Design of a robotic flexible actuator based on layer jamming

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Abstract. This research paper provides an insight into one of the most promising fields of robotics, which brings together two main elements: the traditional or rigid robotics and the soft robotics. A branch of soft-rigid robots can perform and modulate soft and rigid configurations by means of an approach called jamming. Here we explore how to use layer jamming, namely a set of layers within a flexible membrane, in order to design soft robotics.
The paper introduces a quick overview of the history of soft robotics, then it presents the design of a functional prototype of soft-rigid robotic arm with the results of preliminary trials and discussion of future advances where we show the capability of the system in order to lift up possible loads.

Keywords: Layer Jamming, Robotic Actuators, Flexible Actuators.

1 Introduction

In the recent years we can observe the dawn of new subbranch of soft robotics. This new field tries to combine the precision of the traditional, rigid robotics with the flexibility of soft robotics into the same robotic device. An intriguing and potentially expanding technique to this aim, is jamming.

The most advanced research which has been done in this area - i.e. on the possibility of changing the state of robots – looked at different designs such as *granular jamming* or *layer jamming*. Robert D. Howe – from the Harvard John A. Paulson School of Engineering and Applied Sciences - said that such technology will eventually lead to soft-rigid robots which will combine the benefits of soft and rigid robotics (Burrows, 2018, Secco, 2019a).

Nowadays the automatization of enterprises is increasing year by year and robots are replacing the traditional human work-force. Most of these machines - who are replacing the workers - are stiff and they are designed to work on a particular task within a protected environment or work cell without human beings around (Mitra & Das, 2018). Other companies are trying to minimise the impacts of robotization vs people employability, by introducing collaborative robot or *cobots*, which are designed to physically interact with humans in the workplace (Colgate et al.,1996): this has a clear and strong implication on the *safety* of the employers as well. In recent years some researches pointed out that soft robots could be introduced into factories where they can be working alongside humans (Onal & Rus, 2012, Secco 2019b).

However, the soft robots have a big drawback, which is stopping them from being widely used in industries as cobots are. This is due to a fact that they lack precision vs traditional robotics. This is the place where new technology is coming to aid.
The idea behind the soft-rigid robots is quite simple and relies on those devices which combine the benefits of the two branches of robotics, namely the standard robotics and the soft robotics, in order to get a versatile machine. They can assume a soft bodied state, which allows them to comply with the safety constrains of the environment, to a rigid state in which they can hold a specific potion and orientation with higher accuracy and precision (Secco, 2019c).
In this context, the main purpose of this work is to design and manufacture a prototype which will allows to test the capabilities of soft-rigid robots and, in particular, to check the advantages of using the granular or the layer jamming approach (Chiramal, 2020).

In this paper, in particular, we take a closer look at layer jamming and we manufacture a functional prototype of a soft-rigid robotic arm. This will allow to test its capabilities and to foresee possible areas of applications for a human-friendly robotics approach.

In order to achieve this objective, the following steps are needed: a research on the field of soft robotics and on the granular and layer jamming techniques, the design of a prototype of the robotic arm, the manufacturing and integration of the arm structure and a preliminary validation with experiments. Accordingly, the paper is organized as it follows: Section 2 presents a brief overview of *soft robotics*, Section 3 focuses on the case study and on examples of *soft-rigid robotics*. Section 4 refers to the *materials and methods*, where detail of the *design* are reported. Then Section 5 reports the *results* with a description of experiments and results. Finally, on Section 6 *conclusions and future directions* are reported.

2 Soft Robotics

Modern classification of robotics divides robots according to the compliance of the materials which are used to build their structure. Therefore, we can define two main types of robotics, the soft and the hard - or traditional - robots.

Looking at the history of robotics, we can observe that the first robots were mainly made of rigid and kinematically non-redundant materials such as copper, magnet or steel (Kim, 2013). We can call this type of design as the ‘traditional’ approach. Most of the time these robots are used in well-defined environments where they safely perform pre-programmed repetitive tasks with an high precision of their movement and pose. In fact, these machines are designed to be inherently stiff in order to preserve (and avoid decreasing of) their accuracy of movements which could be affected by the multiple vibrations of their structure. Thanks to their performance, the hard robots are highly exploited in manufacturing.

On the other hand, the rigid design introduces several issues especially within undefined or changing work cells such as the manufacturing lines where human workers maybe involved. Here bio-inspired soft devices - which are designed in a way that the tip of the robotic arm can achieve any point in three-dimensional space – can be used in order to generate little resistance vs the compression forces (Trivedi et al., 2008).

In other words, soft-robotics can take inspiration from the biological system and, for example, defines continuous and deformable structures which are similar to physiological structures, such as the octopus' arms or the elephants' trunks. The properties of these solutions are very different with respect to the mechanical characteristics of the traditional chains of rigid links and sliding or rotational joints (Iida, Laschi, 2011; Baxendale, 2019).

Soft mechanism are widely used in medical field to assists in surgeries, as their shape shifting abilities helps to navigate inside the human body. They also can be used in rehabilitation, as for example, the soft exoskeleton suit (exosuit) developed by the Wyss Institute at Harvard University, which can assist human walking (Lee et al., 2018).

Moreover, while traditional industry robots are mostly isolated from the workers due to the safety concerns, soft bodied robots would minimise the risk of injuries in case of collision between the human and the machine. Thanks to their compliant nature, soft robotics are a wonderful opportunity to develop human friendly manufacturing robots.

3 Granular Jamming

In soft-rigid robotics two design techniques can be used: *granular jamming* and *layer jamming*. In this Section both these approaches are discussed on particular case studies.

Jamming is a physical process in which an enlarged number of particles are used to increased the viscosity of some mesoscopic materials (Biroli, 2007; Jiang, 2013; Jacob, 2020). In simple words, the elements of the structure act like a fluid or semi-fluid in normal condition but - when an external condition is applied - they lock into a solid-like state. Such an external condition can be, for example, the removal of the air from the container of the particles (Figure 1).

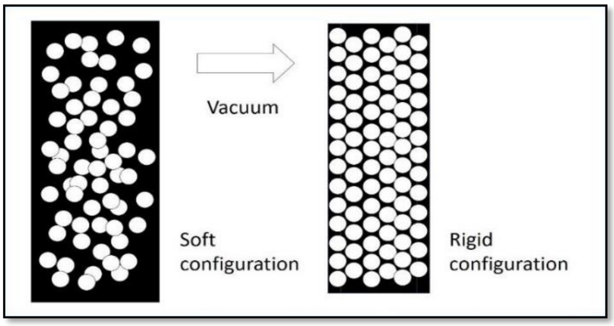

Fig. 1. Rational of the granular jamming approach

3.1 Granular Jamming

The case study of Figure 1 shows a physical process where the granular jamming is performed – for example - in a vacuum-packed coffee bag: when an external negative pressure is applied, the coffee granulates get locked in a solid-like state. According to this approach, stiffness-controllable octopus-like robot arm can be designed for applications such as robotics *Minimally Invasive Surgery* (MIS). Moreover these designs can be inspired by the biological system, such as, for example, the behaviors of octopus arms which can naturally alter their body from soft to rigid configuration (Jiang, 2012; Jiang, 2013).

3.2 Layer Jamming

Layer jamming is another strategy on most recent research which is performed by using the jamming process in order to develop soft robotics. In 2018, researchers from the Wyss Institute for Biologically Inspired Engineering at Harvard University and the Harvard John A. Paulson *School of Engineering and Applied Sciences* (SEAS) build a simple device made of multiple stacks of layers which are wrapped into a closed plastic envelope and connected to a vacuum pump. Similarly to what happens in the granular jamming, when the vacuum is applied in such structure, then the envelope becomes rigid and it can be shaped into different forms (Figure 2).

On the other hand, when the negative pressure is removed, then the arm recovers its property such as it can bend and twist with a similar behavior observed on the octopus' tentacles. In some applications, the device has shock absorbent capabilities and therefore it can serve as a landing assistance system for drones (Narang et al., 2018).

These examples or case studies shows that soft-rigid robots are a good alternative to soft robots. Most of these soft-rigid robots may be used in medical applications and in other contexts where precision and flexibility are simultaneously required.

4 Materials & Methods

The main objective of the proposed design is to provide a prototype of a soft-rigid robotic arm, which is able to change its configuration from a soft state to a rigid state. The device should also enhance precision at the cost of flexibility.

In order to design the device, some decisions had to be made during the process. This section focuses on the main aspects of these decisions and presents the functional diagram and components which have been adopted.

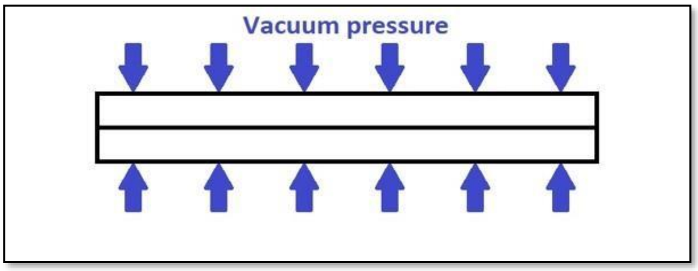

Fig. 2. Rational of the layer jamming approach

4.1 Design

A. Vacuum controllable stiffness

The design have to ensure that the machine will be able to change its states. The prototype is then designed with a layer jamming approach as it was discussed in the previous section.

To get s proper functioning of the structure, several layers of a compliant material are used: long and thin paper sheets are enclosed within an airtight envelope made of a transparent and flexible film. In this way the arm will have the flexibility of a soft robot. On the other hand, thanks to the increased friction between the paper elements of the layer jamming – when the vacuum is applied - it will be possible to stiffen the structure.

In order to test and monitor the system behavior, clear and transparent plastic film has been chosen as the external material of the envelope, as it will help to observe the layers during the testing phase. Such a material also ensures the airtightness of the structure as it is not permeable to the air.

To build the overall system, it will be necessary to use a vacuum pump. A double staged vacuum pump will provide the congenial vacuum pressure.

A plastic film sealer will be used to seal the sides of the aforementioned envelope as well as to seal any possible gaps that could cause any leakage.

A4 paper sheets will serve as layers of the compliant material. To provide a sufficient stiffness of the structure when vacuum is applied, at least 10 stripes of paper will be embedded within the envelope. As other studies in layer jamming shown, the higher is the number of layers, the higher is the achievable stiffness. Precisely, the stiffness increases when more layers are added to the structure by a factor of the amount to the power of two. It is also important to mention that the structure will sustain this greater rigidness only for small loads (Kawamura, 2002).

Figure 3 shows the functional diagram of the proposed design, where a vacuum pump, connected through a pipe, is feeding an envelope with the layers.

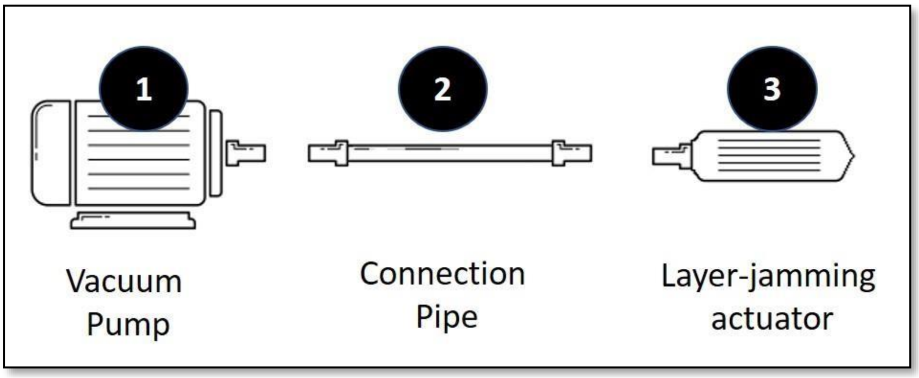

Fig. 3. Overall design of the system: an electrical vacuum pump (1) feeds the connecting pipe (2) into the (3) laminar- jamming robotic actuator

B. Pros and Cons

The proposed design of Figure 3 has inherently some *advantages* and *disadvantages*.

The main *advantages* are:

- ✓ The structure can be switched between a soft and a rigid state
- ✓ When in soft state, the structure can be shaped according to the operator's will
- ✓ The system is simple to be implemented, thanks to the low number of components which are needed for the design
- ✓ The used material is unexpansive
- ✓ The device has a lightweight

At the same time, some of the *drawbacks* are:

- ✓ The proposed design needs to be manually operated by switching a vacuum pump on and off. This is one of the major weaknesses as the robot arm is hard to operate and switch between states flawlessly.
- ✓ The design does not integrate – at this stage - any form of input device which would allow to modulate the pressure and - as a consequence – the values of the stiffness of the arm. Therefore, it is possible to switch between a maximum rigidness state and a maximum flexibility state without any condition in between.

- ✓ The system requires to be connected through the pipe to the vacuum pump at all times, which limits the movement of the operator.

C. Integration

One of the possible improvements vs. the design of Figure 3 is to add a controllable valve and then make the structure more flexible and easier to operate. In order to be able to control the valve from, for example, a personal computer, the system would require a sensor which measures the effective value of the vacuum pressure. A *Data Acquisition Card* (DAQ) would be responsible of collecting the sensor readings and of sending thee parameters to the computer in a digitalized form. Then the operator, by using a customized software interface, would be able to control the valve accordingly. Such an architecture has not been developed in this project, however it is worth to mention as it could be organized for future development of the proposed design. An overview of the system is shown in Figure 6 (right panel, scenario B).

An electronic vacuum or pressure regulator is a device to control the pressure in the system, whose value is proportional to an electric input signal of the regulator which is provided by, for example, a personal computer. For example, the ITV pressure regulators by SMC which have been explored in this project are lightweight and small size devices. Their monitor output is available by either Analog or switch output and additionally they have a very good response time and they deliver high stability.

National Instruments DAQ™mx is another device explored in this project: it is a data acquisition card. The process of data acquisition consists of sampling the signals that measure the physical conditions and converting the results into numeric values which allow the computer interpreting the incoming signals. The NI-DAQ™mx model is easy to use and have improved performance compared to other traditional NI-DAQ drivers. This device acts like an interface between the vacuum regulator and the computer. It digitalizes the received Analog signals and codes or digitalizes them for the computer interface.

After the digitalized signals are sent to the computer, the user could control the operation of the DAQ device. the overall system would also allows to process, store and visualize all the data.

The application software would play a role of a communicator between the user and the computer, allowing to acquire, analyze, and present measurement data: *Laboratory Virtual Instrument Engineering Workbench* (LabView) - developed by National Instruments - is a system design and development environment for visual programming language, which is commonly used for instrument control and data acquisition. A brief overview of th system is reported in Figure 6 (right panel, scenario B).

The programming language used in LabView is called G and it is high level graphical programming language. It allows to program with the benefit of visual expressions and it is designed to develop applications which are interactive, multicore and can be execute in parallel. The data input and results can be manipulated and displayed directly in the *Graphical User Interface* (GUI) window (Kodosky, 2008).

4.2 Implementation

This section shows step by step how the proposed solution has been manufactured and implemented. In order to manufacture the basic construction, it is important to gather all the necessary elements. The components used in the structure are the following ones:

- VPUMP® model VPB-1D 2CFM double stage vacuum pump
- PFS plastic film sealer
- Flexible connection pipe
- FF2440 clear film APAC Packaging Limited
- 1 mm thick sheets of paper

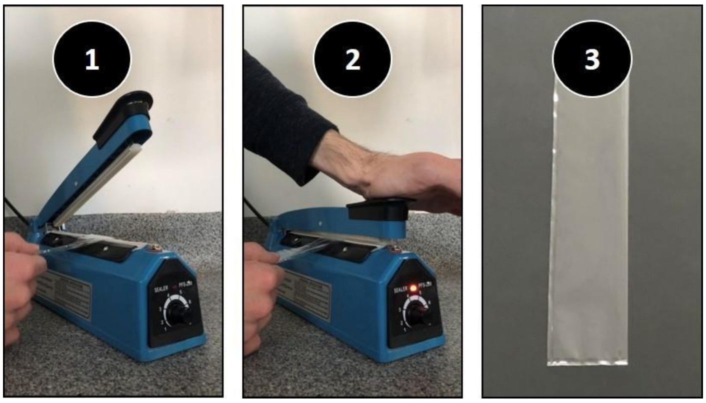

Fig. 4. Manufacturing of the actuator flexible pocket

To construct the airtight envelope, the clear plastic film has been cut into a rectangle with the dimensions of 9 cm x 19 cm. Next, the film has been folded in half and, by using the plastic film sealer, two sides have been sealed in the form of envelope with a gap on one of the 4,5 cm wide side for the paper layers.

The paper sheets are used to cut 10 rectangular layers of 3 cm by 15 cm. Following this step, the sheets are placed in the envelope and sealed by leaving only some room on one side for the connection of pipe.

Figure 4 and Figure 5 show the main steps of this process.

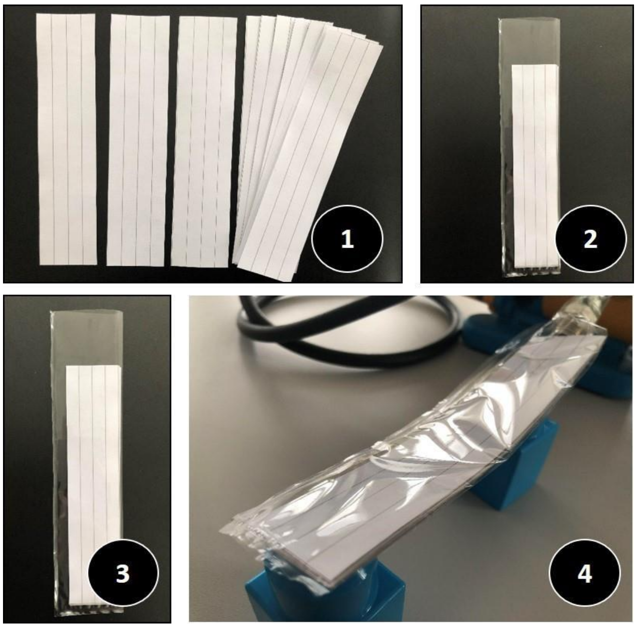

Fig. 5. Preparation of the layers: (1) 3x15 cm paper strips, (2) layers housing, (3) layers and flexible pocket, (4) sealed jacket connected to the vacuum pump

Finally, the elements are connected with the pipe and the vacuum pump according to Figure 5. The following picture (Figure 6) shows the overall system and the improved version of the design with the pressure regulator and the DAQ card.

In order to prepare such a system, additional equipment is needed, namely:

- DAQ™mx 16.0 driver
- ITV0090-2BN SMC electronic vacuum regulator

To communicate with the DAQ device a DAQ™mx 16.0 software has also to run on the personal computer.

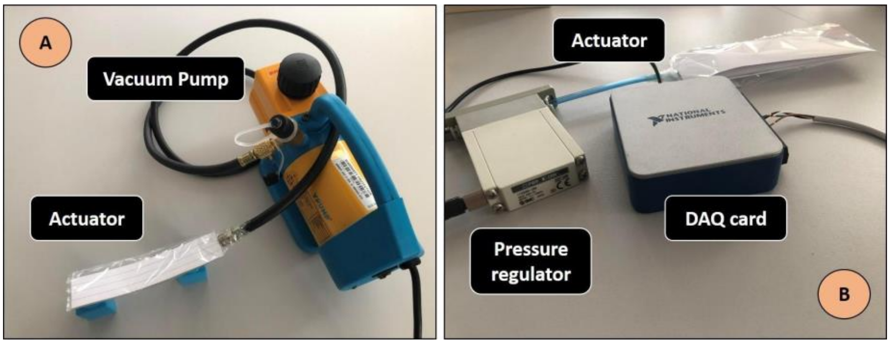

Fig. 6. On the left and right panel the set-up A and B, respectively: (A) vacuum pump directly connected to the actuator and (B) vacuum pump connected to the pressure regulator – which is controlled through the National Instruments DAQ card - and then to the actuator

5 Results & validation

Testing is one of the most important steps in the development process. It allows to check the capabilities of the device and to prove the utility of the vacuum controlled soft-rigid robots.

In the presented design, the layer jamming construction is supposed to be able to change the state from soft to rigid. Before the other experiments were conducted, the integration was tested several times to ensure that the materials used to assemble the envelope was not leaking any air, making then the arm unable to stiffen when the vacuum would have been applied. After these trials gave a positive result, different capabilities of the structure were tested.

Fig. 7. On the left, central and right panels, respectively: the baseline or rest configuration, the actuator under the vacuum pressure and a freezing' postural configuration of the actuator

Before the pressure is applied the arm displays a low bending stiffness (Figure 7, left panel). However, when the vacuum pump is switched on and the air is being sucked from the envelope, then the friction between the sheets of paper increases: this phenomenon makes the arm rigid as expected (Figure 7, central panel).

To additionally ensure that the system is working properly, simple tests were conducted in order to check the bending properties. In its base state the arm is prone to deformation (Figure 8, left panel) and bends without forces applied form outside. However, when the vacuum is applied the structure becomes rigid thanks to increased friction between the elements. This allows to form the arm in the preferable way and later stiffen it in this position (Figure 8, right panel).

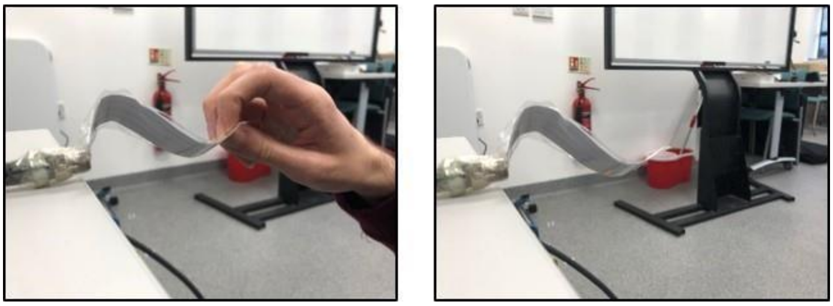

Fig. 8. On the left and right panels, respectively: imposition of the shape and preservation of the shape as soon as the vacuum pressure is applied

Moreover, the bending properties of the structure were additionally examined using a small calibration weight applied in the middle of the arm which was constrained on two blocks on its extremities. Thanks to the increased friction between the layers - after the vacuum is switched on - the structure is able to withhold the weight and shows lower bending tendencies (Figure 9). The biggest difference between the vacuum on and off configurations is that while in the first scenario the layers bended independently, after the pressure has been applied the elements of the structure flexed all together as a cohesive unit.

Finally it was noted, during the bending experiments, that when the force applied to the structure exceeds its critical point, then the layers lost their cohesiveness. The value of the critical point can change depending on the type of material and on the number of layers.

Fig. 9. Preliminary trial of the actuator while holding a weight

Each one of the experiment which is reported in the previous section has been performed 5 times to ensure that all the components were working properly and all the trials were giving the same results. Tests showed that the robotic arm is working as it was expected and there is no need for main changes of its structure.

The structure can withstand relatively higher external force. It is easy to modify the arm into different shapes and to freeze such shapes in a particular configuration which is desired by the user. This property makes the device effortless to adjust vs different tasks.

The robot arm is made of light materials: even with strong vacuum pressure, it cannot carry too heavy pieces of equipment. This fact may have some implications on the limited applications of the robot. Nevertheless, with a proper number of layers the structure can be modulated in order to withstand bigger weights.

Moreover, the bending test showed that the structure itself could be used as a quite useful gripper. Improved version of the design – such as the proposed Scenario B in Figure 6 - would be very helpful in this field, as electronic vacuum regulator would allow for rigidness regulation and an overall better control over the arm.

6 Discussion & Conclusion

This paper presents the design of a flexible layer jammed actuator for soft robotics, in the attempt of connecting the advantages of traditional robotics and soft robotics. The proposed design is simple and can be furtherly improved by adding the possibility to modulate the stiffness of the device. Using LabView software, a DAQ driver and a pressure regulator, it may be possible to achieve a more reliable system which will allows the real-time control of the vacuum pressure applied to the arm.

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This design clearly shows the potential laying behind the soft-rigid robotics, and, in particular, the layer jamming method. The system is able to bend when it si configurated into its ‘floppy’ state and then it can freeze and preserve the desired configuration when it is set in the ‘rigid’ state.

The soft-rigid robots can become a great tool in different areas thanks to their precision and flexibility, with clear benefits towards safety of humans in the working environment.

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