EXPERIMENT DEVELOPMENT AND VALIDATION OF A GRANULAR JAMMING ROBOTIC GRIPPER

By

Jacob R. Dowd

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Jacob R. Dowd

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Master of Science in Engineering - Mechanical Engineering
Department of Mechanical Engineering

Paul Oh, Ph.D.
Examination Committee Chair

Kwang Kim, Ph.D.
Examination Committee Member

Woosoon Yim, Ph.D.
Examination Committee Member

Brendan Morris, Ph.D.
Graduate College Faculty Representative

Alyssa Crittenden, Ph.D.
Vice Provost for Graduate Education &
Dean of the Graduate College

ABSTRACT

A granular jamming gripper (GJG) is widely known as a Universal Gripper because of the wide range of objects that it can grasp and the simplicity of control, design, and manufacturing. Despite multitude of research improving the GJG, here, we focus on the base version of the GJG and attempt to glean the range of objects that it may reliably grasp. Despite the limited range of objects, which were a sphere, rectangular prism, and cylinder, we gleaned geometric properties as it relates to successful and unsuccessful grasping. This was based on the two types of testing: push and pull testing that measured the grasp ability, and grasp strength, respectively. The experiment results were surprising because we used the load cell in different orientations, but we attained the expected results as if the load cell was in the same orientation. These experiments attempt to validate and build upon current research by economically developing and testing the apparatus and gripper. From these experiments, we validated that the gripper grasp ability depends on the gripper diameter, and the contact angle with the object via introducing a “pressure” parameter that is the force by the surface area contact. Since a cartesian machine was used, we can nearly guarantee the depth into the object and therefore calculate the surface area contact using the 3D model.

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To the late Mrs. Mary Switalla, to whom I owe my successes.

She taught me to live every day to its fullest,

and to pay it forward.

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CHAPTER 1: INTRODUCTION

More than one billion dollars was generated by the robotic gripper market in 2020, and it is forecasted that this number is going to more than double by 2028 [1]. Continuous funding from medicine, space exploration, and manufacturing leads to better and more robust robotic grippers Tai et al. [2]. Since grippers often attempt to mimic human-level manipulation, traditional grippers and multi-fingered hands require complex computation and sometimes learning algorithms for diverse objects. This approach can be time consuming and expensive, and this is not a good solution for unknown objects. However, many *soft robotics* grippers excel at handling unknown objects due to their inherent compliance. One type of soft robotics gripper is a granular jamming gripper which also does not have these complexities because it passively adapts to the object's geometry for form closure [3]. Granular jamming grippers (GJG) demonstrate a proficiency in grasping many objects to the point it has been dubbed a "Universal gripper." However, there are some objects where the GJG is less effective. Current research in GJGs involves improving and optimizing the granular material [4], actuating the granular material in different orientations and enclosures [5], and determining the characteristics and quantification of successful grasping [6].

Granular jamming grippers (GJGs) utilize exhibit of granular jamming: which employs small particles, such as coffee grounds, to exhibit a phenomenon when enclosed and in or near a vacuum state, where they become very stiff. Consider an unopened bag of coffee from the store is very stiff due to its vacuum sealing, but loose upon opening. This example highlights that granular matter exhibits a duality in that it behaves like a fluid when at atmospheric pressure, but then like a solid at relatively low pressures. This is possible because some membrane encloses the granular material allowing it to reversibly transition between stiff and loose granular states.

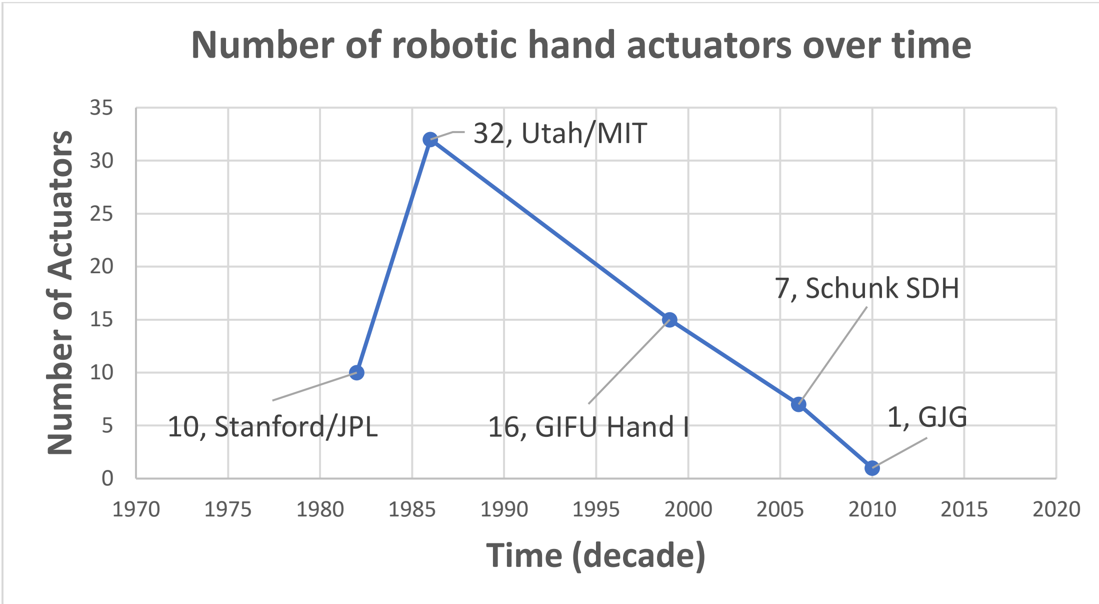

Figure 1: Various robotic hands over time [7]; In the last 40 years, we see a decreasing trend in the number of actuators used in robotic hand development. The GJG is not a robotic hand, but the comparison serves because some tasks the GJG may be used instead.

From Figure 1, we see the first development of a robotic hand that is the Stanford/JPL Salisbury hand [7]. From here we see a sharp increase in the number of actuators (5.5 actuators/year) with the Utah/MIT hand, and then a gradual decline (<1 actuator/year) with the introduction of soft robotics hands until we have the GJG in 2010. The number of actuators adds functionality but greatly increases the cost and complexity. Regardless of these factors, robotic hands still are not good for unknown objects as they require grasp planning algorithms; but granular jamming grippers (GJGs) do not. They utilize exhibit of granular jamming: which employs small particles, such as coffee grounds, to exhibit a phenomenon when enclosed and in or near a vacuum state, where they become very stiff. Consider an unopened bag of coffee from the store is very stiff due to its vacuum sealing, but loose upon opening. This example highlights that granular matter exhibits a duality in that it behaves like a fluid when at atmospheric pressure, but then like a solid at relatively low pressures. This is possible because some membrane encloses the granular material allowing it to reversibly transition between stiff and loose granular states.

Granular jamming also greatly simplifies grippers. Consider that a single finger on a traditional robotic hand has at least two to three degrees of freedom (DOFs), therefore, a four finger hand has ten to twelve DOFs, which becomes increasingly difficult to control. Various soft grippers are underactuated [2], but the complexity is still greater than that of the gripper shown here. While sensors aren't typically needed for GJGs they are needed to attain characteristics of the forces involved. For GJG research, it is common to use a load cell because it can be accurate and is a continuous measurement of the applied force needed to pick up the object. This gripper is based on the change in granular matter rigidity, which is driven by pressure difference of the "air-tight" granular matter and atmospheric pressure. If the pressure difference is small, then the granular material will remain somewhat stiff. Since we can use the vacuum generator on command, we can control the low pressure so that we may grip and un-grip the objects on command.

A commercial product, VERSABALL, was developed in Amend et al. [8], which improved several aspects of GJGs, including the membrane durability and wear, granular material, cost, pushing force, pulling force, noise level, and many more factors based on customer specifications, which are all listed later on. Since we are not developing a commercial product, we just want to develop a minimum viable product, which will lead to further testing and improvement of GJGs. Therefore, we limit our research scope to that of key customer specifications including pushing force, pulling force, cost, and building the GJG with basic materials and hardware. We recreate the experiments featured in other works, but to push the envelope, we attempt to develop a geometric standardization, so that we may quantifiably determine the success or failure of the given object.

CHAPTER 2: LITERATURE REVIEW

A robotic gripper is the interface between the robot and the physical world. Commonly, it is expected that a robotic gripper acts as a human hand to automate repetitive tasks, such as those found in a manufacturing environment. Emulating human dexterity, movement, and control requires significant overhead; specifically, data acquisition, grasping strategies, kinematic complexity, and force feedback [9]. It is common to place soft materials in between the interaction point of the gripper and the object, but this does not address the root cause. Soft robotics uses soft materials in actuators and enables human-like responses even under disturbances [10] and is generally biologically inspired [11]. The distinctions of soft gripping are by i) actuation, ii) controlled stiffness, iii) and controlled adhesion according to Shintake et al. [10], in Figure 2.

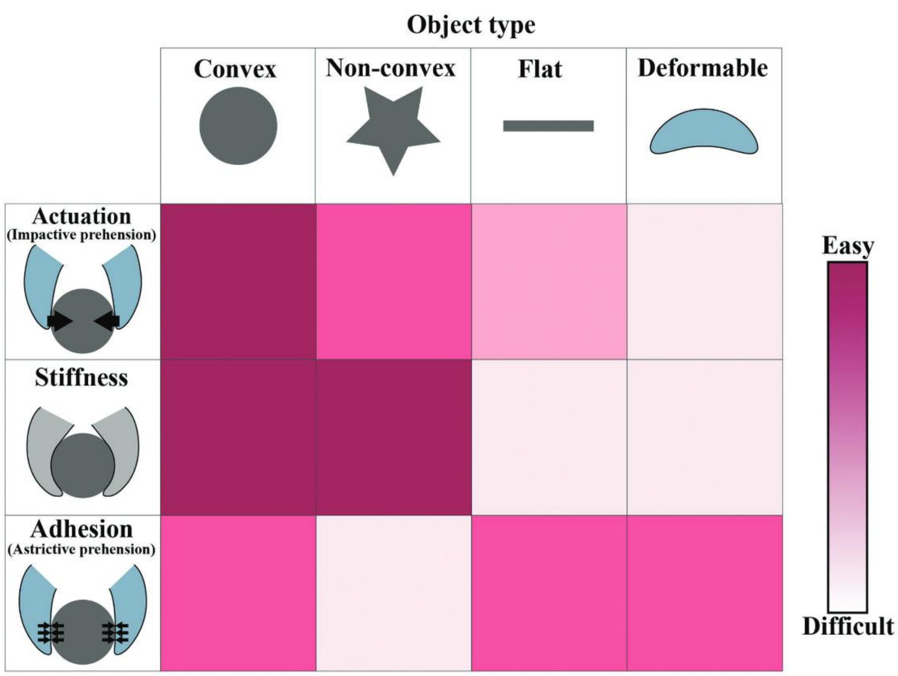

Figure 2: Soft grippers by type and object [10]; Various soft grippers categorized by row into their type and by column the grasped object. Color coding is for representation of the difficulty of the grasp.

Figure 2 shows the various types of soft grippers and the objects that are ideal for them based on difficulty. Grippers by controlled stiffness are similar to control by actuation but the force is generated by the stiffening of the material. Grippers controlled by adhesion involves “sticking” between two surfaces. Each of these actuation methods are suited more for different objects, e.g. as noted in Shintake et al. [10], flat objects are difficult for the first two actuation methods mentioned above, but simple for the adhesion method. Looking at Prattichizzo and Trinkle [3], we can see that force closure and form closure are the two prominent forms of grasping and that a GJG closely resembles form closure.

There is a plethora of grippers to choose from, but we chose to make a granular jamming gripper which is an envelope enclosed collection of granular material. This is a type of “gripping by controlled stiffness” as shown in Shintake et al. [10], where the stiffness is a function of pressure. When the pressure inside the membrane is at or above the atmospheric pressure the granular material freely flows, similar to a fluid. When the pressure inside the membrane is much below atmospheric pressure, the gripper becomes stiff, like a solid.

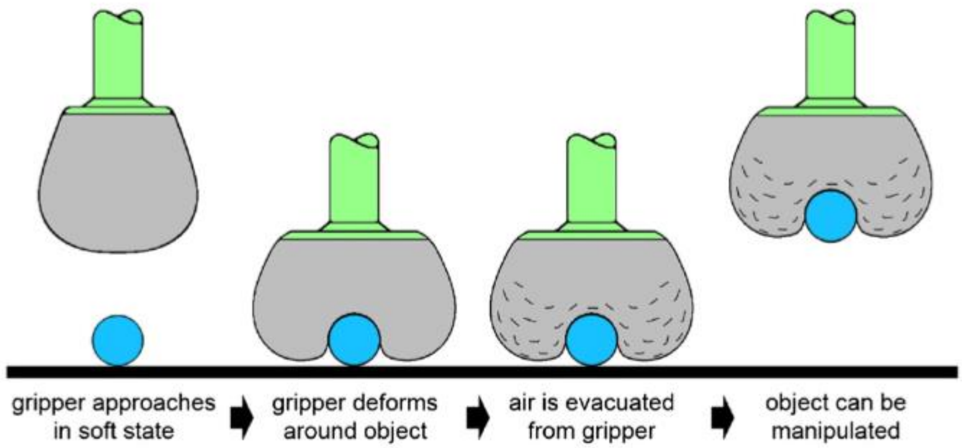

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Figure 3: Granular jamming gripper (GJG) concept [12]; Conceptual diagram that describes the vertical motion, object adaptation, and process for grasping. Does not show the fluidization (positive pressure) that is sometimes needed for gripper deformation around the object.

The formalized concept of a gripper that uses granular jamming was first introduced with the seminal paper, Brown et al. [12], as shown in Figure 3 which uses a venturi vacuum generation device, producing a vacuum of one-quarter atmospheric pressure. It was determined in Brown et al. [12], referred to as 'B', that we have three components of grasping, as shown below:

B1. The contact angle that results in geometric interlocking.

B2. Static friction at the contact points.

B3. Vacuum generation given that the gripper can seal off an enclosed portion of the object's surface geometry.

In Brown et al. [12], the gripper picks up various objects such as a triangular pyramid and a spring but fails to pick up a coin shaped object because a minimum contact angle is needed that is related to the depth of the object, specified as B1, so that static friction may develop, as specified by B2, shown as $F_f = F_N(\mu sin\theta - cos\theta)$. Certain objects comply with B3, but these are highly dependent on the type of material and geometry. For example, aluminum cans comply with B3 and the previous two rules, therefore, GJGs have especially good grasping with aluminum cans. The work in Brown et al [12] determined that the holding force for a sphere that is porous, where B3 does not apply, is:

$$F_h = 2\pi R d\sigma^* (\mu sin\theta - cos\theta) sin^2\theta$$

Where σ^* is the magnitude of the stress applied at a small width $\delta\theta$, that is centered at θ. With Amend et al. [13], the gripper was developed with the added feature of positive pressure. This eliminated the issue of waiting for the gripper to return to atmospheric pressure. This positive pressure was essential to quickly eject the object, even introducing the concept of "throw" that may be used for sorting purposes. Additionally, in Amend et al. [13], a case study was conducted in pick-and-place of seven unique objects where the applied force and the required force to remove the objects from the gripper's grasp were both measured.

The passive compliance shown in positive pressure universal gripper [12], [13] is desirable because the control and design is simple, and with effective, sensor-free grasping. However, this jamming gripper approach is limited due to its perceived durability based on the latex shield/membrane. Another limitation of this gripper is that the object should be on a plane perpendicular to the downward motion of the gripper, so it is generally not suited for pick-and-place tasks on shelves, as in the Amazon picking challenge [14], except when the gripper could be operated from above the object. For this reason, it is also not a suitable replacement for dexterous manipulation tasks such as handling a cordless drill as shown in Tran et al. [15] as shown in Figure 4. Clearly, a GJG would not be able to grasp or manipulate it for a function such as using the drill. While extensive research has been conducted on traditional grippers, and despite the limitations discussed above, GJGs have been shown to be effective for various objects in repetitive manufacturing and medical settings, and so, ongoing research is focused on optimizing the GJG, determining the well suited objects, and implementation.

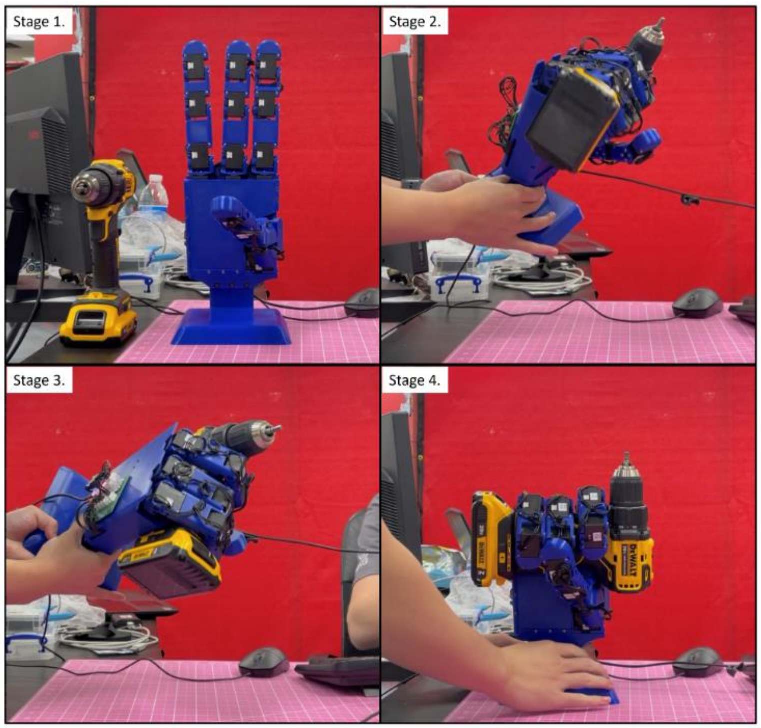

Figure 4: Highly dexterous hand grasping a cordless drill [15] that was developed for Avatar systems. This provides scope in that for the many objects that do not require dexterous manipulation, we may grasp them with a GJG, to avoid purchasing/developing a robotic hand.

Gotz et al. [4] showed that soft/deformable expanded polystyrene (EPS) particles as granular material leads to higher gripping forces. This contribution leads to improved performance of objects which do not allow geometric interlocking or suction effects. While the static friction (B2) is increased significantly, the gripper becomes soft so that the object may be released due to any additional movement past the hold position. Here we notice the tradeoff in that we may grip more objects since we do not need to have geometric interlocking or vacuum generation (with flat geometry) and rely solely on static friction but that the gripper is now more problematic during a collision.

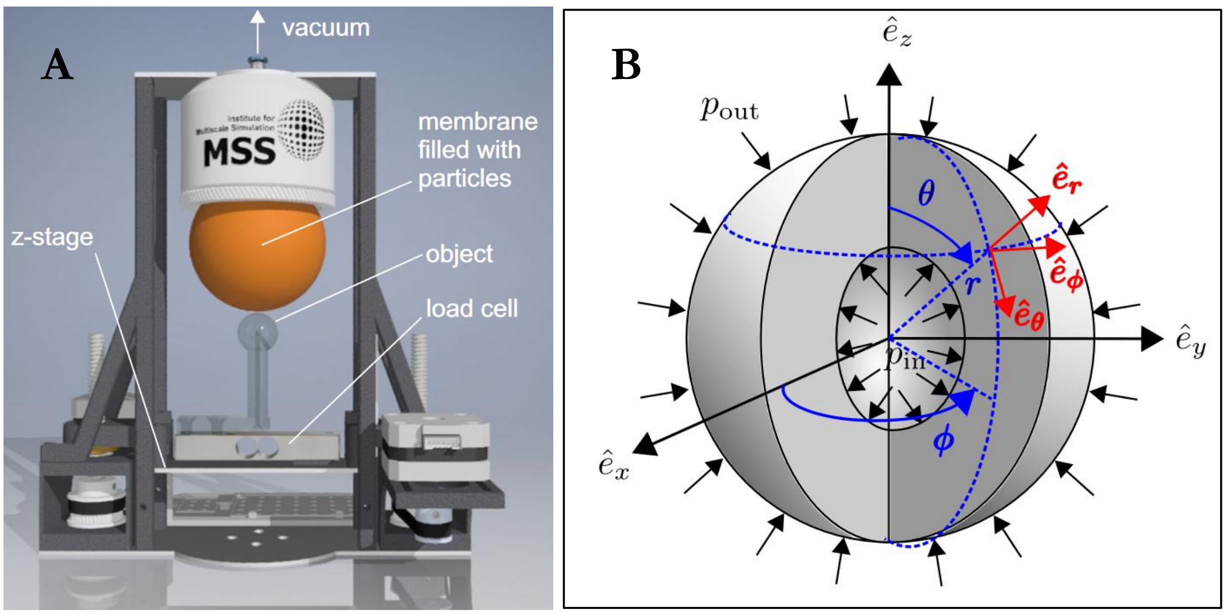

Figure 5: A. Experimental design and B. Theoretical model of gripper [4]; From A, we see that the experimental apparatus is a cartesian machine or gantry that moves the GJG in an strictly up or down motion. From B, we see the theoretical model uses spherical coordinates and assumes that there is an internal variable pressure.

Few works go into detail about the model of a GJG, in contrast to Götz et al. [4]. In Figure 5A we see a depiction of the cartesian machine that is used in the experiment, and Figure 5B is the spherical model that is assumed for the membrane of the GJG. An intrinsic problem with soft actuators is their difficulty to model due to nonlinear effects from the significant deformation during use [16]. Regardless, the model developed in Götz et al. [4] in Figure 5B has the simplifying assumptions that the grasped object does not deform, and that the granulate is a linear elastic solid.

Notably the granular jamming gripper is not well-suited for flat object manipulation such as a coin. However, Piskarev et al. [17] improved the granular jamming gripper by adding electro-adhesion. This supplements the granular jamming gripper since now it can complete a task such as opening a book and turning a page, see Figure 6. The combination of these two modes is somewhat complementary, considering the benefits just mentioned, and that electro-adhesion fails at greasy objects, but the GJ gripper does well in. And vice versa in a task such as picking up a flat object. Additionally, the GJ gripper conforms to the geometry of the object, but if the object is not rigid enough to make an impression in the GJ gripper, then it will not grasp well. For example, a balloon is a non-rigid object that cannot generally be grasped by a GJ gripper, but this grasping is feasible with electro-adhesion [17]. Although the tasks as shown as independent, they may complement each other as well, where EA provides direct improvements to grasped GJ objects, thus expanding the range of objects for a so-called "Universal gripper."

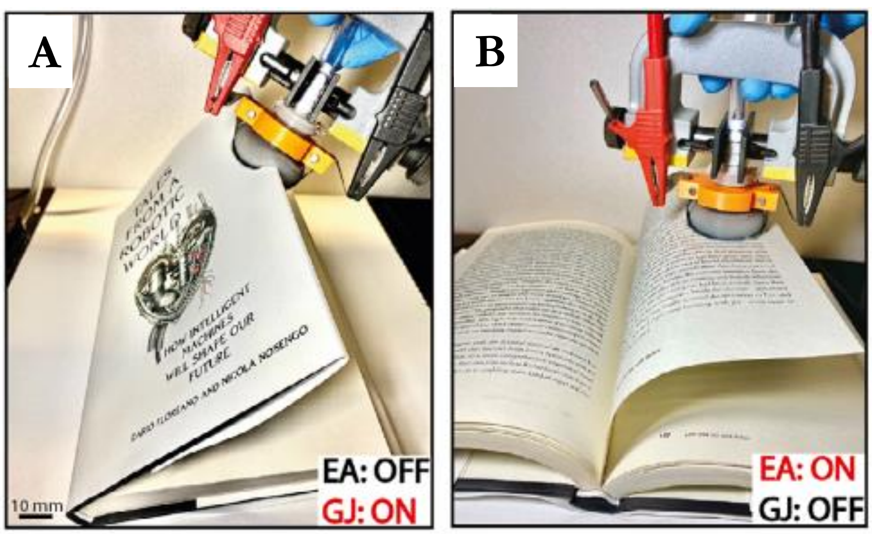

Figure 6: GJ+EA gripper; A: opening book with GJ only, B: turning a page with EA only [17]; This combined action is allows the gripper to complete an otherwise near impossible task of moving a rigid object and then carefully actuating to move a flat object (paper).

Concerning the granular material in the gripper, Howard et al. [18], provides a dataset for strength and shock absorption properties for varying sizes of granular particles that compose the granular material. While there are applications with granular jamming grippers, this is especially useful with granular systems, that is systems composing of granular materials, that are not necessarily used as grippers as shown in Cheng [19]. We can see from Figure 4A that the envelope is unjammed lowering to the object, then jammed for Figure 7B, and Figure 7C shows the pull-off after testing of the object. The purpose of this research was to determine the effects of the granular material shape and size effects on the performance of the gripper. This was completed via testing four types of ellipsoids (not shown), one of which is a sphere. To ensure equivalent volume, the granular materials were tested with sphere volume equivalent (SVE), e.g. 5SVE means equivalent volume to a sphere with diameter of 5mm. The testing occurred with the pull-off force of four different objects, which were a ball, cube, coin, and a 3D star. Notably, even the coin-shaped object has a maximum of 2.5N and 2.25N pull-off force using a 3SVE sphere and ellipsoid, respectively. Generally, flat/coin-shaped objects are not compatible with GJGs.

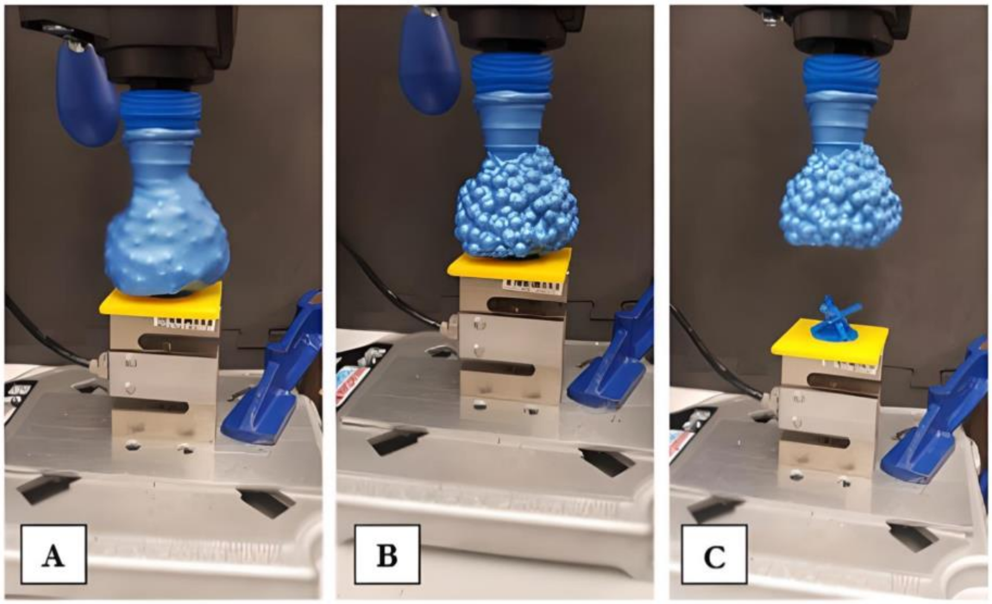

Figure 7: Granular jamming with deformable granular objects [18] which also has a thin membrane explaining why the "granular material" spheres with diameter of 5mm. "A" shows the adaptation to the object, "B" shows the vacuum generation, and "C" shows the release.

For the dataset to be developed [18], the granular particle size and shape effects were discussed [20]. Typically, coffee grounds, rice, and different geometric objects, compose the granular materials but these are prone to defects, therefore that the effects of uniform granular particles composing the granular material cannot be explored rigorously. It was shown that there is some relationship between the grain size and shape and the object to be grasped. For example, it is well known that the granular jamming gripper cannot grasp a coin shaped object, but it was found here that if the granular material were shaped like a sphere or ellipsoid, then it has about 2N of force to remove the object. Generally, the sphere or ellipsoid performs best as the shape of the granular particles. Additionally, there may be some effect since the 3D printed granular particles are smooth, whereas any standard particle is not generally smooth.

The work of Rodrigo et al. [9] needed to solve a manufacturing picking problem which involved boxes with unknown movements inside. They developed a decision matrix and found that the optimal solution is the granular jamming gripper due to its ability to adhere to unknown shapes. From here, they discussed optimization of the granular material and the envelope membrane enclosing the granular material. Optimization of the envelope membrane is difficult because the grasping ability decreases as the membrane thickness increases, as shown in left to right in Figure 8. Notably, Rodrigo et al. [9] developed a new metric which is determining the energy stored or work done during gripping, since the force and distance are measured. This quantitative metric is helpful in determining the efficacy of the grip relating to the granular material and the envelope membrane.

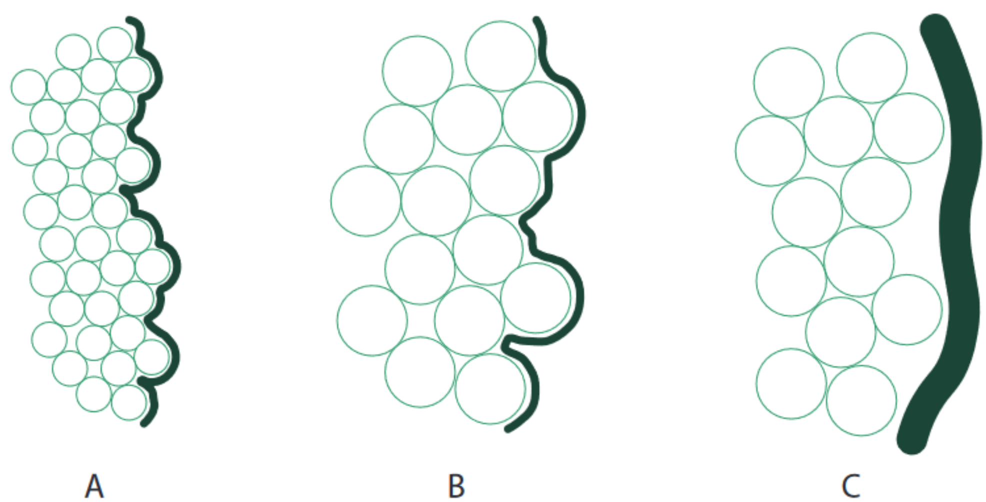

Figure 8: Granular material and envelope membrane increase [9]; We see from A to B that the membrane is the same thickness but the granular material volume increases. From B to C, the granular material volume is unchanged but the membrane thickness increases. The purpose is to show that thinner membranes are better for object adaptation but at the cost of durability.

Expanding the concept of granular jamming to liquid jamming is shown [21], where jamming involves that the stiffness of the media changes for desired object manipulation. In liquid jamming, the media is oil which has liquid and solid states based on the temperature. The stiffness change occurs because of heating and cooling of the media based on the desired state. This work improves on the problem with the original granular jamming gripper [12] which had a difficult time with reverting back to the neutral state. Notably, positive pressure was introduced to the granular jamming gripper [13] which resolved this problem. The liquid jamming gripper is less bulky than the improved granular jamming gripper [13], but takes about 20 seconds to change states even with the developed and tuned oscillator [21]. This work also helped in expanding the concept of a jamming gripper since a parallel jaw gripper utilizing liquid jamming "pockets" were used.

Discussing granular material, in general, we see that when the pressure is much lower than the atmospheric pressure, that the granular material has a macro-behavior of increased rigidity or otherwise called nonuniform force networks, Jaeger and Nagel [22]. This work discussed the "granular state," where random close packing is discussed, mainly about the qualities of granular matter during excitations and in slip conditions. These discoveries are not directly related to GJGs, since shock and excitations causing slip conditions are not commonly present. Understanding the micro-behavior is also discussed previously [18], [20] in effort to optimize this granular behavior.

While the granular jamming gripper or universal gripper may be used with many objects, most of these are assumed to be less than the gripper's radius. The work in [16] shows a learning strategy determining the optimal grasping point for a universal gripper with an object that is greater than the gripper's diameter. While the universal gripper generally avoids learning algorithms because it conforms to the objects shape, it becomes necessary when there are many grasping options as shown in Figure 9, which is the gripper holding tongs. They use an RGB-D sensor for object detection and depth perception since much of the previous work uses open loop control of the robotic system that the GJ gripper is attached to. Granular jamming gripper research generally relates to small objects so that the "… center of mass of the object be located in line with the gripper's central axis" [16]. Notice that the center of mass on tongs is not located on the physical tongs in Figure 9. Therefore, the decision making algorithm weights minimizing torques and maximizing contact area, this was compared to the "centroid method" which always grips the center of the object. This "centroid method" term is defined in this paper because related works generally assume this method and no alternative. It was determined that the centroid method and the learning method are comparable for small objects, but the learning method was better for larger objects such as that shown in Figure 9.

Figure 9: Grasping point strategy [16] for determining a rectangle for the ideal position for grasping an object. This refined other work as employing the "centroid method" since at every grasp, the gripper moved towards the centroid of the object.

The work of Cheng [19] involves granular jamming systems with emphasis on bulk performance, stress dependence between granular particles, and a robotic jamming manipulator, where the latter is of most interest in this work. This progression from the micro/meso/macro scale progression is shown in Figure 10. The manipulator developed is a trunk shaped granular jamming manipulator, which has the advantage of manipulation of an object into different orientations.

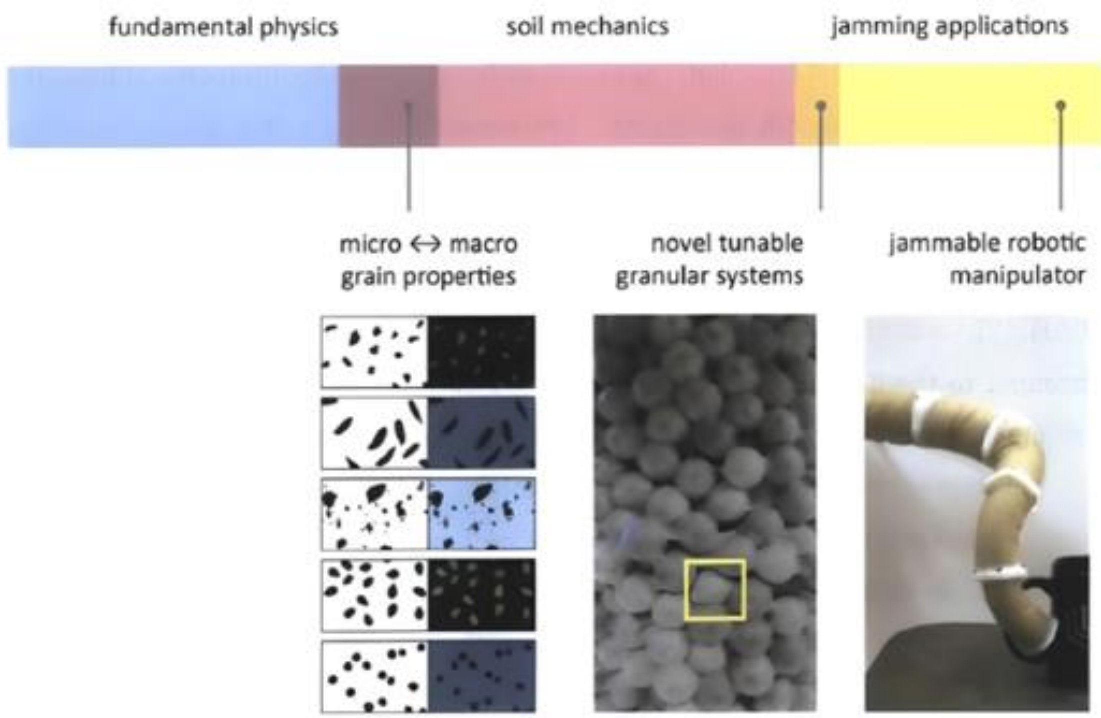

Figure 10: Micro to macro-scale granular jamming [19]; There are complex physics involved relating to the particles used, the force networks of the individual granular particles, and then engineering these to be tunable for a robotic gripper.

The jammable robotic manipulator as shown in Figure 10 highlights the benefits of granular jamming in that, generally, few actuators are needed, complex orientations may be achieved, and with a high strength to weight ratio. Exploring this strength to weight ratio, quantitative results show that the coarsely ground coffee is the best all-around granular material compared to finely ground coffee, hollow glass beads, diatomaceous earth, solid glass beads, and saw dust [19]. A similar gripper is proposed in [23], which is a cable driven trunk robot. Another granular system could be the gripper proposed in Hu et al. [24] which is a flexible membrane that jams into a locked position, and is good for large objects including a 3D printer spool, large bottle, etc., all shown in Figure 11A. This is similar to the jammable robotic gripper proposed in Cheng [19], but with less DOFs. In Figure 11B, we can see the testing apparatus for an individual jamming "finger."

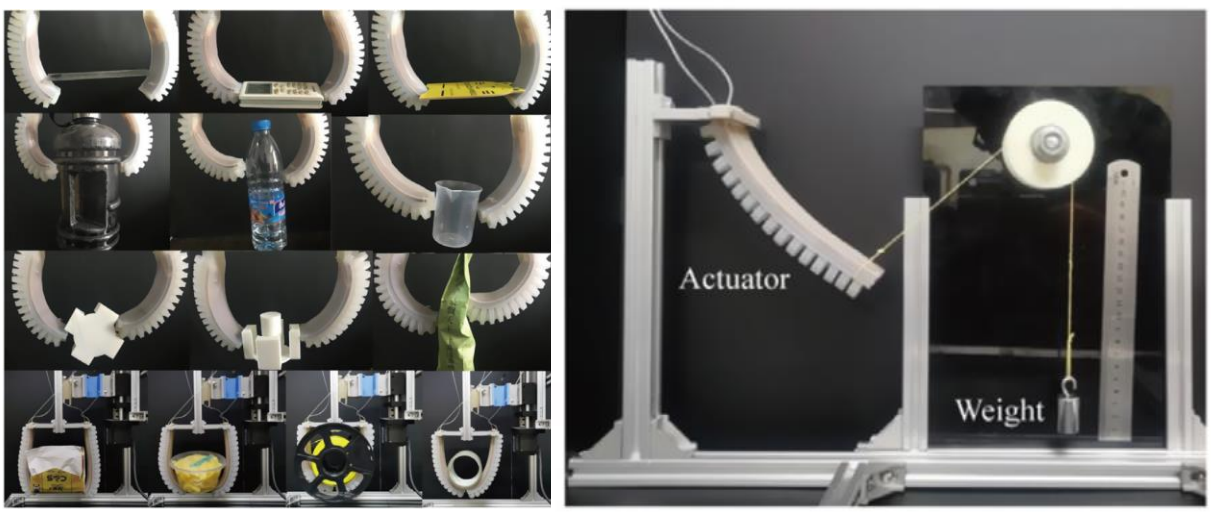

Figure 11: Granular Jamming variable stiffness soft actuator: A. Testing with various objects, B. Testing with weights; From A, we see that this type of gripper is not limited to the same size restrictions that the GJG is. From B, we see calibration testing for the gripper.

A robotic scrub nurse (RSN) is presented in Shafer et al. [25] which is a collaborative robot that has assists in repetitive tasks that nurses typically would do. It is assumed that the GJG is sterile and disposable though this standard operating procedure (removal, replacement, etc.) is not developed. The robot scrub nurse is shown in Figure 12 where the two GJGs are at a 90 degree angle to one another: which is for object loading and storage until the other tool is needed, then the robot arm rotates as necessary. The difficulty with this RSN is that flat objects are not easily grasped, consider scalpels, forceps, and clamps [26]. There are other issues relating to hospital protocols, but flat object grasping is a systemic problem in other GJG research areas. Recall that this was generally solved in Piskarev et al. [17], for various flat and deformable objects, but metallic objects were not discussed. Despite the conceptual solution and development, a commercial solution is needed for RSN to be used in real settings.

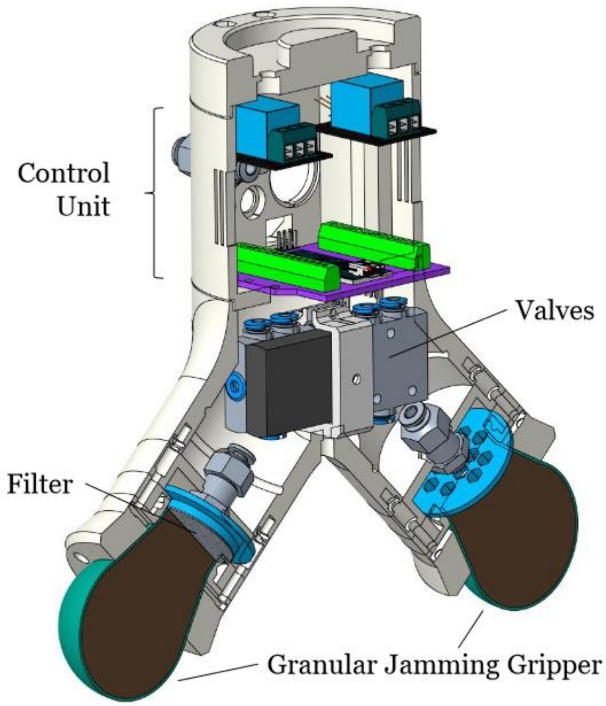

Figure 12: Robotic scrub nurse with two GJGs [25]; This work shows a dual GJG system that is developed for the rapid tool switching that is necessary in a surgical setting.

Tramsen et al. [27] presents passive jamming, occurs when a high applied load, typically a normal force, induces granular jamming against a surface. Consider that any locomotive movement generally relies on friction, and so using a jamming system that passively adheres to the geometry of the surface, and passively jams to the surface would create a high friction force. The benefit of this system is that it is passive and does not need actuation. The difficulty is finding a useful application for it. One example is using passive jamming as a humanoid robot foot, since a large normal force is present, and perhaps the humanoid needs to traverse rough terrain as shown conceptually in Figure 13. In regard to robot arm manipulation and gripping, perhaps this may be used as well for rough object surfaces, but sufficient force would need to be applied for a proper application.

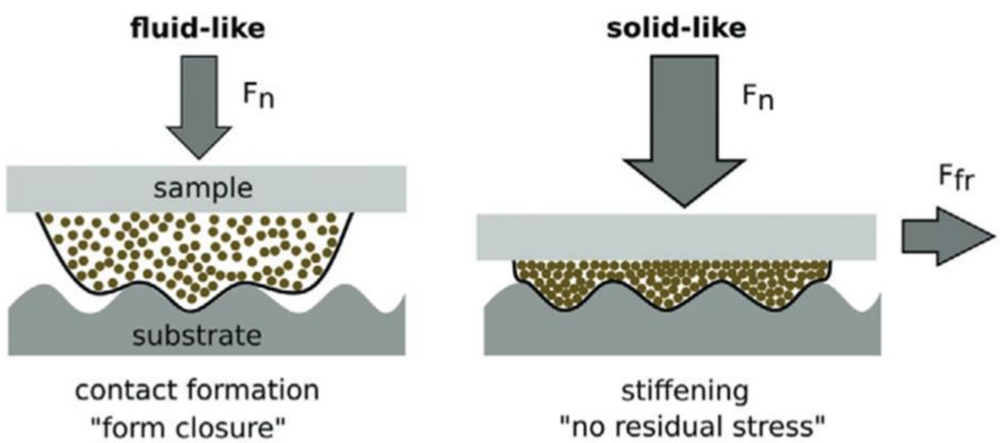

Figure 13: Passive jamming on rough terrain [27]; This shows that jamming can occur simply due to applied pressure, this is convenient since it is passive but difficult to find a robust use for.

Passive jamming is a simple control strategy as shown previously, and *under-actuation* is another method to simplify control and improve reliability. Under-actuation means that there are more degrees of freedom than the number of actuators, which is immediately cheaper and simpler than a fully actuated system. Some of the results of Wang et al. [28] are shown in Figure 14 which is the gripper picking up various objects and aptly adopting the name "Universal gripper," similar to

[12], [13]. Similar to the GJG, the gripper in Wang et al. [28] is underactuated but it still has the rigid and robust manipulators compared to the GJG, while grasping various objects.

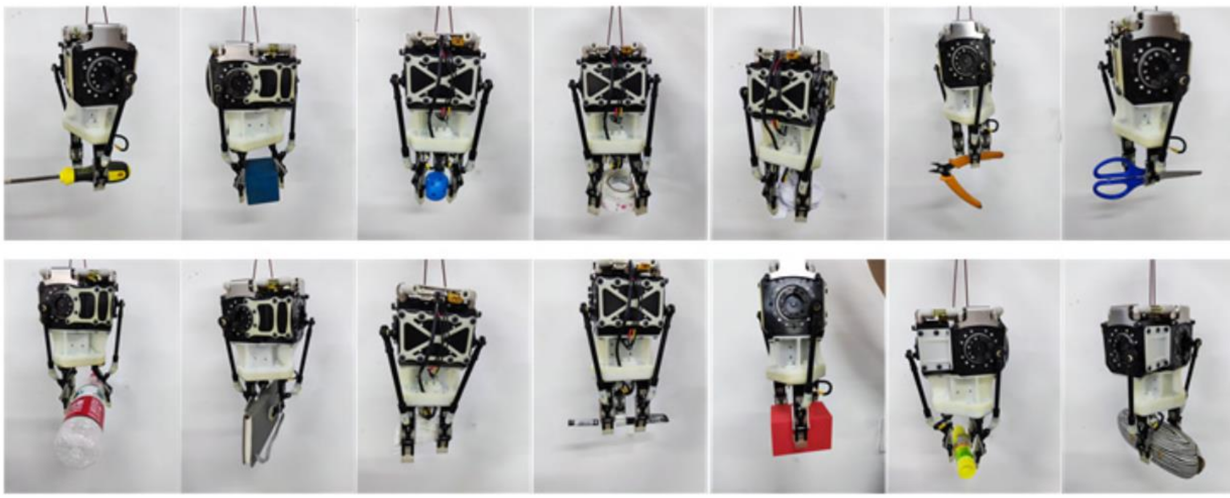

Figure 14: Underactuated three finger universal gripper [28]; This gripper does not use granular jamming but is still shown to be a robust underactuated gripper of various objects and is labeled as a Universal gripper just as in the original paper for GJG [11].

It is common to exclude commercialization as a factor for pursuing research but in Amend et al. [8], the various aspects and challenges of bringing a granular jamming soft gripper to market are discussed. A granular jamming gripper is formalized in early work [12], [13], but compared to bringing this to the market, these works are regarded as a proofs of concepts. A former robotics company “Empire Robotics” formally developed a granular jamming gripper and named it the “VERSABALL.” They conducted various trade studies and did business for years developing the customer specifications and decision criterion as shown in Table 1, that was tailored for their biggest customers which were in the industrial sector.

Table 1: Jamming gripper product specifications that influence customer purchasing decisions [8]

	A	B	C
1	Ancillary components required to operate (e.g. robot, compressed air, PLC)	Electrical connection and control requirements	Pneumatic connection and air supply requirements
2	Air consumption per grip	Mechanical connection and mounting provisions	Weight and size of all components
3	Sensing grip information	Sensing to pre-empt and detect breakage or failure	Membrane durability
4	Time and frequency requirements for maintenance	Life and maintenance requirements for non-wear components	Maximum payload
5	Required contact (deformation) force	Actuation speed	Placement precision
6	Required clearance around target object	Operating volume (noise)	Safe operating temperature range
7	Lubricant and chemical resistance	ESD rating	IP rating
8	Material safety considerations during use	Shelf life	Price and payment terms

VERSABALL was developed as an optimal granular jamming gripper through the membrane durability, membrane shape, grain size, air filtering, and other avenues which the work did not go into depth. The company was unable to sustain a business model from the VERSABALL GJG. Improving on this, one could focus on the customer specifications and try to improve those.

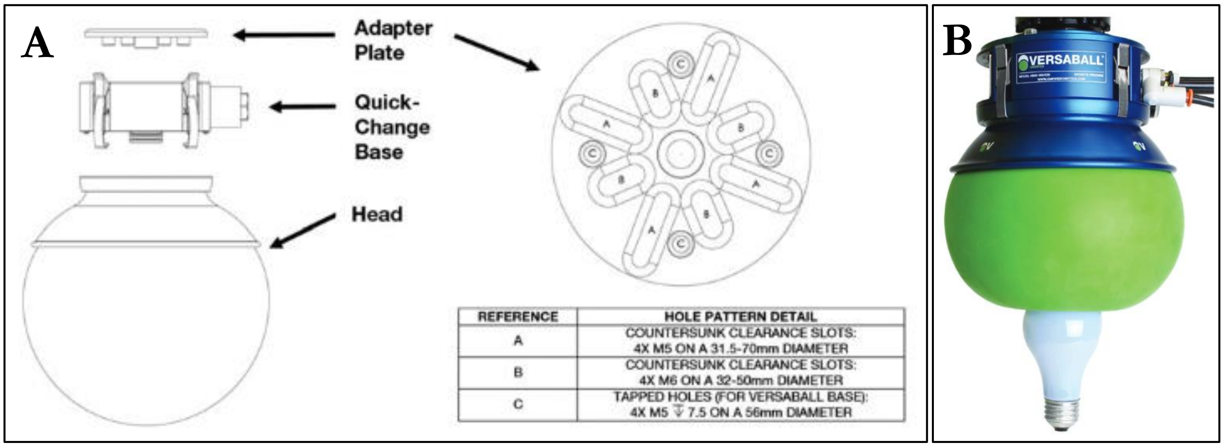

Figure 15: A: Tool changer integrated with gripper, B: VERSABALL commercial product [8]; From A, we can see the developed tool changer that is used to switch to a new VERSABALL when inevitably it wears out or is not reliable. From B, we can see the GJG grasping a light bulb which has a very low average contact angle, so it primarily relies on the material-bulb static friction (B2).

In Figure 15A, we see the engineering drawings of the Versaball that is integrated with a quick tool changer device. The tool changer was needed because it is estimated that the Versaball will last 50,000 grips on average, so it would need to be changed every 35 workdays (8hr long), and the manual tool changing process would mean too much downtime. In Figure 15B, we see the finished VERSABALL product which has seen more than seven design iterations. The best practices that were implemented in the VERSABALL product, are that the membrane is made out of poly-chloroprene with the shape "more oblong" [8] compared to a sphere, which seems to be a slightly prolate spheroid [29]. Some key takeaway points from Amend et al. [8] are that (1) elliptical grippers increase holding force while decreasing the contact force, (2) jamming gripper holding force is strongest when the target object is 50% of the gripper's radius, (3) the jamming gripper is most reliable when the objects are 30-70% of the gripper's radius, cited as 30-90% [12], [13]. And lastly, (4) the 9cm and 16.5cm GJGs are satisfactory for most requests using 5-10kg robot arms in industrial applications. From Amend et al. [8], we see several design and build specifications based on best practices and research developments, where one could see this as a how-to guide for developing or recreating a GJG.

Since the GJG is generally used in a *closed-space,* the work in Joseph et al. [30] sought to use the GJG in an *open-space*, that is, the grasped object is not able to press against a rigid body, e.g. a table. This design was that of a rigid outer torus or donut, with deformable inner body filled with granular material, that creates the rigidity needed for a GJG. In agriculture, soft grippers are useful because they can grasp soft objects without damaging them, compared to traditional rigid grippers, which commonly grasp by force [3]. Figure 16 shows various agricultural objects being grasped in open space, highlighting the deformation (contact area) and variable stiffness (force generation) needed for grasping these items.

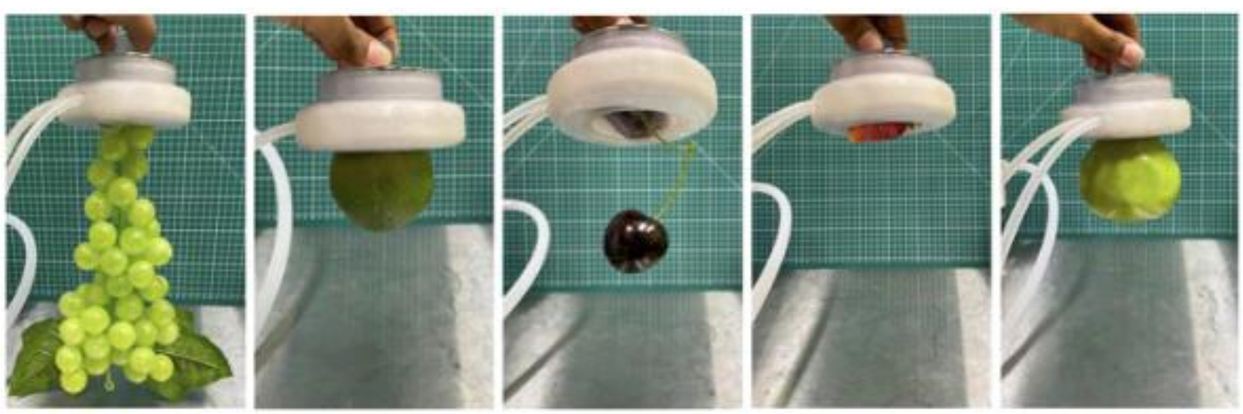

Figure 16: Various grasped objects using the donut design gripper [30] for grasping objects in open-space. Given that most GJG grasping is done on a table or other rigid object, the GJG needed to be modified for grasping in an open area, an agricultural environment for example.

As in other research, a GJG is suitable for picking various objects with complex or unknown shapes due to its passive adaptation to geometry. However, when the object is in a narrow space, additional sensory data is needed. In Meng et al. [31], visual based grasping with a GJG is employed for grasping objects in narrow spaces. Since the GJG implemented is visual based, it has a camera and an additional DOF for rotation. From Figure 17 A: Camera perspective robot approach, B: Bystander perspective robot approach [31]Figure 17A, we can see the camera perspective robot approach to pick up a bottle, and in Figure 17B, we can see a bystander perspective robot approach to pick up the same bottle. Other items are tested, including a small screwdriver, tape roll, utility knife, and spray bottle. This work develops the idea that while a GJG does not generally need visual feedback, and a GJG is typically employed to avoid complexities, it does enhance the gripping function. Since the position of the object is not always known, and with visual feedback, the gripper can adjust the position as necessary. However, the apparatus is only configured for motion in the z direction, therefore, future work will include scenarios which require xy-plane reconfiguration.

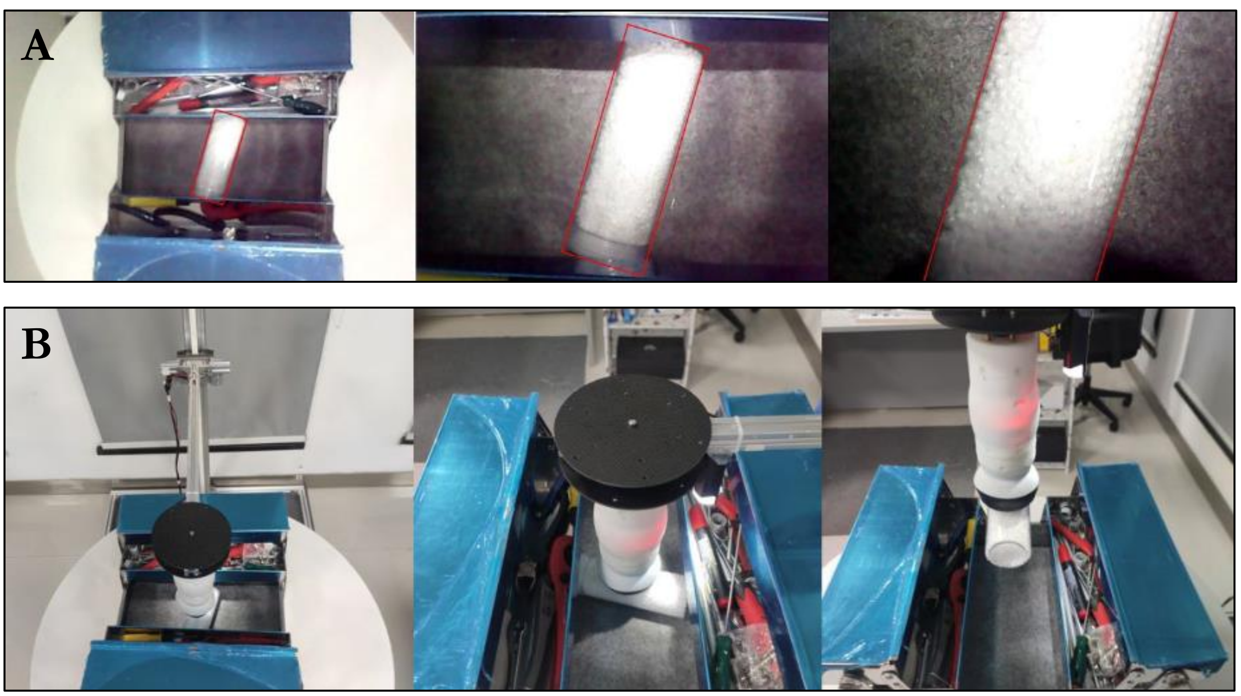

Figure 17 A: Camera perspective robot approach, B: Bystander perspective robot approach [31]; This development pushes the GJG towards reliable autonomous grasping because cluttered environments are common, so perception is needed.

Similar to the work in Meng et al. [31] and Jiang et al. [16], but D'Avella et al. [32] uses a perception algorithm for autonomous picking in cluttered environments. In contrast to Meng et al. [31] which studied picking in narrow or small spaces, and Jiang et al. [16] which the algorithm proposed optimal grasping points on various objects for the granular jamming gripper. D'Avella et al. [32], uses a setup shown in Figure 18 which has a GJG on its right arm and a claw gripper on its left arm, which emphasizes that different grippers are better for certain tasks, e.g. a GJG would not be able to grasp a bag of chips, whereas a claw gripper would be able to grasp it arbitrarily.

Figure 18: Baxter dual arm robot [32] which highlights the complementary role of GJG similar to [16] with GJG+EA. The GJG shown here may not be good for grasping the cup shown, where the parallel gripper would be. However, the duck and other small objects might be more difficult for a parallel gripper and simpler for the GJG.

The work discussed here highlights current research in granular jamming grippers liquid jamming grippers, passive jamming, GJG fixed onto robots for assistance technology, commercialization, GJG without hard surface to press on, direct benefits of electro-adhesion plus GJG, computer vision enabled GJG, developing a model for GJG, and the effects of deformable granular material, to name most of the work discussed. These topics are synthesized as the breadth and depth of GJGs and related granular systems. While many of the topics are important for understanding ongoing research, some topics are not directly beneficial or are not related to the scope of this project.

To synthesize the depth of related works, we've learned that basic GJGs work well with objects that are rigid, have a minimum z-height, working in an open space, picking along the object's center of mass, a thinner granular material membrane that is limited by durability, and several improvements for a developed commercial product [8]. There is also a relationship if the granular material is deformable, where the pull-off force is much greater but there is a larger risk of failure due to disturbances or collisions.

The breadth of related works includes granular systems may include grippers which have jamming "pockets" for driving a change in claw deflection [19], [24]. These approaches push the envelope about what a universal gripper is and could be, expanding graspable objects. The base GJG is useful for a variety of objects, but not tasks such as that shown in Tran et al. [15]. More so, the GJG is beneficial for general grasping tasks of unknown objects. Therefore, the GJG is well suited for pick and place tasks, given that the objects are not flat or deformable. Considering the wide range of feasibly graspable objects, and the low-cost and complexity of this gripper, more work can be developed to determine quantitatively what a successful/unsuccessful grasp is and by how much.

In developing a GJG, we cite Table 1, and focus on key parameters such as C4: maximum payload, A5: required contact (deformation) force, and C8: price and payment terms.

CHAPTER 3: METHODS

The experimental design, development, and building processes are discussed here relative to the GJ gripper and the testing methods for the experiment. The gripper system includes the end-effector plus the pneumatic system and control circuit. Many papers provide a brief description of the design and build of the GJ gripper and system, but few go into detail, in contrast to this section. The gripper design was provided from previous work, He Y.H [33], as shown in Figure 19.

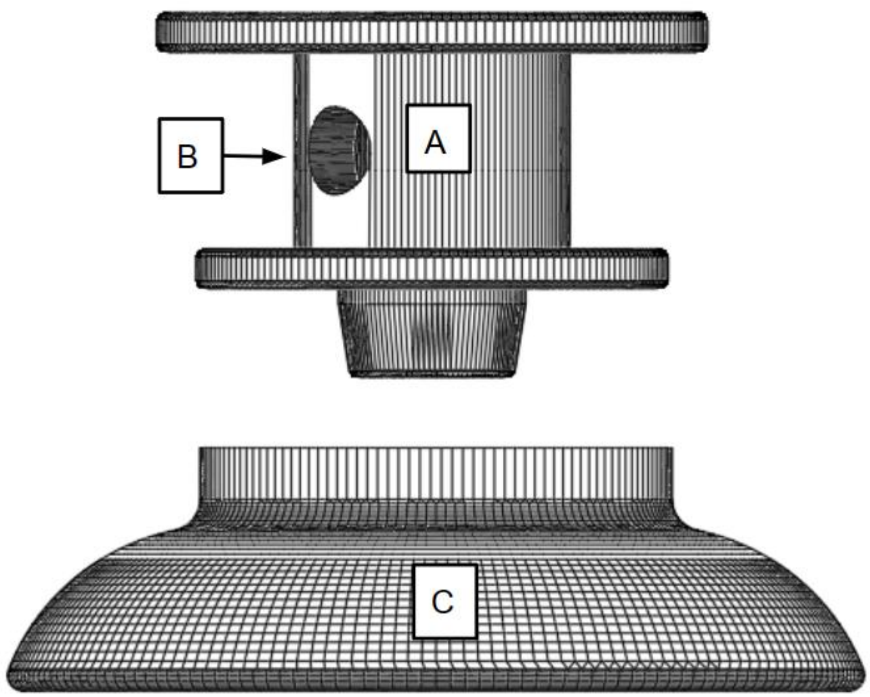

Figure 19: Expanded GJ gripper design; "A" the base attaches to a robot, "B" is the pressure inlet, and "C" passively directs the granular material around the grasped object and attaches to "A" via four M3 screws.

Referencing Figure 19, "A" is the granular jamming gripper mount that fixes to a robotic arm or as a robotic hand. And "B" is the pressure input that is a specific part of the GJ gripper mount, for either positive or negative generated pressure. Lastly, "C" is the gripper base that passively directs the granular material inside of the latex membrane/balloon (not shown). For building the gripper, it was determined that sealing the gripper was a difficult task. As shown in Figure 20, we made a circular washer cutout of the gripper base to make room for the balloon lip.

Figure 20: Improved gripper base design that has a washer cutout. This is for a better connection and less gap between "A" and "C" in Figure 18.

Building the gripper involves 3D printing the design components the gripper base and mount as shown in Figure 19, that are provided in He, Y.H. [33]. At the interface between the mount and the base, to prevent granular material intake at the vacuum, a filter must be used for the granular material. It is recommended to use a regular coffee filter coupled with 10+ mesh wire screen to enhance durability, but using a very high mesh may be sufficient without the coffee filter, but this was not needed. From here, one would glue the filter plus mesh to the bottom of the "A" as referenced in Figure 19. Then using shears, cut away the excess coffee filter and mesh, to match the circular geometry at the bottom of "A" in Figure 19. Hot glue works well to protect the balloon from possible sharp cut ends of the metal mesh. From here, one would pull a balloon filled with granular material through the hole as shown in Figure 20. The partially completed process is shown in Figure 21A with the balloon nub cut. From here, one can use their pointer and thumb skin friction to roll the balloon material down until it reaches the GJG base, as shown in Figure 21B, and then glue on the rest of the way. From here, the parts "A" and "C" in Figure 19 may be connected via screws, ensuring an air-tight seal, but one must thread the pipe connection at "B" in Figure 19, which connects to the dual control solenoid.

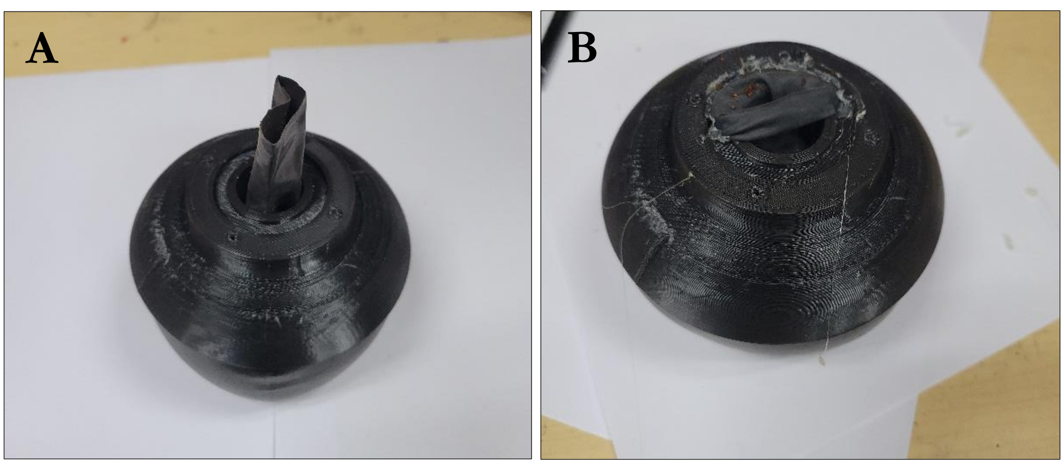

Figure 21: GJG development: A. Balloon end cut, B: Balloon end rolled and partially glued; One can use skin friction (rolling pointer finger and thumb) to assemble the gripper transitioning from A to B.

A complete system design was developed [33], but the compact PNP positive/negative pressure generation device, was not available, so this design was not feasible. In this work, we redesigned the system using cost-effective components. We used a dual control solenoid where a summing junction combines the positive and negative pressure to the gripper. This works because the solenoid valves are one-way only, i.e. they are closed when off. As a consequence, the pressure cannot be measured downstream of the solenoid valve since air continuously escapes out of the venturi aspirator. However, the supplied air pressure, that is the air between the solenoid and the air compressor, can be measured and is notably a parameter of the performance of the gripper.

The pneumatic system uses low side transistor switching with two NPN bipolar junction transistors (TIP120). Arduino microcontroller digital input/output pins (5V) write to the gate of the TIP120 allowing 12V to power the solenoid, which either fully opens or fully closes the valves, as shown in Figure 22 once the solenoids are inductive loads, they are shown as inductors. However, a single solenoid is a 3-terminal device where the third wire, not shown, connects to ground. The initial difficulty with this is that the control voltage (5V) is lower than the operating voltage (12V), which works as expected in low-side switching but not in high-side switching. We initially used high-side (PNP transistor) switching, based on the available components, but this was unsuccessful. Having this voltage difference highlights the fact that high-side and low-side switching are not equivalent processes. This is in contrast to many circuits that have the same operating voltage as supply voltage. Therefore, it is a misconception to think of them as undergoing the same process but with slightly different programming.

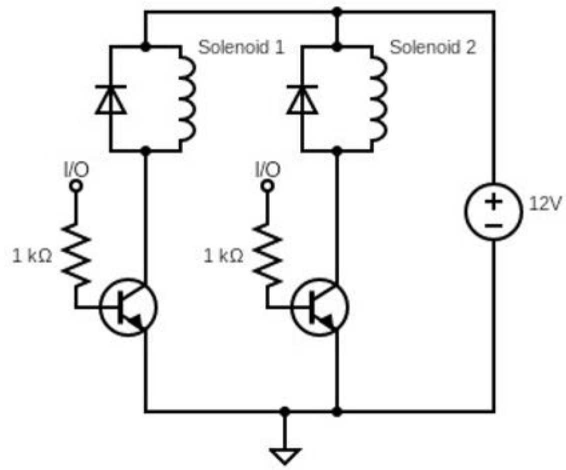

Figure 22: Circuit diagram for pneumatic control; Two NPN transistors for low-side switching and diode protection

Normally the GJ gripper would be mounted on a robotic arm such as an MK2 HDT arm or an RB5, but problems arise with the positional inaccuracies involved with the robotic arms [34]. To counteract this, we use a 3-axis cartesian machine to decouple the robotic arm inaccuracies from the GJ gripper performance. While the GJ gripper is known for pick-and-place of various objects, it is still susceptible introduces moments i.e. slipping and tipping conditions, which are non-ideal picking conditions. A cartesian machine generally has an inaccuracy of 1mm, compared to 5+ mm for many robotic arms. The testing for this project uses a three axis 3D printer which only uses the z-axis for vertical motion. The GJ gripper is directly mounted on the z-axis mover. However, the x-axis and y-axis motors are removed and unused, respectively. The overall system diagram is developed in Figure 24 as it relates to the integrated system that is the control circuit and pneumatic system, which is shown physically in Figure 25.

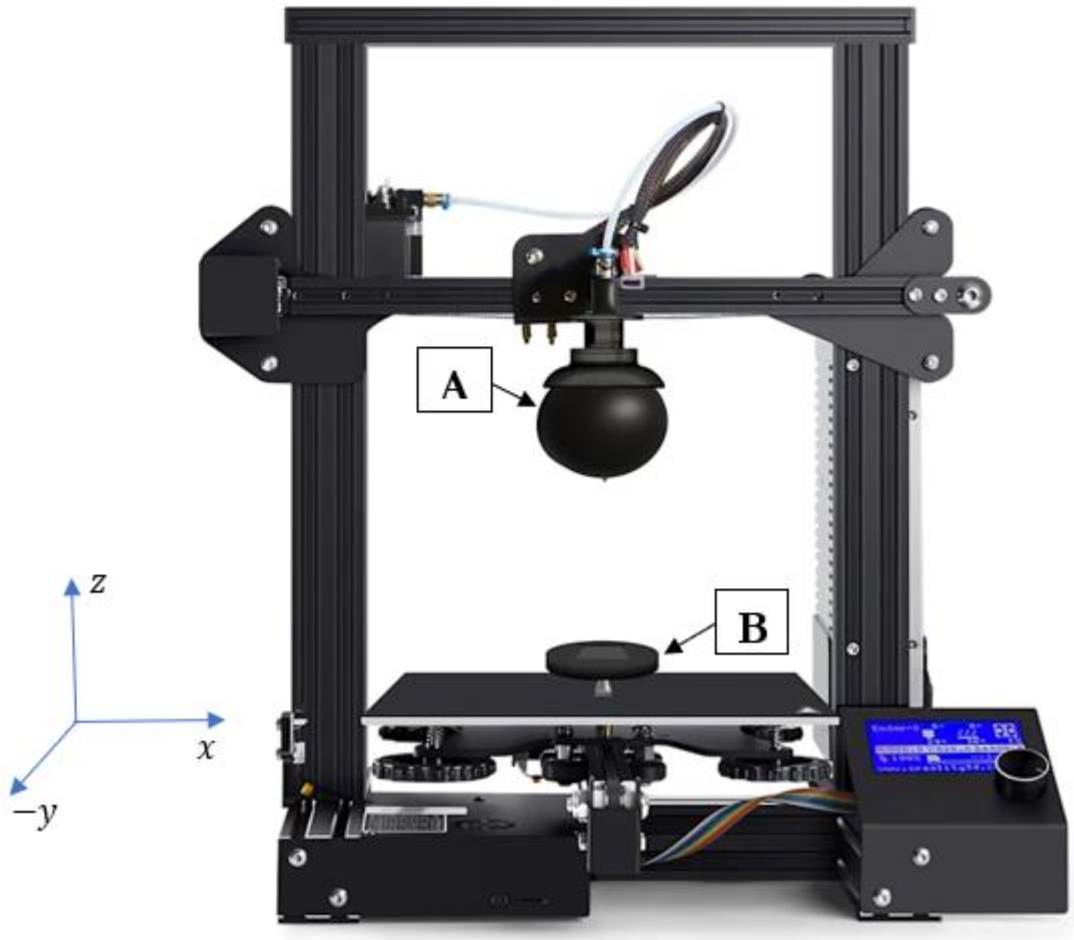

Figure 23: Granular jamming gripper testing apparatus

From "A" in Figure 23, we can see the GJG mounted to the z-axis mover. From "B" in Figure 23, we can see a small black plate that was designed to securely hold a juice box. This plate attaches to the sensor (load cell) and it is reconfigurable, meaning that it can be changed for different objects, and in push/pull testing. This is of main importance as it relates to the research scope developed. Which has the GJG attachment to the bar driven by the z-axis stepper motor. Additionally, we used a laser cutter to make a custom printer plate (1/8th in) to rigidly fix the load cell, and consequently, plate fixtures to the bed were developed and 3D printed, which are not shown in Figure 23.

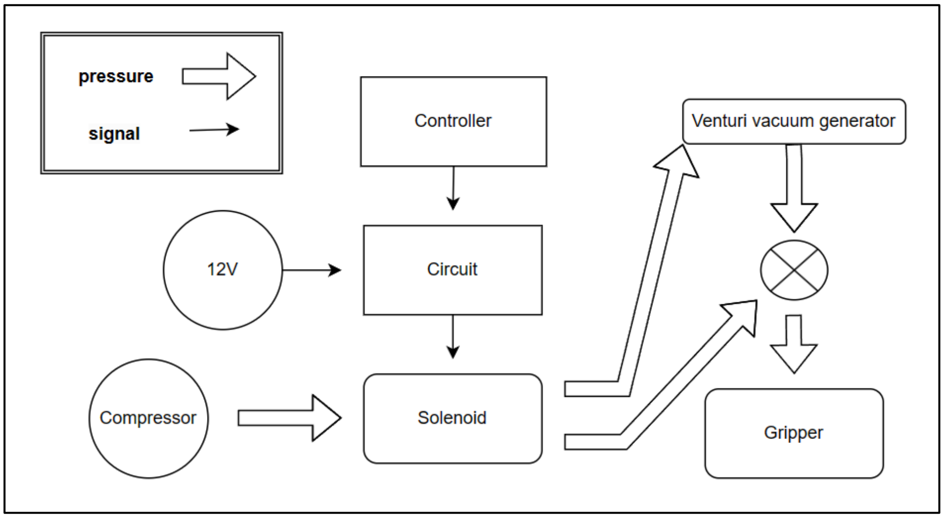

Figure 24: System diagram for gripper control; Pressure is shown with the larger arrow and the signals are shown as smaller arrows. The two outputs of the solenoid, we see one go to a summing junction and the other goes to the vacuum generator then to the summing junction. The summing junction is just a two-to-one valve, then to the gripper, shown in Figure 23.

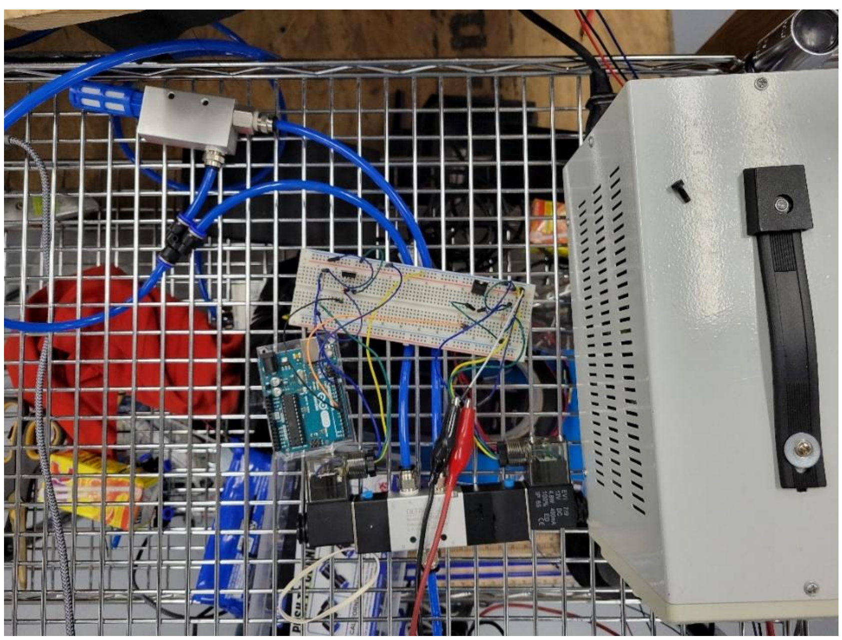

Figure 25: Physical system configuration for gripper control

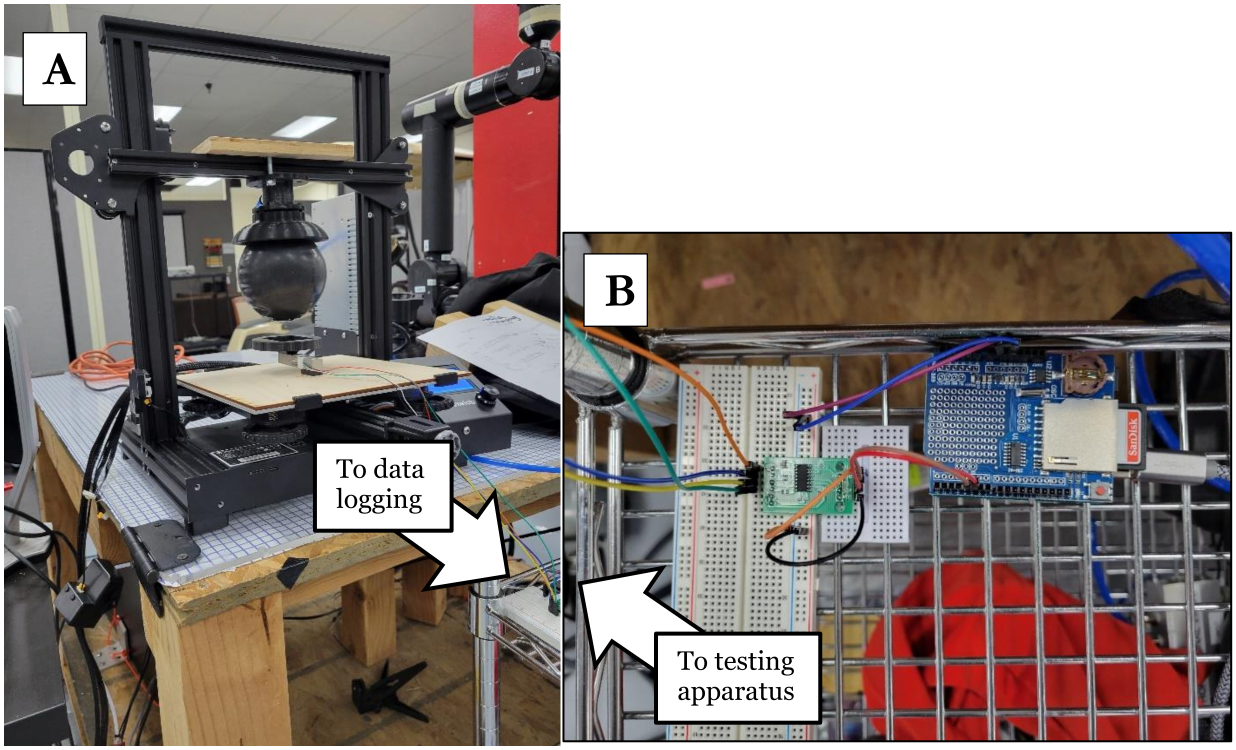

Figure 26: A. Physical testing system and B. Data logging system; From A, we see the printer plate that was laser cut with precise hole locations for the load cell placement and then the load cell attachment for the specific object. From B, we see the load cell wires which enter an HX711 amplifier which is connected to an Arduino with a data logging shield.

We chose common objects for picking test, as shown in Figure 27, which are a small apple, Juicebox, and soda can, not to scale. These three objects were specifically chosen because they are so different. In learning grade school geometry, these are the first three objects that are discussed. A rectangular prism has six flat sides where at least two sides are equal, and three axis symmetry at the center of the object. A cylinder has rotational symmetry about its central axis, two flat faces connected by a curved surface. A sphere doesn't have any sides and every point on the surface is equidistant to the center, so it has complete symmetry. We avoided pointy objects like cones and pyramids which would degrade the life of the GJG and would be difficult to mount.

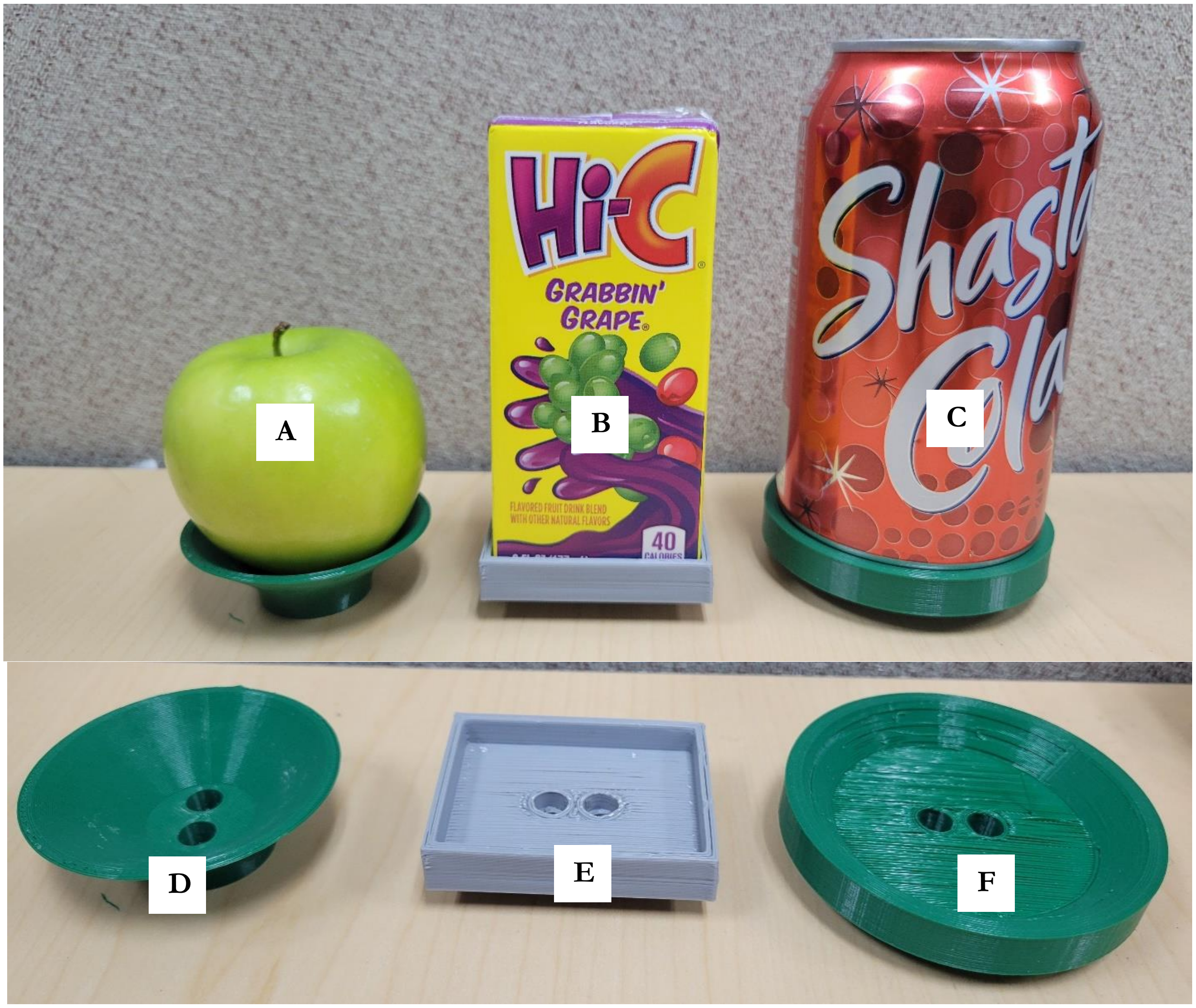

Figure 27: Picking objects for common object testing. A. Apple, B. Juicebox, C. Can;
D, E, F: Load cell attachments for the three objects, A, B, C, respectively

The purpose of the load cell attachments shown in Figure 28 are needed because the sole objects in Figure 27 would not be securely on the load cell. Note that the push testing load cell attachments are loose to the objects so that the objects do not experience additional forces upon moving up.

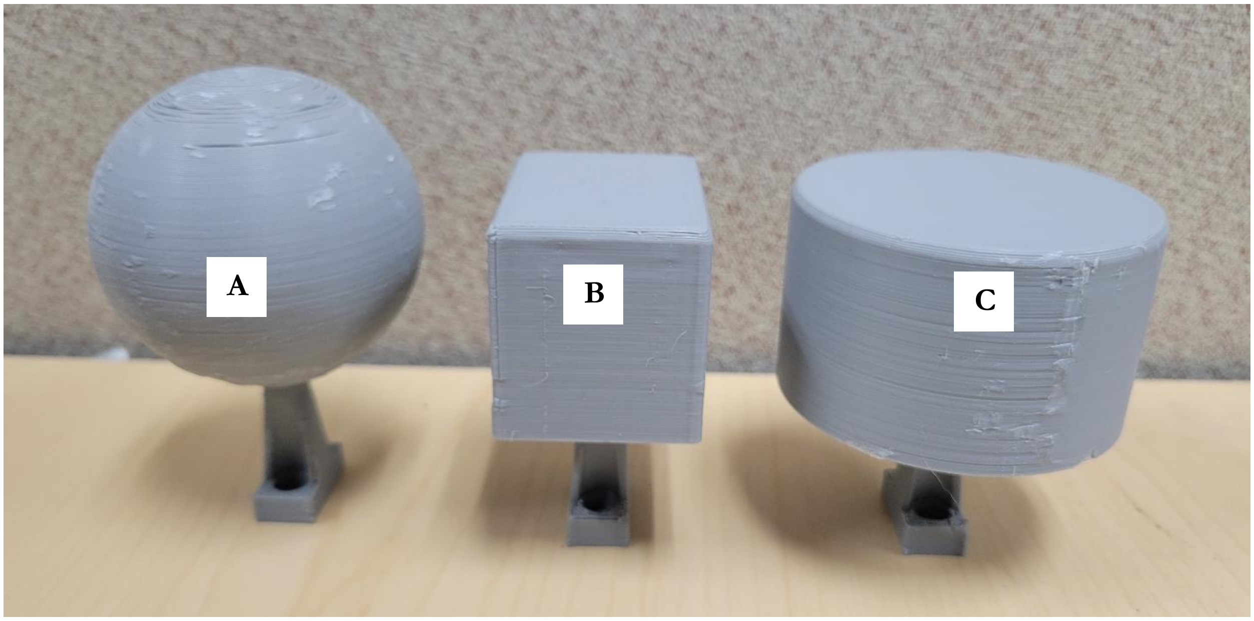

Figure 28: 3D printed load cell attachments for pull-off testing based on common objects: A: Sphere, B: Rectangular prism, C: Cylinder

The objects in Figure 27 are common objects that could be grasped by a GJG. We use these objects in push testing to determine the required force for success/fail outcome of grasping. The limitation with this is that if it is unsuccessful, we haven't learned anything, and just assume that the GJG is unable to grasp the object. Therefore, we had to do pull-off testing because this will tell us a quantifiable value about the point of failure determining the grasping. Then we took the objects in Figure Figure 27 and developed them into a load cell fixtures in Figure 28.

We designed the height, h, to be at least 25mm to fix to the load cell with an M4 machine screw using the short end of an Allen wrench. Our gripper has diameter $O_D = 107mm$, therefore, the minimum diameter object must be greater than $G_D \approx 32mm$, $O_D/G_D = 30 - 90\%$, based on Brown et al. [12] and $O_D/G_D = 30 - 70\%$, Amend et al. [8]. We performed two basic tests using a load cell as shown in Figure 29, where we used the same calibration factor for both types of tests.

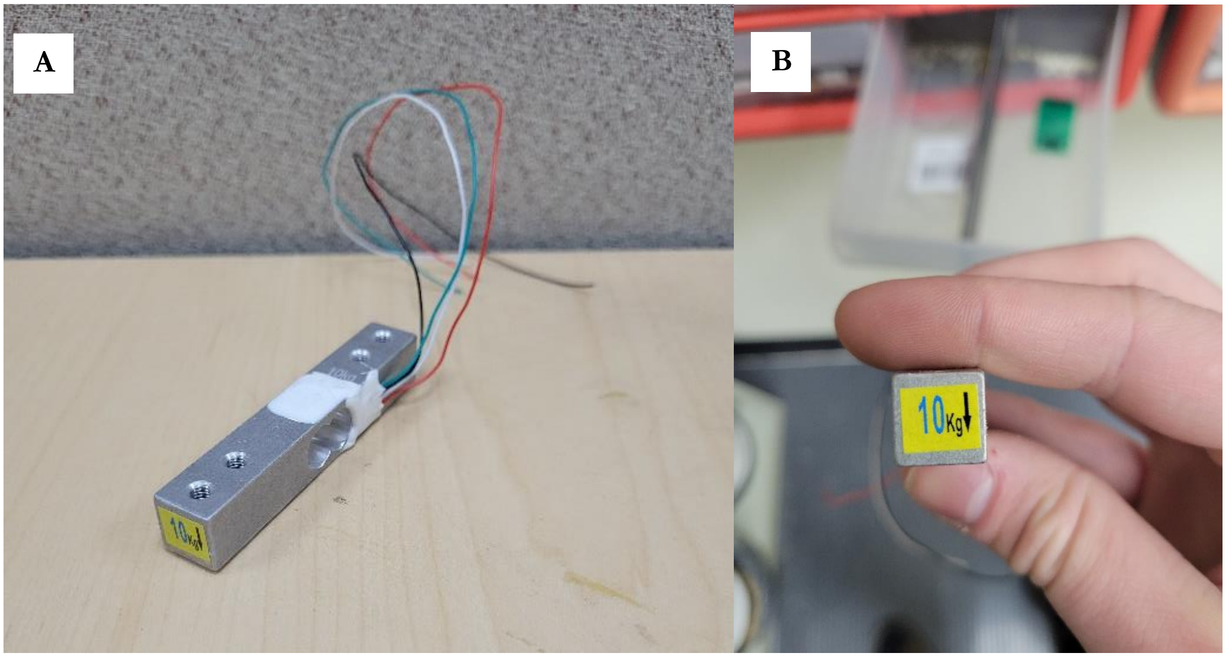

Figure 29: 10kg load cell used for testing [35]. A. Rectangular beam load cell used, B. Orientation (arrow) of load cell in common object testing

Figure 29 shows the load cell that we used for testing. The HX711 is mentioned [36], which provides the middleware between the load cell and the controller, which also shows that it is an amplification module that runs on 2.6-5.2V. The load cell is validated with a traditional weigh scale which determines a calibration factor that was sourced from a repository [37]. We used a 10kg load cell because it provides a margin of safety above the 5kg load limit commonly associated with robotic arms, but also to maintain sensitivity compared with load cells that are 20kg and up. Once the load cell was calibrated, it needed a 5V power bank to power which collects data on the Arduino when the power is on. For more specific information about the testing and protocol, see the Appendix.

CHAPTER 4: RESULTS

Initial testing is developed for the GJG which is to check which objects are graspable by this gripper. Each object to be grasped is rigid and with a significant depth, avoiding the general issues that the GJG has with grasping objects such as balloons and coins, respectively. In this research, we don't seek to improve these deficiencies, we just want to quantitatively work towards developing standards for when the GJG can and cannot be used. Therefore, Table 3 and Figure 28 contains load cell attachments that were closely modeled after the physical objects shown in and Figure 27.

Table 2: Maximum force for common object testing with depth = 35mm

	Apple (100g)		Juicebox (170g)		Can (212g)	
Trial #	S/F	Force (N)	S/F	Force (N)	S/F	Force (N)
1	F	6.192	S	5.593	S	5.085
2	F	7.730	S	7.781	S	4.502
3	F	8.949	S	10.416	S	3.941
4	F	8.376	S	5.643	S	6.429
5	F	7.965	S	7.514	S	5.850
6	F	8.124	S	6.262	S	5.962
7	F	10.448	F	6.650	S	4.582

In Table 2, we have push testing of various common objects, including a rectangular Juicebox, spherical apple, and circular can. In general, a lower force is better in push testing because less energy is expended in picking the object. The limitation of this test is that we can only see if the object grasp is successful or a failure (S/F), and the maximum force applied to achieve that grasp. We defined grasping as successful if it holds on to the object even while moving (600 mm/min). We can see from Table 2 that the apple tests were all deemed unsuccessful. However, in each trial, the gripper grasped the apple but broke grasp when the gripper started moving. This test sets the base comparison for other two tests. Therefore, it was important to do pull-testing which uses objects that were modeled after the push testing objects. From this, we can quantify both the successful and unsuccessful objects from the previous push testing. Given that grasping in the push testing was successful, we want to determine how successful it was with pull testing. And vice versa, when the grasping in push testing is unsuccessful, we can associate a quantity that the gripper can grasp for a given object.

Table 3: Maximum force for modeled object testing depth = 35mm

	Sphere (46g)	Rect. prism (42g)	Cylinder (52g)
Trial #	Force (N)	Force (N)	Force (N)
1	-4.958	-9.851	-8.360
2	-5.169	-9.206	-11.426
3	-2.908	-8.370	-11.210
4	-6.338	-8.477	-10.094
5	-6.708	-8.798	-12.268
6	-7.973	-8.918	-10.990
7	-6.886	-8.304	-11.567

From Table 3, we can see the force quantity associated with each test. Compared to the previous test shown in Table 2, we don't visually know whether the test was a success or failure. Generally, a higher force in pull testing is better because it implies better grasping. We use a sample standard deviation which is defined as:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

Although there can be variation for many reasons, we have limited the number of factors in this testing to just the object's geometry, weight, and material composition, since these factors are infeasible to remove.

Table 4: Common object testing force average (±SD) and success rate results

	Apple (100g)	Juicebox (170g)	Cylinder (212g)
Average force (N)	8.25±1.29	7.12±1.68	5.19±0.91
Success rate	0%	86%	100%

From Table 4, we can see that it is summary results for Table 2. The success rate is defined as successful grasping of the object and moving at a relatively low speed 600mm/min. We can see the average force decreases from left to right. It is worth noting that the Juicebox did deform at times during the testing and there were many failure-to-grasp trials where the Juicebox moved out of the way before grasping. So these were not marked as failures in Table 2, because it did not fail after grasping.

Table 5: Modeled object testing force average (±SD) and force/surface area parameter

	Sphere (46g)	Rect. prism (42g)	Cylinder (52g)
Average force (N)	-5.85 ± 1.53	-8.85 ± 0.51	-10.84 ± 1.18
Force/surface area (N/m^2)	-863.89 ± 226.55	-1705.81 ± 97.87	-1009.29 ± 110

The results in Table 5 shows the average force increases (in negative) from the sphere to prism to cylinder. These results are surprising and more in-line with ideal pull-testing results, which we did not do, as they suggest a stronger grasp. Again, due to the orientation change, we expected positive values but acquired negative, meaning that the push testing was completed twice, for common object testing and for modeled object testing. This is in contrast to the experiment design and concept. Despite this, the force/surface area parameter is interesting because it is highest for the rectangular prism. This suggests that the various parameters involved in the gripper grasping in this type of testing such as the depth, gripper diameter relative to the object, and contact angle are related to the surface area contact. The gripper exerted the most force on the cylinder, but the gripper had the best grasp per surface area on the prism. The sphere may serve as a base case, since it has a surface area comparable to the prism, but low grasp ability as we saw with the apple testing, validating the importance of the contact angle. The contact angle influencing the surface area suggests a quality of the surface area. For example, the prism and cylinder have a relatively high quality, but the sphere has a relatively low quality. For graphical data collection results of all trials, see Figures A1-A6 in the Appendix.

CHAPTER 5: CONCLUSION

The main contribution of this work is recreating the GJG experiment for load testing by is of mounting a GJG on a 3D printer (cartesian machine), moving towards geometric standardization, and cost minimization. In summary, we developed control and testing of a granular jamming gripper using readily available and inexpensive components. Citing key customer specifications including the cost, push down force, and pull off force, we attempted to improve these key characteristics of the GJG. Given inaccuracies in typical robotic arms, we used a (formerly) 3-axis cartesian machine, which has a 1mm resolution, compared to robotics arm inaccuracies of 5mm, to decouple the gripper performance from the robotic arm performance. The testing results show that certain objects are grasped better than others. We found a base case which did not perform well and compared it to the other two objects which performed much better. The three models were developed from three common objects, and the pull test focused on emulating this gripper-object interaction. We determine that the reason for the success of some objects and not of others is primarily because of the contact angle that the gripper makes with the part (B1). If the contact angle is greater than $90°$, then the part generally cannot be grasped where the static friction (B2) cannot develop.

CHAPTER 6: FUTURE WORK

Future work includes tasks that could have been completed in this work, but which were out of scope or infeasible given the available resources. Improving the GJG in future work, we could add the x-axis of the gripper as a controllable element. Given 3-axis control, we could ensure 0.5mm uncertainty related to movement of the GJG and we could determine failure characteristics relating to applied moments on various common objects. This future work could add to developing visual feedback control of the granular jamming gripper, since autonomous grasping is still an ongoing research area. More immediately, we could increase the z-height of the cartesian machine using custom 4020 aluminum beams, to increase the range of tested objects. After developing the 3-axis control, the next step is to put the gripper back onto a robotic arm. The focus would be more on the performance of a pick and place task since the GJG performance was solely explored here. Additionally, it is evident that the load cell did not perform as expected, so future work could use a different load cell or a force torque sensor, which could improve the experiment with more accurate sensing.

APPENDIX

In push testing, we take the height for the GCODE as the height of the object plus the load cell attachment, shown in Table 6. Contrarily, we take weight as the object only since it will be lifted out of the loose fitting load attachment.

Table 6: Sizes and weights of the pushing and pulling objects

		Apple	**Juicebox**	**Can**
A	Weight [g]	100	170	212
	Dimensions [mm] (LxWxH)	59x63x70	36.5x47.5x114	66x66x125
	Area type	Circular area	Rectangular	Circular area
B		**Sphere**	**Rectangular prism**	**Cylinder**
	Weight [g]	46	42	52
	Dimensions [mm] (LxWxH)	61x61x92.25	37x49x72.5	65.5x65.5x72.5
	Area type	Circular area	Rectangular	Circular area
	Surface area	$2\pi r^2$	LxWxD	$\pi*r^2+2\pi*r*D$
	Symmetry	Symmetric	Asymmetric	Symmetric
	Calculated surface area (cm^2)	67.7	51.86	107.45
	Contact angle (degrees)	0-90	90	90

Table 6 shows the objects that are used in testing. With objects standing upright, we determine the planar dimensions with the small dimension as "L", and the larger dimension as "W."t When the object is upright from top to bottom, the measurement is labeled "H." While the "LxW" dimensions should be generally the same, the "H" should not be the same due to the load cell attachment necessity. In the case of the apple, the load cell attachment is taller, but for the juicebox and can, the physical objects are taller. From these six objects, we develop six g-codes for the testing. First, the physical objects in "**A**" are tested using the heights "H". The load cell attachments in "**B**" are tested with the "H" difference compensated compared to the objects in "**A**." We precisely locked the y-position with GCODE because we have a dimension of the laser cut 3D printer plate and the load cell attachment (100mm), given that the origin of the parts is in the center of the two screw holes in the load cell, therefore we have an uncertainty of 1mm in the z and y axes. Therefore, we determined the y-axis offset to be 100+(75-3.93-(13.5+6.53)/2)=161.055mm, rounded down to 161mm, based on Figure 30. For implementation, we have a negative 30mm y-axis offset that is built into the 3D printer because of the filament extruder. Therefore, our y-axis offset is adjusted to be 131mm (161mm-30mm). However, since the gripper mounted manually, we used more primitive methods with placement in the x-axis, therefore we have an uncertainty of close to 3mm, based on the uncertainty of an eight inch.

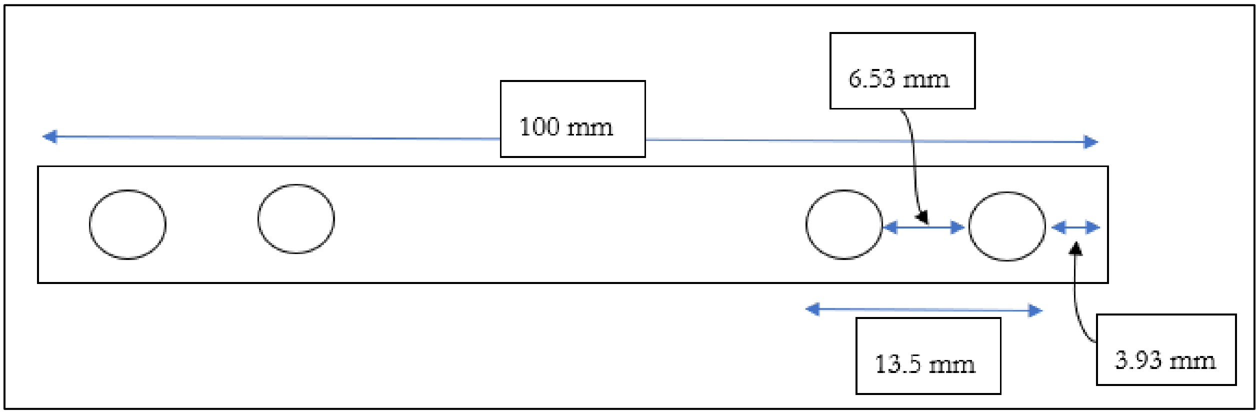

Figure 30: Load cell measurements for y-axis holding

For implementation of the gripper on the 3D printer, we had to develop GCODE for each object height. Since the objects are in the same position relative to the load cell, we only had to control the Y and Z directions, where the X position is fixed on the 3D printer.

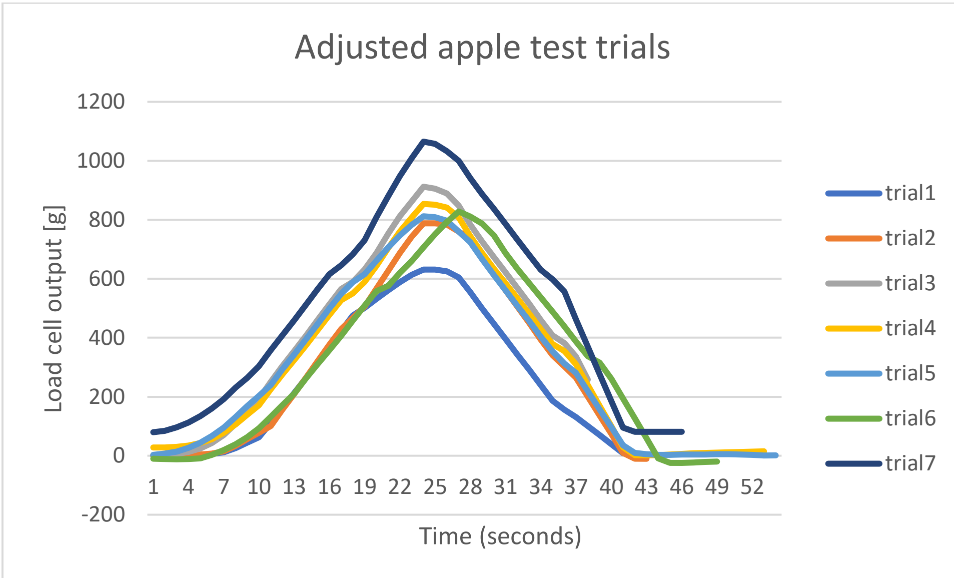

Figure 31: Physical object testing of apple

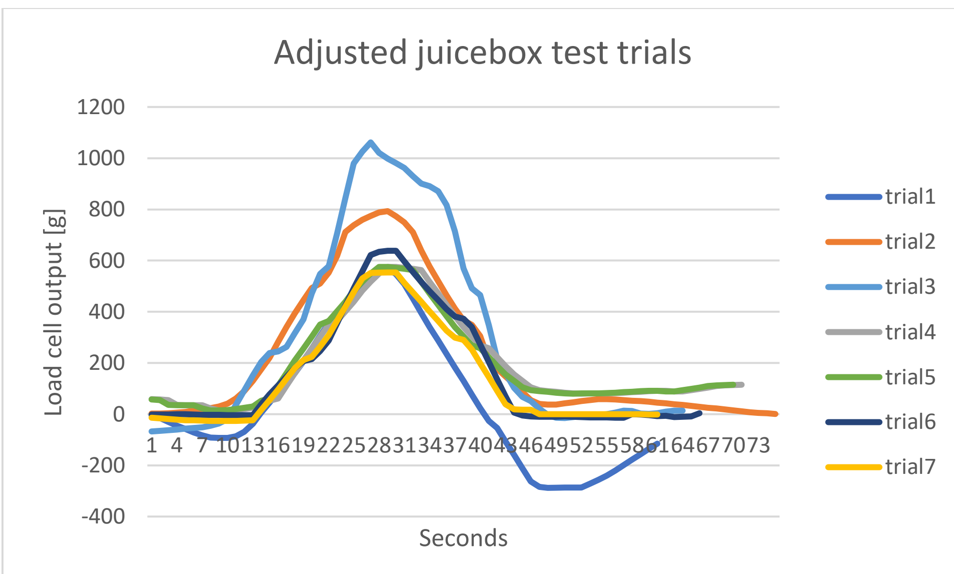

Figure 32: Physical object testing of Juicebox

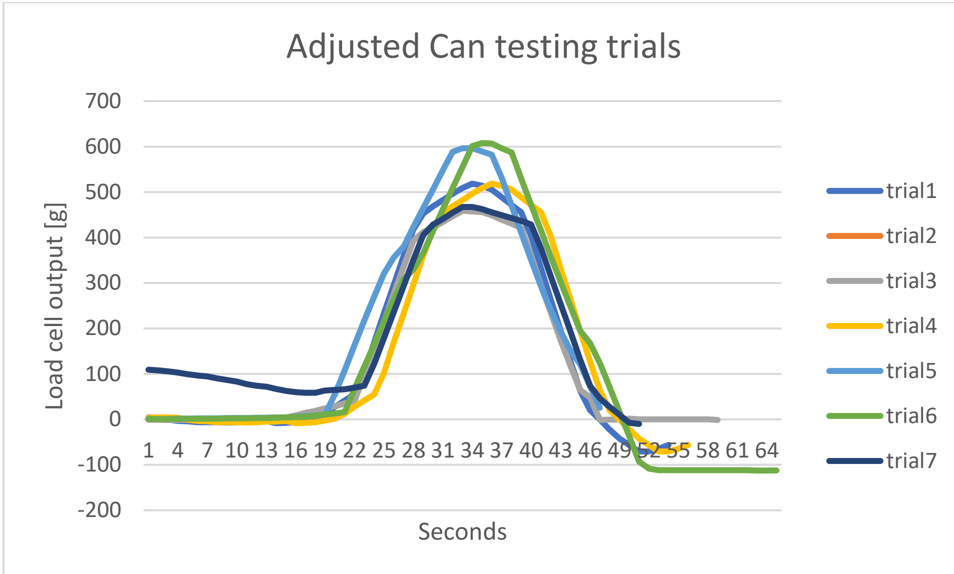

Figure 33: Physical object testing of can

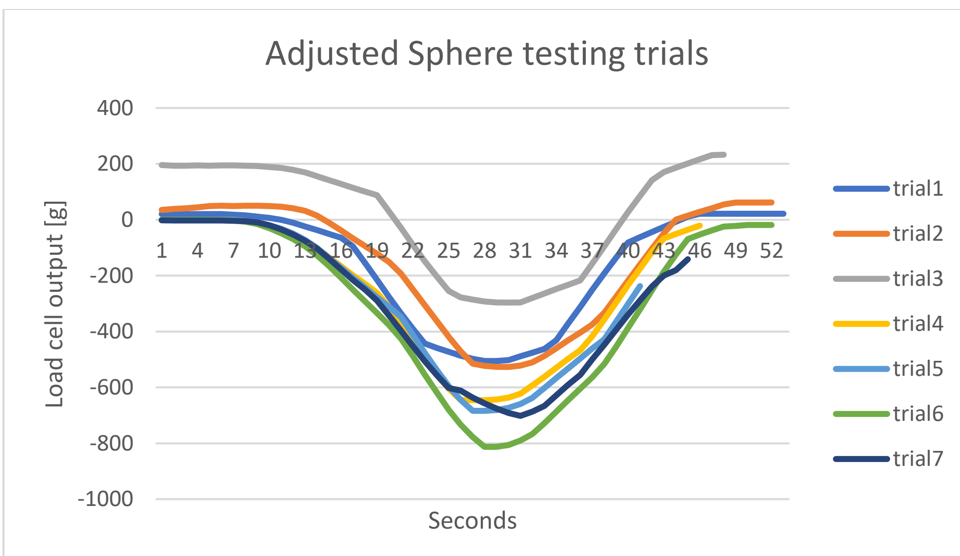

Figure 34: Modeled object testing of sphere

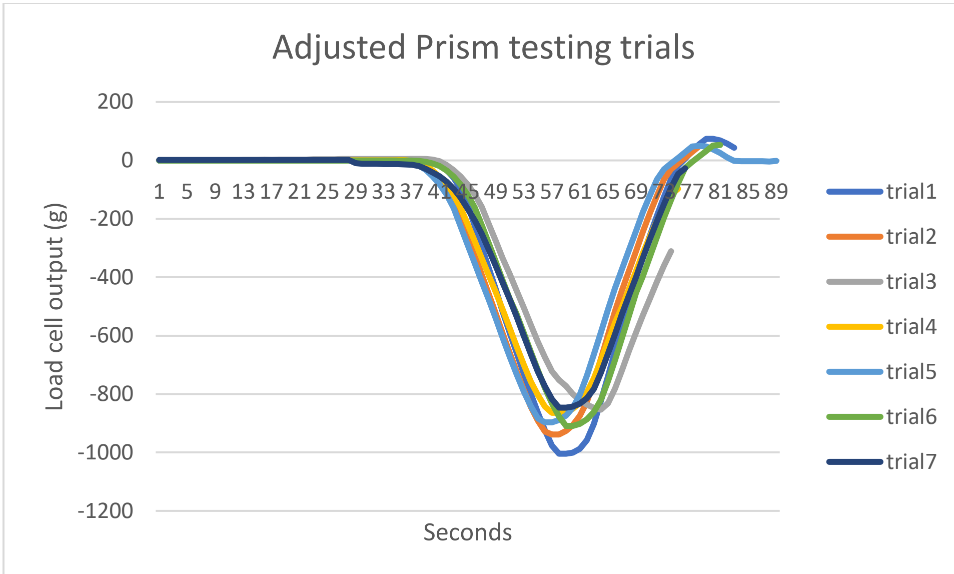

Figure 35: Modeled object testing of prism

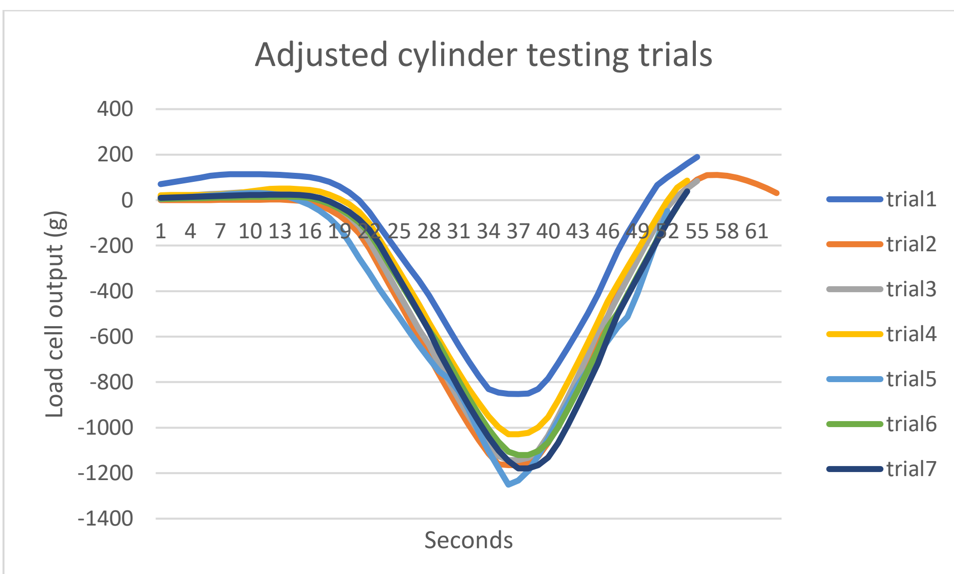

Figure 36: Modeled object testing of cylinder

Sample GCODE for testing

G90 ; absolute positioning

G28 Y ; home Y position

G1 Z-135 ; start from the top position and move down 135mm from the top (account for new tool length)

G92 Z0 ; spoof (new) home Z position

G01 Z155 F600 ; move to Z position for testing on cylinder

G01 Y131 F600 ; move to Y position for testing

G01 Z73 F600 ; move just above cylinder Z position for testing

G04 P5000 ; Pause for 5000 milliseconds (5 seconds)

; execute command to inflate which then waits 3 seconds to vacuum

G01 Z38 F600 ; move down 35mm for testing

G04 P5000 ; Pause for 5000 milliseconds (5 seconds)

G01 Z155 F600 ; Home Z position after moving up

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CURRICULUM VITAE

Graduate College
University of Nevada, Las Vegas

Jacob R. Dowd

Email Address:

Jacobrdowd@gmail.com

Education:

Bachelor of Science in Engineering, Mechanical Engineering, 2020

University of Nevada, Las Vegas

Thesis title:

EXPERIMENT DEVELOPMENT AND VALIDATION OF A GRANULAR JAMMING ROBOTIC GRIPPER

Thesis Examination Committee:

Chairperson, Dr. Paul. Y. Oh, Ph.D.

Committee Member, Dr. Woosoon Yim, Ph.D.

Committee Member, Dr. Kwang Kim, Ph.D.

Graduate Faculty Representative, Dr. Brendan Morris, Ph.D.