Deep-Sea Sediment Sampler for Hadal Depths

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***Abstract*—Sediment cores are gathered to collect data on seabed chemical and mineral composition. This paper reviews the process of designing and testing a purely mechanical sediment sampler for use at hadal depths. These samples are important in determining the health of the surrounding environment and give us insight into what organisms currently live or have lived on or under the seabed. Sediment samples are relevant to many fields of research, including marine archaeology, biology, ecology, geology, and climate science. Over the last few decades, attempts to collect sediment core samples have been made from as deep as the Mariana Trench, which contains the deepest known point on Earth's surface at 11,000 meters [1] [2]. The environmental history and trajectory of our ocean floors are not well understood, and deep sea sediment cores are crucial in filling this gap.**

Working in conjunction with Inkfish, a submersible technology company, we developed a deep-sea sediment core sampler that will travel to the Mariana Trench aboard one of Inkfish's submersible landers and will collect four inches of sediment at ambient pressures of 110.32 MPa [3].

The first phase of this project was to design and fabricate a prototype sediment core sampling device. This prototype had to fulfill several design requirements that resulted from environmental conditions, lander constraints, and sample condition specifications. We designed an entirely mechanical sampler because underwater actuators suitable for use in hadal conditions are difficult to source and require additional communication and power resources. The extreme pressure in the Mariana Trench imposed restrictions on the materials we could use and led our design to incorporate low-precision interfaces. Additionally, the sediment core sampling system is limited in size and weight to avoid interfering with the functionality of seafloor landers. Most importantly, the layers of the sediment core samples must be preserved and secured as the lander ascends to preserve relative time scales within the sample. Our purely mechanical sediment collection system consists of the collection tube subsystem, responsible for collecting and retaining the sediment, and the frame subsystem, whose objective is to facilitate insertion and retraction of the tube from the seafloor.

The next phase involved testing the functionality of different subsystems of our device. In this paper, we considered two different sediment collection apparatuses and one-way valves for our collection tube. We performed field testing in the Charles River in Cambridge, MA to assess which apparatus and valve combination would provide the best results based on the volume of sediment collected and retained. Additionally, we tested the frame subsystem and evaluated the performance of the spring pulley system based on reliability and consistency.

Ultimately, we believe that our sediment sampler presents a viable purely mechanical solution to collecting deep-sea sediment from profoundly unexplored areas at hadal depths like the Mariana Trench. Our sampler can easily be mounted onto any surface where it would touch the ocean floor, requiring no electronics or controls. Though we were constrained by the particular seafloor lander used by Inkfish, the size of the sampler is scalable, allowing both the sample diameter and depth to be adjusted for a given mission. By making these sediment samples more accessible, we believe we will have an impact on a number of marine research areas.

***Index Terms*—Sediment, sampler, core, hadal region, Mariana Trench**

I. INTRODUCTION & BACKGROUND

The environment near the aquatic floor is one of the most biodiverse areas of an aquatic ecosystem. These environments are heavily dependent on the sediment present as the sediment provides substrate, shelter, and nutrients to the flora and fauna [4]. Scientists often determine the health and trends of environments by analyzing the chemical and material composition of the sediment using sediment samples. Sediment samples are collected using a variety of devices depending on the texture, depth, and intended use of the sediment. One such type of device is sediment corers, which collect a specific kind of sediment sample: a sediment core. Sediment core samples are cylindrical tubes of sediment whose layers are preserved. If analyzed layer by layer, they help shine light on the environmental history and trajectory of our aquatic floor ecosystems. Sediment core sampling has been used for research ranging from tracking pollutants [5] to analyzing aquaculture trends [6].

Sediment core samples are collected from ecosystems ranging from marshes to open oceans. They are also collected at depths as shallow as the surface level to as deep as the hadal zone. The hadal zone, the deepest area of the ocean, is between 6000 to 11000 meters in depth and consists primarily of ocean trenches and troughs. Although it only occupies a horizontal floor area roughly half the size of Australia, these trenches make up roughly 45% of the oceanic depth range [7], [8]. The environment at these depths is characterized by low temperatures, lack of natural light, and extreme pressure, which results in unique speciation and adaptation behaviors [10]. Additionally, microbial processes at hadal depths have significant impacts on nearby and surface ecosystems [2], [8]. These organisms may be present in sediment core samples if they live near the sea floor which could help shed light on these novel species and their impacts.

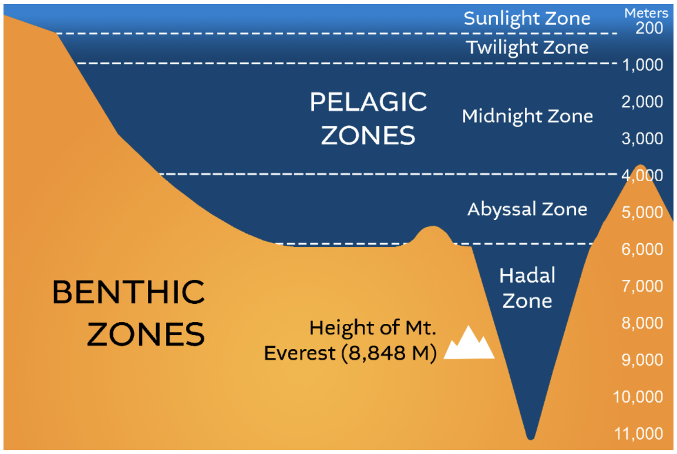

Fig. 1. The 5 different pelagic zones and their depths (figure adapted from [7]).

However, the extreme characteristics of the hadal zone that allow for these distinctive organisms also pose significant technological challenges. The hadal zone is one of the least explored environments on Earth, largely due to the extreme pressure and distance from the surface. Over the last few decades, a few attempts to collect sediment core samples have been made. For example, in 2006, a gravity type core sediment sampler named “Asyura” was deployed to the deepest part of the Mariana Trench, the Challenger Deep, and successfully collected a sediment core [11]. Similarly, a novel pressure-retaining sampler was also deployed to the Challenger Deep in 2021 and was also able to successfully collect a sediment sample [2]. However, the technology used for these expeditions are complex, heavy, or large. The “Asyura” system weighed 100 kg in air and occupied a 75x75x107 cm space. The pressure-retaining sampler weighed 65 kg in air and utilized motors and onboard computing. Additionally, many of these devices require a dedicated vehicle, whether a submersible, ROV, or lander, for the expedition. “Asyura”, for example, was deployed using an ROV and two cables that stretched the 11,000 m distance from the surface to the Challenger Deep. As a result, these devices are not particularly accessible for organizations unable to dedicate such resources and funding to sediment sampling.

We are working in conjunction with Inkfish, a submersible technology company, to develop a sediment collection device that can be easily attached to their landers. Inkfish landers currently collect video data and biological samples during their expeditions to hadal depths. Our deep sea sediment sampler must operate without disturbing or adding undue complexity to Inkfish’s current research. This requires that our device be small, lightweight, and purely mechanical. As a result, our sediment sampling device is simple and can be easily added to vehicles with other primary objectives, increasing the accessibility of hadal sediment core samples and broadening our knowledge of the deep sea.

II. DESIGN

A. Overview

Our sediment sampler device is designed to work in conjunction with an Inkfish lander. The landers have little to no onboard computation and an extremely limited available power supply of 48V DC. Additionally, our device must fit within one of the lander’s bays, which has roughly 50x60x100 cm of space and a 40x50 cm opening to access the seafloor. Our device must also weigh less than 10 kg in water (roughly 15.8 kg in air) to avoid interfering with the lander’s ability to resurface.

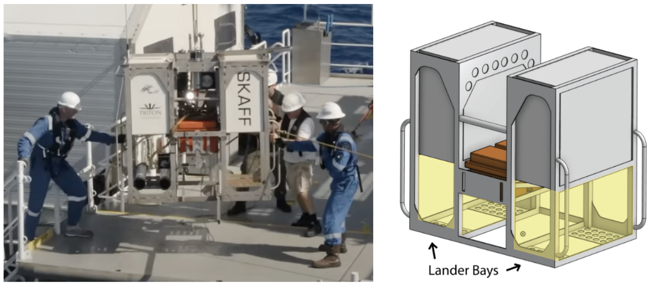

Fig. 2. Inkfish lander being recovered after an expedition [12] (left) and a 3D model of the lander with the bay areas highlighted in yellow (right).

As seen in Fig. 3, there are three stages to the sediment collection process once the lander nears the seafloor. In the first stage, the base plate lands and settles against the seafloor. In the second stage, the lander continues to sink down until it also makes contact with the seafloor. The weight of the lander and the force of the seafloor upwards acts on the base plate to trigger a spring-pulley system that inserts the collection tube into the sediment. In the third and final stage, the tube is retracted from the sediment and the base plate reaches its final position within the lander’s bay.

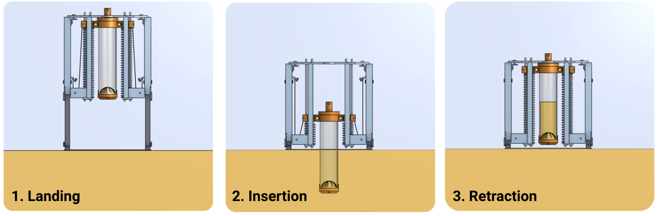

Fig. 3. The three stages of the sediment collection process of our mechanical deep sea sediment sampler device: landing, insertion, and retraction.

The sediment core sampling device consists of two main subsystems: the frame and the collection tube. The collection tube collects and retains the sediment while the frame inserts and retracts the tube from the seafloor without the use of any electrical components.

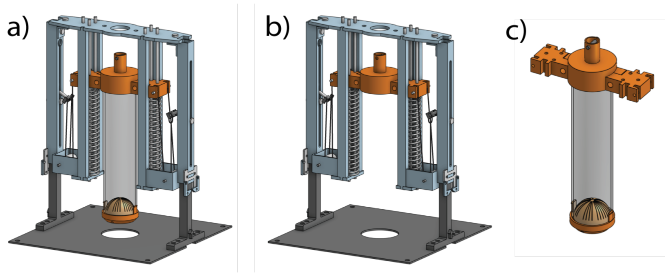

Fig. 4. A-C. 3D models of our deep sea sediment sampler device: (a) full sediment sampler system, (b) sampler's frame subsystem, (c) sampler's collection tube subsystem.

B. Collection Tube Subsystem

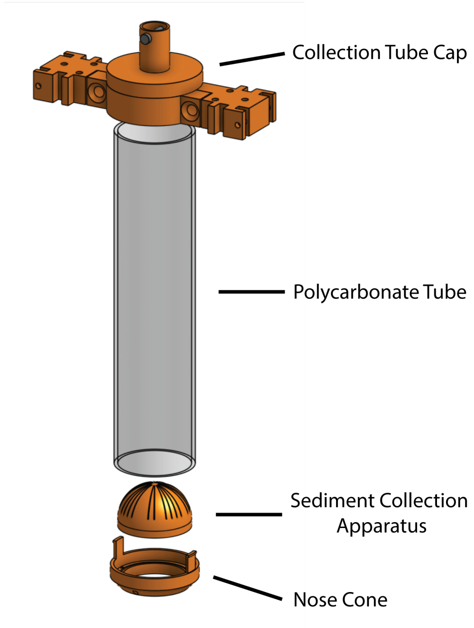

Fig. 5. Components of the collection tube subsystem.

The collection tube captures sediment once the lander has reached the seafloor and secures the sediment until the lander is collected from the ocean. The sediment should be able to enter the tube without much difficulty in order to minimize the disturbance to the top layers of the seafloor. The ascension from the bottom of the Mariana Trench to the surface is estimated to take roughly 4 hours and the lander will spend between 30 minutes to an hour bobbing at the surface of the water before it is recovered. The collection tube must be robust and secure enough to be able to retain the sediment sample throughout this process.

At the top of the tube is a 3D-printed cap made of Markforged Onyx that allows the tube to be connected to the spring-pulley system. Furthermore, the top of the cap functions as a one-way valve that allows water to escape as sediment is collected within the tube. The valve also creates a pressure seal that helps prevent sediment from escaping. We explored two potential valves: a spring-loaded ball valve and a rubber flap valve (seen in Fig. 6).

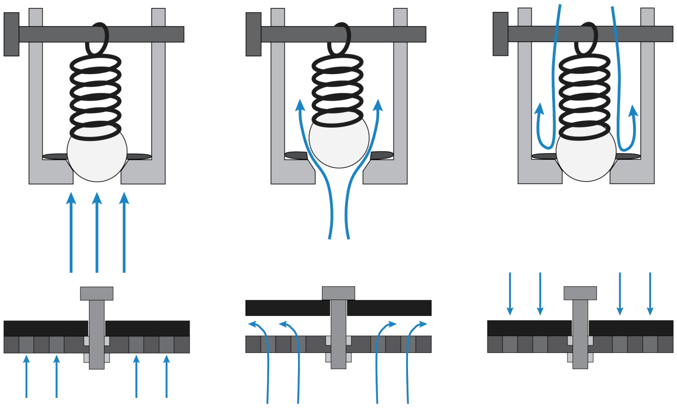

Fig. 6. Stages of spring-loaded ball valve during sediment collection (top) and stages of rubber flap valve during sediment collection (bottom).

For the ball valve, the spring and o-ring creates a strong seal that prevents water from entering from the top of the tube during ascension and driving out the collected sediment. The valve requires roughly 2 lbs of force to operate and has a 1.82 sq cm opening for water to escape.

Alternatively, the rubber flap valve is a simpler system that utilizes the movement of the lander to drive the valve. During descent and as the tube is driven into the sediment, the rubber flap slides up the center shaft and exposes the holes at the top of the cap, allowing water to escape through the 7.07 sq cm of available space. The upwards motion during retraction of the tube and ascension to the surface pulls the rubber down the shaft. The rubber presses against the holes, deforms, and creates a seal.

At the bottom of the collection tube is a nose cone that helps dig into sediment. The nose cone is fabricated from onyx which is less brittle than the polycarbonate tube and helps prevent the fracturing of the tube if the lander encounters rocky terrain. The nose cone also serves as the component that secures the sediment collection apparatus to the collection tube. There are two collection apparatuses considered: a core catcher and a rubber mud flap.

The core catcher apparatus (seen in Fig. 7) is extremely simple in design and consists of only a plastic hollow demi-sphere shaped component. The hollow demi-sphere shape is formed by a ring of slightly triangular shaped fingers that are pushed open by entering sediment and closed upon retraction from the upwards motion of the tube paired with the weight of the sediment. This design results in sediment layers mixing at the edges of the core sample, but we hypothesize that sediment layers at the center of the sample will be preserved.

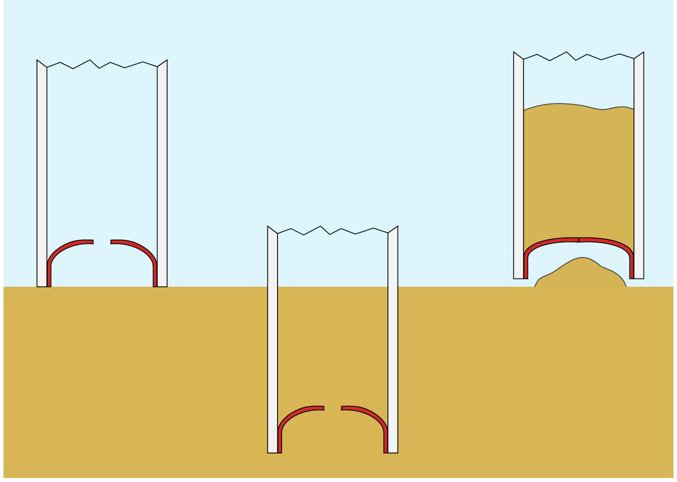

Fig. 7. Stages of core catcher apparatus during sediment collection.

The rubber mud flap (seen in Fig. 8) consists of a circular rubber flap, an aluminum shaft, steel loop clamps, and a unique onyx nose cone. The rubber flap is secured onto the aluminum shaft using loop clamps. When the tube is inserted into the sediment, the rubber flap deforms, allowing sediment to enter. The nose cone for the rubber mud flap has a lip that protrudes into the tube. This lip paired with the circular rubber flap creates a seal that prevents sediment and water from escaping during retraction and ascension. However, since the mud flap only allows the sediment to enter through one side, the stratification of the sediment layers is unlikely to be preserved.

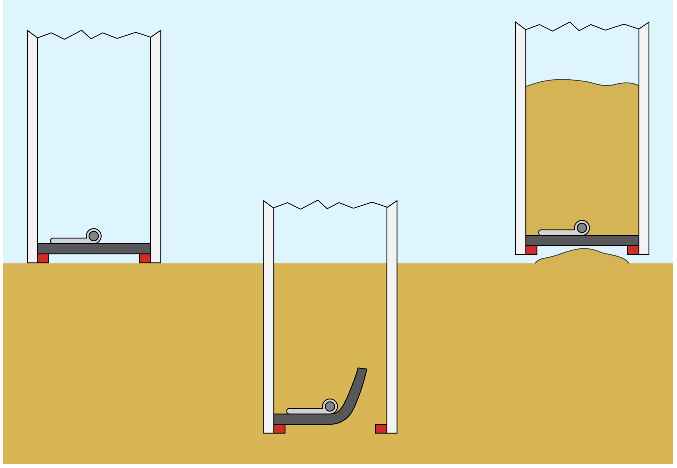

Fig. 8. Stages of rubber mud flap apparatus during sediment collection.

C. Frame Subsystem

The frame subsystem, responsible for driving the collection tube into and removing from the sediment, can be further separated into a static segment and a dynamic segment. The static segment (seen on the left in Fig. 9) is permanently fixed relative to the lander and primarily provides structural support and stiffness to allow the dynamic segment to actuate sediment collection. The top plate, two rod plates, as well as the two box tube extrusions act as the foundation of the static segment and provide the majority of the stiffness. Furthermore, four aluminum bars between the two plates supply additional stiffness in addition to acting as rails to prevent the cap of the tube from sliding or bending. Similarly, the six fixed aluminum rods prevent the springs from shifting or buckling during compression.

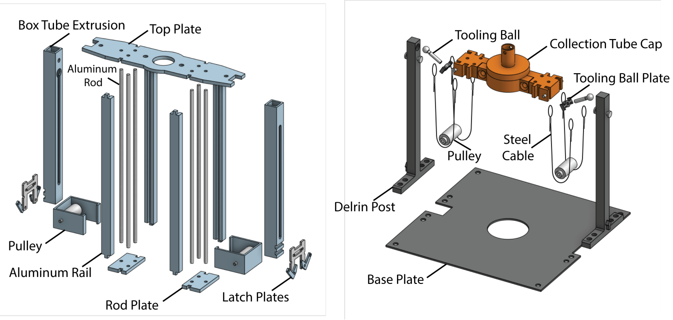

Fig. 9. Components of the static segment of the frame subsystem (left) and components of the dynamic segment of the frame subsystem (right).

In addition to providing stiffness, the static segment also provides support to the dynamic segment (seen on the right in Fig. 9). The two pulleys of the spring-pulley system are permanently fixed between the rails and the box tubes. Additionally, there is a spring-driven latch system attached to the box tubes that ensures that the base plate of the dynamic system is safely enclosed within the bay of the lander before ascending.

The dynamic segment is the core of the purely mechanical sediment collection system. The dynamic segment consists of a base plate with two Delrin posts fastened to the plate. At the top of each post is a pocket where a tooling ball sits. Each of the four steel cables is looped around a pulley. One end of the cable is fixed around an arm of a tooling ball plate while the other end is connected to a rod at the side of the collection tube cap.

At the core of the frame is a spring-pulley mechanism that utilizes the change in distance of the base plate relative to the lander as a trigger to push the collection tube into the sediment. Before reaching the seafloor, the base plate is positioned below the bottom of the lander. Once the base plate makes contact with the ground, the upward force from the base plate-ground interaction and downward force from the weight of the lander results in the two box tubes sliding down the two posts. As the posts travel up the box tubes, the cap of the collection tube is pulled down and the two springs are compressed. The posts slide until they travel the maximum length, roughly 159 mm, at which point the tooling balls are pulled out of the posts due to the tension from the steel cable. With the tension released, the springs are then able to decompress and push the cap of the tube up.

In order for the sediment sampler device to perform reliably, most of the components are made of aluminum due to its minimal volumetric strain under maximum hadal pressures (less than 3%). Furthermore, all systems, such as the sliding, pulley, and latch systems have low precision interfaces. Thus, material compression under extreme pressures would not result in diminished performance but may even induce increased efficiency.

III. TESTING & VALIDATION

A. *Collection Tube Subsystem*

Fig. 10. Retrieving sediment sample from our setup for sediment collection apparatus and one-way valve testing at the Charles River in Cambridge, MA.

We began by testing the sediment collection and retention of our apparatuses and one-way valves. For our field testing, we attached our sediment collection tube to a 5 m pole and manually inserted and retracted the tube into and from the Charles River bed, which was roughly 3 m under the water surface. Each collection apparatus was tested with each of the three valve options: no valve, spring-ball valve, and rubber flap valve. Three samples were collected for each configuration.

From the measured data, shown in Table I, the rubber mud flap collection apparatus and the no valve configuration, on average, result in the most sediment and water collected and the highest sediment to water ratio. This is to be expected as no valve means there is little to no hindrance when the sediment is entering the tube. The rubber mud flap and ball valve configuration, with only a 0.33 g difference, comes in a close second for total sample weight collected. This indicates that to maximizing the total weight of the sample collected, the rubber mud flap used in conjunction with the ball valve produces results that are near the ideal conditions.

Meanwhile, the core catcher and ball valve combination has the second-highest sediment to water collected ratio but is only a little over half the ratio for rubber mud flap and no valve. This indicates that the presence of a valve significantly impacts the ability to collect sediment. This is likely due to the force required to activate the valves in order to displace the water within and replace it with sediment.

Between the core catcher and rubber mud flap apparatuses, the mud flap consistently outperformed the core catcher with all 3 mud flap combinations always ranking in the top 4. Additionally, the highest average weight of sample collected using the mud flap is 71.3 g greater than the highest weight sample collected using a core catcher. The highest average ratio of sediment to water collected using the mud flap is 0.18 greater than that collected using a core catcher. Furthermore, the lowest average weight of sample collected and lowest ratio using the mud flap is 534.2 g and 0.11, respectively, greater than that collected using a core catcher. Thus, the data strongly indicates that the rubber mud flap apparatus is superior when considering the volume of sample and volume of sediment collected.

While the ball valve does not outperform the no valve combinations, the ball valve does perform better than the rubber flap valve. For the highest average weight of sample collected and sediment to water ratio, the ball valve collected 52.3 g more and had a 0.08 higher ratio than the flap valve. For the lowest, the ball valve collected 178.6 g more and had a 0.13 higher ratio.

From the visual data in Fig. 11, several trends can be noted. Firstly, sediment samples collected using no valve had more leaves than sediment collected using the ball or flap valve. Sediment samples collected using the spring-load ball valve or the rubber flap valve were more mud-like and mostly consisted of silty clay. Based on Inkfish's previous expeditions, the sediment we expect to collect in the Mariana Trench contains more clay than leaves or other vegetation. This suggests that despite more volume of sample can be collected using no valve, the ball or flap valve is preferred because they collect the more desired clay sediment.

Additionally, from Fig. 12, we observed that the water from the ball valve resulted in clearer water than that from the flap valve. This suggests that the ball valve minimizes the mixing of the water and sediment of the sample while the flap valve allows the water and sediment to move more freely and homogenize. Thus, between the two valves, the spring-loaded ball valve appears to maintain sediment layers better than the rubber flap valve.

Overall, the data suggests that the rubber mud flap and ball valve is the best combination for maximizing overall sample collection and sediment collection. Visual data also suggests that the ball valve is preferable when considering sediment layer preservation. However, further testing must be conducted before any conclusions can be drawn.

TABLE I
WEIGH OF SAMPLES COLLECTED USING DIFFERENT COLLECTION APPARATUSES AND VALVES

	Core Catcher								
	No Valve			Ball Valve			Rubber Flap Valve		
Sediment(g)	34.9	44.9	31.9	142.9	155.8	174.9	3.9	15.9	45.9
Water(g)	484.9	278.9	294.9	542.9	796.8	903.8	554.9	644.8	915.8
Total(g)	519.8	323.8	326.8	685.8	952.6	1078.7	558.8	660.7	961.7
Avg Total(g)	390.1			905.7			727.1		
Avg S/W	0.114			0.217			0.027		
	Rubber Mud Flap								
	No Valve			Ball Valve			Rubber Flap Valve		
Sediment(g)	242.9	318.9	262.9	176.9	74.9	138.9	104.9	99.9	122.9
Water(g)	760.8	636.8	708.8	942.8	858.8	737.8	862.8	736.8	845.8
Total(g)	1003.7	955.7	971.7	1119.7	933.7	876.7	967.7	836.7	968.7
Avg Total(g)	977.0			976.7			924.4		
Avg S/W	0.397			0.154			0.134		

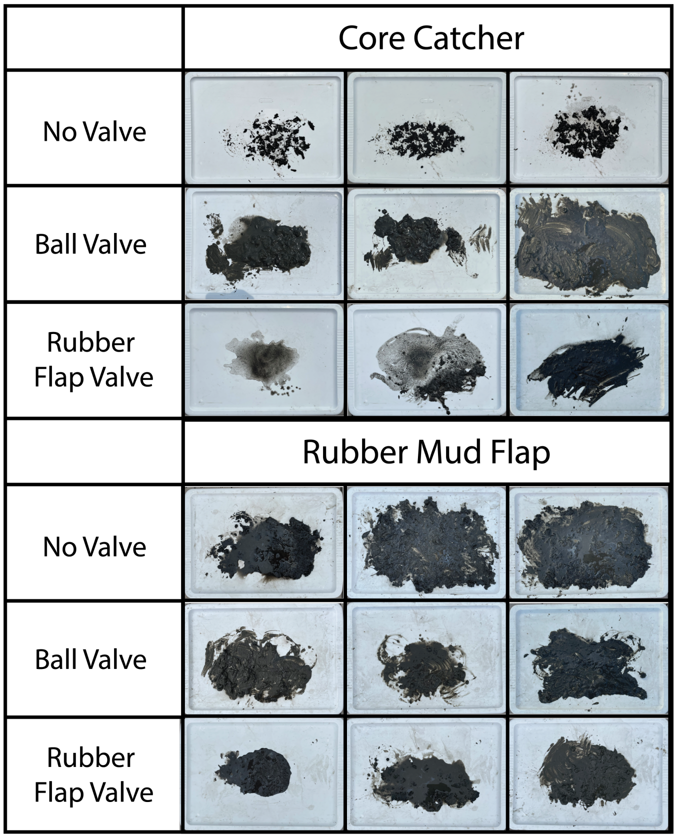

Fig. 11. Sediment collected from the Charles River.

Fig. 12. Water collected using the core catcher and ball valve (left) and water collected using the same core catcher and flap valve (right).

B. *Frame Subsystem*

After fabricating and assembling the frame subsystem, we tested the spring-pulley system in a lab test tank. The frame was tied to a crane and weighted with 41 kg of weight in air before being lowered to the bottom of the tank.

As the 41 kg of weight was slowly lowered onto the frame subsystem, the spring-pulley mechanism compressed until roughly 8 cm and then jammed. Even once the full weight was lowered, the springs did not compress sufficiently for the tooling balls to trigger and allow for spring decompression. Additionally, as seen in Fig. 13, significant bending can be observed between the left and right halves of the frame subsystem.

The cause of the jamming was determined to be a variety of factors. Firstly, the tabs on the onyx cap sliding on the aluminum rails were generating unwanted friction. The tooling balls were also determined to be generating friction and causing jamming when rubbing against the inside of the box tubes. Furthermore, the 4 cables of the pulley system were not precisely the same length, which led to asymmetric tension on the cap. This resulted in the cap tilting rather than sliding along the vertical axis and getting stuck. The inwards bending of the frame as well as the cap prevents the cap from sliding smoothly as the rods are no longer parallel.

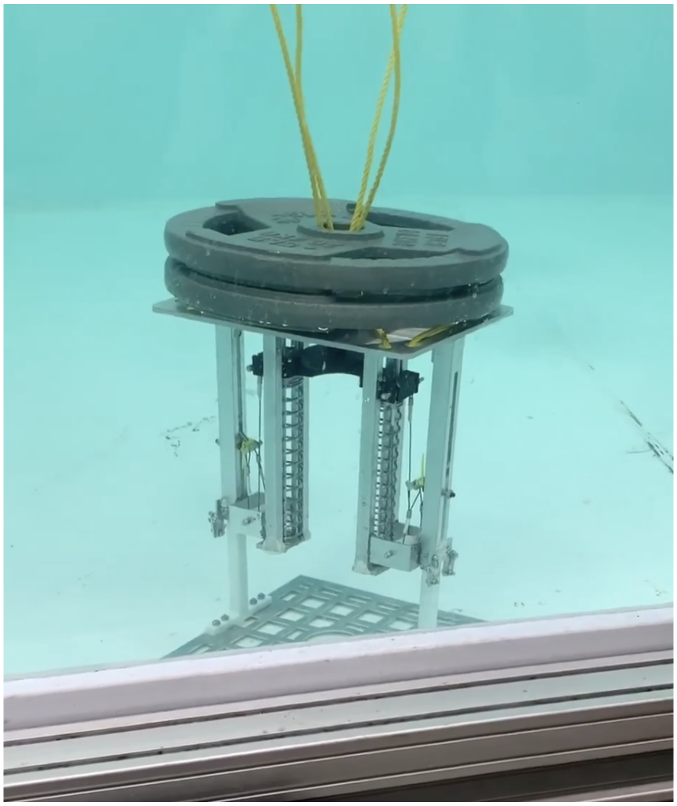

Fig. 13. Frame subsystem in testing tank with 41 kg of weight applied. Note that the subsystem deforms under the weights and the left and right sides do not stay parallel. Rather the left and right sides bend inwards towards each other.

As seen in Fig. 14, several changes were made to the frame system to minimize the chance of jamming. Firstly, the onyx tabs were removed so that the cap could slide down more freely, moving along the rails rather than within. Secondly, a nylon washer was placed between the tooling ball and the aluminum box tube, significantly reducing the friction of the sliding mechanism. The four steel cables were reduced to two, one on each side, to minimize the potential for tilting. Additionally, a plate was added near the bottom of the spring rods to increase stiffness and keep the rods parallel. A brace-like plate was also added to the top of the cap in order to prevent the cap from bending under the force applied by the steel cables.

After these changes, we did preliminary tests of the improved system. After applying 27 kg of force, the springs were compressed roughly 75% before the system failed. The press fit that connected the tooling ball and the tooling ball plate failed. We theorize that because of the angle at which the tooling ball sits in the pockets of the Delrin posts, the steel cables applied a moment on the plate and widened the hole of the pressfit. The next step is to strengthen our weakest components, the press fit and the crimping of our steel cables. For both cases, we plan to increase the friction by increasing the surface area of the interfaces before testing the frame subsystem once again.

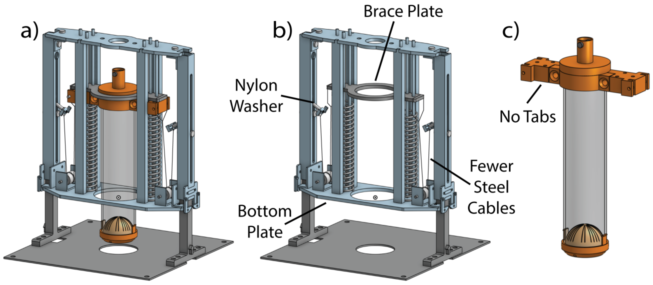

Fig. 14. A-C. 3D models of our improved deep sea sediment sampler device: (a) new full sediment sampler system, (b) sampler's frame subsystem with an added bottom and brace plate, (c) sampler's collection tube subsystem with cap tabs removed.

IV. FUTURE WORK

From our testing, the rubber mud flap and ball valve is the best combination for maximizing overall sample collection and sediment collection. However, further testing is required to validate our conclusions. In-lab simulation of sediment core collection will be performed in order to observe the full collection process. Additionally, as part of in-lab sediment collection testing, we will create our own sediment bed and visually assess the sediment layer preservation capabilities of the different collection apparatuses and valves. Sediment retention after ascension and recovery can also be evaluated in the lab using a towing tank to emulate the motion of the lander as it bobs in the water prior to recovery. After this data has been gathered, sediment collection apparatus and valve designs for the next iteration can be finalized.

Once sufficient in-lab testing has been performed, the design of the collection tube and frame subsystems can be finalized, and a next iteration prototype will be fabricated. For this prototype, the Markforged Onyx cap and Delrin posts will be replaced with aluminum parts in order to increase stiffness while minimizing the number of system parts. Additionally, the majority of fasteners will be removed and, instead, most of the parts will be permanently fixed through brazing in order to reduce the complexity and increase the strength of the connections between parts. Furthermore, this prototype will undergo PTFE anodizing, which will reduce the sliding friction as well as strengthen the structure of the system.

After fabrication is complete, this prototype will be shipped to Tonga and be tested at 2,000-3,000 m depths. This test will assess the reliability and capabilities of our full system when mounted to a lander. Our device will be evaluated on a number of criteria including the ease of attaching the device to the lander, the volume of sediment collected, and the reliability and robustness of the device.

V. CONCLUSION

We believe our purely mechanical sediment sampler device is a viable solution to reliably collect deep-sea sediment from profoundly unexplored areas at hadal depths like the Mariana Trench. From preliminary testing, the combination of the rubber mud flap sediment collection apparatus and the spring-loaded ball valve is the most ideal combination in order to maximize the volume of the sample collected and the ratio of sediment to water collected. However, additional testing is required to determine which combination of collection apparatus and valve will best meet all our design criteria, including preservation of sediment stratification.

From in-lab testing, we determined that this simple spring-pulley system is a feasible mechanism for deep-sea sediment collection. The next step is to strengthen our weakest components, the press fit and the crimping of our steel cables. Once these changes have been made, the retraction ability of the prototype frame subsystem can be assessed. Once further testing has been completed, an improved prototype will be fabricated and tested.

Ultimately, if testing is successful, our device will increase the accessibility of deep-sea sediment samples, as it can be easily mounted onto any surface where it would touch the ocean floor, requiring no electronics or controls. Furthermore, our sediment sampler device is scalable, allowing for samples of different diameter and depth to be collected with minimal changes to the system. By making these sediment samples more accessible, we believe we will have an impact on a number of marine research areas.

REFERENCES

[1] X. Dai, T. Xu, and J. Chen, “Physical and Mechanical Properties of Deep Oceanic Sediments Cored from the Bottom of Challenger Deep, Mariana Trench,” Geofluids, vol. 2021, no. 1, p. 9109132, 2021, doi: 10.1155/2021/9109132.

[2] H. Wang et al., “Collection sediment from Mariana Trench with a novel pressure-retaining sampler,” Deep Sea Res. Part Oceanogr. Res. Pap., vol. 183, p. 103740, 2022, doi: https://doi.org/10.1016/j.dsr.2022.103740.

[3] “Seven miles deep, the ocean is still a noisy place,” National Oceanic and Atmospheric Administration, Mar. 02, 2016. https://www.noaa.gov/media-release/seven-miles-deep-ocean-is-still-noisy-place (accessed Apr. 23, 2024).

[4] “Sediments — NSF NEON — Open Data to Understand our Ecosystems.” Available: https://www.neonscience.org/data-collection/sediments (accessed Jul. 28, 2024).

[5] S. Kılıç, Ö. Kılıç, M. Belivermiş, and H. A. Ergül, “Chronology of PAH and PCB pollution using sediment core in the Golden Horn estuary (Sea of Marmara),” Mar. Pollut. Bull., vol. 187, p. 114570, Feb. 2023, doi: 10.1016/j.marpolbul.2023.114570.

[6] X. Sun, X. Song, Z. Jiang, Q. Tang, and Y. Sun, “Biogenic silica in sediment core indicates the historical development of off-bottom oyster farming,” Sci. Total Environ., vol. 947, p. 174591, Oct. 2024, doi: 10.1016/j.scitotenv.2024.174591.

[7] “Ocean Zones,” WorldAtlas. Accessed: Aug. 01, 2024. [Online]. Available: https://www.worldatlas.com/oceans/ocean-zones.html

[8] T. Shank, “The Hadal Zone: Aqua Incognita.” Accessed: Jul. 22, 2024. [Online]. Available: https://oceanexplorer.noaa.gov/okeanos/explorations/ex2102/features/hadalzone/hadalzone.html

[9] A. J. Jamieson, T. Fujii, D. J. Mayor, M. Solan, and I. G. Priede, “Hadal trenches: the ecology of the deepest places on Earth,” Trends Ecol. Evol., vol. 25, no. 3, pp. 190–197, Mar. 2010, doi: 10.1016/j.tree.2009.09.009.

[10] “ECO Jan/Feb: Extreme Exploration: The Hadal Zone.” Accessed: Jul. 22, 2024. [Online]. Available: https://digital.ecomagazine.comhttps://digital.ecomagazine.com/articles/extreme-exploration-the-hadal-zone

[11] “Sediment Sampling at a Depth of 10,131m in the Challenger Deep by ROV Kaiko.” Accessed: Jul. 31, 2024. [Online]. Available: https://ieeexplore-ieee-org.libproxy.mit.edu/document/4302339

[12] Caladan Oceanic, Deep Sea Planet, (Mar. 23, 2022). Accessed: Aug. 01, 2024. [Online Video]. Available: https://www.youtube.com/watch?v=lc8Ovo33fNc