The Vacuum-Compacted Regolith Gripping Mechanism and Unmanned Flights via Quad-rotors

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During the course of the Kennedy Space Center Summer Internship, two main experiments were performed: The Vacuum-Compacted Regolith Gripping Mechanism and Unmanned Flights via Quad-copters. The objectives of the Vacuum-Compacted Regolith Gripping Mechanism, often abbreviated as the Granular Gripper, are to exhibit Space Technology, such as a soft robotic hand, lift different apparatuses used to excavate regolith, and conserve energy while executing its intended task. The project is being conducted to test how much weight the Granular Gripper can hold. With the use of an Animatronic Robotic Hand, Arduino Uno, and other components, the system was calibrated before actually conducting the intended weight test. The maximum weight each finger could hold with the servos running, in the order of pinky, ring, middle, and index fingers, are as follows: 1.340N, 1.456 N, 0.9579 N, and 1.358 N. Using the small vacuum pump system, the maximum weight each finger could hold, in the same order, was: 4.076 N, 6.159 N, 5.454 N, and 4.052 N. The maximum torques on each of the fingers when the servos were running, in the same respective order, was: 0.0777 Nm, 0.0533 Nm, 0.0648 Nm, and 0.0532 Nm. The maximum torques on the individual fingers, when the small vacuum pump was in effect, in the same order as above, was: 0.2318 Nm, 0.3032 Nm, 0.2741 Nm, and 0.1618 Nm. In testing all the fingers with the servos running, the total weight was 5.112 N and the maximum torque on the all the fingers was 0.2515 Nm. However, when the small vacuum pump system was used, the total weight was 19.741 N and the maximum torque on the all the fingers was 0.9713 Nm. The conclusion that was drawn stated that using the small vacuum pump system proved nearly 4 times more effective when testing how much weigh the hand could hold. The resistance provided by the compacted sand in the glove allowed more weight to be held by the hand and glove. Also, when the servos turned off and the hand still retaining its position, energy is being saved because the vacuum created the same resistance the running servos did without using power.

The Unmanned Flights via Quad-rotors are built because multi-rotor dynamics are an important starting point and fair analog for space craft control systems and they make good terrestrial development platforms for various aspects of control for space crafts. The project is being conducted to see what the thrust response is going to be when a pulse width modulation command is sent to the control system since the quad-rotors are PWM controlled. A simulation environment in constructed so that one can quickly iterate and test different designs such as control systems, PID control vs. LDR control, and state estimation. Using two DIY Quad Kits, APM 2.6, testing apparatus (called a data acquisition system) to test the quad-rotors, and a simulation program such as Simulink, two quad-rotors are built and controlled via a simulation program, which is designed to be as realistic as possible and not idealistic. Due to the quad-rotors not being completely built nor ready for testing, there are no results or conclusions to report.

Nomenclature

F	=	force due to gravitational pull/weight of sand on fingers (in N)
g	=	gravitational constant – 9.80 m/s^2
m	=	mass of object (in kg)
τ	=	torque (in Nm)
r	=	distance (in m)

[1] NE-S, EDL, KSC, and Florida A&M University.

I. Introduction

The Vacuum-Compacted Regolith Gripping Mechanism is first step in more effectively gripping, lifting, and possibly moving space materials and mechanisms used to excavate regolith. Regolith is “a layer of loose, heterogeneous material covering solid rock. It includes dust, soil, broken rock, and other related materials and is present on Earth, the Moon, Mars, some asteroids, and other terrestrial planets and moons.”[1] With the use of an animatronic robotic hand, powered by 5 individual servos, each attached to its own finger, connected to an Arduino Uno and DC power supply, code is written in the C++ language to control the fingers and make them perform realistic human range of movement. The animatronic hand is pre-made and the Arduino Uno is ordered from the Arduino website, the DC power supply is located in the Engineering Design Lab, the breadboard and wires used are also located in the Engineering Design Lab. The Vacuum-Compacted Regolith Gripping Mechanism experiment is being conducted to exhibit Space Technology, such as a soft robotic hand, lift different apparatuses used to excavate regolith, and aim to conserve energy while executing its intended task. This project is simply aiming to test how much weight the Granular Gripper can hold initially, which is before the vacuum is pulled on the granular material, and terminally, which is once the vacuum is pulled on the granular material and the servo motors are no longer running. If the same amount of weight can be held once the servo power is terminated and the vacuum is still being pulled on the granular material, the question is raised can more weight be added, and if so, how much more weight can be added while still conserving energy (by not running servos).

A similar project has already been produced by John Amend, a roboticist, called Versaball. In his project, Amend uses a lime green balloon and a particular type of granulated substance to fill the balloon. This project executes the same process the Granular Gripper executes, the ability to sit on top of an object, conform around the shape of the object, and once the vacuum is pulled on the granular substance inside the balloon, the balloon tightly grips the object and is able to lift and move the object. Once, the vacuum is released, the balloon releases the object. Joseph Flaherty, author of the article The Beanbag Robot Hand That Works Insanely Well, writes, “The Versaball uses industrial-grade granule…which creates grip strength in three ways. First, when the vacuum kicks in, there is approximately half a percent of contraction in the volume of the gripper, which paired with the friction from the balloon, creates a pressurized clamp. Second, for many objects, the ball envelops a portion of the object, creating a stronger mechanical grasp. Finally, if there is a smooth area on the object being grasped, a vacuum forms between the gripper and object.”[2]

The grip strength that the Versaball displays is the same grip strength the Granular Gripper displays, the only difference is the skeletal setup and the type of granulated material used. This project is being studied because this will teach those working in the laboratory, on a much smaller scale, what they can use to further improve robots that are designed to grip and lift space materials. This could be used for commercial use as well as space technology. If used commercially, this could prove more effective than cranes, claw-grippers, or other machines used to lift materials. If used for space technology, the gripper could replace the current grasping mechanisms already installed on rovers.

Quad-rotors are built because multi-rotor dynamics are an important starting point and fair analog for space craft control systems and they make good terrestrial development platforms for various aspects of control for space crafts. A quad-rotor is a “multirotor helicopter that is lifted and propelled by four rotors. Quadcopters are classified as rotorcraft, as opposed to fixed-wing aircraft, because their lift is generated by a set of rotors(vertically oriented propellers).”[3] Two of the rotors (propellers) spin clockwise and the other two propellers spin counterclockwise. Quad-rotors, also known as quad-copters, have become a prominent figure in the world of upcoming technology. Quad-copter designs “have become popular in unmanned aerial vehicle (UAV) research. These vehicles use an electronic control system and electronic sensors to stabilize the aircraft. With their small size and agile maneuverability, these quadcopters can be flown indoors as well as outdoors.”[3].

There are several quad-copter projects that are available to the public. For example, scientists have made quad-copters mimic an eagle. In order to do this, scientists study the movement of an eagle, its body, and more specifically, how it catches its prey. To replicate the eagle’s action of catching its prey, the scientists “3D print an eagle’s claw and attach it to the bottom of the quad-copter. The drone starts with the claw pointed forward, and keeps flying past the object as the claw latches onto its target and pivots backwards. That gives the claw extra time to make a secure grip, without compromising speed.”[4] Scientists like using quadrotors because they're “stable in flight and can be easily modified.”[4]

There are several other examples of quad-copter use. This type of technology is becoming widely favored by scientists and those who are just interesting in new and upcoming technology. The quad-copter that is being used in this project uses pulse width modulation commands which simply measures the fluctuation of pulse widths when a certain command is sent from the controlling program to the quad-rotor’s control system. This project being studied will give scientists, on a small scale, how space technology can be further improved with the use of quad-copter dynamics.

II. The Vacuum-Compacted Regolith Gripping Mechanism

A. Granular Gripper

June 9th, 2014 was the first official day of the beginning of the technical work as a Kennedy Space Center Intern. The task of working on the Vacuum-Compacted Regolith Gripping Mechanism, otherwise known as the Granular Gripper, with Jim Mantovani was mentioned in the first GMRO (Granular Mechanics and Regolith Operations) Lab meeting. We ordered a Mecha TE Limited Edition Animatronic Hand from the company Custom Entertainment Solutions, Inc. (shown in Figure 1), which served as the skeleton for this version of the Versaball. Opposed to this being a beanbag gripper, this skeletal system included fingers which would better grip an object and maintain that grasp once the vacuum is pulled. The hand included five 5.0V servos, one servo per each finger, and each servo was connected to brass rod (attached to the servo horn), which in turn was connected to a rod, with springs, bolts, and screws as seen in Figure 2. These motors and rods are what made the fingers bend and flex. The springs would get compressed and release when the servos completed a span from 0^o to 180^o.

Figure 1. Animatronic Hand

Figure 2. Bolts, Screws, and Rods on Animatronic Hand

We also ordered an Arduino Uno (Figure 3), which is a microcontroller that allows one to control different objects, such as motors, LEDs, take data, and write code, while also acting as a great teaching tool for those new to the world of programming. Wires, breadboards, USBs, and a DC motor supply were all supplied by the GMRO lab. A personal laptop was used to download the Arduino software and codes were also written on the laptop. However, before actually using any of these gadgets, much research was conducted due to the lack of experience I had with programming, microprocessors and microcontrollers, and robotics. Several YouTube videos on How to Use the Arduino Uno were watched, several notes were taken on essentials to programming the Arduino Uno including digital pins, analog function, how to write C and C++ code, ground pin, serial.read function, and how to connect the breadboard to power and the Arduino. Getting familiar with the art and basics of programming and learning the Arduino Uno itself took approximately a week to complete.

Figure 3. Arduino Uno

After a sufficient amount of research[6--20] was conducted, the notes and knowledge acquired about the Arduino Uno and programming were ready to be put in use. The Arduino software was downloaded onto the personal laptop being used and the Arduino Uno was connected to the laptop via the USB supplied with the microcontroller. The Arduino software has terminals where you write the code called sketches and within the sketch options, they have example sketches that can be uploaded onto the Arduino and will show how the Arduino works, also it will show how to write the code for the Arduino using the C++ language. The first code/example that was used on the Arduino was called the Blink Sketch. Since the Arduino has a built in LED on the board, this sketch simply made the light blink on and off. The length between each blink could be adjusted, which was done several times in the process of learning how to work and write code for the Arduino by myself.

Once that code had been memorized, the next step was trying to hook up servo motors to the Arduino and use code specific to servos to make them move. The example code for the servos was labeled Sweep Sketch. Within the sweep sketch, all the different types of libraries (basic functions that certain codes use or code functions that are invented for certain codes are located in a code's library) were introduced, but this particular code used the Servo library. At first one servo was connected to the Arduino, by using an orange wire to represent the voltage (which corresponded the red wire on the servo—representing power), a green wire to represent the ground (which matched the black wire on the servo—representing ground), and a yellow wire to be the signal wire (which corresponded to the white wire on the servo – representing the signal). There were also 2 other wires, one orange and one green. One end of the orange wire went into the 5 V pin on the Arduino and the other end of the wire went into the positive column of the breadboard. One end of the green wire went into the GND (ground) pin on the Arduino and the other end went into the negative column of the breadboard. One end of each of the three wires mentioned prior to the 5V and GND wires are all inserted in the corresponding digital pins of the servo. The other ends of these wires are as follows: the free end of the orange wire is connected to the bread board in the positive column on the breadboard (same column that the 5V wire is in), the free end of the green wire is also connected to the bread board on the negative column (same column that the GND wire is in), and the free end of the yellow wire is inserted into the 3rd digital pin on the Arduino.

Once all the wires were plugged into their correct positions, the code for the Sweep Sketch was ready to be uploaded to the Arduino. The setup can be seen with two servos and part of the corresponding sketch can be seen in Figures 4 and 5 respectively. In order to upload the sketch, the upload button was pressed and the servos started moving from its initial position to the terminal position, which is this case was from 0^{o} to 180^{o} (the full span of the servo motors). I continued to add servos to the Arduino and breadboard until I reached the point where 5 servos were connected. The reason five servos were connected to the Arduino was because that would prove that I could connect all the servos that were infused in the animatronic hand and the servos could be programmed to move simultaneously and at different angles.

B. Programming Individual Fingers

The multiple servos test and sketches proved to be successful. The next step was to start programming the skeletal hand. The hand was ordered and delivered with a pre-set calibration point. Not clear about what the calibration point meant by 1500 ms (milliseconds), we concluded that the hand just be recalibrated while it was being programmed so that the fingers would know where the initial point was in respect to the code and where the terminal point was. All the springs and bolts were left in place on the rods connected to the servos. No mechanical work done on the hand, only trial and error was used in trying to calibrate the fingers and make the fingers curl and uncurl, which was the main goal.

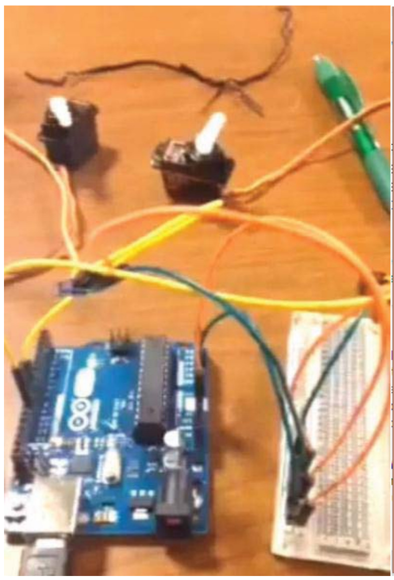

Figure 4. Wiring for Two Servos

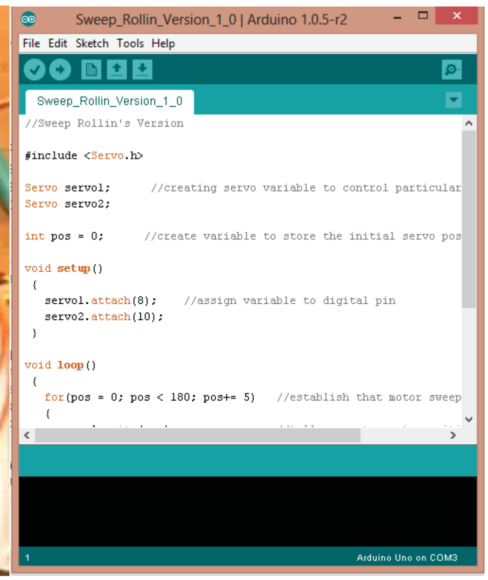

Figure 5. Sweep Sketch for Two Servos

The fingers were all connected with the corresponding wires at the same time, but were programmed individually. Since each finger was connected to a servo, they were all connected like the servos were connected in the multiple servo test. The fingers contain screws that can be adjusted at three main points on each finger (one screw near the fingertip, one screw at the middle joint, and one screw at the knuckle point). These screws could be screwed tightly to keep the finger relatively one position or with limited movement, making the servo work even harder to try and move the finger a little. The screws could also be unscrewed to loosen them, giving the finger limited yet more range of movement, making it easier for the servos to push and pull on the rod thus making the fingers uncurl. It was difficult trying to find the perfect position of each screw on each finger so that the fingers would operate with as much efficiency as possible. The combinations of tightening and loosening certain screws while trying to find the best angle for each finger to have the most realistic range of motion of a human finger were endless.

Angles were eventually found that worked perfectly for each individual finger. A perfect angle mean that the fingers were not going too far back when fully extended and they would completely curl making a fist-like hand

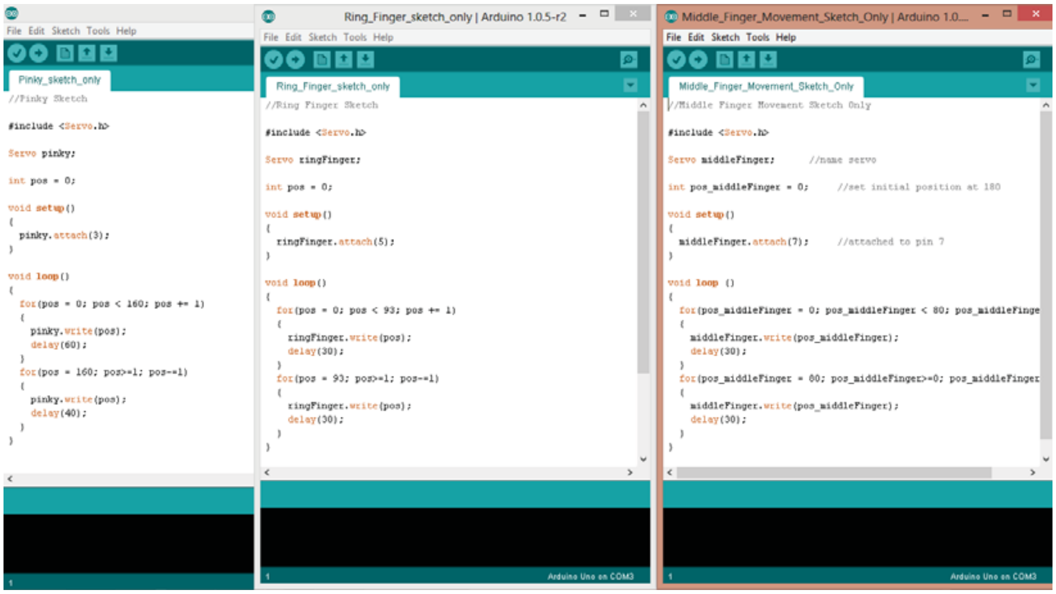

Figure 6. Arduino Sketches for Pinky, Ring, and Middle Fingers (Individually)

motion. Starting from the pinky (ring, middle, and index fingers were programmed in that order) and working up to the thumb, the angles were, respectively: 160°, 93°, 80°, 100°, and 105°. The pinky, ring, and middle finger sketches can be seen in Figure 6. After the most effective angles were found through trial and error, there were still problems with the finger movement. It was observed that if the program was left running too long, or if the program was run the next day, after two or three loops of the sketch (loops are the code that is repeated by the microcontroller until told to stop or the moving object or microcontroller is turned off), the fingers would start having difficulty bending or extending. There was nothing wrong with the codes that were written, so the problem was assumed to be mechanical, which proved to be correct. The springs on the rods were either not getting compressed all the way or did not have enough room to fully extend. The solution to this problem was to test each finger individually again and through trial and error, figure out which fingers worked better with spring adjustments, without springs and screws, and which worked well with the springs without adjustments.

Starting with the pinky, the Pinky Only sketch was run. The pinky was having trouble curling and when it did curl, it was having problems extending. The hand was turned over and the springs were compressing and extending just fine. After trying to readjust the springs, screws, and bolts along with trying different angles to try and accommodate the new adjustments, the pinky did not work as well as it had the first time, when the sketch was first run. The decision was made to remove the springs and bolts with the corresponding screws so that only the brass box, attached to both the servo horn and rod moving the finger, was responsible for making the finger move. After removing the springs, bolts, and screws, the angle had to be manipulated to accommodate these new changes to the pinky finger. A table was made for these trial and error tests, however, the finger was extending too far back for realistic human range of motion and it did this for every angle tried. The table with the results from having no springs on the rod can be seen in Figure 7. Since the pinky finger did not exhibit realistic range of human motion of a finger, the springs and screws and bolts were put back on the rod and used the best angle found for those new changes, which was 150°.

Pinky (without bolts and springs)

Trial Number	Angle Number	Results
1	105	Doesn't really move/uncurl for that matter. Limited range
2	180	Too far back regarding paralleling how far back a human pinky can go, curls and uncurls, however, does not curl enough to grip something firmly.
3	160	Same as above
4	130	Same as above
5	170	Same as above
6	150/145	Same as above/ Same as above
7	135/140	Same as above/ Same as above

**Ended up putting springs and bolts back on finger---worked better that way. Adjusted screws and position of motor head. Still strained when curls up. No matter if it has springs, bolts, neither—it still will not curl all the way. It curls, but it's not enough to grip anything.

***Final result was 150° with springs for pinky

Figure 7. Table for angles tested for Pinky without bolts and springs

The next finger tested was the ring finger. The original code for the ring finger only was run. The finger was having difficulty curling. It was stiff and when it extended, it extended too far back. The screws and the bolts were adjusted and the same results kept reappearing for every angle that was input into the code. The testing angles were also centered around the original angle, since that was the angle that worked best for the finger before the problems occurred. However, the springs, bolts, and screws were removed and only the brass box, which is connected to the rod was responsible for making the finger move. Not having anything on the rod proved to be more effective. The finger was no longer stiff and curled with ease and did not go as far back. The angles were once again manipulated to accommodate the changes made on this finger and the angle that worked best for this finger turned out to be 93^{o}, which was the angle started out with in the original sketch.

The Middle Finger was then tested and checked. The middle finger had difficulties curling with the angle that it was executing. The only problem with that finger was that it needed a small bolt/screw adjustment. Therefore, the angle stayed the same, which was 80^{o}. The last finger was the index finger. The index finger would not curl and or uncurl without difficulty. The screws and bolts were adjusted, but the finger still had difficulty bending and extending. The screws, bolts, and springs were removed and the brass box was the only thing connected to the rod. The finger worked more effectively and the angle remained the same, which was 100^{o}, the problem was that the servo was getting stuck and would not complete an entire span because the rod would hit the rod from the middle finger, which made the finger have difficulty trying to bend and extend fully (to a realistic human range of movement). The thumb was not bothered because it did not have screws nor bolts or springs when it was ordered. It moved without any difficulty every time the code was run.

C. Moving More Than One Finger

The next step was moving more than one finger at a time and trying to move them simultaneously. However, enough power was not being generated from my computer to power all these fingers. Taking heed of the suggestion that we should use a DC power supply as oppose to powering the hand with my computer, the DC power supply became source of power for the hand. Instead of the 5V wire being connected to the Arduino Uno, the free wire would be connected to an alligator clip (with a red protective covering, thus resembling voltage/power) on one end of another wire, and the other end of the wire would fit into the socket for the voltage on the DC power supply. There would be an additional ground wire added, but the ground wire that was connected to the Arduino was disconnected from the Arduino (one end still in the breadboard), attached to the other wire with black covered alligator clip, and the other end is inserted into DC power supply. One end of the additional wire would now be inserted into the column with the ground wire on the breadboard and the other end inserted into the GND pin on the Arduino. A picture of this setup can be seen in Figure 8.

Figure 8. Setup of Hand with DC Power Supply

Now that all the wires were connected to their corresponding places, code was ready to be written for two or more fingers to move simultaneously. The catch with writing these types of code is finding a "compromising angle" (angle that works effectively for both fingers that are supposed to be moving simultaneously) for the two fingers being observed. The first two fingers that were being tested were the pinky and the ring finger. Since the angles were far apart with the pinky being 150^{o} and the ring finger being 93^{o}, the code was written to accommodate each finger. Their individual angles were used, they were just listed in the same sketch. Since the ring finger's angle was written in the code separate from and after the pinky's angle, the fingers moved in sequence. First the pinky moved then the ring finger moved. This was not moving the fingers simultaneously, so a compromising angle was found for these fingers and it turned out to be 100^{o}. At this angle, the fingers worked effectively. Although the angle was not their maximum performance angles/individual angles, the fingers did display realistic human movement. Five different angles were tried before the most effective angle was found.

The next two fingers that were tested were the ring and middle fingers. The ring finger had an original angle of 93^{o} and the middle finger had an angle of 80^{o}. These two fingers did not cooperate as well as the pinky and ring finger did. The chosen was 80^{o} because the middle finger at 85^{o} went too far back for realistic human motion of a finger. However, at 80^{o}, the ring finger could not fully extend which was a problem because both fingers needed to exhibit realistic human movement. These two fingers were looked over as the next two set of fingers began to be tested, which were the middle and index fingers. The original angle for the middle finger was 80^{o} and the angle for the index finger was 100^{o}. The compromising angle was found to be 80^{o}. At this angle, these two fingers proved to be the most in-sync and displayed realistic human movement which was the goal. The thumb was not paired with any of the fingers because it worked fine on its own and manipulating its angle to any other angle would completely hinder and limit its range of motion. The thumb would not extend too far back because it could not extend back to a real human's range because of how it was manufactured, but it would not curl completely if the angle was anything below 105°. Thus, the thumb was left separate.

After moving two fingers at a time, code was written putting all the fingers together based on their compromising angles. The pinky and ring fingers were written under the same angle and the middle and index fingers were written under the same angle. The thumb was excluded from the first couple of sketches because the goal was to see if the four fingers would move simultaneously while still maintaining realistic human movement. The code was not as successful as hoped. The fingers were coupled off meaning the ring and pinky fingers moved first, then the middle and index fingers moved next. They repeated this manner, bending and extending, until the power supply was turned off. Once the mistake was recognized that the reason the fingers were moving two at a time was because of how the code was written, a new code was written in which all the fingers were written under the same angle. The compromising angle chosen was 88°. The fingers worked fairly well. They all bended and some extended fully and some did not. However, an example of what they could hold is Figure 9 and the corresponding code is in Figure 10. After the fingers proved capable of actually gripping items, code was written to make the hand perform tricks such as tickling, shaking hands, and performing the "come here" motion. Once those in the lab saw what tasks the hand was capable of performing, we unanimously concluded that the hand was ready to be tested with the sand.

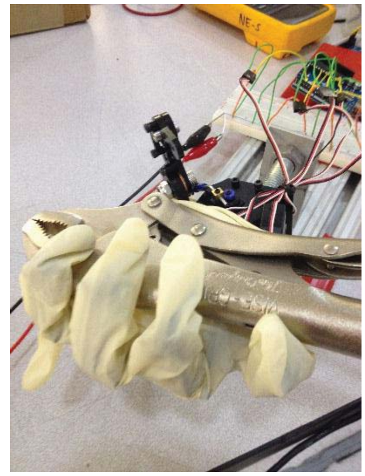

Figure 9. Hand Grips Wrench

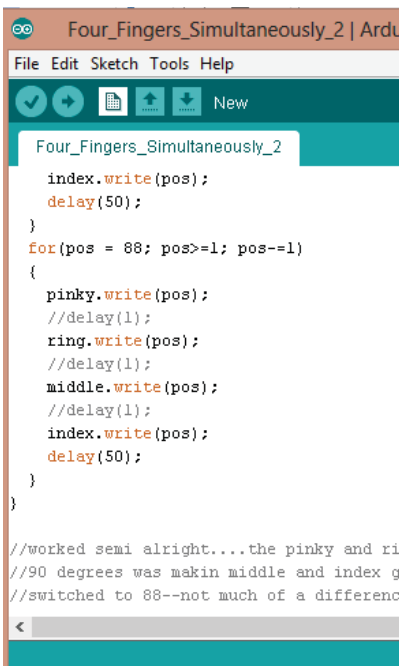

Figure 10. Sketch of Fingers Moving Simultaneously

D. The Sandy Gloves and Weight Test

Before the sand could be placed around the hand, a glove had to first be put on the hand. The Electrostatics Lab had an abundance of gloves and a couple of gloves were given to us to use for the hand. The gloves were made out of latex and they were purple. The original glove used was also latex, but it was too small to cover the entire hand and popped when taken off of the hand the second time. The purple glove was placed over the hand, which proved to be sturdier and bigger than the previous glove.

A weight test had to be performed before putting another glove on the hand and filling the second glove with sand. Since there was no weighing apparatus to measure how much weight the hand's fingers could hold, one had to be made. Being innovative, the weighing apparatus was made with bucket handle clasps (clasps that go around the handle of a bucket so that the handle would not break) found in the GMRO Lab, the fishing wire, and three little aluminum cups that look similar to cupcake holders. Two of the bucket holders were taped together with duct tape, then, two pieces of fish wire were taped to the aluminum cups so that when held up, the fish wire crisscrossed at the top. The fish wire was done that way for two more aluminum cups and all three were attached to the two taped bucket holder clasps, one at each end and one in the middle. One aluminum cup was weighed and the two bars that were taped together were weighed prior to being assembled together. The bar (the two taped bucket handle clasps) was placed along the joints near the fingers' fingertips and sand was poured into the three cups until the bar tipped over, the sand fell into a bin which was weighed and the mass of the bin plus the sand was measured (in grams). The weight is calculated with Eq. (1) and the torque can be calculated with Eq. (2).

$$F_g = m \times g \tag{1}$$

$$\tau = r \times F \quad (2)$$

The maximum mass that the fingertips could hold while the servos were running was 33.6 grams, which means the maximum weight was 0.32928 N and the maximum weight the fingertips could hold when the small vacuum pump was in effect was 1.75518 N. The maximum torque on the fingers while the servos were running was calculated to be 0.0162 Nm. The maximum torque on the fingers when the small vacuum pump was in effect was 0.0864 Nm. The reason the weight test was performed at the fingertips was because that was the only part of the hand that would show when the weight was at its maximum by the fingertips giving out and going in the opposite direction of the forward curling motion. Refer to Figure 11 for an example of the weight testing apparatus.

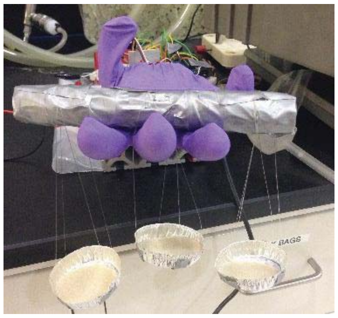

Figure 11. First Weight Testing Apparatus

Once the weight testing was complete, the already gloved hand was sealed with a twist tie so that no sand would get in that glove and affect the servos or gears. Another purple latex glove was placed over the already gloved hand and sand was poured into the second glove. A tube was placed inside the glove and the glove was sealed with red duct tape and a tube clamp. The tube was connected to a small vacuum pump apparatus that was previously constructed. This apparatus involved a tube attached to an eductor which was connected to another tube which would connect to the air supply. The eductor acted as a vacuum which is what it meant when the paper states "to pull a vacuum on the sand". However, because the hand was propped on a stand, the second glove would not close completely because the tube and the stand were creating extra space. Therefore, air was leaking out when the vacuum was pulled and did not give the desired effect we were looking for.

Now that the hand was engulfed in a sandy glove, the movement of the fingers inside the glove needed to be tested. The same program was run where all four fingers, with the addition of the thumb, moved simultaneously. The thumb moved separately because it was not hindering the gripping process. With the sand in the glove, the fingers could not fully bend. The amount of sand in the glove was decreased and the fingers still did not curl completely. The index and middle fingers got half way and the pinky stayed still. The fingers could not bend when they were supposed to and when they were fully extended, it was as if the sand was pulling down on the fingers too hard so they could not bend. We concluded that the 5V servos were not providing as much power and did not provide the amount of strength we needed, so we ordered 6V servos.

E. Changing the Servos

Once the new servos arrived, the entire project had to be started over. First, the servos had to be tested individually to make sure each one worked properly. Then, all the servos had to be connected to the bread board and Arduino like the previous servos were at the beginning of the project. Once all the servos were checked and wired, everything was disconnected so the new servos could be installed into the hand. At first, only one servo was removed from the hand, which was the pinky's servo, and the new servo replaced it. The new servo, however, had different servo horns as well as its holes not matching up with the holes in the hand so that the servo could be screwed in place. After consulting with some of the lab technicians, it was suggested that the servo horn be cut to look like the original and file the hole to make it bigger so that the screw can be screwed into the smallest opening possible in its assigned spot on the hand. A picture of the new servo horn before it was altered can be seen in Figure 12. The new servo, after alterations, and the

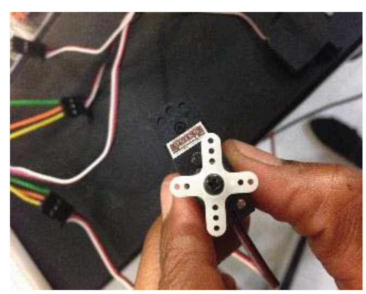

Figure 12. Servo Horn of 6V Servo

Figure 13. 6V Servo Horn vs. 5V Servo Horn

original servo horn can be seen in Figure 13. The new servo horn is white and the original is blue. The brass box connected to the original servo horn also had to be taken off so it could be attached to the new servo. After it was detached from its original servo horn, the brass box was inserted into the new servo horn and the horn was placed on the new servo facing the left, since the rod would be on the left hand side of the servo once the servo was installed in the hand. The hole that needed to be enlarged took approximately 4 minutes to widen so that the screw could fit through the servo hole which just barely aligned with the screw's assigned hole in the hand. Once the servo was screwed down and the rod was placed through the brass box and screwed in place, the code was run for the Pinky Only Sketch, where the angle was 160^{o}. That angle did not completely allow the finger to extend all the way back. After many trial and error tests, the most effective angle was 165^{o}.

The ring and pinky sketch was run to compare the 5V servo to the 6V servo. The 6V servo worked much better than the 5V servo as it provided 6.001 V, with a total corresponding current measurement (read from the DC power supply), to the finger(s) being tested. It had more power and as a result was stronger than the 5V servo. The pinky finger had no difficulties trying to bend and extend. One by one, the fingers' servos were replaced by the 6V servos and new codes were written for each finger. The fingers' angles from ring to middle to index are as follows: 65 ^{o}, 80 ^{o}, and 55 ^{o}. These angles are smaller than the original angles when the fingers used 5V servos. The Hand Shake Sketch was run for the 6V servos with a new compromising angle of 68^{o} for the four fingers and 105^{o} remaining as the thumb's angle. The thumb's servo did not cause any difficulties, therefore it was left alone. The hand runs better, however, the middle finger will not fully extend, but it extends far enough to where it is not still half way bent. The index finger also extends back a little too far for realistic human range of motion, but this is the only angle that would work for all the fingers and they still bend successfully and extend.

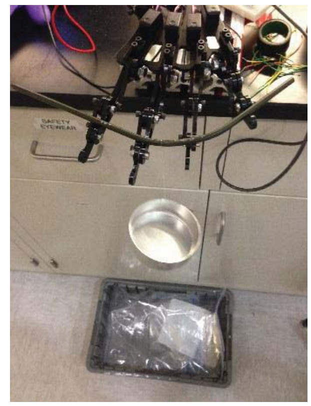

Figure 14. Aluminum Container & Malleable Tube Weighing Apparatus

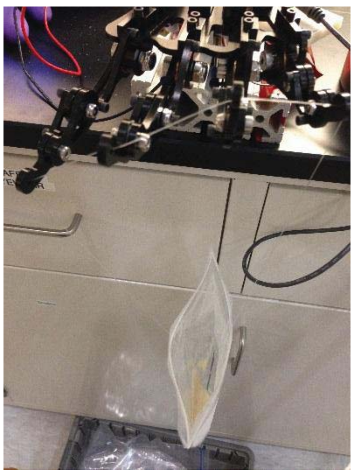

Figure 15. Ziplock Bag Weighing Apparatus

A weight test was conducted and another apparatus had to be built. The first apparatus was made from a small aluminum container and a piece of fish wire was connected to it. The apparatus could hold about 175 g of sand. Refer to Figure 14 for a picture of the first weighing apparatus. The fish wire connected to the aluminum container kept detaching from the container so another apparatus had to be built. A tube used for putting brake fluid in the car was found in the lab, which was malleable, and bent it so that it would cross all the fingers and not just 3 out of the 4 fingers that were being tested. The tube had another aluminum can and fish wire attached to it. This apparatus worked for two trials and then the tube kept turning in the opposite direction, causing the sand to spill, because the sand was getting too heavy. Refer to Figure 15 for a visual of this apparatus. Finally, fish wire was treaded through the fingertip holes of the hand and was attached to a ziplock bag on both sides and sand filled the bag until the fingertips flung backwards. This proved to be the most effective. Only one of these tests were taken. The maximum weight that could be held at the fingertips was 2.0178N.

F. 6V Servo Weight Tests

Although a weigh test was conducted with the skeletal hand alone, more weight tests were conducted after a glove filled with sand was placed over the hand. However, before the sand could be placed over the skeletal hand, an apparatus had to be constructed to be able to suck the air from between the sand grains, while preventing the sang granules from entering the tube acting as a vacuum as well as from getting into the first glove during the vacuuming process. Jim constructed this apparatus out of a white plastic tube, a type of plastic cap, while drilling holes in the tube and cap for the screw, which acted as a base for the hand to be supported by, and the vacuum tube. The servos' wires were taped to the top of the plastic container with a sponge material covering them. This sponge material secured the wires while making sure no air would seep inside or outside of the external glove, containing the sand, when the vacuum would be pulled on the sand. A picture of this setup can be seen in Figure 16.

The first glove was put on the skeletal hand and sealed with a zip tie. The next glove was put over the already gloved hand and pulled up to ensure that it covered the sponge material that secured the wires in place. The glove was successful in covering the sponge material. The hand was held upside down so that just enough sand could be poured into the glove and the fingers could still move. A piece of tissue paper was cut, folded into a thin strip, and wrapped around the base of the glove (the part that covers a person's wrist, but in this case the sponge material on top of the plastic container). A tube clamp, big enough to clamp the plastic tube acting as a wrist for the hand, was then placed around the tissue paper and screwed to secure the glove in place.

Figure 16. Apparatus used to secure sand from getting into vacuum tube

The Hand Shake code was run to insure that the fingers could still move with the extra weight pulling down on the fingers due to the sand. The fingers could move, however, they only curled halfway, but they could extend to their assigned angle. The curl movement that the fingers did perform, although not fully curled, was enough to be able to perform a weight test because it provided enough resistance for the bag to contain more weight as oppose to the skeletal hand alone. A new and improved weighing mechanism was also created. We took two ziplock bags, cut one of the plastic bags into a strip, leaving a large piece of the actual zip lock part at the bottom of the bag (more surface area) and attached the two ziplock parts from the strip of the first ziplock bag to the corresponding zip lock part of the second ziplock bag. Once the bag was made, smaller individual ziplock bags of sand was placed inside the bag. Refer to Figure 17 for a picture of the weighing apparatus.

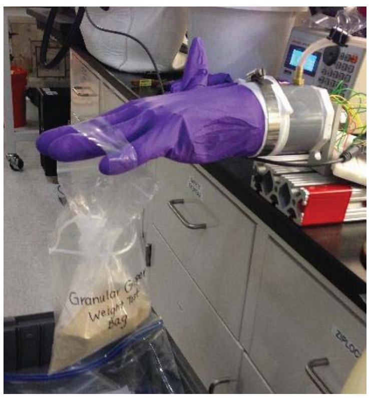

Figure 17. New weighing apparatus

Each finger was tested separately and then all the fingers were tested together, excluding the thumb. There was not enough sand in the glove to cover the entire hand, so sand was not covering the thumb, as that would have been too much sand in the other fingers for them to actually move. It would have been too much weight on fingers for the servos to try to move. The weight of the sand in the glove was 2.0070 N. The individual fingers could not be measured because most of the sand that was inside the hand landed under the palm of the hand and when the glove was taken off all that sand fell into the fingers of the glove, thus manipulating how much sand was actually in each finger. The weights that the individual fingers could hold without the vacuum being pulled, but the servos were running, (from pinky to ring to middle to individual) were: 1.340N, 1.456 N, 0.9579 N, and 1.358 N. The total amount of weight that those four fingers could hold was: 5.112 N. The maximum torques on each of the fingers, in the same respective order, were: 0.0777 Nm, 0.0533 Nm, 0.0648 Nm, and 0.0532 Nm. The maximum torque on the all the fingers was 0.2515 Nm. After these measurements were taken, the air was turned on and run through the series of tubes Jim put together to create a vacuum effect. When the vacuum was pulled, the weights were taken again to see how much more weight the fingers could hold before giving out even with the vacuum being pulled on the sand. The weights, in the same order as before, were: 4.076 N, 6.159 N, 5.454 N, and 4.052 N. The total amount of weight that the four fingers were able to hold was: 19.741 N. The maximum torques on the individual fingers, when the small vacuum pump was in effect, in the same order as above, were: 0.2318 Nm, 0.3032 Nm, 0.2741 Nm, and 0.1618 Nm. The maximum torque on the all the fingers was 0.9713 Nm. The total difference in the weights when the servos were running with no vacuum and when the vacuum was pulled (the servos were not running as the vacuum's purpose was to create the same resistance as the servos, even more resistance actually,

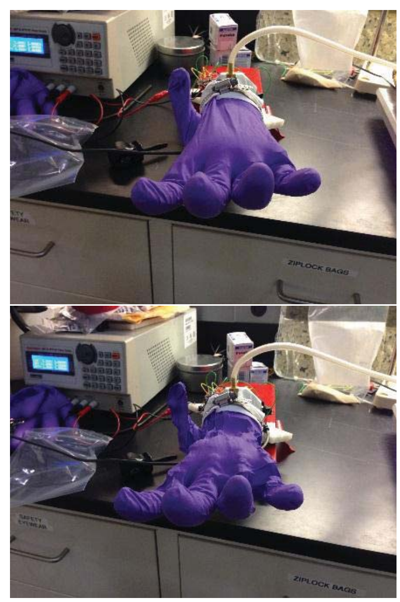

Figure 18. Top: Before vacuum was pulled Bottom: After vacuum was pulled

but conserving energy) was: 14.629 N. Since the sand was not evenly distributed throughout the fingers, some fingers were stronger than others when the vacuum was pulled and therefore could hold more weight. Refer to Figure 18 for before and after pictures of the hand when the vacuum was and was not pulled on the sand.

III. Unmanned Flights via Quad-rotors

A. Building the Quad-Rotors

This project was started very late in the internship. This was another opportunity to explore the intertwining nature of both mechanical and computer engineering. This opportunity was brought up in a teleconference with Rob Mueller and other lab technicians and the mentioning of intern help being needed on this particular project. Having some knowledge about quadcopters, at least knowing the basic structure of one and seeing one in flight, it seemed very beneficial to help out with this project. Working with, and under, Michael Dupuis was a great experience in the sense that he explains step by step what each part is, if one is confused about a specific part's function, and helps out when help is needed. The quad-copters came in a QIY Quad kit. There were two kits along with several other miscellaneous parts that would be needed in addition to what the Kit provided. There were instructions online as to how to put together this multi-rotor and we simply followed the instructions.[21]

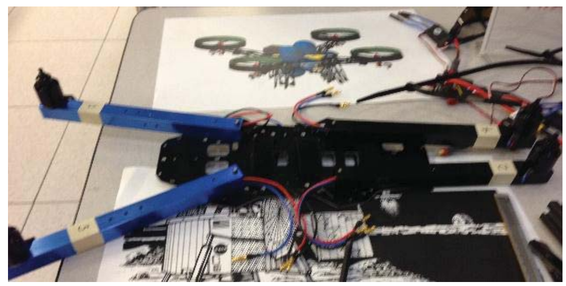

Figure 19. Body Plate Assembly of Quadcopter

The parts of the quad copter that have already been assembled are the power system wiring, the motor assembly, the body plate assembly, the legs of the quad-copter have been pieced together, however, they have not been attached to the quad copter. A picture of the body plate is in Figure 19. The only thing that was not in the instructions was how to wire the APM 2.6 because the QIY Quad Kit uses a Pixhawk instead of an APM 2.6 for the control system.

Once half way through building the two quad-rotors, Mike realized that we did not weigh the individual parts of the multi-rotors. Taking apart the quad-rotor was relatively easy because the parts had already been assembled and all one had to do was either refer to the online instructions or remember what went where on the robot. The individual pieces were weighed and the quad-rotor that was taken apart was put back together. Neither of the quad-rotors are completely built. One propeller is attached to one arm that has been severed from the rest of the quad-copter. AJ, the lab technician, is building a data acquisition system, which will determine what the exact thrust response is if a pulse width command is sent to the rotor from the simulation program.

IV. Conclusion

After doing the weight tests for the Granular Gripper, the results proved that when vacuum is pulled on sand, the object can hold a significant amount of weight as opposed to when a vacuum is not pulled. Therefore, the compacted sand, with no air between the particles, provides a more stable foundation for the position of the hand allowing it to hold more weight. This project, although small scale, can help designers of rovers, or other space technology being used to grip/grab other objects, know what types of granular material can be used in conjunction with a vacuum system to pick up the most weight. This project was declared successful in accomplishing the assigned task to see how much weight the hand could hold. This project opens doors in the field of computer engineering and mechanical engineering in the sense that both of the fields are intertwined in this project and the gripper can be used for more than gripping. If attached to a wrist or arm or body/mechanism, the hand can be programmed to be able to do other human functions, which is a medical benefit, such as writing or playing instruments. Regarding the quad-rotors, they are not completely built therefore no tests can be done on them and no conclusions can be drawn at this point in the experiment.

Acknowledgments

R. L. Scott thanks Phil Metzger, Lab manager and personal mentor, Rob Mueller, second main mentor and deals with concerns of interns when Phil is not available, Jim Mantovani, Computer Engineering and Granular Gripper mentor, Mike Dupuis, Quad-Copter mentor, and any of the other lab technicians that helped throughout the internship.

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