# Design of Bio-inspired Gripper Arm for Mars Sample Retrieval

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**Abstract**

In the last decades, the idea of traveling to Mars has become increasingly popular as technology progresses and the journey is becoming more than just fiction. As a result, existing rovers on Mars are preparing drilling samples of Martian soil for eventual pickup. These soil samples can be located on rough terrain in all orientations and angles and need to be retrieved. The geometry and mass of these samples are predefined, it is cylindrical with a length of 15.2 cm, a width of 2.3 cm, and a mass of 57 g. Traditional gripping approaches focus on opposed fingers, industrial-style scoops, or vacuum adhesion which are very orientation specific and not secure enough for a drone. Our MARS-DOG design acquires sample tubes securely without precision positioning nor orientation in a sandy environment. The biomechanical-inspired design is a spring-loaded claw inside a net that closes the gaps between each claw. The net's aperature is closed with a string on the claw tips. A 3D printed prototype is capable of picking up, carrying, and droping a sample tube analog that is at least 57 g, regardless of the object's pitch and yaw in a dusty environment. Stress-testing the unit revealed lifting capability in excess of 6 kg which is sufficient for additional sample collection tasks in addition to the original Mars sample tube goals.

**Keywords:** Claw, Axiomatic Design, gripper Arm, Design

# 1 Introduction

The problem we are trying to solve is the retrieval of rock and dust samples on Mars. Currently, a rover or drone digs up samples, puts them in tubes, drops them on the ground, and moves on. The proposed way to retrieve these samples is to have a drone fly to them, pick them up and transport them back to base. This poses problems, since the samples can be oriented in any way, i.e. roll and yaw, and could be sitting at an angle, i.e. pitch. The idea and goal for the project is to create a gripping mechanism that can easily grab the sample, which has a predefined geometry and mass. The sample is cylindrical with a length of 15.2 cm, a width of 2.3 cm, and a mass of 57 g.

The gripping mechanism needs to be able to pick up the samples regardless of the samples' orientation and angle. The name of the gripping mechanism is MARS-DOG, Mars Drone Omniorientational Gripper because it's a gripping mechanism that goes on a drone that will be on Mars and will be omniorientational, i.e. it can pick up items, regardless of their orientation as long as they fit in the net. The gripping mechanism is going to be created for the RIOT lab at Reykjavik University, the customer and stakeholder of this project. The product can also be used by other potential customers, for example, other space agencies, such as Space X or NASA, that would have an interest in picking up samples on planets, and even be applied to other fields such as garbage companies, cities, municipalities, and anyone that needs to pick something up easily and reliably.

## 1.1 The sample

The sample tube upon which all FRs and CNs were based on and tested was made using a 3D printed replica of the Perseverance Sample Tube 266 from NASA[1]. This sample was chosen as it was the newest sample tube that could be found and is used by the Perseverance rover on Mars. The length of this sample is 15.2 cm, the width is 2.3 cm and the mass is 57 g. An STL drawing of the sample tube, created by the Jet Propulsion Laboratory, California Institute of Technology [2] was used to create the 3D printed sample. The 3D printed sample tube can be seen in figure 1.

## 1.2 Customer Needs

A customer need is a way of noting down what the customer needs the product to be able to do. Our customer needs were acquired by brainstorming what the customer might need from this project, and from what information Joseph T. Foley, a professor and a member of the RIOT lab at Reykjavik University, told the team about it. Using that information, we developed a top-level need ($CN_0$), which was then decomposed into smaller, more manageable pieces ($CN_1$-$CN_4$).

The team's main priority is stated in $CN_0$ from our Axiomatic Design[3].

**Figure 1**: FDM printed model of NASA's sample tube to test gripper compatibility

**$CN_0$** The gripping mechanism needs to be able to grab, carry and drop the sample no matter its pitch and yaw in a dusty environment.

After the top-level need is identified, it is broken down into the following smaller customer needs $CN_1$–$CN_4$ in our Axiomatic Design.

**$CN_1$** The gripping mechanism needs to be able to pick up the sample regardless of the sample's pitch.

**$CN_2$** The gripping mechanism needs to be able to pick up the sample regardless of the sample's yaw.

**$CN_3$** The gripping mechanism needs to be able to pick up, carry and drop a sample that is 57 grams[4].

**$CN_4$** The gripping mechanism needs to be able to pick up, carry and drop a sample that is covered in dust.

# 2 Background and Prior Art

There are many applications for which a drone or a robot can be used to grab stuff. Cities and municipalities could have use for a drone with a gripper to pick up trash around the city, or to transport small objects between offices quickly. Production lines could have use to transport material between different warehouses, conveyor belts, or production lines.

Picking up objects has been a goal for many companies for various reasons. As the usage of drones for commercial and personal use has increased in the last decade a link between them has emerged. Grabbing objects with little complexity in any orientation of the object has been the goal of many companies and these companies have achieved this goal in various ways, such as using a four-armed gripped like the Small Hammer Robot Arm Gripper by AlexNLD[5], a drone with 5-axis robotic arms by ProDrone[6] and a vacuum gripper by Robotiq[7]. There exist many other ways to pick up objects that

(a) A four arm gripper[5].


(b) Robotiq's vacuum gripper[9].

don't use claws or a vacuum to do so, such as a purse seines net, which is often used by fishing boats to catch fish[7], or the Ogre-Eyed Spider, which spins web between its legs to securely hold on to its prey[8]. These methods will be shown and talked about in this section 2.

## 2.1 Small Hammer SNM2500 Robot Arm Gripper

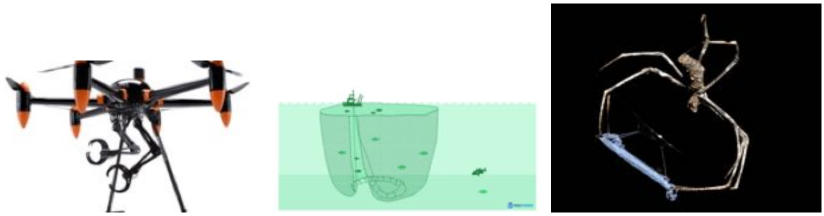
The Small Hammer Robot Arm Gripper is your typical four-armed gripped and can be seen in figure 2a. The problem with having only the claws is that it will have problems holding onto the sample during flight, and the sample will fall out of the claws, this design, therefore, does not fulfill our requirements.

## 2.2 Robotiq's Vacuum Gripper

The Robotiq Vacuum Gripper picks up objects by creating a vacuum between the vacuum cup and the object[9]. This works when the difference between atmospheric pressure and the negative pressure, is enough to provide the ability to lift, hold and move the object. This would not work on Mars, since the atmospheric pressure there is extremely low and therefore the suction needed to pick up an object would be gigantic in comparison to the atmospheric pressure. Another problem with vacuum grippers is that they are extremely sensitive to dust and require a lot of electricity to power a vacuum or air pump, as well as having the requirement that the object it is grabbing has to be compatible with a vacuum gripper, which is not suitable for this project.

## 2.3 ProDrone PD6B-AW-ARM commercial-use drone

The ProDrone is a large-format drone equipped with two internally-developed high-performance, completely original 5-axis robotic arms[6] used to pick up



(a) ProDrone PD6B-AW-ARM drone[6].

(b) Purse Seines net caching fish[7].

(c) Ogre Eyed Spider using net to catch prey[8].

objects, as can be seen in figure 3a. This on the other hand has the problem that it needs both grippers to secure the sample and each arm has to be rotated based on the rotation of the sample on the ground. It also runs the risk of the sample falling out of the grippers, if it is not held on precisely by the ends of the claws, and since the sample is cylindrical it is likely to slip and result in the gripper losing grip and dropping it during flight.

## 2.4 Purse Seines

A purse seine is a net that is deployed like a wall encircling an area and any fish inside it. The seine floats along the top line with a lead line threaded through rings along the bottom. Once a group of fish is located, a vessel encircles the group with the net. The lead line is then pulled in, "pursing" the net closed on the bottom, preventing fish from escaping by swimming downward. The net is then either hauled aboard or brought alongside the vessel. This method can be seen in figure 3b. The problem with using a purse seines net is that since one of the sides is open until the line is pulled, the sample may slide out of that hole if it is oriented in that particular way, resulting in the gripping mechanism not being able to pick up the sample.

## 2.5 The Ogre-Eyed Spider

The team decided to look outside of standard technology and viewed how nature solves the problem of picking objects up. One of the best animals using “claw”-like arms to grab things were spiders. Thus the ideal spider was found, The Ogre-eyed Spider. The spider is faced with the same problems that we are, it has to somehow grab, secure, and bring its prey back to itself, despite the prey having different orientations, sizes and being in versatile terrain. How the Ogre-eyed spider solves these problems is by not simply relying on its four legs to grab its prey, but also spinning a net between its legs to secure the prey[8]. As seen in figure 3c.

Our idea is bio-mechanically inspired, to create a gripper with claws similar to the design in figure 2a. We want to add a net that connects to each claw, inspired by figure 3c and 3b. By adding a net to the claws we think the sample will be more secure, i.e. the net will help the claws to hold onto the sample no matter the orientation of the sample, and prevent it from falling out of the gripper.

### 2.6 Functional Requirements

Using Axiomatic design the project was broken down into the following Functional Requirements(FR) and Constraints(CON)[3].

The team's main requirement is stated in $FR_0$ from our Axiomatic Design:

**FR**$_0$ Picks up, carries, and drops the sample tube regardless of its yaw and pitch.

From the Customer Needs, we built a list of Functional Requirements and Constraints.

**FR**$_1$ Grab the sample geometry regardless of its yaw.

**FR**$_2$ Grab the sample geometry regardless of its pitch.

**FR**$_3$ Release the tube when commanded.

**CON**$_1$ Grab the sample in the presence of granular contamination (sand).

**CON**$_2$ Hold 57g while structure is moving $22\,\mathrm{km\,h^{-1}}$ (Approximate speed of existing Mars drones.)

## 3 Design

The only assumption the team has in this project is that the maximum angle the sample will be laying at is 15° since another drone has to land and mine the sample so we can retrieve it, and we assume that the drone can not land and mine it out at angles exceeding 15°.

### 3.1 Design methodology

This project is developed and implemented with the methods and guidelines found in the books *Design Engineering and Science*[10], *FUNdaMENTALS of Design*[11] and Axiomatic Design[3].

Axiomatic design is a systems design methodology developed by Nam P. Suh. The method gets its name from its use of Axioms, which control the analysis and decision-making process in product design. The two axioms are The Independence Axiom (i.e. maintain the independence of the Functional Requirements) and the Information Axiom (i.e. minimize the information content). The Independence Axiom provides adjustability and control while avoiding unintended consequences. It focuses on modularity, which in turn ensures that teams can progress on any part without delays. The Information Axiom focuses on robust designs, compensating for errors, and minimizing the effect of wear and tear. Axiomatic Design analyses the process of transforming customer needs into functional requirements, design parameters, and process variables. The coupling between FRs and DPs is extremely important and can

**Table 1**: First level FR-DP mapping.

| ID | Functional Requirement | Design Parameter |
|---|---|---|
| 1 | Grab the sample regardless of its yaw | Net on the end of grippers |
| 2 | Grab the sample regardless of its pitch | Suspended by wire |
| 3 | Release the sample when commanded | Retractable gripper claws |

be mathematically demonstrated using the design matrix, which can be seen in equation 1. In the design matrix, a non-zero entity represents a connection between the DP and FR. When it has a diagonal line of non-zero values, with all other values as zero, the design is said to be uncoupled. This is said to be ideal, as changes in a DP only alter its respective FR[3].

## 3.2 FR-DP Mapping

After building a list of the Functional Requirements, the next step is to develop lists of Design Parameters, keeping in mind the Independence Axiom (i.e. maintain the independence of the Functional Requirements) and the Information Axiom (i.e. minimize the information content of the design)[3].

The team's main Design Parameter is as stated in DP0 from our Axiomatic Design.

**DP**$_0$ Retractable four-fanged gripper claw with a net.

From the Functional Requirements, the following Design Parameters were built.

**DP**$_1$ Net on the end of grippers

The net on the gripper will encompass the item being picked up, wrapping around it, ensuring that it can be picked up regardless of orientation.

**DP**$_2$ Suspended by wire

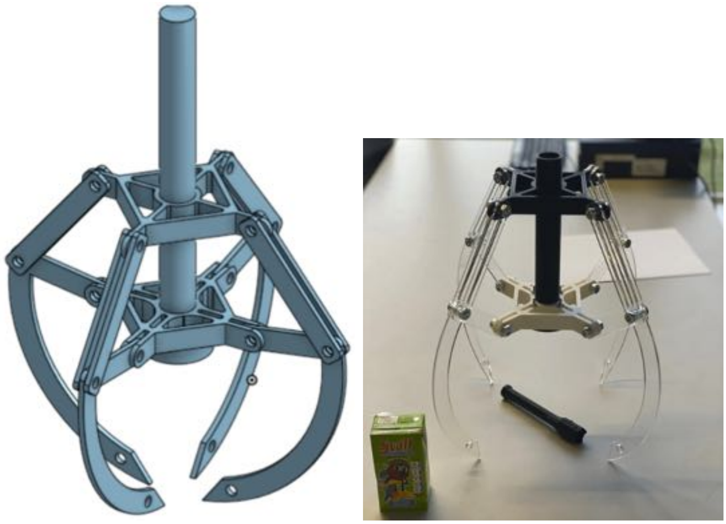
Using a suspension fixture will allow the claw to angle and align itself and the ends of the claws to the surface of the ground as the drone lands, enabling it to grab the sample regardless of its angle.

**DP**$_3$ Retractable gripper claws

Using retractable gripper claws allows for closing and opening the claw, allowing the claw to hold on and release grabbed objects.

We continue a "zig-zag" procedure to decompose and map the Functional Requirements to the Design Parameters as shown in table 1.

From this mapping, we develop an uncoupled design matrix as shown in Equation 1.



(a) CAD model of early design driven along central shaft.

(b) Early design prototype with sample tube for size comparison.

**Figure 4**: MARS-DOG First Iteration

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \\ \mathrm{FR}_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \\ \mathrm{DP}_3 \end{Bmatrix} \tag{1}$$

An uncoupled design is an ideal design, as changes in one DP do not alter more than the only designated Functional Requirement. This is ideal as it satisfies the independence axiom: "to maintain the independence of the Functional Requirements (FRs)"[3].

## 3.3 Design Process

The first design had no passive closing components in mind. All movement of the claws was produced by the movement of the central driving shaft (Lead screw) that would drive the bottom plate which was attached to the claws. The claw was then attached to the upper plate with a linkage. This design can be seen in figures 4a and 4b. This design did not include a net but had holes for a net attachment.

## 3.4 Final Design

The final design consists of a single centerpiece on which 6 gripper claws are attached and passively held open with the use of springs. The final design also incorporates a net that is used to help secure the desired object once grabbed. The gripper claw is closed by pulling a string through the shaft in the middle

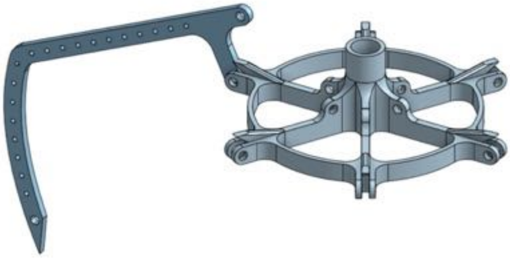


**Figure 5**: CAD model of the final design, with the mounting holes for the springs and net, have been added to the claw and the number of claws is increased to 6. Additionally, a physical stopper has been added to the base plate located above the claw mounting hole.

**Figure 6**: The final state of the prototype with the plastic bag simulated the net functionality.

of the claw. This closes the gripper as the other end of the strings is securely attached to the end of each claw. The final design can be seen in figures 5 and 6.

### 3.4.1 Geometry

When deciding on the geometry of the centerpiece the main focus was on the following 5 aspects, weight, the number of arms, attachment points for the springs, a hole for the strings, and physical stoppers for the springs.

As the total weight of the gripper was not specified by the customer as a customer need no specific weight goal was held in mind when the centerpiece was designed. Although, a goal of minimizing excess material on the centerpiece was aimed for. When the string was added to the 4 claw design of the gripper a weak point of the design came to light. This weak point was that an angle of

45° was between the string and each claw resulting in unsymmetrical stresses being placed on each of the claws. Additionally, too much resistance and wear would be placed on the wire itself providing a weak point in the system. Thus the decision to add more claws was made.

Using 6 claws fixed this problem as it reduced the wear and resistance in the wire and provided a more symmetrical closing pattern due to the increase of the angle between the wire and claw from 45° to 60°. The claws were redesigned to incorporate a spring attachment capability between the claw and the center plate. This spring addition provided the benefit of having the claw passively open and actively closed with the wire. Each claw had holes down the whole claw providing attachment points for the net. Finally, a physical stopper was added to the centerpiece preventing the springs from opening the gripper too much and possibly damaging itself.

The geometry of the claws had to take into account the following 3 aspects, the ability to grab/scoop the sample up, mounting holes for the net, and a reduced diameter when closed. To accomplish this, the bottom section of the claw is curved, allowing for a good scooping/grabbing ability while the rest of the claw is straight to reduce the diameter of the gripper when closed. Finally, mounting holes were added to the claw to securely attach the net to the claws.

### 3.4.2 Manufacturing

Manufacturing the final prototype, seen in figure 6 requires the following 4 materials, PLA plastic, Plexiglass, Nylon, and a Plastic bag.

The centerpiece is 3D printed using a standard 3D print PLA plastic while the gripper claws are made by cutting 4mm thick plexiglass into the desired shape with the use of a laser cutter. The strings used to close the claws were Nylon fishing strings and the "net" was made by gluing a plastic bag around the gripper arms using hot glue. Finally, the springs, bolts, and nuts were added and the prototype was assembled.

## 4 Analysis

When testing the MARS-DOG, the testing criteria was split into the 4 following groups. The ability to grab samples off the ground, the ability to securely hold the grabbed sample, the ability to release the sample once grabbed, and finally tests the design against a heavier load. These 4 groups were broken down into 6 tests and each test was conducted 30 times to ensure reliable and accurate test results. The sixth test was conducted 10 times for 5s each. Below is a list of tests that were done.

1. Grabbing the sample in different angles (pitch) ($FR_2$), section 4.1.
2. Grabbing the sample in different orientations (yaw) ($FR_1$), section 4.2.
3. Grabbing the sample in different orientations and angles (yaw and pitch) ($FR_1$ and $FR_2$), section 4.3.
4. Releasing the sample from the gripper. ($FR_3$), section 4.4.
5. Grabbing the sample in a dusty environment($CON_1$), section 4.5.

(a) Pitch of 0°

(b) Pitch of 15°

**Figure 7**: Test setup for grabbing the sample at different angles (pitch) on a flat surface.

6. Grabbing samples of a larger weight than 57g ($CON_2$), section 4.6.

## 4.1 Grabbing the sample in different angles (pitch)

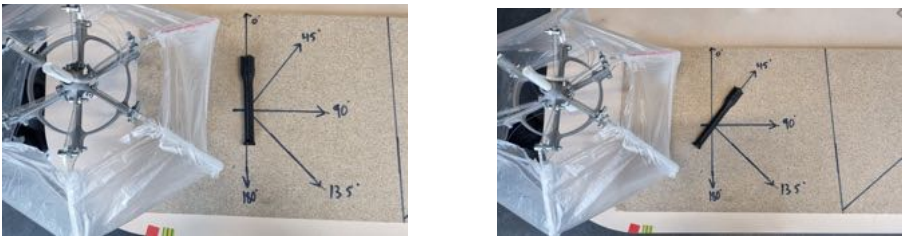
The first test completed tested grabbing the 3D printed sample tube 1 in different vertical angles (pitch). The goal of this test was to see if the angle of the sample gave different results in the grabbing functionality. The sample was placed on a flat surface that was tilted at 5° intervals from 0° to 15°. The setup of the test can be seen in figure 7. The test was deemed a Pass when the gripper managed to grab the sample tube and fully or partially enclose it within the net. In all 30 trials, the gripper was successful.

The test results show that the gripper is capable of picking up the sample tube regardless of the pitch of the sample. A pitch that was larger than 15° was deemed unnecessary since the sample slid/rolled off the testing surface and thus would not stay still long enough for the gripper to pick it up.

## 4.2 Grabbing the sample in different orientations (yaw)

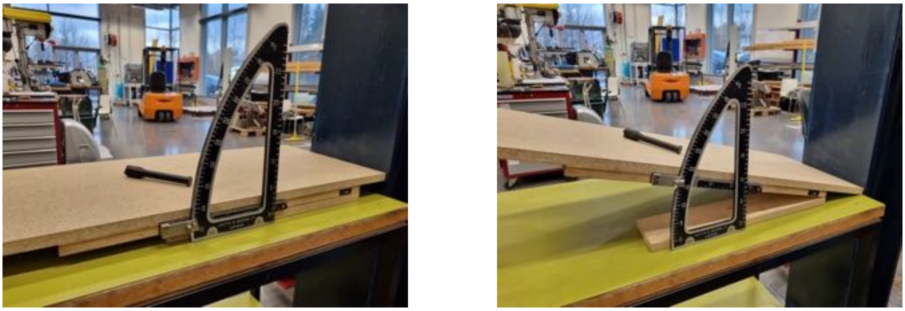
The second test completed was the grabbing of the 3D printed sample tube 1 in different orientations of the sample with respect to the gripper. This was done by placing the sample on a flat surface and rotating it in 45° increments from 0 to 135°. A red line was marked on one of the claws and for each of the tests, that red mark had to be aligned with the 45°marker. The setup of this test can be seen in figure 8. The test was deemed a Pass when the gripper managed to grab the sample tube fully or partially enclose it within the net. As in the previous test, the gripper was able to succeed in all 30 trials.

The test results show that the gripper is capable of picking up the sample tube regardless of the yaw of the sample tube with respect to the gripper itself.




(a) 0° yaw (b) 45° yaw

**Figure 8**: Test setup for different (horizontal) yaw values with respect to the gripper.



(a) Pitch of 0° and yaw 45° (b) Pitch of 15° and yaw 45°

**Figure 9**: Testing grabbing the test sample at different angles (pitch) on flat surface with 45° yaw rotation relative to the gripper.

## 4.3 Grabbing the sample in different orientations and angles (yaw and pitch)

The third test to be completed was a combination of both tests 4.1 and 4.2. The 3D printed sample tube 1 was placed on a flat surface. That surface was incrementally inclined by 5°. The difference between this test and test 4.1 is that the yaw rotation of 45° relative to the gripper itself as in test 4.2 is applied. The setup of this test can be seen in figure 9. Once again, the gripper was able to successfully complete the test each of 30 times.

The test results show that the gripper is capable of picking up the sample tube regardless of the pitch or yaw of the sample tube with respect to the gripper itself.

## 4.4 Releasing the sample from the gripper

This test checks whether or not the gripper can reliably release the sample. This test was performed when tests 4.1, 4.2, 4.3 and 4.5 were performed. After each test mentioned above was performed, the claws of the gripper were opened

(a) Initial conditions

(b) Successful grab

**Figure 10**: Testing grabbing the sample tube in a dusty environment 4.5.

with the actively opening mechanics provided by the springs and noted down if the sample tube fell out on its own or not. In total, the test was performed 390 times, and managed to drop the sample in each test.

## 4.5 Grabbing the sample in a dusty environment

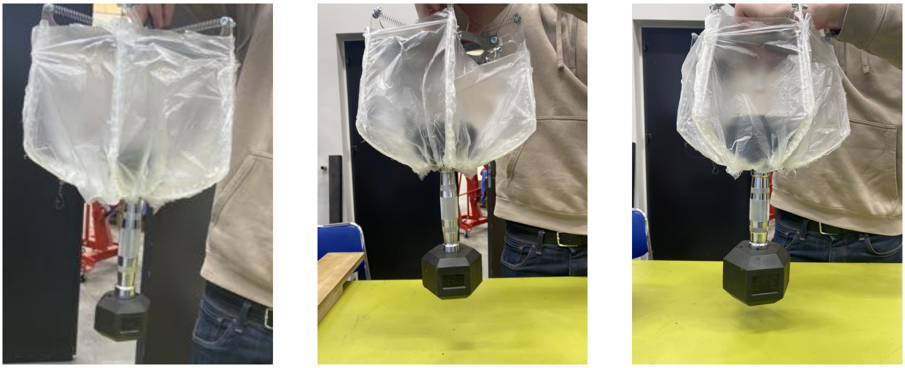
This test checks whether or not the gripper can reliably grab the sample that is covered in dust. This was done by covering the sample in sawdust and then attempting to grab it out of the sawdust. The setup of this test can be seen in figure 10. The test was deemed a Pass when the gripper managed to grab the sample tube fully or partially enclose it within the net while covered in dust. The gripper was successful in all 30 trials.

This test's results show that the gripper is capable of picking up the sample tube regardless of the dust on it.

## 4.6 Grabbing samples of a larger weight than 57 g

The final test performed checks whether or not the gripper can reliably grab objects that are heavier than the 57 g. This test was performed by taking weights ranging from 1 to 6 kg and picking them up with the gripper. These dumb-bell style weights were borrowed from the sports science lab at Reykjavík University. The setup of this test can be seen in figure 11. The test was deemed a Pass when the gripper managed to grab one of the weights ends, lift it and hold it for 5 s. Each test was performed 10 times and the gripper was passed each one.

The test results show that the gripper is capable of picking up weights ranging from 1 to 6 kg. Additionally, The gripper was able to hold each of these weights for 5s indicating that the structure of the design is capable of holding the 57 g sample tube.



(a) 1 kg (b) 3 kg (c) 6 kg

**Figure 11**: Grip strength testing with larger loads (Section 4.5)

# 5 Summary and Conclusion

When testing, the MARS-DOG was shown to be successful in lifting items weighing up to 6kg and securing them with a pickup chance of 100% and a 0% drop rate. These tests were done with the sample in various orientations and angles. The initial goals of the product are stated in the functional requirements in section 2.6. The comparison with the capabilities of the final product can be seen below:

**$FR_0$ result:** Tests for $FR_0$ were successful as the tests for $FR_0$-$FR_3$ where all successful and tests 4.3 (a combination of test 4.1 - 4.2) and 4.5 where the sample is grabbed in a dusty environment were also successful.

**$FR_1$ result:** After conducting tests where the sample was grabbed 30 times with different yaw, the gripper ended up having a 100% success rate and 0% failure rate.

**$FR_2$ result:** A test was conducted where the pitch of the sample was increased in 5° increments from 0-15°. The gripper was then used to grab the sample 30 times on each incline. In each incline, the gripper had a 100% success rate and 0% failure. No tests were conducted at more than a 15° angle as the sample and gripper slid off the test setup with that incline.

**$FR_3$ result:** No special tests were conducted for $FR_3$ as the sample was released in all the other tests. In those tests, the gripper was able to release the sample with a 100% success rate.

It is thus shown that the MARS-DOG successfully met all its functional requirements and is thus considered a success, since the main customer need 1.2 was met.

RIOT lab, the customer from Reykjavik University was excited about the product. The collaboration was considered a success as the main customer need (section 1.2) was met and 100% of the functional requirements were met. Thus the device is deemed to work and can pick up the sample tube from a flat surface. Although further testing and design work have to be made to determine whether the device is capable of picking up the sample tube from a non-flat surface.

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