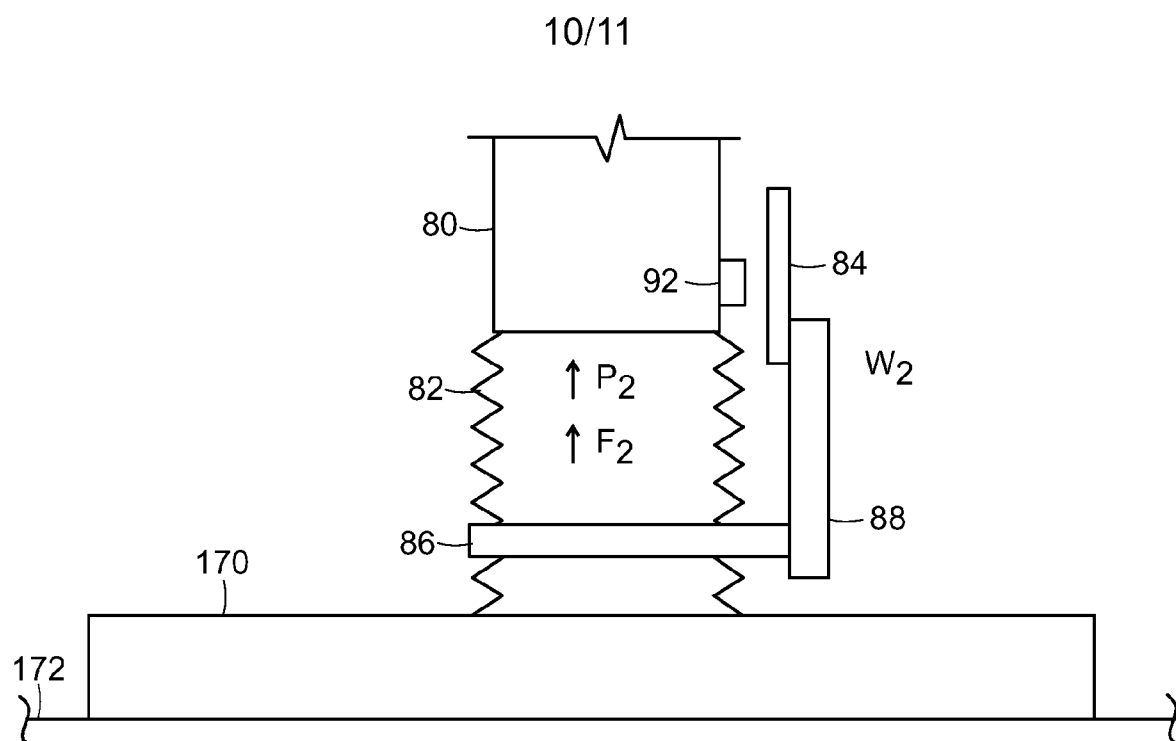


FIG. 12A

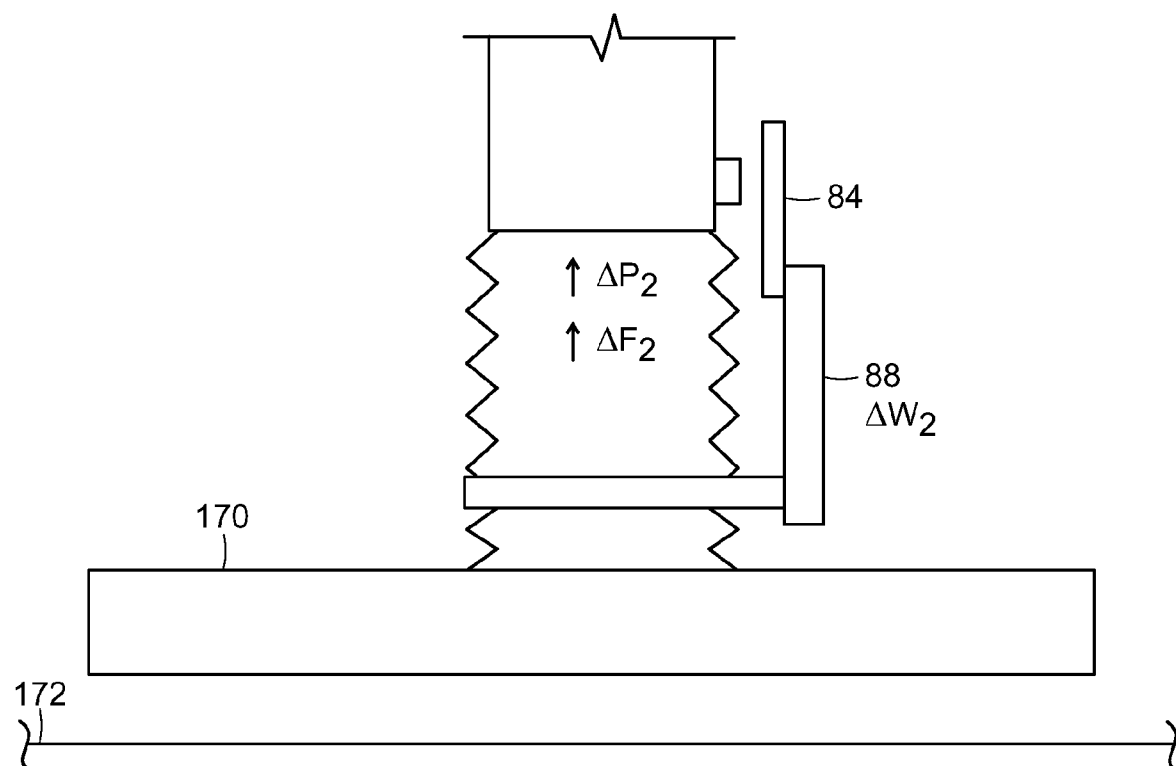


FIG. 12B

11/11

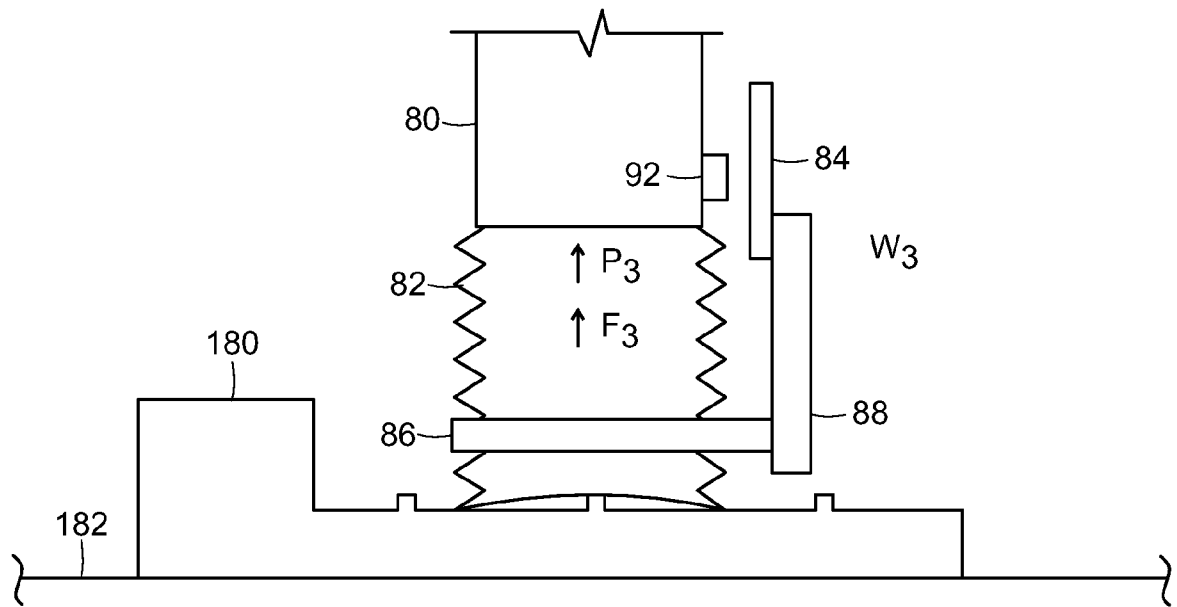


FIG. 13A

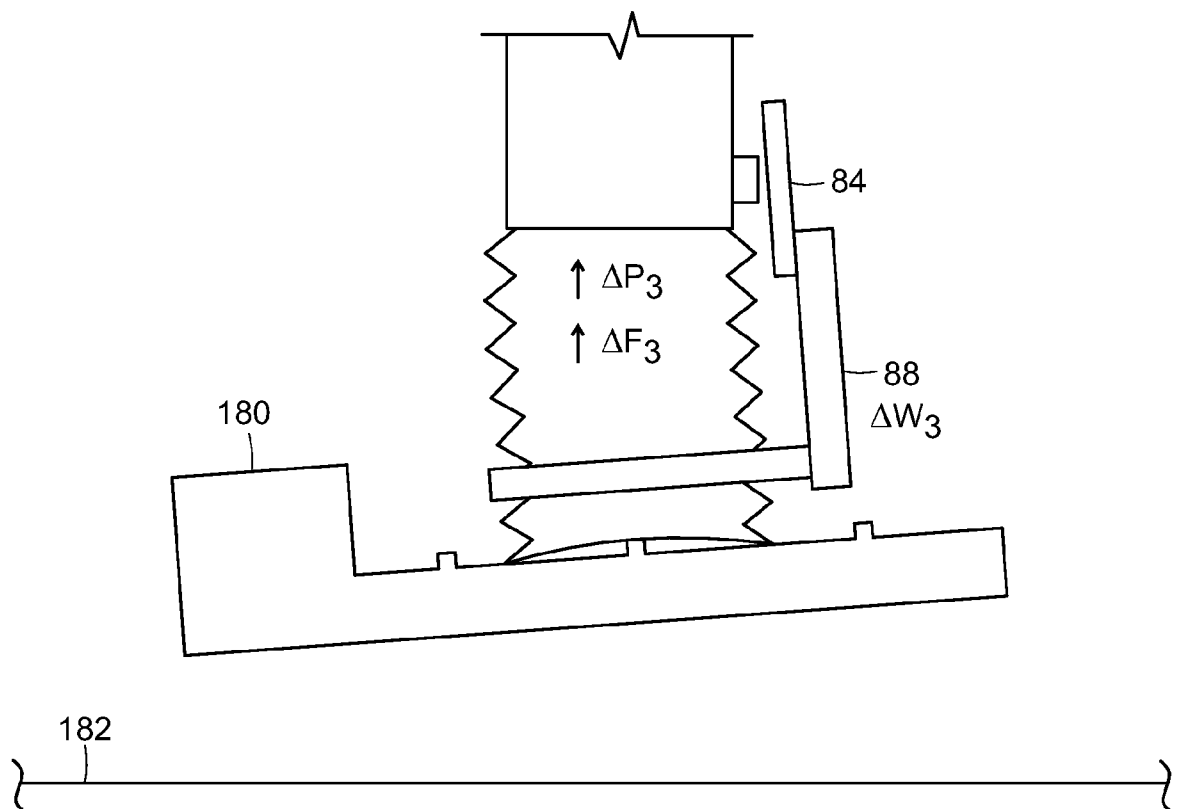


FIG. 13B

