Design of a Granular Jamming Universal Gripper

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Abstract. Robotic gripper design has been an active research area because of its widespread in robotics applications and its high demand in the today's healthcare automation market.
Here we propose the design, integration and preliminary experiments of a universal gripper based on granular jamming: the prototype is based on low cost components and it can be easily assembled and used for a variety of task, including grasping of daily life objects in a domestic context.
The paper presents a set of technical solutions where different type of granules are used and combined with different actuation (i.e. an electric vacuum pump, a medical syringe and manual actuation). Experimental trials performed under the different configurations show that a set of 8 daily-life objects can be firmly grasped with a 100% successful rate by means of an end-effector whose cost is less than 20 $. This represents a novelty in current market of robotic end-effectors and offers the possibility of low-cost robotics for daily life applications in medical application.

Keywords: universal gripper, soft robotics, granular jamming, end-effectors.

1 Introduction

1.1 Background

The usual strategy when manufacturing a robot, is to replicate its end-effector with the human hand. In 2010, a couple of researchers started working on this at Cornell University and University of Chicago at United States. They gave rose a unique developed approach to the soft robotics so as to make versatile and easy to build. They created an amorphous gripper that can shape itself around the object which has to be picked up.

Grasping has been always a crucial topic in the research of robotics. We all know that, in day-to-day life tasks as well as industrial applications, the robots which are capable of grasping techniques are much required to reduce the worktime as well as both hardware and software complexity. Also, man is incapable of lifting heavier objects than his limitations.

Also, we see that most of the robotic grippers which is available in the market fail to adapt to the different grasping techniques or to grasp objects that are dissimilar in size. Also, this is helpful for handicapped ones to pick their desired things and get to their hands. Therefore, some of these major problems are been approached by using robotic hands, as other techniques are quite a little expensive and difficult in controlling them. These are the motivations which lead to investigate an alternative solution for grasping unfamiliar objects.

Figure 1 shows examples of end-effectors that has been used in robotic industries. Nevertheless, these equipment's requires several procedures for their end-effector to be selected, customized and integrated. The selection of an appropriate gripper, the design of the proper plan to the estimated position of target has been a hard-core problem faced since years. Due to these complications, grippers applications are been limited in high-speed automatic factories functioning.

To overcome these drawbacks, various types of end-effectors have been designed to adapt with the specific type of robots for numerous tasks. Many researchers had studied about the design and mechanism of end-effector, selection of grippers and targeting the position of grip planning.

This led to the development of a novel gripper solely to improve the work efficiency for the exchanging mechanism of gripper and to restrain a good estimated position of the targeted gripper (Nishida, 2016).

1.2 Problem Formulation

Grippers are usually used in areas involving hazardous works such as welding at high temperature, or even dealing with radio-active materials, mining and exploring shipwrecks. Also used in places where human intervention is not possible or pick up heavier objects as it is time consuming and risky. We all know that different types of gripper are into use for different applications in small- and large-scale industries. For example, welding gripper used for spot welding, multi-fingered grippers, magnetic grippers, which are extensively used for individual application only.

Therefore, the practical aim of this work is to conduct a study of the universal gripper robot, and to provide a step-by-step demonstration of the proposed design of the gripper and of its interaction with *unstructured objects*. A model has been established to correlate the relationship between the end effector and the joint coordinates. Here, a universal gripper robot is been designed with 3 *Degrees of Freedom* (DoF) to grab and perform pick and place tasks with daily life objects.

The proposed design should be able to hold objects and allow performing human-like tasks, such as grasping daily-life objects, drawing and painting and so on. The selected technique should solve the major problem of designing grippers because it has been associated with vacuum-based device that can hold objects of any dissimilar structure, irrespective of their stiffness (McCulloch, 2016).

Before introducing the design, a brief overview of current gripper design is given.

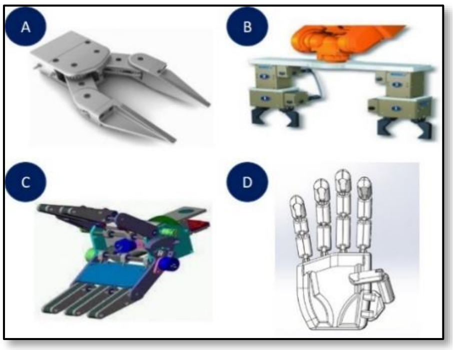


Fig. 1. Examples of robotics gripper: Mechanical Gripper and Dual Gripper (ljmerr, 2013), Multi−Fingered Hand (ljmerr, 2013; Secco, 2018) on panels A, B, C and D, respectively.

1.3 Related work

The gripper part of a robotic device, namely so-called end-effector, is used to handle applications which include loading and unloading a particular machine, picking parts from a conveyor, arranging products on pallets. The basic function of a gripper is to grasp the object of interest and manipulate it during the work cycle. Accordingly, the gripper maybe customized with a particular design in order to match with the shape, weight and physical properties of the object and of the surface of the object which must be grasped. A robotic end-effector can also be used as a tool to carry out processing operations on the specified work cell, such as, for instance, arc and spot welding, spray painting, rotating spindle during drilling process, grinding, routing. Other operations may involve the use of heating torch, use of water jet cutting, dispensing, assembly which may occur during the tooling process. Thereby, the accuracy of the gripper in terms of positioning, force control and even impedance control has been increased year by year (Ijmerr, 2013; Singh, 2013).

1.3.1. Industrial Robotics Grippers and Tools (e.g. Spot-Welding application)

A simple linkage actuation mechanism is used in the spot-welding robotic gripper to achieve its functioning. An alternating current cycle motors is been used along with a set of spur gears and a shaft arrangement of thread type. A direct current cycle mechanism is been used for the spot welding in order to perform basic functions such as picking, holding and grasping the objects. IN this context, the robot is usually interacting with Computer Numerical Control (CNC) machine which are used to easy the automation process, as well as transfers systems combined with conveyors (Singh, 2013).

1.3.2. Mechanical Grippers

Mechanical Grippers are basically a set of mechanical fingers that are actuated by the grasping mechanism of the robotic device. The finger like structures can be called as jaws where it comes to contact with the object acting as the gripper appendages (Singh, 2013).

Usually a minimum of three finger design is conceived: these prototypes can also be used as per the use of application. The finger like structure can be easily replaced or removed, as they maybe replaceable, allowing interchangeability and convenience. The robot either requires a pneumatic drive system or electric, hydraulic to produce the power. The holding of the given object in the mechanical gripper is done using two methods predominantly i.e. either using deformable finger pads to adapt to the shape of the object during grasping, or using soft material fingered pads (Robotics Bible, 2011).

1.3.3. Dual Grippers

The gripper which has two gripping devices at the end of one end effector and can function independently is called a dual gripper which is extensively used for loading and unloading (Figure 1). Since there are two gripping device which can work independently, irrespective of the task, then the process time is reduced, hence increasing efficiency and productivity. This gripper enables the user to adapt the configuration to a specific application, instead of requiring modifications of the applications (Cobots, 2019).

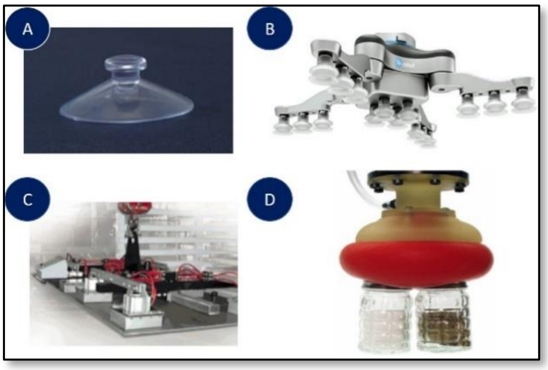


Fig. 2. Examples of a single Vacuum Gripper (ljmerr, 2013), Multiple vacuum grippers in a single chassis (Onrobot, 2019), Magnetic Gripper and Universal Gripper using vacuum pump (ljmerr, 2013) on panels A, B, C and D, respectively.

1.3.4. Multi-fingered Grippers

These grippers are mainly used for grasping, lifting and manipulation of objects, even if - in terms of versatility and dexterity - it is usually very hard to properly mimic human performance while maintaining a simple design (Figure 1). These devices also inherently require quite complicate control system where the trajectory of the contact points on the grasped object have to be tracked with the use, for example, of tactile or force sensors on the fingertips. An important factor to be taken into consideration is that, the stability of the grasping – especially during the manipulations - should be preserved, irrespective of the frictional forces between the two players, i.e. the gripper and the object (Nefzi, 2006; Sathishkumar, 2017).

1.3.5. Vacuum Grippers

These grippers are mainly designed to hold flat objects by using suction cups (Figure 2). Smooth sheets of material like metal, glass, plastic and wood panels, can be lifted using strong suction cups. The vacuum does not necessarily require high power, but misalignment between the cups may affect the airtight seal (Ijmerr, 2013). Multiple vacuum grippers solutions have been proposed where, for example, a dual gripper controls both left and right sides of the vacuum gripper independently (Onrobot, 2019).

1.3.6. Magnetic Grippers

Magnetic grippers are electromagnetically designed to pick up different sized of parts in a very faster pace which are easier to control but at the same time requires Direct Current (DC) power supply and an appropriate control unit. When permanent magnets are used, then no need of external power is required to operate (Ijmerr, 2013): a push-off pin is connected at the end of the end-effector in order to separate the parts from the magnetic gripper; even if a blackout occurs, the gripper remains active. The grasping speed is faster when compared to other grippers with the advantage of a very minimum level of maintenance. These grippers can also catch parts with holes, which is usually not easy to perform with other grippers (Bernier, 2014).

1.3.7. Universal Grippers

The standard design of a universal gripper is usually characterized by a multi-fingered configuration, involving hardware and software complexities as it requires many controllable joints. Individual finger like grippers can be replaced by a mass or bag of granular material, which is forced to press on the targeted object, and then conformed to the shape of the object itself. By applying a negative or vacuum pressure to the bag, the granular material contracts and get hardened so that is can hold the object firmly; conversely, the bag relaxes when the vacuum is released. Since a slip can happen when picking up the object, the design has to prevent this either by applying friction from the vacuum pressure or by exploiting the geometric constraints (Ijmerr, 2013). In this context, MIT has developed interesting designs such an 'origami magic ball' where a cone structure collapses around the objects [28]. A different approach has been followed by the soft hand where elastic components inherently replicate human hand synergies when the effector is activated and it surrounds the grasped object [29].

2 Design of the Universal Gripper

Before entering into the details of the prototype, Figure 3 shows a block diagram of the proposed concept. Firstly, an elastic membrane is used and filled with granular materials; this is fed through a filter to prevent the granular materials from entering the vacuum source which is the latter diagram block. The proposed system may then be interfaced with a real time simulation software called CPRog in order to control a Mover6 6 DoF robotic arm.

The developmental model of this study foresees (phase A) the design of the gripper, first of all, in terms of its shape and configuration with specs on the design which refers to the possibility of engaging the effector on a robotic arm (phase D). In a second stage (phase B) we will look at the integration of the granular jamming components and - only in a third stage, i.e. phase C - at the integration with the vacuum application. Finally (phase D) we will embed the system on the robotic arm.

According to this block diagram, the modelling, analysis and prototyping of the device can be now detailed.

Fig. 3. Functional set-up of the proposed gripper.

2.1 Design

Thanks to a literature review on previous universal grippers' design, the prototype has been conceived with a simple mechanical design, whose main components are a funnel, a latex balloon, a fabric or textile patch and a 60 ml VET-type syringe (Figure 4, top panel).

In particular, we aim at designing a system which is (1) low cost and (2) allow us to integrate in an easy manner an ended-effector on whatever robotic device we are going to use, while (3) performing grasping in a dexterous fashion.

These specs should allow the integration of such a system with low-cost robotic arms which can support medical application such as – for example – those ones where pick and place systems are required for patients with impaired movements.

The latex material was selected through a preliminary where balloons were inflated and monitored after 24 hours. The material which was better preserving the inflation was then chosen.

The pointed part of the funnel had been cut to half an inch so as to make sure that the latex balloon could fit the inset of funnel properly: the two parts were taped with duct tape to hold them firmly. A small piece of fabric was positioned and attached at the end of the funnel so that the granular powder was not passing into the vacuum source when the negative pressure was applied.

Fine coarser powdered coffee granules were filled into the latex balloon, providing jagged edges of the granules which collide each other when the vacuum is applied. The balloon was filled about on three-fourth of its volume such as - when the vacuum pressure is released - the granules have enough space to move around and behaves as a ‘flowing’ powder again (Figure 4, bottom panels).

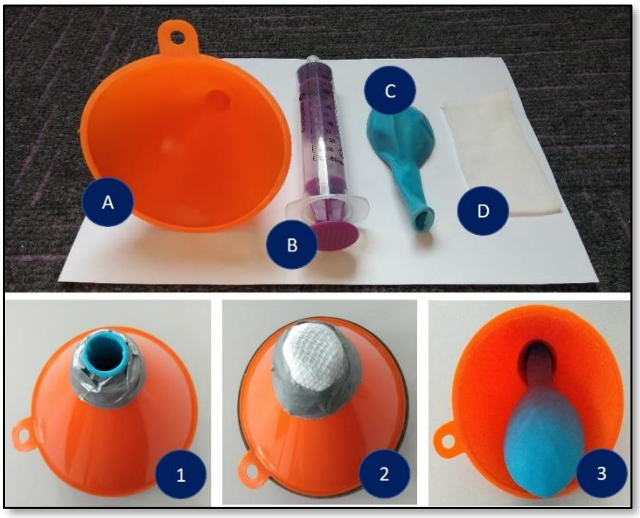


Fig. 4. The gripper components and preliminary manufacturing on the top and bottom panels, respectively. Components: funnel (A), syringe (B), balloon (C) and cloth filter (D). Manufacturing: (1) inset preparation, filter positioning (2) and balloon insertion (3).

Stage 1 - Manual deflation

To check the functionality of the system, an initial test was done by manually inflating the balloon with the coffee powder in. From this test it was found that the resistance vs the air to be inhaled was not so high. Even with vacuum, the coffee became a rigid powder and the fabric at the end of the funnel was properly filtering and blocking the powder.

Stage 2 – Vacuum Pump deflation

To take the prototype to the next stage, an air hose pipe was connected to the funnel and to a 220 V/50 Hz vacuum pump, model VPB-1D. The main characteristics of the pump have been reported in Table 1. The hose pipe and the pump are shown in Figure 5.

Table 1. Properties of the VPB-1D vacuum pump.

Model VPB-1D			
Free Air Displacement	45 l/m @50 Hz	**Oil Capacity**	5 oz./140 ml
Ultimate Vacuum	38 Micron	**Weight**	≈ 3.5 kg
Voltage	220v/50 Hz	**Total Pressure**	22.5 micron
Power	200 W	**Dimensions**	230*90*165
Motor Speed	3400 r/m	**Partial Pressure**	3*10-1 Pascals
N* of Stages	2	**N.W.**	9.9 lb/4.5 kg

The VPB-1D V-Pump uses an oil lubrication system, and it is a dual vacuum pump which can be used for suction applications and vacuum condenser in power industries. The oil thank allows the ability of the pump to reach a deep vacuum. This device can also be used to deal with sewage water, compress gases like methane and purification in environmental industries. The device reliability has been improved with high quality bearings and copper which are double brushed (Zensen, 2019). The oil level was checked and kept at least at 75% level of the whole scale.

Fig. 5. The VBD-1D Vacuum pump and the auxiliary air-hose pipe.

At this stage, the latex balloon with the granules was taken to the test and it was noticed that the vacuum pressure of the pump was not enough to make the granules jammed and therefore to show grasping capability of the balloon. Following this experiment, it was noticed that two constraints must be taken into consideration i.e.

- The fabric material should not have many pores which might disturb the vacuum pump with the coffee powder. It would be more appropriate to use a fabric that easily ‘breathes’ so that the pump will be able to quickly inject or remove the air in and out the balloon.

- The balloon should not be over-filled, as coffee granules will not have enough room to move around the balloon during the transitions.

Stage 3 – Optimization of the granular filling

A new balloon was filled with the coffee granules at half of his volume. Gently pressing the balloon on the top of an object and removing the existing air, the balloon deflates completely: in this configuration, the coffee grains are locking around the object and holding it firmly. As a result, the device was able to pick up a pre-set of objects of dissimilar size (Figure 6).

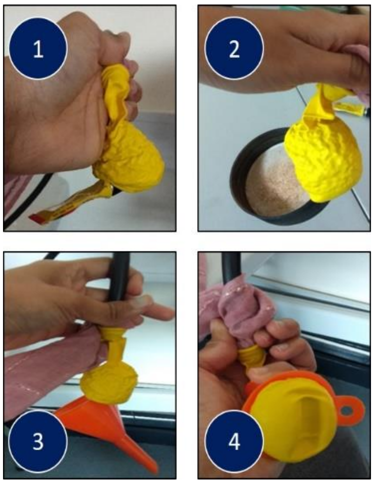


Fig. 6. preparation and testing of the gripper (50% filling).

Stage 4 – Optimization of the funnel geometry

The balloon was taped to a 3.5 cm radius funnel and then the above steps were repeated: this time it was noticed that the radius of the funnel plays a crucial role when the vacuum is applied as the balloon takes the shape of the object but does not hold it firmly: even though the coffee granules are compressed around the shape of the object, the gripper does not finalize the grasping because of the size of the funnel which constraint the granules re-configuration. To avoid such a behavior a bigger 4 cm radius funnel was used.

At this stage the end effector is a single prototype, however the only one presented design is the result of an optimization process which has involved the testing of different solutions which have not been fully reported for brevity.

3 Integration

A funnel combined with a vacuum pump has shown grasping capability when combined with a latex balloon filled of coffee granules. We want now to adapt such a design to a low-cost medical syringe and see how to develop a possible design where the pump is replaced by a 60 ml syringe. We also want to explore different type of granules out of the coffee beans which were initially tested. Either the vacuum pump or the syringe may then be integrated with a robotic arm, such as, for example, a Mover6 6DoF robot arm.

3.1 Integration with a Syringe actuator

The geometry of the coffee granules is a specific one and the nature of this powder can clearly influence the performance of the gripper. As a proof of concept, we also want to consider another type of powder with different properties in terms of granularity, as well as consistency and friction: to this aim, fine flour was used as well.

Therefore, to experiment the performance of a gripper, a 60 ml VET syringe combined with granular materials into the same flexible membrane were tested. Here, we used two types of granules, namely (i) ground coarse coffee powder and (ii) fine gram flour powder. A comparison of the characteristics of both the geometric materials while gripping the target was done.

Table 2. Gripper with syringe actuator and two types of powder (set 1).

S et 1	**Granules filling [material]**	**Syringe [compressed configuration]**
1	 Coarse coffee powder	 Syringe in compressed state, holding an *air hose*

2	 Fine gram flour powder	 Syringe in compressed state, holding a *cap*

Table 2 shows an example of the gripper performance while grasping two objects (namely a pipe and a cap): from the results of the tests, both granular materials had good gripping property when the balloon was pressed against the object. Gram flour powder showed higher gripping performance when compared to the results of the gripper filled with the coffee powder. The geometry of the flour granules, in fact, is finer and it has higher interlocking capabilities vs the one of the coffees. In this context, other types of granules or grains like rice or fine powders could be considered for future experiments.

Because of the syringe actuator, the time taken to conform the elastic membrane against the object is in the order of less than 2 seconds (as the user just need to get the syringe halfway pulled up). Certainly, the use of an electric vacuum pump would introduce more regularity and even the possibility to decide and modulate such transition time.

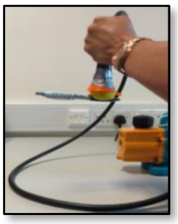
3.2 Integration with a Vacuum Pump

A similar set of experiments was done in order to check the functionality of the overall system when the gripper was connected to the vacuum pump. Table 3 shows some examples of these experiments as they were performed by using the coffee granules and the flour powder into the latex balloon. Both the coarse coffee powder and fine gram flour powder allow the gripper to pick up the tested objects (a pen and a bottle cap are reported in Table 3).

During these experiments it was noticed that the grasping force of the gripper fluctuated according to the amount of filling within the elastic balloon. This fact suggested that the differences in the volume of the air within the latex membrane modulates the gripping force on the object that is grasped.

Such integration is currently based on the combination of the end-effector with a direct connection to the vacuum 'source', however future development should include the integration of a set of pressure regulator which will allow a proper modulation of the vacuum pressure vs the grasping performance (see for example previous design on [30] and [31]).

Table 3. Gripper with vacuum pump actuator and two types of powder (set 2).

Set 2	Granules filling	Gripper [soft configuration]	Gripper [suction configuration]
1	 Coarse coffee powder	 Released state	 Applied negative pressure - gripper grasping a *pen*
2	 Fine gram flour powder	 Released state	 Applied negative pressure - gripper grasping a *bottle cap*

4 Testing

4.1 Integration of the Gripper with a 6 d.o.f. Robotics Arm

So far, a manual handling mechanism to grip the object from one place to another place was used. This approach is only applicable when either there are few objects to move or the moving parts are not heavy. On the contrary, a robotic arm may automatically perform the task without depending on manual handling.

Therefore, we explore how to integrate the gripper with a Mover 6 robot arm: the specifications of this 6 DoF robot are reported in Table 4. This robot is supported with a 3-D real environment software or CPRog which allows simulation and preparation of the robot trajectories and movements.

The arm has 4 joint modules and two servos with joint connectors and a cable loom provided with the emergency stop. The main connector and digital I/O are located at the base of the robot. The structure is made of plastic and aluminum. A full integration should foresee the use of two power supplies, one for the robotic arm and the other one for the universal gripper robot. Figure 7 shows the robotic arm and the simulation software which allows the planning and execution of the trajectories.

Table 4. Properties of the 6 d.o.f. Robotic arm.

Mover 6 Robot Arm			
Weight	3.5 kg	**Gripper Power Supply**	+12 V and GND for gripper
Payload	200 g	**Software**	CPRog (Windows), ROS (Linux)
Reach	625 mm including gripper	**Construction**	Standard six axis kinematic
Communication	USB, internally CAN at 20Hz	**A1-A4**	Servo joints with gear motor, encoder and µC per joint
Power Supply	12V via main adapter < 60W	**A5-A6**	Smart servos
Digital Inputs	3*24 V	**Gripper**	Digital two finger gripper
Digital Outputs Base	4 Relay outputs	**Version**	2016
Digital Outputs Flange	2 Digital Outputs, 5 V	**Current**	5 Ampere

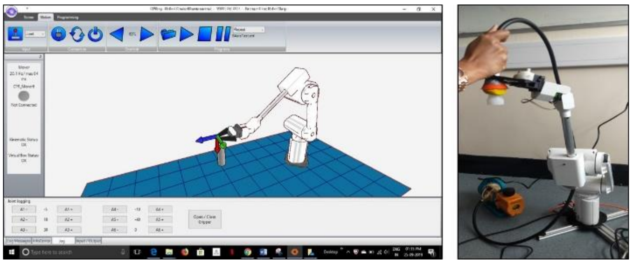


Fig. 7. The robotic arm and CProg Software.

4.2 Experiments with daily life objects

A set of experiments was designed in order to check the reliability and performance of the gripper vs the task of grasping multiple objects with different shapes, weights, geometry and consistency. The rationale behind the choice of these objects is based on a selection of daily life objects rather than industrial objects, given that such a low-cost gripper may be also integrated into home robotic applications.
Table 5 report the list of the objects that were used in the experiments. The table also emphasize the geometric main characteristic of the objects.

The protocol of the test was organized as it follows:

- three types of ‘actuation’ were tested, namely applying vacuum by means of the 220 V vacuum pump, applying it with the 60 ml syringe and, finally, testing the possibility of manual deflation (through a straw connected to the filter and the balloon)
- For each one of this condition, all objects were tested 5 times, namely the object was put in contact with the gripper and tested the grasping capability.

- Therefore, a total of 120 trials - 8 (objects) x 5 (trial per object) x 3 (condition of vacuum source) – were performed

Table 5. Type and geometry of the objects.

Object		Geometric Features
1	**Bottle cap**	Round shaped
2	**Glue stick**	Long and Irregular
3	**Pen Drive**	Rectangle shaped
4	**Small pebble**	Sphere shaped
5	**Ball pen**	Long and uneven radius
6	**Funnel**	Sharp edges
7	**Coffee lid**	3 cm in radius
8	**Air hose pipe**	Elongated long pipe

Each grasping trials was performed according to the following sequence:

1. The vacuum negative pressure was applied
2. The universal gripper was manually handled
3. The object (Table 5) was positioned in the projection under the gripper
4. The gripper was moved down to be in contact with the object
5. The gripper was lifted and kept on hold for 5 seconds
6. The result was recorded as successful whether the object remained attached for the time being
7. The vacuum pump was switched off after the object was placed in the desired destination and later got removed
8. The experiment was repeated for other 4 times from step 1 in order to test each object for 5 times

Figure 8 displays some captures while performing the tests. Table 6 reports the quantitative results of the tests.

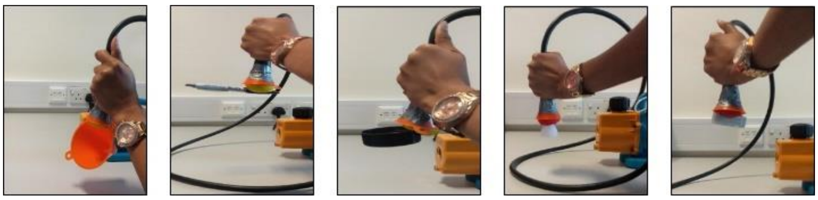


Fig. 8. Testing of the Gripper on grasping of a subset of objects as reported in Table 5.

From the quantitative analysis of Table 6, we infer that the actuators used for each of the object have shown somehow a gripping capability, nevertheless the vacuum pump could clearly show higher efficiency on grasping all the 8 objects, whereas the syringe pump (and the manual approach) failed to reach such a rate. Also, from the table we notice that the objects being grasped or picked up by the end-effector had dissimilarity in their size regardless of their stiffness or softness.

The adopted metrics in order to evaluate the successful rate is based on the count of the successful trials out of the overall set of trials for each object and each condition.

Table 6. Quantitative analysis of gripping performance.

Actuator	**Object**	**Number of successful trials out of 5 trials**	**Rate of successful grasping [%]**
Lung	Small Pebble	3	60
	Bottle cap	2	40
Syringe	Pen-Drive	4	80
	Bottle cap	4	80
	Air hose pipe	4	80
	Pen	5	100
	Glue Stick	3	60
	Funnel	5	100
	Coffee Lid	5	100
	Small Pebble	4	80
Vacuum Pump	Pen-Drive	5	100
	Bottle cap	5	100
	Air hose pipe	5	100
	Pen	5	100
	Glue Stick	5	100
	Funnel	5	100
	Coffee Lid	5	100
	Small Pebble	5	100

These tests are clearly a preliminary set of trials which should be followed by a proper campaign of testing where the system is validated in a laboratory scenario and then in a real 'pick and place' industrial scenarios. Despite the limits of these test, results show the potential and efficacy of the system, as well as the applicability of such a system in the medical and health world applications.

These findings suggests that, in a daily life use, object can be successfully grasped with such a universal gripper, provided that the object is not too small (i.e. bottle cap and glue stick): in this latter case the performance downgrades to a successful rate of 40%, whereas in all the other cases the overall performance is above 80%.

5 Conclusion

In this paper a granular jamming gripper is proposed in order to grasp daily life objects with the support of simple design and a 220 V vacuum pump. The proposed system can successfully lift up objects of different size and shape, despite their geometry. Although the behaviour of granular materials used here - such as coffee powder and fine gram flour - showed slightly difference in their gripping mechanism, both considered types of granules seems to offer acceptable performance. The stiffness of the elastic membrane also plays a role on the grasping capability of the gripper, as well as the amount of powder that is used to fill the volume of the soft end-effector. This is considered to be best used in health applications as it is versatile to pick up any objects for the handicapped or paralyzed ones.

In this type of application, only a fraction of the objects surface can be engaged in order to finally hold the object securely: therefore, simple sensory feedback on the gripper could be used in order to furtherly simplify the design and reduce the cost of the system.

The overall cost of the proposed system is approximately less than 20 $ (≈ 15 GBP), excluding the vacuum pump and the Mover6 6DoF robot arm as it was provided in the robotic lab. This solution could also be very versatile, allowing the gripper to manipulate rigid components (e.g. metal parts), nut, also food and fragile elements (e.g. eggs). The gripper offers the possibility to face the object from different orientations, due to its shape and properties.

There is clearly a limit on the proposed validation of the system, due to the fact that the presented tests are a set of (1) preliminary trials and (2) they are laboratory trials, namely conducted in a protected environment. However the proposed protocol and the type of objects that we have selected on purpose (i.e. daily life objects) aim at proof the efficacy and potential of the proposed system vs daily life application especially in the world of the medical application where the cost has a huge impact on the patient.

Future scope involves adding a pressure sensor or a strain gauge to the gripper in order to record the pressure that is applied within the flexible container of the granules (i.e. the latex balloon). A better characterization of the gripper performance vs the shape, size and nature of the granules would clearly help the refinement of its design (Jiang, 2013). Stiffness analysis, more in-depth characterization of the forces, interaction between the granules and between the gripper and the object should be performed by means of a Finite Element Method (FEM) analysis and experimental set-up.

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