A vacuum-based bonding mechanism for modular robotics

Ricardo F. M. Garcia, Jonathan D. Hiller, Hod Lipson

***Abstract*— We present our progress on the design and implementation of Vacuubes, a set of robotic modules that exploit vacuum as adhesive force to form and hold structures. We use a first prototype to perform basic experiments that demonstrate the vacuum sealing capabilities of the modules, as well as the proper actuation of a valve designed to propagate vacuum between two of these modules. Based on these results, we expect that vacuum is a viable connection principle for any modular technology where easy attachment and detachment is required.**

I. Introduction

A modular robot is a robot built from many similar modules that attach to each other by using connection mechanisms. Although single modules have limited uses, they are able to combine into more functional structures according to the task being performed [1].

The advantages of modular robots over robots made from a few special-purpose parts are three. First, their ability of assembling task-suitable structures makes modular robots more *flexible*. Second, their redundancy of modules makes them more *robust*. Third, their similarity between modules makes production of modular robots potentially *cheaper* [2].

As reconfiguration plays an important role in these robots, modules must be easy to attach and detach. Additionally, connection between modules must be strong enough to hold large configurations and to support additional loads of, for example, manipulating tasks. Hence, a very important part of design of modules involves the connection mechanism [3], [4].

One connection mechanism of modular robots is active hooks. In this approach, modules are loaded with motor-driven protrusions that hook either holes or complementary protrusions in neighbouring modules to achieve attachment [5], [6], [7], [8]. Although strong, these mechanisms require many motors to drive many connectors (one per active face) with the consequent increase in complexity and price of modules.

Another connection mechanism is passive hooks. Here, modules are loaded with passive connectors that are manually plugged into complementary sockets of neighbouring modules to achieve attachment [9], [10], [11]. Although this approach is also strong, autonomous attachment, if desired, would demand dexterous robots and precise alignment of parts.

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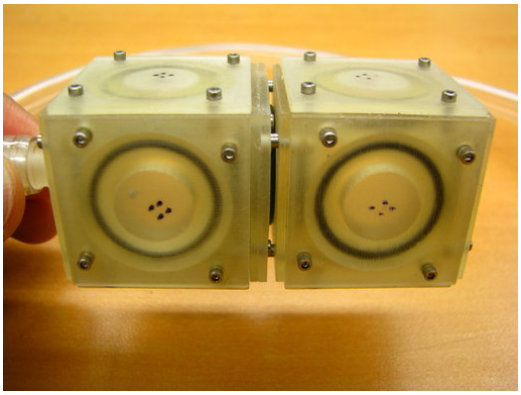


Fig. 1. Vacuum holding two modules together. Vacuum is at first generated inside the body of the cube on the left and then propagated to the cube on the right by using a pneumatic valve that opens only when their faces are brought into contact.

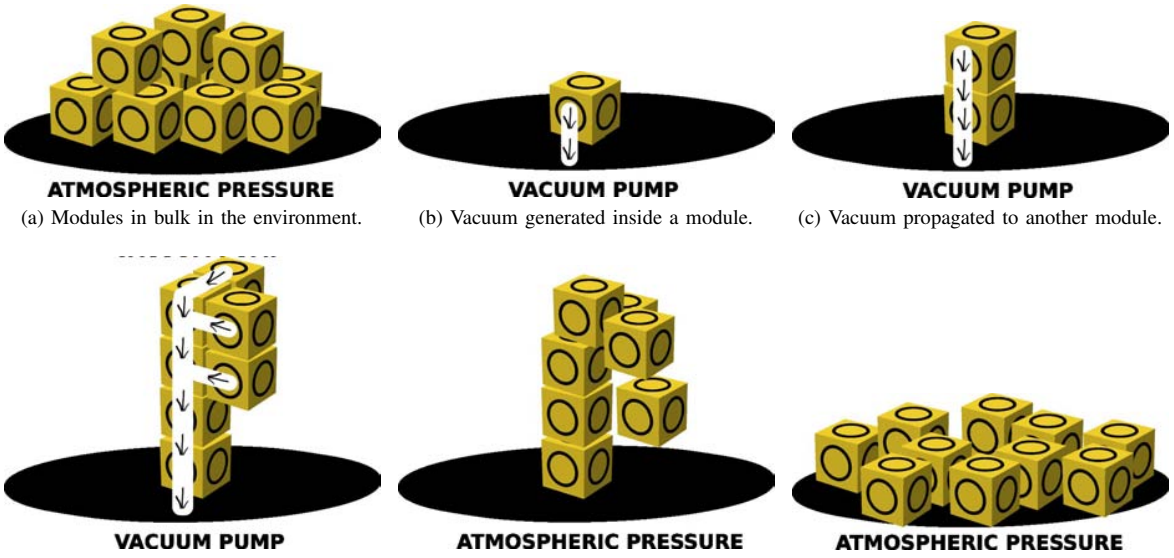
The next connection mechanism is magnetic attachment. In this approach, faces of modules loaded with magnets, such as permanent magnets [12], electro-magnets [13] or Magswitches[1] [14], are brought into close proximity to achieve attachment. Although this is perhaps the easiest way to put modules together, connection strength may not be suitable for large constructions. Additionally, permanent magnets can be (one-by-one) difficult to detach, electro-magnets consume too much power, and Magswitches also demand a motor per connector to turn them on or off.

A final connection mechanism is Velcro. In this case, faces of modules covered with Velcro stripes are brought into close proximity to modules with complementary stripes to achieve attachment [15]. Unfortunately, the strength of this approach is also not suitable for large constructions.

We explore vacuum as adhesive force to form and hold structures made of modules. Our idea is to keep vacuum inside a cubic module loaded with normally-closed pneumatic valves in all faces, and then propagate vacuum to another module when their faces are brought into contact, as shown in Fig. 1. Besides simplicity and easy attachment, we believe that this approach allows for easy detachment of modules by releasing vacuum to atmospheric pressure, as shown in Fig. 2 for a structure made of many modules. We call our modules *Vacuubes*.

In the coming sections we show initial design and implementation of our modules as well as basic experiments that demonstrate fulfillment of important requirements, such as

[1]A Magswitch is a magnet that can be mechanically turned on or off. http://www.magswitch.com.au/



(a) Modules in bulk in the environment. (b) Vacuum generated inside a module. (c) Vacuum propagated to another module.

(d) Vacuum holding a structure of modules. (e) Vacuum released to atmospheric pressure. (f) Modules in bulk in the environment.

Fig. 2. Representation of the principle of vacuum holding structures of modules. The vacuum is propagated between modules by opening normally-closed pneumatic valves placed in all faces of all modules. The valves open automatically in response to the contact between neighbouring faces.

vacuum sealing and adhesion capabilities of the modules, and the proper actuation of a valve designed to propagate vacuum between two of these modules. Based on these results, we expect that vacuum is a viable connection principle for any modular technology where easy attachment and detachment is required.

II. Requirements

Considering easy attachment, easy detachment, strong connection, and that attachment forces are described by the equation $F = P * A$, the modules should:

- reach good vacuum levels, and
- maximize contact-area to weight ratio.

Considering also our lab resources, the modules should:

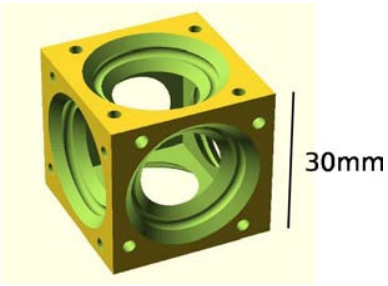
- be 3D-printed during prototyping, and
- have a maximum dimension of 30x30x30mm.

The dimensional requirement relates to the printing speed of our 3D-printer. 30x30x30mm is a good balance between size and printing time.

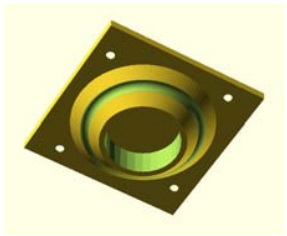
III. Design

A. Modularity

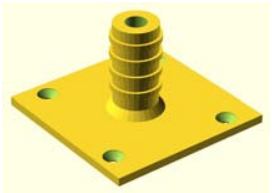
As we wanted to isolate sources of problems, we decided to design our modules in incremental steps. We wanted to test, at first, the permeability of the 3D-printing material, then, different approaches to pneumatic valves, and, finally, different alignment mechanisms for the faces of the modules. To this end, we followed a modular approach in which the cubes have exchangeable faces that can be loaded with different valves, alignment mechanisms, or whatever is needed to perform tests (e.g., a nozzle to connect a vacuum pump). Fig. 3 shows the CAD models of the cubes' skeleton and of a "nozzle" face.



(a) Skeleton of our modules.



(b) Bottom of a nozzle face.



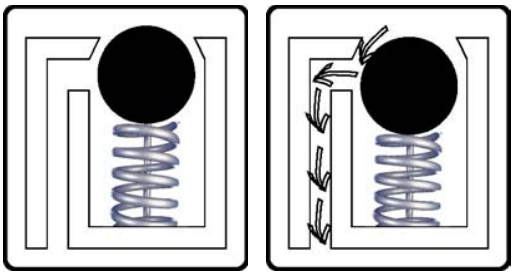
(c) Top of a nozzle face.

Fig. 3. In order to develop our modules in incremental steps, we followed a modular design. To this end, we made a supporting skeleton (a) and faces (b,c) that can be screwed into the skeleton. At the interface between skeleton and faces, there is a male-female mechanism loaded with a sealing o-ring to allow for the generation of vacuum inside the body of the module.

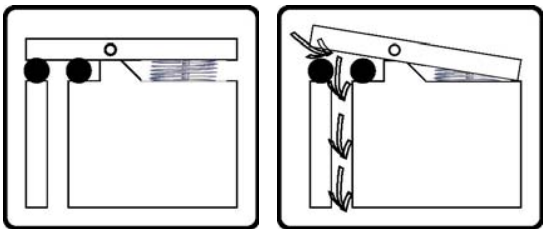
B. Pneumatic valves

Besides sealing vacuum to a high degree, the normally-closed valves had to open in response to contact with an approaching face of a neighbour module. By doing so, the valves could establish a *vacuum channel* between neighbour modules and, therefore, propagate vacuum. That said, we needed a push-actuated mechanism able to drive the valves from close to open state.

Our first idea to solve this problem was to use commercial



(a) Ball valve closed. (b) Ball valve opened.



(c) Pivoted valve closed. (d) Pivoted valve opened.

Fig. 4. Our initial ideas of two 3D-printable mechanisms to implement push-button normally-closed pneumatic valves. Here, we assume that the contact forces opening the valves approach them from the top. The advantage of the first mechanism (a,b) is little force required to open the valve, and the advantage of the second mechanism (c,d) is good sealing.

push-button valves, but, unfortunately, the smallest ones we found[2] were too big to fit in our modules. Afterwards, we figured out two 3D-printable mechanisms, which are shown in Fig. 4. The first mechanism (Figs. 4a and 4b) consists of a spring that pushes a rubber ball up in the vertical axis to seal a vacuum channel in the horizontal axis, and the second mechanism (Figs. 4c and 4d) consists of a pivoted cover that seals a vacuum channel along the vertical axis with the assistance of an o-ring and a spring. Notice that, in both cases, forces exerted by vacuum cooperate with the sealing strategy, and also that springs enable operation of these valves in all orientations.

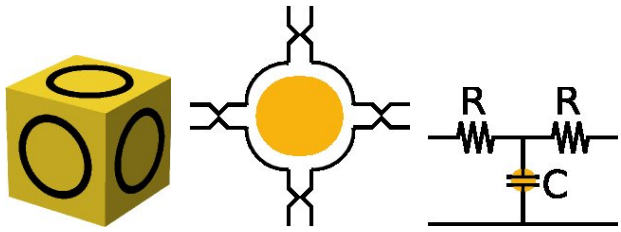
C. Simulation

At this point, we wanted to know the influence of the internal volume of the modules and the resistance to flow of the vacuum channels on the strength of the structure when adding a new module. In other words, we wanted to know which combination volume-resistance affects the vacuum levels in the modules the least. Big volume and small resistance? Big volume and big resistance? As we did not have the answer, we decided to simulate the pneumatic system determined by our modules.

We first considered internal volume as a pneumatic accumulator and channel's resistance as a constriction in a pipe, and then determined the equivalent electronic circuit, as shown in Fig. 5. We then simulated the behaviour of the sequential connection of four modules into a chain by using the LTspice[3] electronic simulator and the equivalent circuit

[2]http://www.valve-push-button.com/

[3]http://www.linear.com/

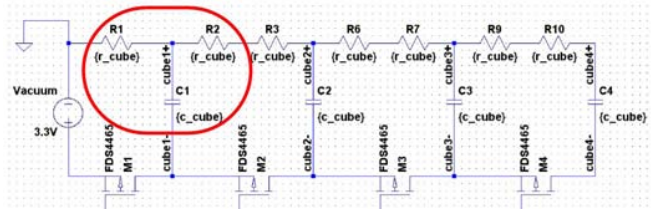


(a) A module. (b) Equivalent accumulator. (c) Equivalent circuit.

Fig. 5. To simulate the fluid dynamics of the structures made of our modules, we considered internal volume as a pneumatic accumulator and channel's resistance as a constriction in a pipe. Then, we determined the equivalent electronic circuit as a capacitor representing the accumulator and resistances representing constrictions.



(a) A chain of four modules connected to a vacuum pump.

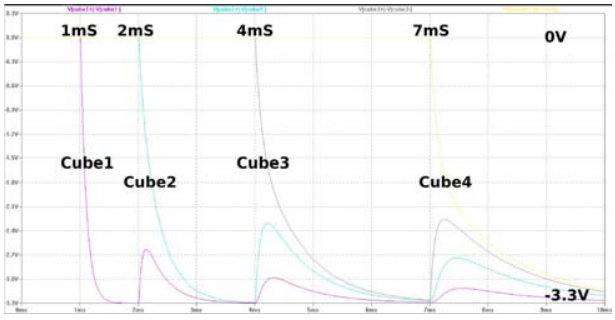


(b) Equivalent circuit of a chain of four modules.

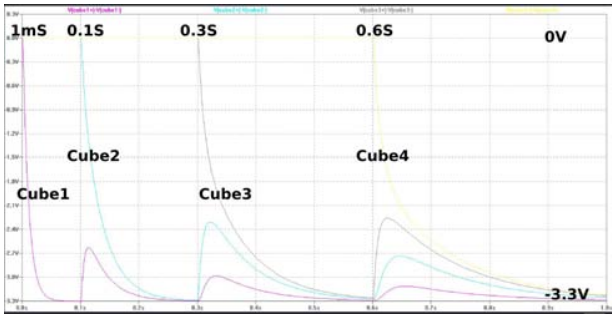
Fig. 6. Pneumatic system made of a chain of four modules (a) and its equivalent electronic circuit (b). In this figure, the red circle shows the electronics related to only one module, a negative power supply simulates a vacuum pump, and transistors allow to simulate sequential connection of modules to the chain.

shown in Fig. 6. In our setup, we gave arbitrary initial values to capacitors (volumes) and resistances (constrictions), and, then, we proceeded to vary these values to perform comparisons. Thus, our analysis is only qualitative.

Our simulation results, shown in Fig. 7, provided interesting insights. For example, we observed that, when adding a new module to the structure, the entry module receiving this new module suffers the highest decrement in the vacuum level and recovery time. We also observed that the larger the chain the worse is the effect on the entry module (which is always the last module in the chain). Most interestingly, we observed that increasing volume and keeping resistance small or keeping volume small and increasing resistance produces exactly the same output: the magnitudes of the vacuum drops in the cubes are the same as in the initial simulation, but the times required to recover from these drops are, in these cases, larger and proportional to the product of both parameters (i.e., $\tau = RC$ constant). Keeping in mind that vacuum level is dependant on the amount of air molecules enclosed in a volume (the less the better), we interpret last observation as follows:



(a) Simulation result for small R and small C.



(b) Simulation result for small R and big C.

Fig. 7. Simulation of the sequential connection of four modules into a chain. In this simulation, peaks in voltage values represent the moments when a new module is connected to the chain, and $-3.3V$ represents a perfect vacuum level. The results provide valuable information about the influence of volume of modules, C, and resistance to flow of the vacuum channels, R, on the strength of structures when adding a new module.

- big volumes resist more air molecules in the system before collapsing but also bring more of these molecules to the system when adding a new module, and
- big resistances slow down the rate at which air molecules enter the system but also the rate at which they leave.

Thus, according to our interpretations of the simulation results, small volume and small resistance (i.e., big vacuum channels) would improve recovery times but would do little in terms of vacuum drops. This is problematic because structures would still collapse with big vacuum drops for short periods of time, and these times would take longer as the structure grow. Despite that, we now believe that a possible solution to the problem of vacuum drops would be: big resistance to the entry of air molecules and small resistance to the exit of them.

IV. Implementation

A. 3D-printing material permeability

We began implementation by 3D-printing the skeleton of our modules, a nozzle face to connect a vacuum pump, and simple faces without any valve or hole just to test the sealing properties of our material (sealing faces). Fig. 8a shows the implementation of the skeleton and the sealing faces. We 3D-printed the parts in an Object Eden 260V 3D-printer loaded with a translucent acrylic-based photopolymer material called Fullcure 720[4], and, with a thickness of 1.5mm, the material allowed us to reach and keep vacuum levels of 27.5 in.-Hg. We interpret this results as positive in terms of permeability.

B. Pneumatic valves

Unfortunately, the 3D-printed implementation of the ball valve design (Figs. 4a and 4b) was not able to keep vacuum. Even with a protrusion at the sealing height to pull the ball towards the hole in the horizontal axis, the sealing achieved was not acceptable. We believe that the reason of this problem is the high precision demanded on the spring extension to position the valve at the correct sealing height.

Despite that, the previous mechanism allowed us to test an interesting approach. We simply pre-stressed the spring pushing the ball up, so that the sealing point would now be at the top hole (not at the horizontal axis), and we succeeded at sealing. This approach is similar to "Schrader" valves of cars and bikes, with the difference that, now, the spring has to overcome the vacuum force pushing the ball down. Fig. 8b shows a diagram of this modified ball mechanism, and Fig. 8c shows the implementation of the same valve. Notice that we replaced the ball with a button with o-rings in order to adjust the point of actuation by varying the length of the button's knob, and also to play with the resistance of the vacuum channel by varying the cross-section of the same knob. Our idea to apply the insights from simulation (i.e., big/small resistance to entry/exit of air, respectively) is to vary the knob's cross-section, going from wide to narrow and then from narrow to wide again.

As the modified ball valve mechanism worked, we did not test the pivoted valve mechanism (Figs. 4c and 4d).

C. Alignment mechanisms

Up to this point, we have not designed nor tested any alignment mechanism.

V. Experiments

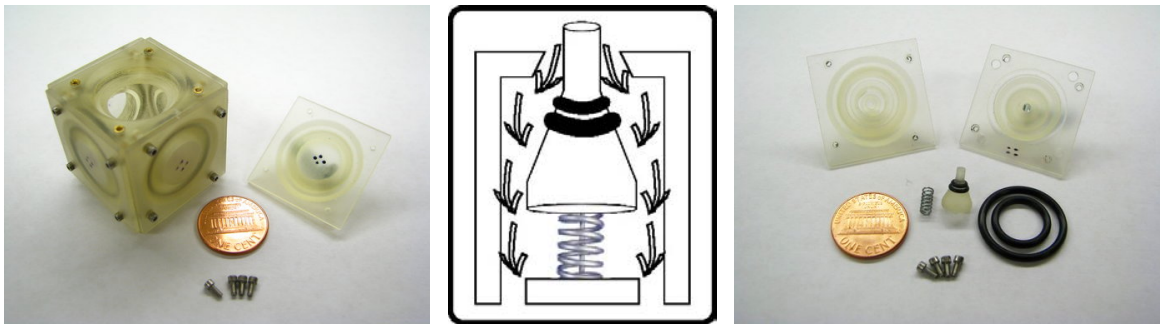
A. Vacuum holding-releasing

Fig. 9 shows an experiment to demonstrate the vacuum holding capabilities of Vacuubes as well as the proper actuation of the valve. In this experiment, we assemble a module with two nozzle faces (one to connect a manual vacuum pump and another to connect a pressure gauge), a valve, and three sealing faces. Then, we build up vacuum inside the body of the module, and, after a couple of seconds, we release vacuum by pushing the button of the valve.

B. Attachment-detachment

Fig. 10 shows an experiment to demonstrate the idea of modules sticking together by using vacuum. In this experiment, we basically use the same setup as the previous experiment, but we also assemble a second module with five sealing faces and a valve. We perform the experiment as follow: first, we place the two valves of the modules face-to-face with an o-ring in between, then, we build up vacuum

[4]http://www.objet.com/Materials/FullCure720_Transparent/



(a) Skeleton and sealing faces of modules. (b) Diagram of valve. (c) Parts of valve.

Fig. 8. Implementation of our modules. Although most of the parts of our modules are 3D-printed, we also use standard components, such as screws, springs, threaded inserts, and o-rings. (a) shows the implementation of skeleton and sealing faces of our modules, (b) shows a diagram of our final implementation of the normally-close valve to propagate vacuum between neighbouring modules, and (c) shows the parts of the same valve.



(a) (b) (c) (d) (e)

Fig. 9. Experiment to demonstrate the vacuum holding capabilities of Vacuubes, as well as the proper actuation of our normally-closed pneumatic valve. In this experiment, we build up vacuum inside the body of the modules by using a vacuum pump (a,b,c), and, after a couple of seconds, we release vacuum by pushing the button of the valve (d,e). Vacuum levels can be continuously observed in the vacuum gauge (from 0 to 30 in.-Hg) connected to the module.



(a) (b) (c) (d) (e)

Fig. 10. Experiment to demonstrate the idea of modules sticking together by using vacuum. Here, we use two modules loaded with valves, and a manual vacuum pump connected to one of these modules. We perform the experiment as follow: first, we place the two valves of the modules face-to-face (a,b), then, we build up vacuum in the body of the modules (c), after that, we manipulate the structure for a while (d), and, finally, we release the vacuum to atmospheric pressure with the consequent detachment of the structure (e).

in the body of the modules, after that, we manipulate the structure for a while, and, finally, we release the vacuum to atmospheric pressure with the consequent detachment of the structure.

VI. Conclusions and Future Work

We presented our progress on the design and implementation of modules able to attach to each other by using vacuum as adhesive force. In addition to that, we performed simple experiments that demonstrated fulfillment of important requirements, such as vacuum sealing and adhesion capabilities of the modules, and the proper actuation of a valve designed to propagate vacuum between two of these modules. Based on these results, we expect that vacuum is a viable connection principle for any modular technology where easy attachment and detachment is required.

In the near future, we will address not only alignment mechanisms and assembly of larger structures but also the construction of a robot able to manipulate our modules. The idea is then to explore reconfiguration of passive structures; a challenge known as machine metabolism.

Acknowledgment

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