Compliant gripper Using the Jamming principle

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***Abstract*—Traditional robotic grippers focus on using control electronics to limit motion and stop crushing. However, in recent years soft compliance has started to take over to reduce the pressure on accuracy. There are very few grippers that have incorporated hard and soft elements of the gripper. Where this is used, soft tendons are the primary method. In this paper, we attempt to mimic the soft pads of the human hand and apply the particulate jamming transition in them to gain grip. 3D printed Polylactic acid (PLA) was used to make the gripper whilst due to the nature of jamming, multiple particles had to be tested.**

Keywords—Robotic gripper, Jamming, Soft robotics, grasping.

I. Introduction

Gripping various abstract objects is a task that comes naturally to the human hand and is a passive task we perform that is very often overlooked. Whilst this is the case for a human, for a robot gripping is a complex task requiring positional awareness and attaining the correct grip strength to not crush the object. This has led to an ever-expanding sector of soft robotics looking at different elements of compliance, favoured mainly by the bio-inspired tendons in the hand [1]. Regarded as an evolutionary success, seen in various animals, this tendon design allows for both underactuated manipulators and for complex control to be developed looking at the motion of the hand. Although the tendons provide precise control and a small bit of compliance, potential slip of an object is still a problem that exists. This is traditionally solved using a surface with high contact friction or by using protrusions of an object to wrap around.

The aim of this paper is to investigate applying multiple soft elements of robotics into a hard-robotic gripper, something that is not often done [2]. This is in hope of further development to help create a universal gripper that can be applied to robots in working environments alongside humans. Competitions have been set out to look at this principle of a universal gripper, however none have achieved it to the same degree a human can. The development and research of this device looks to help progress along this path.

The jamming phase transition is used to describe the range of phenomena shown by granular and viscous liquids to change between states [3] [4]. This complex behavior of materials is commonly supported by a jamming phase diagram which can be seen in Figure 1 The jamming phase diagram by Liu and Nagel . This shows the ability for jammed materials to support a load. This jamming transition has been described to use three independent variables: packing fraction, a functional temperature and pressure. If one of the variables is not sufficient the phase transition does not occur. However, it is through this phase transition that elements of both soft and hard robotics can be used. To satisfy the needs of a universal gripper a hybrid approach must be taken to allow precise grip at the end of the digits whilst maintaining the broad ability of a traditional gripper. To combat the problem of traditional jamming grippers having to apply force from a direction onto the target object, this gripper uses multiple contact points, then the jamming transition is applied. This allows traditional gripping means to be used and hence compatible with previous generations for grippers, however it adds the grip that is obtained through the jamming and hence for tasks that occasionally have gripping failure, allows higher success rates.

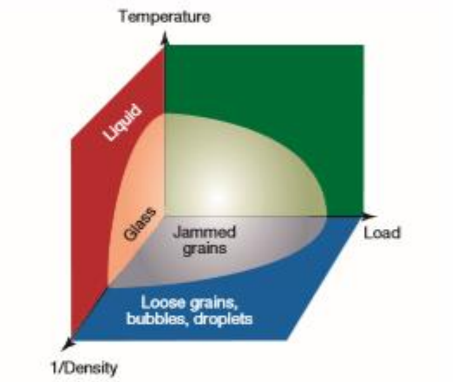

Figure 1 The jamming phase diagram by Liu and Nagel [5]

II. Similar and relevant work

There is an increasing number of researchers looking into use of the jamming transition in soft robotics due to the compliance it allows [6] [7] [8] [9] [10].

There are similar works that look at the use of the jamming transition to fix the position of the joint. Although some grippers have been developed as a single soft object to wrap around a target. These grippers still encounter issues when an object cannot find an edge, or it cannot be wrapped around [6] [7].

Although typically anthropomorphic designs use independent control of each joint. It is still an active area for research which companies, such as DLR, are designing upper limbs and hands. However, there is also research into underactuation with limited control providing complex motion [11] [12] [13]. The underactuation allows for the actuator to be placed in either the hand or wrist to allow for the joints to be slimmer and hence gain added control [14]. This also allows for a smaller and lighter design as the actuation can be moved away from the end effector. Examples of this tendon driven design include the i-HY hand design, [15] the multi-fingered Robotic Hand by Mizushima et al [16] and the Meka M^2 Gripper [17]. This is a popular design which focuses on attaching a tendon to the finger link and then the joint is rotated through the pulling of this tendon.

Although tendon control is commonly used, there is still large funding and resources going into mechanical designs for robotic grippers. This is shown by the production of the SARAH gripper for use on the ISS [18].

Ying Wei et al. in their paper "A Novel, Variable Stiffness Robotic Gripper Based on Integrated Soft Actuating and Particle Jamming" [19] show that there is a desire for abstract designs to be developed over traditional designs. In the paper they looked at using the jamming principle for a similar purpose to mimic adding grip to the digit. However, the principle used in this paper is to use completely soft elements as the spine of the design and it is using air actuation instead of traditional gripper designs. It was shown that using the jamming transition provided an improvement in grip which led to further the designs looking at passive jamming [20]. However, Ying wei et al. in this paper ended up going with the soft design completely.

Another application for the jamming transition in grippers is to lock the digit in place. This was investigated by Mizushima et al. using a soft rubber sleeve and a large granular material, which in this case was rice [16]. Numerical data was gathered, and they found that using small granular material for stiffness jamming was not as good as using larger grains such as rice. This is contrary to the Topical review conducted by M. van Hecke where it was discussed that as the grain size was increased, the grip strength exerted through the jamming transition was lower [21].

III. Design Process and analysis

Due to the nature of keeping the gripper linear in a similar manner to a human digit, it means that the primary method used in many tendon-controlled grippers cannot be used [22]. This is due to the primary means of control being a single linear tendon down the middle of the digit. However, the primary design principle is keeping the middle of the digit free to allow for a vacuum pump to be used.

Given sufficient resources this could be adapted with specifically built granular packs to allow for a small vacuum pipe to be used. This could be then made linear in-line with the tendons, simplifying the design. However, the design addressed in this paper was based around this principle of avoiding the middle of the digit to allow space for the vacuums to be attached to the granular packs.

For deciding the material of the granular packs, a short unscientifically valid study was conducted on various materials. It was found that the use of Coffee or table salt were the best options. These findings were supported by Liu and Nagel [5]. However due to common use of coffee in jamming transition grippers it was decided to use this to keep the results comparable to other studies [6] [7]. An important point to note is the lower density of Coffee provides an overall reduced weight to the gripper head [7].

Rapid prototyping was conducted using computer aided design (CAD) and computer added manufacture (CAM) using fused filament fabrication (FFF) printing, commonly known as Fused Deposition Modelling (FDM). This meant that logical steps could be taken to improve on each design as problems were encountered. When used in combination with a logical design process it can help to speed up design to allow for additional data to be gathered.

A. *Finite Element Analysis (FEA)*

When some of the parts were tested in a real environment it was found that they were breaking in certain areas repeatedly and hence FEA was performed to analyse why this was happening. FEA can be used to gauge the strength of a design and find weak points. Although FEA is a powerful engineering tool for finding weaknesses it is hard to accurately model FFF printing as the method of construction changes the properties drastically. This is due to the strength of the print varying depending on which axis the FFF printing is done from. This alongside temperature and the composition of the filament make performing FEA in CAD difficult. Hence to form an algorithm to perform FEA, the strength of the bonds between each layer must be examined.

Polylactic acid (PLA) is a common material used for rapid prototyping and 3D printing. However, it can be found that the performance of FEA is questionable and that some of the results found in one direction are not valid in another. Hence in common CAD software, such as Solidworks and Fusion 360, the material is not found in the materials database and hence properties must be assumed or become a collage of multiple different data sets. In real application, it can be found that plastic deformation will occur in the stressed parts of a 3D printed design. This can be addressed partly by increasing the infill of the parts or reducing the layer height. But this will directly affect the print time. Table 1 shows print times of the initial digit iteration 1 with the changing of the infill and the layer height.

Although, as a rough outline Acrylonitrile butadiene styrene (ABS) can be used to simulate PLA poorly, though to solve this issue a new orthotropic material must be created [23].

There is a lack of information about the topic of PLA, however research is being conducted to find out the material properties of different PLAs [24] [25] [26]. In the case of this paper, an isotropic material is assumed for simplicities sake as the FFF connection strength between the layers of the extrusion cannot be found.

Table 1 Print time comparisons between layer height and infill

Layer Height	*Infill*	*Print Time*	*Layer Height*	*Infill*	*Print Time*
0.1	10%	3H10Min	0.2	10%	1H35Min
0.1	20%	3H34Min	0.2	20%	1H47Min
0.1	30%	4H02Min	0.2	30%	2H01Min
0.1	40%	4H25Min	0.2	40%	2H13Min
0.1	50%	4H49Min	0.2	50%	2H24Min
0.1	60%	5H11Min	0.2	60%	2H36Min
0.1	70%	5H32Min	0.2	70%	2H47Min
0.1	80%	5H53Min	0.2	80%	2H57Min
0.1	90%	6H15Min	0.2	90%	3H08Min
0.1	100%	8H21Min	0.2	100%	4H12Min

The variability in connection strength depends on a minimum of 5 factors: material, print temperature, room temperature, room humidity and cooling ability [24]. To keep the calculation simple ABS material properties were used as a Prusa I3 3D Printer could be loaded with ABS filament and printed with full infill to closely mimic the FEA Modelling. The results from this FEA will not be completely accurate due to the layering that occurs in FFF printing. However, this process gives a rough overview of how the design will perform.

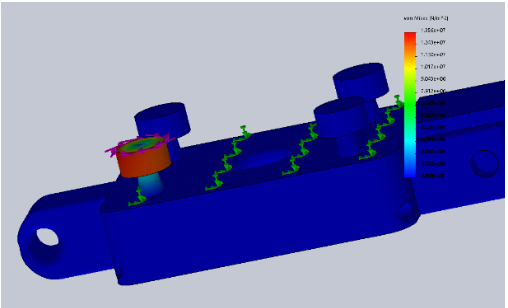

Figure 2 FEA of the elastic antagonist of the joint

Figure 2 displays the initial iteration of the elastic posts on the reverse side of the digits. Upon manufacturing the part using FFF; the posts were exhibited to show fragile behavior and displayed a flexible movement where the part should have been rigid. FEA for torque forces showed how a rotational force would affect the post, in Figure 2 the forces act entirely on the top of the post. Figure 2 **Figure 3** Thickened elastic antagonist anchorsshows the upgraded post, where the force exerted is spread downwards and forms a

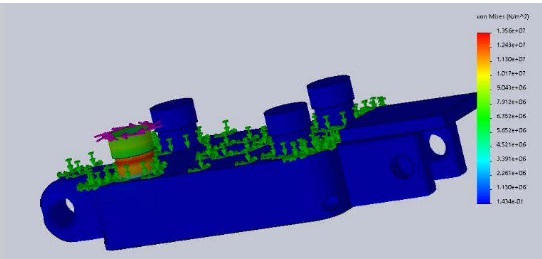

Figure 3 Thickened elastic antagonist anchors

secure connection to the base.

Overall, the design of the project went through multiple design steps to reach its final iteration. This was due to gradual progression from rapid prototyping. The main progression was the improvement from static pivots to rotating pivots. It was found that the static pivots provided too much resistance to the rotation of the digit. A progression of all the middle digits can be seen in Figure 4.

Figure 4 Iterations of the middle link design

B. Tensile Testing

The tendon used to retract the digit assembly is required to be strong whilst displaying some elastic properties to add compliance to the design. This increases the impact resistance of the design as the tendon stretches instead of snapping. Figure 5 shows the agonist tendon and how it runs through the digit assembly. This was based largely off the design from the M^2 gripper [17].

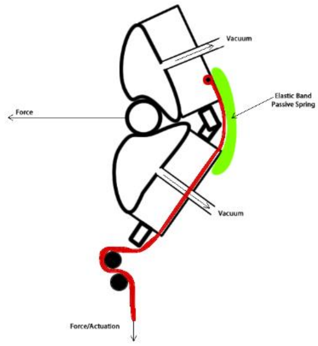

Figure 5 Graphical representation of the agonist(red)-antagonist(green) nature

Each samples result was plotted and collated into Figure 6 and Figure 7. The elastic and plastic deformation regions are the parts that are of interest. The graphs helped to determine the material to use for each tendon.

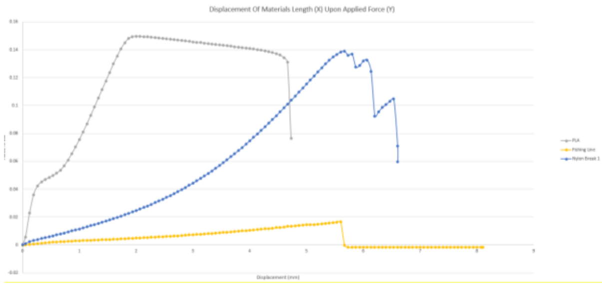

Figure 6 Tensile test results for PLA, Nylon and Fishing line

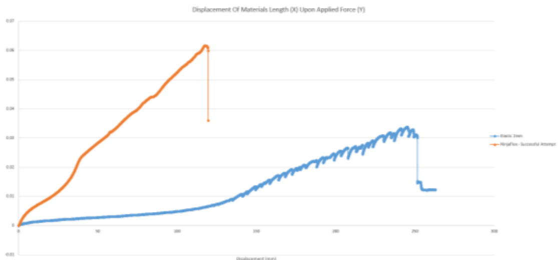

Figure 7 Tensile test results for flexible PLA and elastic rope

A summary of the data for each material is shown in Table 2 which displays the numerical data displayed in Figure 6 and Figure 7.

Table 2 shows that the candidates for the agonist tendon are Nylon, Fishing Line and Flexible PLA. Each material exhibits a large elastic deformation with high load force, this allows for the agonist tendon to drive the digit assembly with high torque and not run the risk of plastic deformation.

Table 2 Different Material Properties found using tensile testing

Sample	***Maximum Force (KN)***	***Displacement at Maximum Force (mm)***	***Maximum Displacement (mm)***	***Force at Break (Standard) (KN)***
Elastic 2mm	0.03	245.1	262.81	0.01
Flexible PLA	0.06	117.6	119.63	0.06
PLA	0.15	28.59	30.87	0.14
Fishing Line	0.15	2	4.73	0.13
Nylon	0.14	5.67	6.6	0.07

Whilst for the antagonist joint the elastic 2mm thick material and the flexible PLA are suitable. Each material shows a clear elastic deformation before a sudden fracture. Flexible PLA, according to the tensile test, will be better as the antagonist due to the high ultimate tensile strength, and short displacement.

IV. Testing

The jamming transition is the process of granular material locking its structure when a pressure difference is applied in a closed environment [27]. Unfortunately, due to the experimental set up, the pressure difference in the jamming transition is small.

A few assumptions were made at the beginning of the granular packing experiment. For the experiment it was assumed that the room was at a normal dry room temperature of 20°C with an atmospheric pressure of 101,325 Pa. The density of coffee was assumed to be $0.561 g/cm^3$ and there was an 80% removal of air from the balloons with the assumed gas constant of $8.314 J\ mol^{-1}\ K^{-1}$ Hence the volume of air in the balloon was calculated. The balloon was a uniform radial sphere of 2.25cm. All values in calculation were exact, however in display 3 significant figures was used.

$$V_{ball}=\frac{4}{3}\pi 2.25^3=47.7cm^3 \quad (1)$$

$$V_{Coff}=\frac{15}{0.561}=26.7cm^3 \quad (2)$$

$$\therefore V_{air}=V_{ball}-V_{Coff}=21.0cm^3 \quad (3)$$

$$\therefore V_{air}=21.0\times10^{-6}=2.1e^{-5}cm^3 \quad (4)$$

Using the ideal gas law.

$$PV=nRT \quad (5)$$

$$(P_{Change})\times(V_{air}\times 0.80)=n\times R\times T \quad (6)$$

$$(P_{Change})\times(2.1e^{-5}\times 1.20)=1\times 8.314\times 21 \quad (7)$$

$$P_{Change}=\frac{8.314\times21}{2.1e^{-5}\times 1.20} \quad (8)$$

$$P_{Change}=69.4kPa \quad (9)$$

This is a value that when compared to a paper conducted by T. S. Majdamur et al. a pressure difference of one and a half times provides an isostatic value of 3.5, [27] in this case the calculated number of contacts between particles, which is a significant increase from its original non-jammed value of 2.5 [21]. This value is 10kPa less than the value calculated by Eric Brown et al. where 80kPa was used for the pressure difference for jamming [6]. Whilst their findings also suggest that the jamming transition is a reversible mechanism and that by releasing the vacuum and having no stimulation the pack can still be manipulated. Although only roughly examined, the difference between an unjumbled granular pack against a jumbled granular pack was noticeable. Hence to keep the results accurate, the granular packs were jumbled randomly between each test.

Two main experiments were conducted through the design process, these were to decide on the granular material used in packing and to test the grip strength of the granular pack. Testing the grip strength of varying shapes was tested through use of a force meter pulling on the test shape. Each of the edge test shapes was made to be a cube of 20mm x 20mm x 20mm. The experimental data has been displayed in Figure 8.

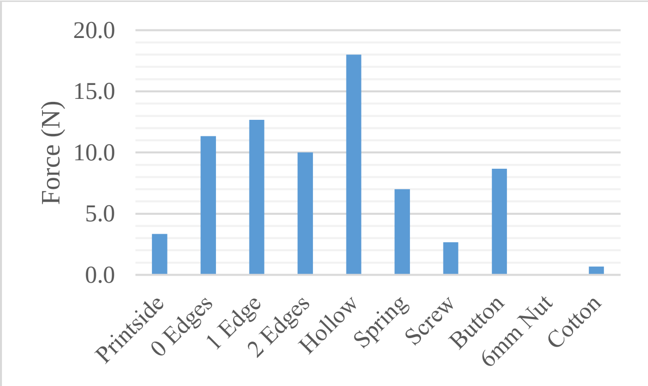

Figure 8 Comparing grip strengths compared to their shape

Figure 9 Displaying the different test shapes

It was possible to gather some interesting results that agree with some similar papers [6] [16]. The results gathered in this paper support the hypothesis that the ability to grasp an object depended on its contact area and the grip strength [7]. As it can be seen in Figure 8, there was a large disparity in the ability to grip certain objects. One of the interesting points to note is that difference in the orientation of the PLA test parts influences the ability to grip. Although the 0 Edges and the rotated object were the same shape, there was a 500% increase in the ability for the object to be gripped.

This supports the hypothesis that if the object is wrapped around, that the grip strength will drastically increase [7]. It was also noted that the smaller objects such as the screw and the 6mm nut could not be gripped easily. This was perhaps caused by the crude experimental set up applying a directional force to the object being tested.

From experimental results it was possible to see the success of the grip depending on the contact percentage. The results gathered in Figure 8 were only from successful attempts to grip apart from the 6mm nut which was not possible to grip at all.

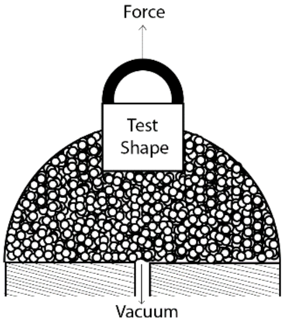

Figure 10 Experimental set up for testing grip strength

The experimental set up that is seen in was used. Of the 40 results obtained there was a 70% success rate with 2 anomalous results which suggests that the results obtained are like findings by Amend et al. [7].

The second experimental set up was examining the effects that removing volumes of air had on the grip strength. This was conducted using a syringe to gauge volume of air removed. This is shown in Figure 11, which shows an increasing trend in the grip ability as air is removed. This is in line with the results found by Amend et al. [7] such that an increase in pressure influences the ability to grip.

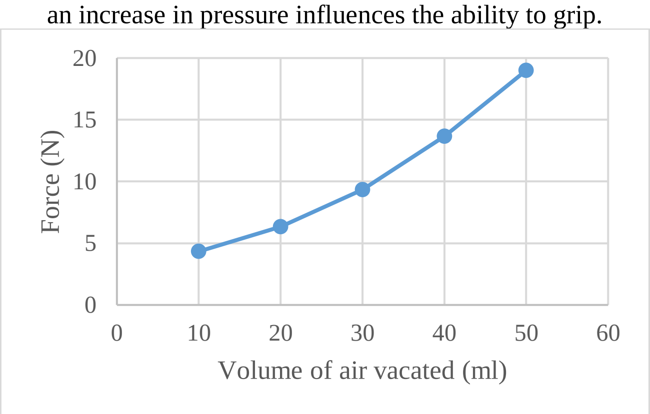

Figure 11 Grip strength compared to air vacated

The two experiments show that the jamming transition functions even at low pressure differences that and that it is not required to have a high actuation force. These results are parallel with the results found when the use of two digits around an object. This is potentially due to the hemispherical soft pads on the end of the finger [28] [29].

Although this data has been gathered, due to the limitations in testing apparatus it was not possible to form a complete vacuum and hence the full experiment was not possible. Previous studies on the pressure differences required for the jamming transition to be high pressure (600KPa+ [7]) whilst there have been few articles that look at the ability for the jamming transition to work at low pressure values.

A short study on the effect of combining the use of tendons and jamming transition was conducted. However, it returned inconclusive results with high variability. It was possibly due to the limitations in the parts used.

V. Conclusion

This paper has addressed the design and testing of a universal jamming transition gripper. There have been very few hard and soft robotic gripper hybrids with even less experimental results. This is in part caused by the difficulty of getting valid experimental data on grip strength due to the inherent chaotic nature of jamming. The difference of grip depending on the contact surface varies greatly. Hence to validate the results a large data pool is required suggesting a better repeatable experimental set up is required. Whilst the a relatively primitive experimental set up was used, it was possible to obtain valid data, that is supported by other periodicals and journals. The current limitations in data analysis and progression are due to limitations in manufacturing facilities and testing methods.

The elements of design displayed in this paper were a combination of factors that are still being researched; the underactuation of a robotic gripper, the jamming transition and manufacture of a universal gripper. The applications for this combination have not been thoroughly explored as soft robotics is an expanding area of research. This design is a prototype requiring further development but through the experimental data it is possible to infer that the principle works. Through the combination of the soft and the hard-robotic elements, it allows for adaptations to current designs in manufacture and with some of the findings regarding soft pads on the end of fingers supporting this. The jamming transition is a suitable technology to use in soft robotics but the ability to form a vacuum is the main limiting factor, especially in this situation. The development has covered low pressure jamming transition which has some support, but the best results have been shown at to be at high pressure differences, reaching up to ten times the values used in this paper.

VI. Further Development

Due to resource constraints, there are several changes that can be theorized but not implemented. This will be adapted in future iterations to deal with the problems. The primary area for improvement is the vacuum and particle pack system. The use of balloons as a proof of concept works, however using the balloons in the long run is not a suitable solution. This is due to the lack of air tight seal, the clogging of the filter and the ability for the coffee granules to reach outside the circumference of the digit bowl. In future, a specially designed particle pack will be used.
Firstly, this will provide the ability to use a traditional tendon gripper design, simplifying the whole structure and reducing the strength of the actuator required. Furthermore, this means that the particle pack can be placed on top of the digit to be bio-mimetic of the human hand. Whilst similarly, irregular shaped surfaces may be used to gain further grip in the system. This will not only make the digit thinner, but it will allow the end digit to be a more familiar shape and make path planning simpler. This leads onto simplifying the

tendon design back to a singular tendon to lower the actuation required for moving the digit.

As shown by calculations, the pressure difference that is possible is much lower than that of an industrial vacuum pump. Hence in future iterations a stronger vacuum will be used. The jamming transition is already beginning to see application in various fields being researched for movement and for irregular gripper designs.
According to the jamming phase diagram by adding extra to one of the key elements of the jamming transition it is possible to increase the grip strength of a normal gripper and hence a pathway to commercialization.

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