Advances in Fiber Optic Microtethered Systems for Deep-Sea Sensing and Exploration

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***Abstract*—The field of deep-sea oceanographic research is commonly restricted to large research vessels and bulky underwater equipment requiring complex deployment schemes. Most equipment is in some way tethered to the deployment vessel, apart from fully autonomous systems. Typical tethers are heavily reinforced industrial grade cables, supplying power and communication to the subsea payloads. By utilizing fiber optic microtethers, specifically Fiber Optic Fishing Line (FOFL), small profile oceanographic sensor payloads and remote operated vehicles (ROVs) can be deployed from any size vessel of opportunity with minimal resources. The goal of developing these tethers further is to not replace, but operate alongside current reliable research methods, enabling deep-sea access to the ocean for a broader community of scientists and students. Here we present our improvements on FOFL, the Fiber Optic Reel System (FOReelS), and various sensing payloads designed to be deployable with FOFL on the FOReelS. We present performance data of the opto-mechanical properties of the microtether, alongside the successful development and deployment of three static modular payloads and two mobile ROVs in the field.**

Keywords*—*ocean robotics, fiber optics, microtethers, deep-sea systems

I. Introduction

Deep-sea oceanographic sensing is dominated by large-scale technology that typically requires heavy and cumbersome deployment platforms. To make the deep-sea more accessible, smaller and more simplified technologies can be utilized. By developing miniaturized modular payloads and pairing them with a unique fiber optic microtether system, deep-sea sensing operations can be obtainable from any size vessel. Fiber Optic Fishing Line (FOFL, Nautilus Defense LLC, USA; US Patent #17/677,651 'Fiber Optic Reel System') is a proprietary microtether capable of high bandwidth data transmission between the topside winch and subsea payload [1]. Due to its slim profile, FOFL can be spooled onto customized commercial fishing reels in place of an oceanographic winch, minimizing the footprint of the system. These technologies cannot directly replace the robust capabilities of traditional vehicles and sensing platforms; however, they fill a gap by utilizing coastal vessels of opportunity and dramatically reducing the typical operational costs of deep-sea research.

Commonly used tethered technologies aboard research vessels are remotely operated vehicles (ROVs), conductivity temperature and depth profilers (CTDs), and various towed sensor arrays. These systems are typically hundreds to thousands of pounds and are deployed/recovered with an oceanographic winch [2]. The cabling used on these devices is typically a steel-jacketed and/or polymer-coated cable with an electro-optical core, allowing for surface power and high bandwidth telemetry. WHOI's Nereid UnderIce (NUI) hybrid ROV system was developed to dramatically reduce the tether to an unjacketed, bare fiber optic to provide live telemetry to the ROV, with power for the vehicle coming from onboard batteries [3]. Hybrid ROVs refer to vehicles that operate under their own power, only using their tether for communication and control purposes [4], [5], [6]. While this system design has proved successful for deep-sea and under-ice operations, the bare fiber optic tether is extremely fragile, unable to be put under tension, and cannot be retrieved once it is unspooled. FOFL microtethers are load-bearing and small diameter, presenting a compromise between strength and size. FOFL has been proven to reliably operate off small boats and deploy camera and sensing payloads to depths exceeding 800m . Here we present advances in using FOFL microtethers for operating ROVs and other novel sensing platforms, as well as steps towards improving the reliability and robustness of the topside reel system.

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II. METHODS

A complete Fiber Optic Reel System (FOReelS) is comprised of a commercial electric fishing reel spooled with FOFL, a fiber optic rotary joint (i.e. slipring), an over boarding slide or large diameter block, and a self-powered static or mobile payload with fiber optic telemetry Fig. 1. Development and testing was performed on each piece of the system, followed by eventual testing of multiple complete systems. In these methods, epoxy potting refers to encasing components in a two-part rigid epoxy (Crystal Clear 200 and 202, Reynolds Advanced Materials, USA) to completely seal off the system from water and 3D printing refers to Stereolithography (SLA) resin printing (Formlabs, USA), unless otherwise stated.

A. Reel Improvements

The fiber optic reel system is designed to be operated on any sized recreational, fishing, coastal or offshore vessel. This system has been developed by modifying a commercial grade electrical fishing reel, converting it from a fishing reel to a mini scientific winch. A fiber optic slip ring (Princetel Inc., USA) is mated to the external face of the drum, allowing the stationary fiber optic on the topside to translate rotationally to the winch without tangling. To improve upon the existing design, multiple 3D printed slides were tested in place of the original large wheel, for the FOFL to slide on before passing into the water. While the slide was adequate for fiber optic deployment, it did not allow enough freedom of motion for vessel heading changes and wave motion. The current system design utilizes a custom heavy-duty fishing rod (Crafty One Customs, USA) and T-10 adjustable rod butt, with a 4in diameter block mounted on the end of the rod. Future work is currently underway to replace the motor and drive electronics within the electric reel, allowing wireless control of the FOReelS for eventual autonomous deployments.

B. FOFL Tensile Testing

The most recently produced spools of FOFL were tensile tested similar to the initial publication, using a fiber optic source/meter in parallel with a tensile testing machine. The new FOFL design is woven differently and uses a tight-buffer fiber optic core as opposed to bare fiber optic. The tight buffer core offers enhanced performance and robustness, while maintaining a small enough diameter to allow for hundreds of meters to be spooled onto a commercial reel. With the original test setup, the FOFL was mechanically terminated and clamped into the machine with the standard vice grips. In our current tests, the FOFL was wound ten times onto a 25mm rod and then secured with a strong adhesive tape to prevent slipping, with a sample length of 10cm between the two rods. Six tests were performed in total, 3 on lengths taken from a 1000m batch of FOFL and 3 from a 500m batch of FOFL. The test was done on a Shimadzu AGS-X 10kN electromechanical test frame, with an AFL SMLP-55-0907PR Optical Loss Test Kit attached to either end of the FOFL to measure when optics were lost during the testing process Fig. 2. Each end of the sample was terminated with an AFL FASTConnect ST connector and a standard fiber optic patch cable was used to connect the sample to the loss kit. Before each test, the system was reset to 10cm separation using a spacer, calibrated, and zeroed. Each test was programmed to stretch the sample at a rate of 5mm/min until mechanical break. The optical loss kit was recorded by video to match up stroke/force measurements with optical loss after the test was finished. The test was completed when the fiber was mechanically severed.

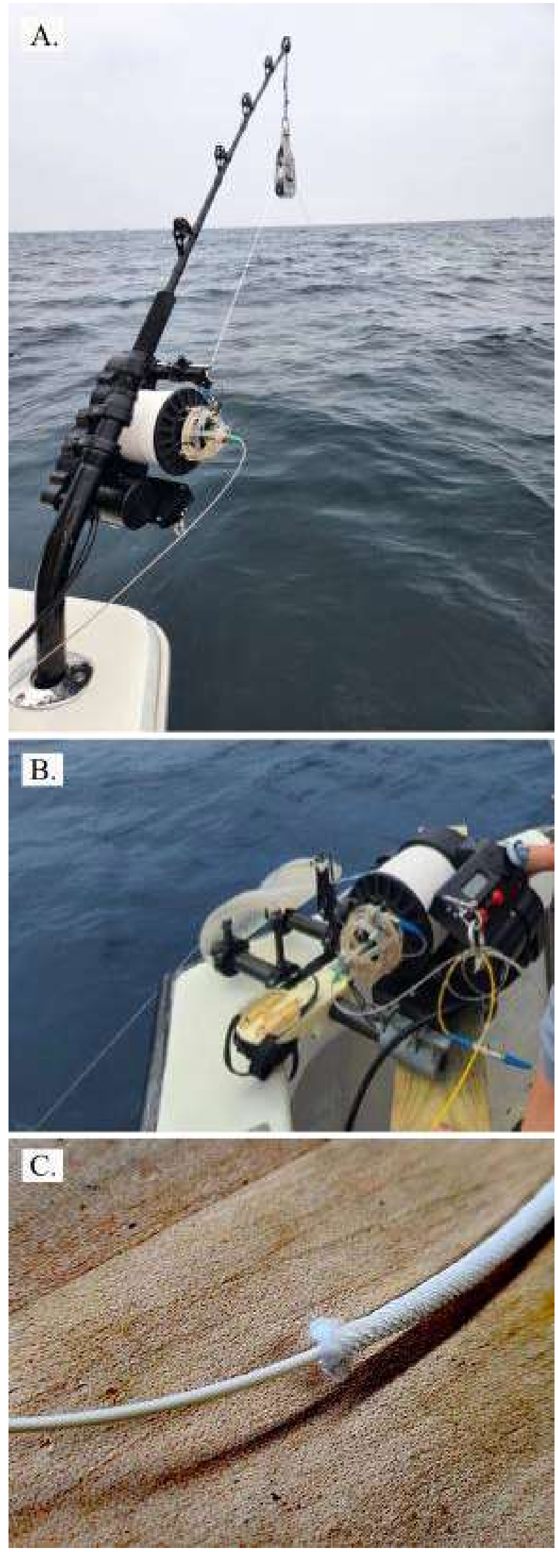

Figure 1: A. The improved and current version of the FOReelS, with the custom fishing rod, adjustable rod butt mount, and large diameter block. B. A previous version of the FOReelS with 3D printed slide. C. Close-up image of FOFL showing outer braid and tight-buffer fiber optic core.

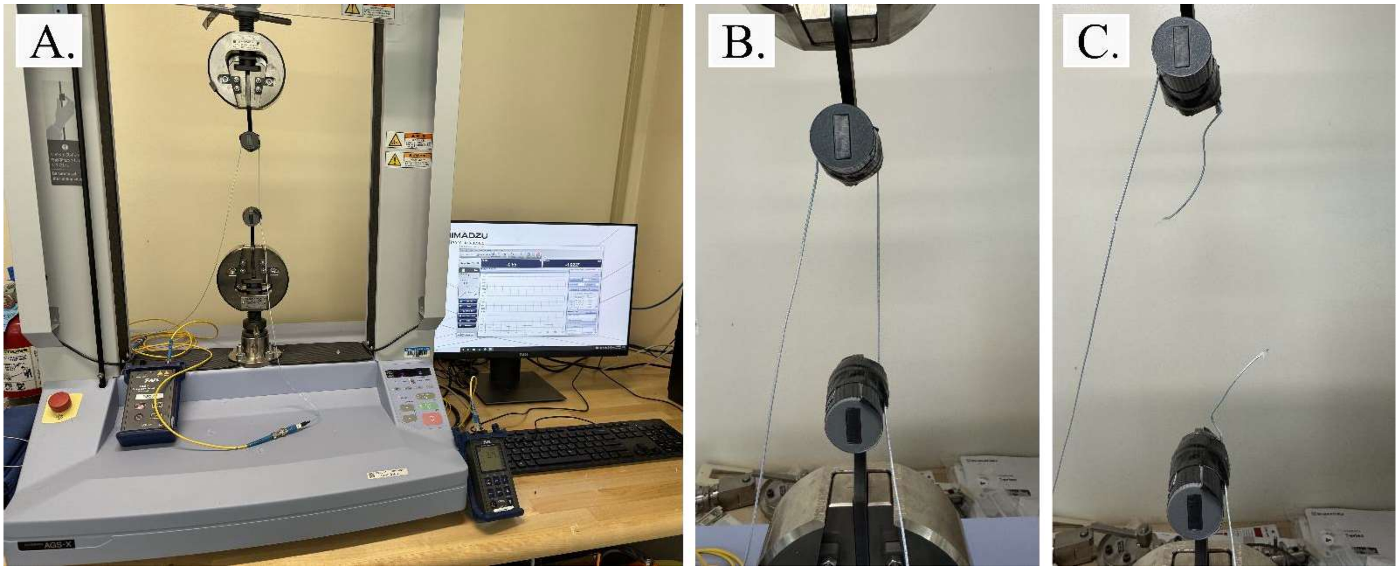

Figure 2: A. Tensile testing setup, FOFL is wound on two delrin rods, both yellow fiber optic patch cables lead to the laser module (left) and the optical receiver (right), the computer program plots force and stroke in real time as the test is underway. B. A closeup of the wound FOFL on the mounting brackets. C. The sample after the test is complete and the FOFL has been mechanically severed.

C. Modular Static Payloads

The compact nature of the fiber optic reel system requires payloads of similar scale. With the implementation of additive manufacturing, epoxy potting electronics, and standard 1atm pressure housings, various modular miniaturized sensing payloads have been developed for deployment via the FOReelS.

The first attempt at a "modular payload" built off an 80/20 aluminum frame and used various 3D printed pressure housings [7] and cameras Fig. 3, A-C. This unit had an epoxy potted light (SiteLite, Juice Robotics LLC, USA), that was supplied power from a lithium battery inside of a 3D printed pressure housing mounted on the frame. Two cameras were used in this configuration, one a DEEPi, a low-cost epoxy potted raspberry pi camera and the other, a DEEPi stereo camera "StereoPi" that took video/images from two lenses simultaneously for photogrammetry [8], [9]. Both cameras had a 13 pin MacArtney SubConn Ethernet bulkhead, which connected to the 3D printed housing. Inside of the housing was the battery as well as an ethernet to fiber optic media converter. This was fed out of an epoxy potted termination in the housing and connected to the FOFL mechanical termination. At the mechanical termination, the weight of the payload was translated onto the delrin sheath around the fiber optic in the FOFL, and the fiber optic was able to pass through, unstrained and connect to the camera allowing low latency live feed video transmission from the payload, through 500m of FOFL, to the surface topside computer. This system was deployed in ~100msw off the coast of Bermuda using the Bermuda Institute of Ocean Science's (BIOS) 42' *R/V Stommel*.

The second payload was an epoxy potted camera/lighting unit with a 1atm acrylic battery housing Fig. 3, D. This payload shed the aluminum frame to reduce weight and attempted to compartmentalize electronics in the epoxy potted portion. After carefully encasing the fiber optic media converter's laser module in a high viscosity two-part epoxy (JB Marine Weld), the rest of the multiplexer could be potted in rigid clear epoxy and withstand pressures of ~1000psi. In the end the camera, Raspberry Pi, lights, and multiplexer were potted in epoxy in 3D printed shell with a custom pressure tolerant endcap and cable passthroughs. Only a battery was kept in the 1atm acrylic housing, with the electronics making up one endcap and the other, another 3D printed endcap with a fiber optic passthrough for the FOFL. These two sides were held together with stainless steel bolts, completing the assembly. This camera was displayed and tested at the Naval Undersea Warfare Center's 2022 Tech Demo Day as well as off the cost of Bermuda in July 2022.

The most recent payload design "TunaCam," is a 1atm 1000m-rated aluminum housing with custom 3D printed endcaps Fig.3, E-F. The intention with TunaCam was to reduce the amount of epoxy potted electronics and keep most of the components in the housing itself. In one endcap, two lights and a camera are potted into a 3D printed endcap. Inside of the housing there is a Raspberry Pi 4, fiber optic multiplexer, and battery bank. The other endcap is also 3D printed and highly customized with a fiber pass through, 4 pin Subconn bulkhead, and a BlueRobotics switch and pressure relief valve. A 3D printed shell was clamped on the outside of the housing, the bottom section for ballast weights and the top section for mounting a live feed StarOddi CTD. This payload was deployed off a 53' coastal fishing vessel out of Rhode Island in August 2023.

D. Mobile Payloads

Two ROVs have been developed for deployment with the FOReelS. The first was "DeepBlue" a BlueRobotics BlueROV2 heavy lift configuration that was modified to communicate via fiber optic telemetry and handle depths greater than the stock BlueROV2 Fig. 4, A. The standard tether for the BlueROV is a cable with four twisted copper pairs and a neutrally buoyant polyurethane sheath. The ethernet expansion board and USB converter called the Fathom-X Board is replaced with a fiber optic multiplexer (10Gtek Co., Hong Kong), and the ethernet tether passthrough is replaced with an epoxy potted blank endcap with a fiber optic whip going through it. The standard acrylic bottle was replaced with an aluminum one, and the motors were spliced into pairs, two per

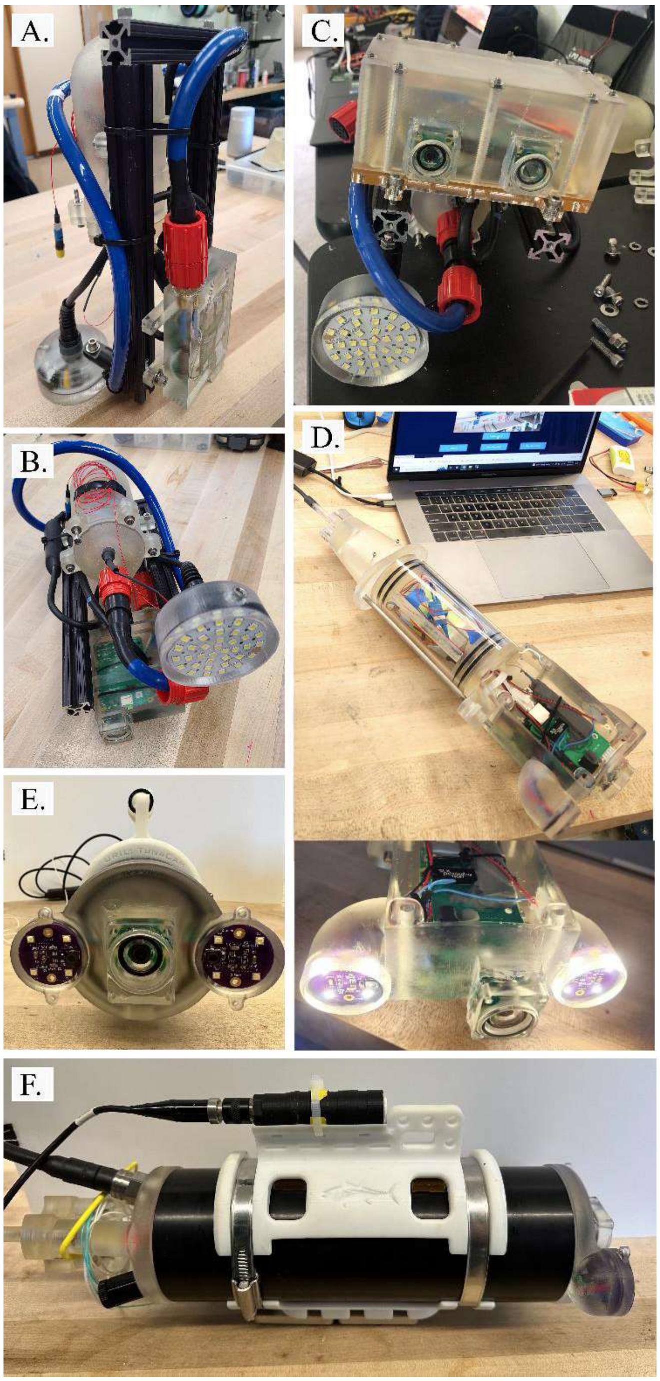

Figure 3: A-B. First modular payload with DEEPi camera, light, and 3D printed pressure housing. C. The same payload but with StereoPi camera in place of the DEEPi. D. The second payload with fully potted electronics and acrylic battery housing. E-F. TunaCam, a 1000m rated payload with various penetrations, a live feed CTD, and an endcap with an integrated camera and lights.

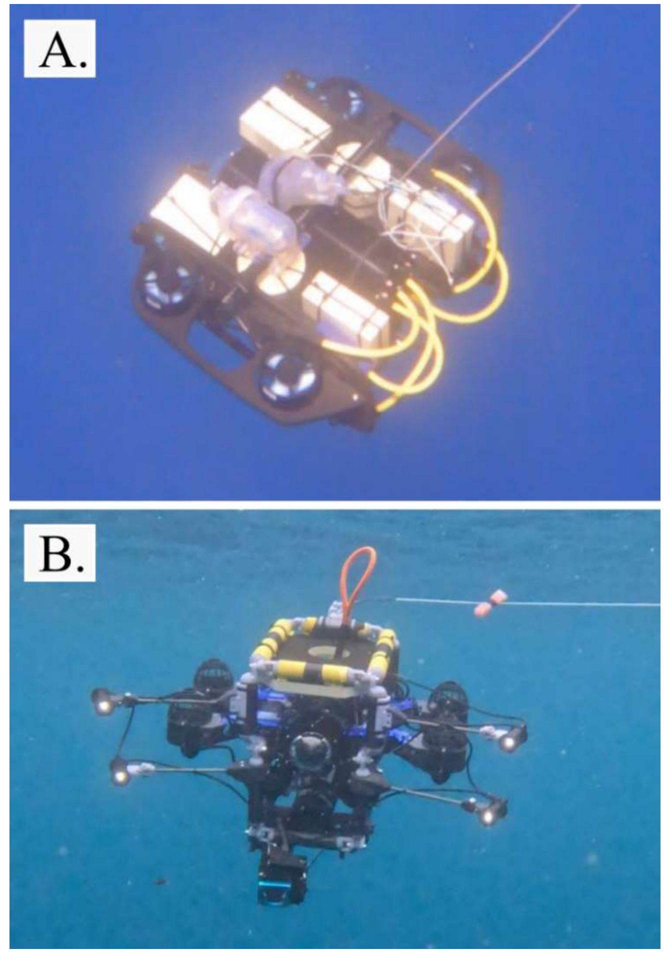

Figure 4: A. ROV DeepBlue, descending in Bermuda. B. ROV FiberFish preparing for descent in the Gulf of Chiriquí, Panama

6 wire cable, reducing the number of penetrations in the endcap from 8 to four. The same mechanical termination from the modular payloads was connected to the frame of the DeepBlue as a mechanical termination for the FOFL. This ROV was deployed off the coast of Bermuda on the *R/V Stommel* up to ~200msw.

The next generation of ROV to be deployed from the FOReelS was “FiberFish” which used the basic framework from a BlueROV2, with a completely custom carbon fiber and 3D printed frame Fig. 4, B. The intention was to develop a compact, lightweight system capable of fitting in standard TSA checked luggage limitations [10]. The electronics configuration was used from the “DeepBlue” ROV, however the frame was made up of multiple carbon fiber pressure vessels with 3D printed and epoxy sealed endcaps. Braces and mounting brackets were printed from a standard FDM printer using 100% infill ASA material. The motors are capable of folding down and the top of the frame is removable to reduce the profile of the vehicle for packing. The mechanical termination of FiberFish differed slightly to the standard, where the potted termination of FOFL clipped into the frame of the ROV and was secured with a safety pin, increasing the portability of the system. This ROV was deployed in the Gulf of Chiriquí, Panama off of the *S/Y Eugen Seibold* to ~250msw.

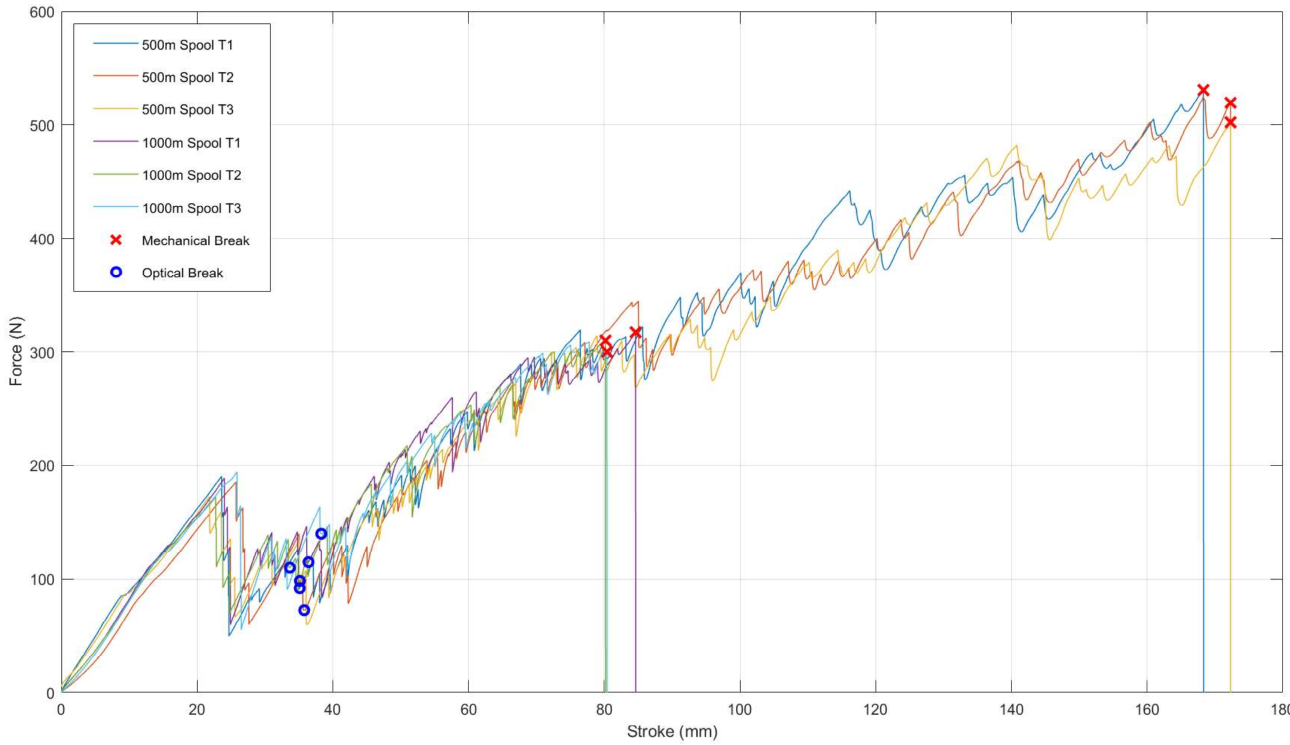

Figure 5: Optical-Mechanical testing results of FOFL. Each line is an individual test and the red x's mark the point at which that test mechanically failed and the blue o's mark where the optical transmission was lost.

III. Results & Discussion

A. Reel Improvements

The first change to occur on the FOReelS was replacing the large diameter wheel with a 3D printed slide, guiding the FOFL into the water off the side of the boat. With the slide, we witnessed persistent issues with the reel's winding capabilities. FOFL would not wind well during recovery even with the aid of a levelwind, building up in the center or side of the reel drum. Occasionally we would see "knifing" in the fiber, where a strand on a higher up fleet was being tightly pulled against another wrap of FOFL, occasionally severing the optical connection. The FOFL would also occasionally slip off the sled, further damaging it along the side of the boat or other object. We decided to treat the reel as what it was originally was, a fishing reel, and mount the FOReelS on a custom fishing rod, capable of lifting payloads of the size we can deploy with the system. A large diameter stainless steel block was tied to the end of the rod, and the FOFL was run through that, then into the water. The rod method ended up greatly improving the levelwind capabilities of the system, and acted as passive heave compensation by bending with the heave of the boat when a payload is deployed.

Figure 6: Mechanically broken sample of FOFL, the tight buffer (turquoise) is sheered in multiple places and the internal fiber optic core can be seen exposed.

B. FOFL Tensile Testing

After performing the six tensile tests on two different spools of FOFL, the mechanical and optical breaking mode can be better understood. The primary difference between the two tested variants is the picks per inch (PPI), with the 500m spool having more PPI than the 1000m spool (PPI can be considered the density of the weave). While the 500m spool could withstand ~200N more than the 1000m spool mechanically, the three samples from the 1000m spool showed a higher optical strength of ~20-40N greater than the 500m spool Fig. 5.

The initial spike in the force data can be seen around the 200N and 25mm mark on the graph, this corresponds to an audible pop that was heard during testing, which was later found to be breakage of the plastic tight buffer sheath surrounding the fiber optic beneath the woven UHMWP sheath Fig. 6. Soon after, the fiber, now exposed between the sheared tight buffer, is severed and transmission is lost. After that point, the data primarily represents the mechanical capabilities of the external woven sheath of the FOFL. This denotes that the initial working load of FOFL before degradation of the tight buffer is up to ~170-200N. After the tight buffer degrades, optical transmission is still possible, but the working load capabilities are reduced to ~70-125N. Regardless of the condition of the fiber optic core, FOFL continues to hold mechanically until it fails at ~300-525N, depending on the specific variant.

The 500m spool shows exceptional elongation after optical break, capable of expanding ~170% of its initial size (10cm) and withstanding well over 500N, whereas the 1000m samples only stretched an additional ~80%. This corresponds to the sample's PPI, as the individual fibers in the weave of the 1000m length engage under tension sooner than the 500m because there is less PPI, providing a smaller weave and less material to stretch when under load.

C. Modular Static Payloads

The first modular payload with the aluminum frame was tested successfully at BIOS. It was initially calibrated dockside off of the R/V Stommel with the StereoPi and then deployed a few miles off the coast to depths of 100-200m. The DEEPi configuration was the first test performed and provided successful live feed video from depth. The StereoPi was the second test and was successfully deployed for some time until retrieval where a breakage occurred at some point in the spool of FOFL. Amongst the deployments, the team was able to view the benthic environment of Bermuda with a steady camera and light, as well as utilize a heads-up virtual reality display that projected video directly to the wearer Fig. 7.

The intention for the following payload was to develop something lighter than the initial design, incorporating more epoxy potted electronics and an integrated 1atm housing. While this payload proved successful for various deployments, the camera was eventually flooded and broken due to an incomplete epoxy potting application.

The most recent payload, TunaCam, with the aluminum housing met a similar fate, while it was the most advanced/technically promising design. The camera was incompletely potted in a similar fashion and video was severed. The TunaCam was successfully deployed once on the F/V Big Game, equipped with a squid on a light tension leader, but was not successful in recording footage of a pelagic fish. Despite the lack of video, the live feed CTD was operational, and improvements are currently in the works for a new design.

D. Mobile Payloads

The purpose of developing these mobile payloads was to prove that the FOReelS could operate in place of a standard tether management system (TMS) for small scale ROVs. DeepBlue, the first ROV to have its tether converted to FOFL, was the benchmark in testing the true capabilities of FOFL and if it was rugged enough to operate with a dynamic, moving payload. The ROV was carefully deployed from the boat, place into the water by a diver, and when cleared, began its descent. The FOReelS was set to free spool, allowing the ROV to pull out as much tether necessary to reach the seafloor. The vehicle descended at a rate of ~1m/s, quickly reaching the bottom. While the dynamic environment posed some challenges to the ROV, having a programmed stability mode kept the vehicle level with the ground and the thin tether allowed the vehicle to maneuver quickly and easily. Three successful dives were performed reaching depths up to 180m. Some difficulties arose with retrieval, breaking the optical connection on two out of the three dives, requiring locating the break, and re-terminating the FOFL.

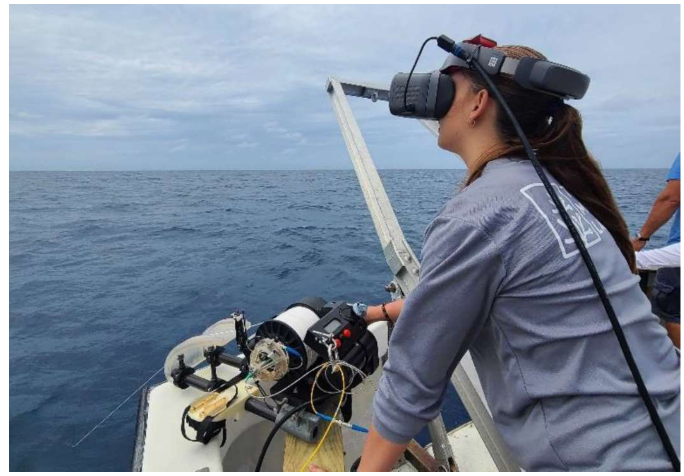

Figure 7: FOReelS system linked into live-feed VR headset, displaying footage from StereoPi.

ROV FiberFish expanded on some of the issues we faced with DeepBlue. We made the overall system lighter and more compact to reduce the strain that it would have on the FOFL. In addition to technical testing, the purpose of these dives were to collaborate with the Smithsonian Tropical Research Institute to observe local megafauna and reef biodiversity. It was successfully deployed 5 separate times spread across two locations of the Gulf of Chiriquí, Panama: Ladrones Bank and Hannibal Bank. FiberFish reached a maximum depth of 251.3m but primarily operated in depths ranging from 20-200m. The optical connection was severed multiple times on retrieval, but typically when the vehicle reached the surface and was within 10m of the boat. This was primarily due to snap loading on the fiber as well as high surface currents. After multiple breaks, re-termination of the FOFL was no longer possible. In its place, FOFL was wrapped 10 times around one of the carbon fiber tubes that made up the frame, then secured with a strong adhesive tape. The fiber optic was then terminated with an AFL FASTConnect connector, allowing transmission between the vehicle and topside with the wraps acting as strain relief for the FOFL. This method inspired the described testing method of the FOFL to determine its breaking properties without being mechanically terminated and proved to be a successful deployment technique. The vehicle is rated to reach depths up to 1000m, and work is currently being done to reach these depths, primarily restricted by the drum size of the current FOReelS.

IV. CONCLUSION

With continued research and development, FOFL will be a reliable tether option for both semi-autonomous and remotely controlled payloads. By understanding the relationship between the PPI on the external weave and the mechanical and optical break of the microtether, deployment and recovery reliability should increase and can be tuned depending on the desired payload. By concurrently increasing the drum size and improving the levelwind of the FOReelS, deeper depths can be reached with both static and mobile payloads, with goals to reach +1000m.

The presented research displays both the challenges and advantages of using experimental microtethers in oceanographic applications. In a profession dominated by large-scale industrial equipment, there is a niche for accessible and easy to develop/deploy oceanographic technologies. Microtethers and small form factor winches/reel systems offer the connection between a deep-sea oceanographic payload and any vessel of opportunity. By further developing FOFL and the FOReelS, alongside various payloads, oceanographic research becomes more accessible for both citizen science, professional research outlets, and commercial businesses that are restricted to small boat operations. This technology will not completely replace the reliable current large-scale oceanographic instrumentation, however it can operate alongside and in different operational scenarios than these systems currently occupy. With improved technical access to the deep-sea, we can continue to increase global oceanographic data collection and offer solutions to a broader community of marine scientists, educators, and explorers.

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