Development and Maturation of a Robotic Anchor for Climbing on Cryoice

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***Abstract*—Icy moons of Jupiter and Saturn have become prime targets in the search for life within our solar system, likely hiding liquid water oceans beneath the icy crust. With NASA's recent focus on travel to Europa and Enceladus, development has begun on anchoring techniques for landing and climbing on these icy worlds. Climbing down vents is of particular interest as they can lead directly to the liquid oceans, necessitating an ice climbing robot. The Ice Screw End Effector (ISEE) has been designed and deployed successfully in multiple Earth science missions in ice caves on Mt. Erebus, Mt. Rainier, and Mt. St. Helens. The use of alpinist ice screws to set climbing anchors and simultaneously extract core samples has been tested and proven on Earth ice, but the crusts of Europa and Enceladus require significant redesign and optimization for a new environment.**

The ice on a target moon is exposed to the vacuum of space, radiation blasted, and far colder than any temperatures on Earth, below -100^{o}C. Ice this cold is known as cryoice and is much harder and more brittle than the glacial ice for which the ISEE is optimized. Here we explore the further optimization of ice screws for cryoice as well as other methods of ice anchoring such as sublimation anchors and high-speed drill-set anchors. Custom test articles are presented along with results of testing that indicate trends that will inform the next generation of ice anchor designs.

1. INTRODUCTION

The next points of interest in NASA's search for extraterrestrial life lie in the subterranean oceans of Europa and Enceladus, but before they can be sampled, a 10km thick crust must be traversed. While some have proposed a herculean drilling operation, it may be possible to climb down existing vents and fissures to reach the oceans. Escaping ejecta through cryovolcanoes indicates connection to the liquid layer similar to volcanoes connections to Earth's mantle. A specialized climbing robot is needed to make the trip down the vents, though here we only focus on the anchoring aspect. The anchors discussed here are intended for use as end-effectors on the limbs of a climbing robot for icy vent traversal.

Any anchoring mechanism designed for Europa or Enceladus must be robust to repeated anchoring, strong enough to withstand gas pressure from erupting cryovolcanoes, and light enough to be used as end-effectors on limbs. Here we explore three destructive methods of anchoring which use sharp teeth, heat, or drilling to bore into cryoice.

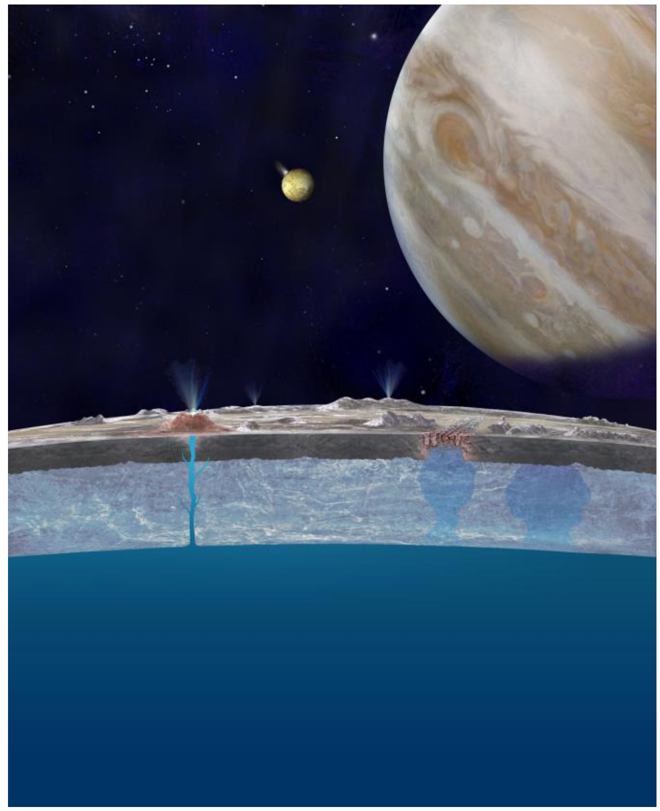

Figure 1: Hypothesized cross section of Europa's crust with vents extending down to liquid water ocean.

2. BACKGROUND

The ISEE project has previously produced three iterations of functional anchoring end effectors, which have been successfully tested on glacial ice in caves. Additionally, Ice Worm, the first ice climbing robot has shown the ISEE's potential for carrying a heavy robot up vertical walls. However, these ice screws are optimized for glacial ice, which is relatively soft compared to cryoice at -200^{o}C, the expected surface conditions of Europa and Enceladus. The design of a new anchor was split into three parallel approaches: redesigning custom ice screws optimized for cryoice, designing sublimation anchors that remove ice to form anchorable cavities, and adapting high speed drill bits to set conventional anchors. These approaches were tested extensively, and the results compared in order to determine viability for a future mission to an icy moon.

3. TESTBED SETUP

To analyze the anchoring performance of ice screws and sublimation anchors, we created a vacuum chamber testbed. The sealed chamber allowed the team to produce a test environment with less than 1 torr of ambient pressure. This pressure drop is crucial for testing sublimation anchors, because liquid water cannot exist below approximately 3 torr in the proposed temperature range. This ensures that the heated anchors will not be affected by unrealistic melting and refreezing and provides an atmospheric condition relatively similar to what is expected on Europa.

The vacuum chamber includes several passthroughs; one for dual output DC power from an Agilent Power Supply to power the heating element and drive motor, a custom passthrough for 120V AC to power large devices, a gauge passthrough for reading chamber pressure and a USB passthrough for data transfer to an operator's computer. Two pumps in parallel vent gas out of the chamber, and the airflow can be cut off when the desired pressure is achieved.

The testbed is built on an 80/20 aluminum frame that can be removed from the chamber for maintenance. It rests on rubber isolating feet to damp out vibrations caused by the pumps. It includes a base plate with clamp subassembly for quickly securing ice samples in place under the test article. The system accepts test articles with a custom electromechanical interface, which fits all ice screws and sublimation tips. These test articles are spun continuously with the drive motor of a deprecated ISEE system. The entire ISEE and test article assembly is free to slide vertically along parallel rails, allowing the article to penetrate the ice samples. Weight on bit is provided by the weight of the mechanism plus cast iron weight plates secured to the top.

The testbed can take several measurements simultaneously, ensuring test data is not confounded by unintended variation in test conditions. The pressure gauge (KJLC 275i Series Gauge) measures chamber pressure in Torr or mTorr within 2% repeatability. A thermometer measures ice temperature with a K-type thermocouple embedded in the sample during manufacture. The depth gauge rides with the ISEE mechanism on its own rail, measuring penetration depth and rate during tests. A 6-axis load cell measures forces and torques imparted to the load cell during a test, essential for ice screw tests. A webcam captures close-up video of each test, which is saved and analyzed for failure modes and correlating force-torque data with ice fracture.

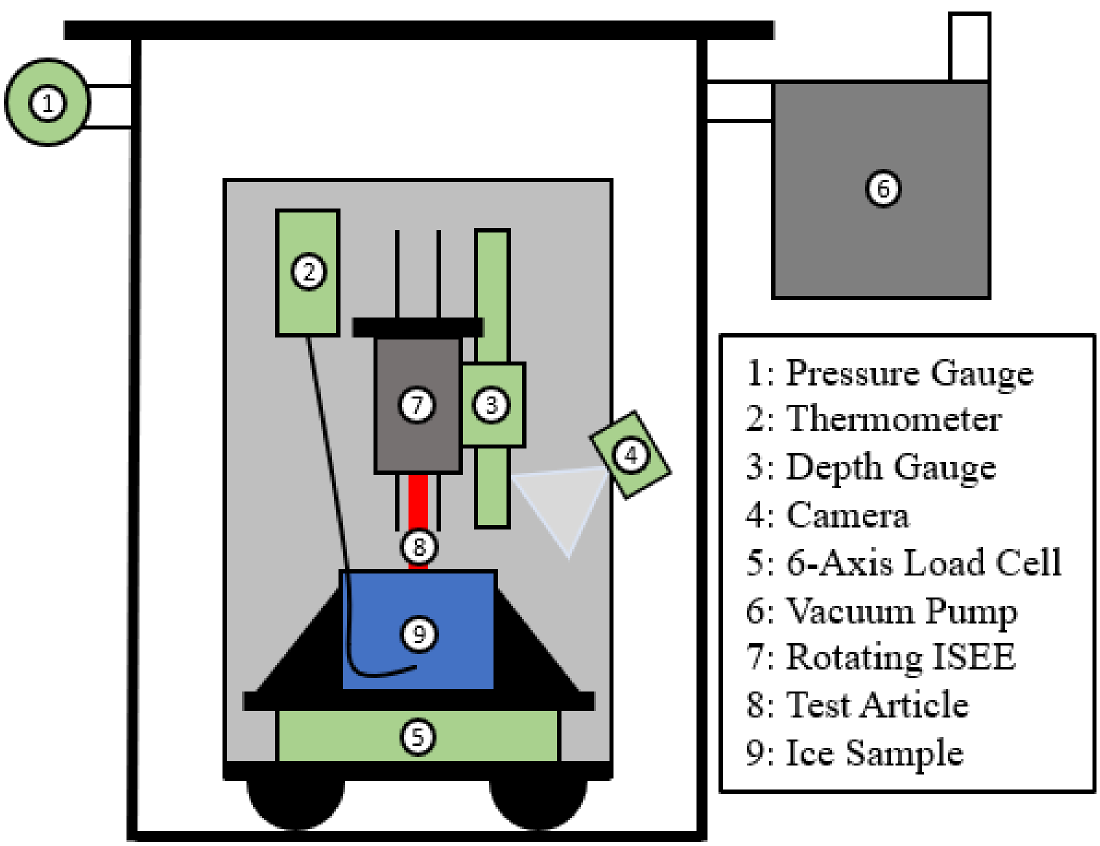

Figure 2: Simplified testbed diagram with actuators (grey), sensors (green), and ice sample (blue) labeled.

4. ICE ANALOG RECIPE DEVELOPMENT

While the alpinist ice screws used for the ISEE have been successful in several test environments on Earth, the cryoice of Europa and Enceladus has physical properties dissimilar to any ice tested thus far. In order to test performance of anchoring methods, a functional analog of the alien cryoice was developed. Knowledge about the exact composition of these icy worlds is still speculative, so the team used tap water to manufacture the sample analog. When information about mineral and gas content and ice composition is gathered by the Europa Clipper Mission, chemically accurate samples can be prepared.

After some experimentation with cryoice fabrication, a process was developed to reliably prepare samples for anchor testing with acceptable repeatability. The produced ice is frozen quickly in a Liquid Nitrogen bath with an embedded thermocouple for temperature sensing. The sample leaves the bath at -180ºC and is usually tested at -120ºC. Removal of the top 1cm of sample provides a more uniform sample structure across batches. The procedure requires Cryo Training and authorization to work with Liquid Nitrogen, and proper PPE should be worn at all times. The procedure, relevant purchased components, and custom lasercuttable files can be found on JPL Wired.

Figure 3: Cryoice sample with embedded thermocouple at -180ºC before anchoring testing.

5. ICE SCREW EXPERIMENTS

Prior to the suite of tests performed in Summer 2018, a handful of tests were conducted on ice samples of various temperatures to determine that anchoring was possible. The preliminary results indicated that custom smaller diameter screws were more promising than full-sized models sold to climbers. However, testing with multiple custom screws of the same design yielded confounding results. Two screws that were machined with the same process using the same drawings and models performed vastly differently. The team determined that more testing was necessary to determine why one far outperformed the other in initial tests.

The devised test suite varied weight on bit (WoB) and test article while holding ice temperature and sample composition constant. To ensure consistency, the tests were run at 100torr in the vacuum chamber with cryoice samples at -120±10ºC. A tighter bound on temperature could be obtained with more precise testing equipment and stronger pumps, but the range was assumed to be a constant -120ºC across all tests. A few tests were run at higher temperatures (-60ºC and -90ºC), but the results were similar to those obtained at -20ºC, where the screws have been previously tested extensively, so the higher temperature testing was abandoned in the interest of time. We suspect that a physical change in the crystalline structure takes place below -100ºC in cryoice and hypothesize that testing at -120ºC ice is representative of performance in Europa or Enceladus-like environments.

Due to time constraints, only a single test could be run on each screw per WoB. However, results were unable to indicate why one of the four identical screws outperformed the others. The consistent result was the dulling or breakage of ice screw tips during anchoring. After only four trials each, the screw teeth were noticeably duller, rendering them useless for cutting into the ice to start tapping. Once dulled, the ability to penetrate cryoice with any WoB, even those higher than listed in the test suite, was diminished. This result may disqualify self-tapping ice screws from consideration for an icy moon anchoring mission, especially if many repeated anchors are required. However, redesigning the teeth and choosing a stronger material such as carbide tool steel may fix this problem for future iterations of the ice screws.

Figure 4: Custom ice screw after cryoice testing exhibiting tooth plastic deformation and fracture.

Another suite of tests sought to determine which thread design performed best for tapping into cryoice. Commercial ice screws from three different companies are under consideration, Black Diamond, Petzl, and Grivel. Each designs their threads differently; Black diamond has traditional triangular threading, Petzl has round threading, and Grivel has reverse threading, inverting the triangular threads. During testing last year, Black Diamond was determined to outperform the others in minimum WoB to tap -20ºC ice. Testing revealed that Grivel screws were unable to penetrate cryoice under any WoB tested. We suspect the reverse threads, which are optimized for maximum pull out force, have poor performance for insertion, which is far more important for the robot's needs. Two Petzl screws were tested, steel and aluminum body. The steel screw outperformed the aluminum screw slightly, but within margin of error. These tests also revealed a strong correlation between WoB and penetration success, with a 100% success rate in trials with 14.5lbs of WoB.

Though significant quantitative data was recorded, all tests were condensed down to binary success or failure based on anchoring capability. A test was considered a success if the screw was able to penetrate at least three threads into the ice and then hold 10lbs of tensile force without dislodging. Common failures were inability to penetrate the ice surface or severe cracking in the ice, preventing the anchor from holding any tensile load.

6. SUBLIMATION EXPERIMENTS

While ice screws perform well in Earth's glacial conditions, the large mechanism required to drive the screws and the repeated anchoring may necessitate an ice anchor that works independently of ice type. Sublimation anchors require multiple heated prongs to be inserted along skew axes to set an anchor. A suite of tests was implemented to explore the design space for a single sublimation prong, varying heater voltage, tip shape, and WoB.

Five test prongs were assembled by adhering 50W soldering iron heating elements to soldering iron tips with Stycast, a high temperature range vacuum-safe adhesive with high thermal conductivity. The five tips selected were intended for varying soldering tasks, and include geometry such as conical point, elongated conical point, rounded tip, straight chisel, and angled chisel. Tests were run with heaters set at 18V or 24V, with either 5lbs or 10lbs of WoB. Torsional failure of heaters inside prongs under load prevented rotation of the prongs, though this was originally intended and may be attempted in future testing.

Tests involving sublimation can only take place under 3 torr, and each test in this suite was run at 1torr, allowing the chamber to continue pumping down lower as the test ran. Long pump down times and rapidly warming ice samples meant that testing had to take place between -70ºC and -100ºC. The tests were run with the coldest possible ice, with a wide variation in temperature due to somewhat inconsistent pump down times, though the chamber conditions were held as constant as possible.

Results were promising for the sublimation prong approach to anchoring, all but one trial of a heated tip was able to successfully penetrate ice to an acceptable depth for a sturdy anchor. With nearly all tests successful, penetration rate was used for test comparison, since penetration rate will dictate the climbing speed of a robot with a sublimation end effector. Higher WoB and higher heater voltages correlated strongly with faster penetration. Some tips underperformed in penetration rate, but all axisymmetric tips performed within the margin of error of each other.

It is important to note that the tests were only run a single time for each set of conditions, and the ice temperature had a wide variation across tests. The sublimation rate is directly dependent on the initial temperature of the ice since all heat is dumped into ice to raise temperature before applying heat of vaporization. Tests with high initial temperatures had high penetration rates, but the data show several strong correlations with experimental variables despite the temperature noise.

Though melting and boiling should be impossible at the low pressures in the chamber, we observed liquid water boiling in several tests. This could be due to inadequate chamber pumps pulling excess vapor out too slowly, but we hypothesize that the prong is able to seal itself in the ice as it melts in, resulting in localized pressure high enough to support liquid water. This observation indicates the viability of melt anchors even on icy moons with insignificant atmosphere. Melt anchors only require a single prong and rely on the adhesion of ice frozen to the prong for anchoring. We observed unintentional freeze anchoring in approximately one third of the tests, some freeze anchors strong enough to resist all manual attempts to dislodge. This opens a new design path that we would like to pursue in a stronger vacuum to determine feasibility on Europa and Enceladus.

Table 1: Results of ice screw Testing in Cryoice at -120ºC, WoB is 4.5lbs+addl. listed.

	Addl WoB (lbs)	Petzl	Petzl 2	Grivel	Tiny #1	Tiny #2	Tiny #3	Tiny #4
Total Tests	0	3	2	2	1	1	1	1
	2.5	3	2	2	1	1	1	1
	5	3	2	2	1	1	1	1
	10	3	2	2	1	1	1	1
Success Rate	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	2.5	33.33%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
	5	66.67%	50.00%	0.00%	0.00%	100.00%	100.00%	0.00%
	10	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%

Table 2: Results of sublimation prong testing; penetration rate (top), ice average temperature during test (middle), and penetration rate normalized by power usage to prevent bias from differing heater voltages (bottom).

		Tip						
WoB	Heater Voltage	0	1	2	3	4	5	
5lbs	18V	0.019	0.0986	0.118	0.137	0.164	0.134	Rate in mm/sec
	24V	0.0531	0.441	0.0987	0.197	0.313	0.402	
10lbs	18V	0.0217	0.185	0.107	0.205	0.133	0.121	
	24V	0.0698	0.718	0.0892	0.300	0.457	0.410	
		Tip						
WoB	Heater Voltage	0	1	2	3	4	5	
5lbs	18V	-73	-76	-65	-79	-86	-90	Ice Temperature
	24V	-67	-90	-87	-90	-82	-92	
10lbs	18V	-71	-81	-72	-85	-85	-103	
	24V	-71	-40	-100	-73	-73	-87	
		Tip						
WoB	Heater Voltage	0	1	2	3	4	5	
5lbs	18V	0.00053	0.00274	0.00328	0.00381	0.00456	0.00372	Power Usage in mm/J
	24V	0.00111	0.00919	0.00206	0.00410	0.00652	0.00838	
10lbs	18V	0.00060	0.00514	0.00297	0.00569	0.00369	0.00336	
	24V	0.00145	0.01496	0.00186	0.00625	0.00952	0.00854	

7. Drilling Experiments

To determine the feasibility of anchoring using a conventional drill bit anchor, several specialized drill bits were tested in ice by hand. This testing was much less formal than the ice screw and sublimation anchor testing for which a computer collected data from a formal test stand over multiple trials, and this approach is in a much earlier state of development. A block of pure water ice at -20°C obtained from an ice sculpting facility was drilled over a load cell to determine required weight on bit for penetration.

Each bit selected for testing was 0.25 inches in diameter for consistency, and 11 bits were tested in total. Most of the selected bits were for specialty application or different materials including aluminum, steel, wood, glass, and masonry. The drill used (Dewalt DWE1014) had only rotary motion, though a rotary percussive drill is the typical tool of choice for anchoring in rocks. A rotary percussive drill system was eliminated due to its tendency to pulverize or crack the ice without drilling a clean hole during testing.

The bits were ranked by weight on bit, where the best bits required the least weight on bit for penetration. Glass, masonry, and abrasive bits were unable to penetrate even with maximum allowable weight on bit. Bits for metal and wood performed well, with the flute design and tip shape dominating performance. Ice does not form chips when cut with a bit in the way metal or wood does. Instead the ice shaves off into a snow-like material, which quickly packs and heats up from friction, then refreezes in the flutes of the drill bit. This disables the bit's cutting edges and prevents penetration, so the bits that are most equipped to deal with extraction of chips were the most successful. Spade bits performed well, and brad points seemed to improve performance over conical points. The most promising bit tested had a light web and a lower pitch angle of flutes, which grants it superior chip removal properties. The deeper flutes and longer flute helices due to lower pitch clogged significantly less and required much less weight on bit than other bits.

A proposed future custom bit would have the light web and decreased pitch of this bit but also include the brad point, which outperformed conical points. It should be noted that decreasing web thickness increases chip flow at the cost of bit durability and a brad point can lower weight on bit at the cost of easily dulling with continued use. Repeated stress testing needs to be conducted before any of these bits can be recommended for use.

Figure 5: All tested drill bits ranked from least WoB required to penetrate to most.

8. Discussion and Future Work

The testing performed this summer has resulted in revelations about anchoring processes that may have deep impact on future development of this project. Ice screws must be made much stronger if they are to cut into cryoice repeatedly. Freeze anchors may be possible even in vacuum due to localized pressure from sublimation. The correlations and results presented here need to be verified with more consistent test conditions, and the data set should be fleshed out with repeat trials and additional test articles. Other test parameters may be considered, such as rotation of sublimation prongs or heating an ice screw, which may achieve the benefits of both methods. The data presented here will inform the design of the next generation of ice anchoring end effectors, which may one day reach the oceans of an icy moon.

9. Acknowledgements

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