FUSE

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FUSE Final Report

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1.0 Introduction

The marine community is at the cusp of completely changing the way observations are routinely conducted on the deep seafloor. But unlike on land, there are significant challenges that need to be addressed not least among them are the properties of sea water that imply the very rapid attenuation of the electromagnetic spectrum underwater. A direct consequence of this phenomenon is that a number of critical technologies available on land including wireless networks, RF communications, and GPS navigation are not available underwater. These difficulties are compounded by requirements for dealing with immense pressure in the deep parts of the world's oceans and the remote nature of most deep deployments. Long term energy storage is also a problem due to cold at depth and the temporal scales which are comparable to self-discharge rates for most battery chemistries.

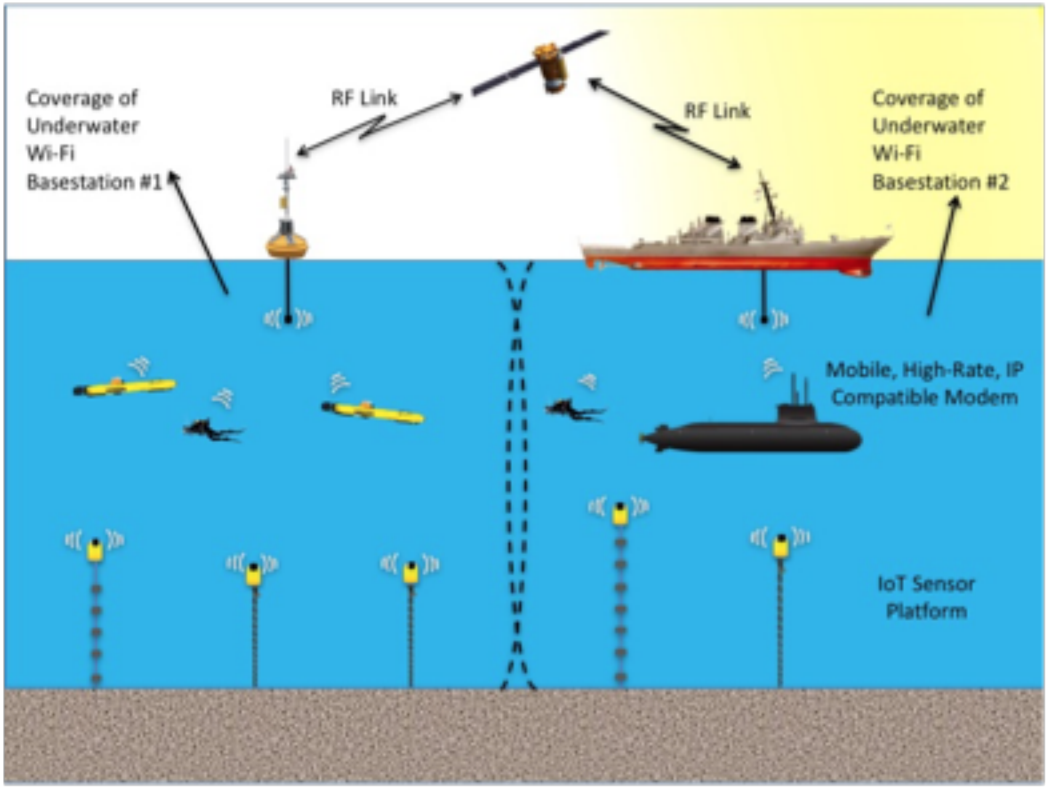

Figure 1. A conceptual diagram of Seanet - the internet of underwater things. This concept visualizes low power (or even zero power) sensors, organized into ad hoc sensor networks, that seamlessly integrate with static and mobile platforms underwater on the surface and out on land.

On land however, the last decade has seen remarkable progress in sensor development networking and platforms. Research is now producing sensors in the nanowatt regime that are capable of stable operation over long periods of time and over large temperature variations. These sensors are forming the backbone of advances in the area of the Internet of Things (IoT). Further advances in networking also hold huge potential for underwater applications even though the underlying basis for communications underwater is acoustic as opposed to communications based on parts of the electromagnetic spectrum. Energy harvesting from the environment and inductive charging underwater are other areas that have seen considerable progress in recent times. Autonomous manipulation, sample return and in-situ sample characterization are all within the realm of possibility. Biodegradable electronics are an active area of research. These efforts all have the possibility of making significant impact to marine seafloor science.

The FUSE Workshop conducted at Northeastern University in June 2018 looked at the problems associated with seafloor science in the deep ocean. Our stated goal was to bring together the diverse communities that comprise the end user oceanographic and the engineering communities. Over the course of the workshop we examined the science drivers and used them to enumerate the challenges and to lay out what turned out to be common areas across the diverse end users that are ripe for engineering research and development. This document lays out the results of the deliberations and aims to build a roadmap that addresses the technology needs and gaps for seafloor science.

In order to accomplish our goals we brought together 70 attendees with expertise in Engineering and various seafloor sciences including Marine Geology/Geophysics, Fluid Flows (cold seeps and hydrothermal vent systems) and Fisheries to examine the issues related to the next generation of platforms, sensors, and networking concepts to explore the world's oceans. Our emphasis was to enhance our ability to look at the seafloor from the perspective of both the spatial and temporal dimensions. An added caveat was the requirement to accomplish these tasks with minimal environmental impact.

We conducted a two-day workshop at Northeastern University in Boston, in June 2018, with targeted invitees as well as those reached through an open call with the basic interests related to the marine seafloor science and engineering scientists. The agenda and the list of attendees are available as appendices to this document. A formal paper is to be submitted to the journal Oceanography shortly.

The focus was on framing the question of technology gaps based on the real requirements associated with seafloor science. In particular, given the expertise within the attendees we focused on three main scientific drivers – Seismology, the Marine Benthos and Fluid Flow (cold seeps and hydrothermal vents). Given the requirements from each of these groups we then examined the commonalities and differences in terms of requirements for Sensors, Acoustic Communications and Platforms and Mapping.

2.0 Science Drivers

2.1 Seismology

Ocean bottom seismology is a well established field of study. In the US multiple facilities exist to build, maintain and deploy ocean bottom seismometers (OBS) for the scientific community. However, the major impediments in this area include

1. A lack of coverage to match seismometer land density. Cabled systems are feasible but very expensive. A higher density would allow a number of economies of scale. In general, miniaturization of sensors using ASIC technology would lower costs allowing more systems to be built as well as help realize better power efficiency.
2. Currently OBS are expensive and time consuming to recover, turn around and redeploy. This in turn strongly affects the amount of ship time that is needed and that cost limits total numbers and locations. The question thus naturally arises – can we deploy an OBS with an autonomous underwater vehicle (AUV)? Can we airdrop an OBS for faster deployment? Both these methods might help reduce the cost of ship time. The sensor cost is far less than the cost of ship time and if we assume that the sensors are expendable the only issue would be recover the data from these systems.
3. While the data management workflow is well developed and established, the total volume of data is 100s of terabytes. One obvious area of interest is that associated with in-situ or near-situ data processing and prioritization for offload. A smart machine learning based algorithm may allow for AUV offloads, and if the AUV visits multiple sensors on-board processing may be extended to the entire sensor array, allowing us to make decisions to surface, or go to different units for further offload of their data. In this regard, it is also worth pointing out that data offload with optical modems, when coupled with in-situ processing could yield future improvements in bits per joule of several orders of magnitude.
4. Systems level issues may also play a critical role. Reliability of overall system from deployment to recovery would be greatly enhanced with the next generation of cables, connectors and clocks.
5. Possible linkages with oil and gas infrastructure or telecommunications - SMART cable, an ability to install sensors with global telecom on repeaters as well as different sensor methodologies such as fiber-based strain measurements using existing fiber may also be game changing.

2.2 Hydrothermal and other Fluid Flows

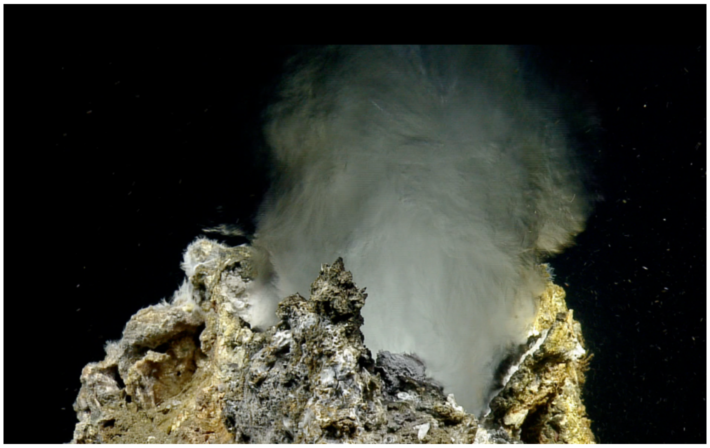

Figure 2 A hydrothermal vent. Understanding the areal and volumetric fluxes and chemical compositions at such vents and along diffuse flows remains a challenging task

The key science drivers for seafloor fluid flow in the coming years derive from our need to understand the interplays between the physics, chemistry and biology associated with fluid flows. Fluid flows themselves are widely distributed spatially and temporally over subduction zones, passive margins, active venting, diffuse flow, and off-axis seamounts and encompassing episodic events and spatial variation at a number of scales. Diffuse flows which might make up half of the total, are also not well-constrained.

Some of the important issues to consider include

1. Can we adapt eddy covariance methods to deep-sea flux studies. Coming up with ways to quantify the importance of point source vents vs. diffuse flow and then making direct measurements of heat flux, chemical flux, and fluid flow over scales of the order of $100m^2$ would be a notable step forward.
2. How do we measure the relative vertical/horizontal spatial impact of chimneys/chronic plumes vs. large spatial area diffuse flow at the seafloor? E.g., what is extent and impact of iron stabilization and transport
3. How do we precisely position sensors to cover a lot of ground with physical and chemical sensors across broad areal coverage without sacrificing areal resolution.
4. At a vent orifice, we can measure temperature & collect Ti Majors but the transition from vent orifice to plume which accounts for the next 10 minutes of fluid transport is not well understood. How can we make measurements to understand speciation, rates, and processes during this transition.

2.3 Benthos

Independent of fluid flows and seismology there is also a strong need for characterizing seafloor habitat at different scales for a wide variety of applications including biological characterization for fisheries, seafloor characterization, and for siting of offshore energy (wind, wave, oil and gas).

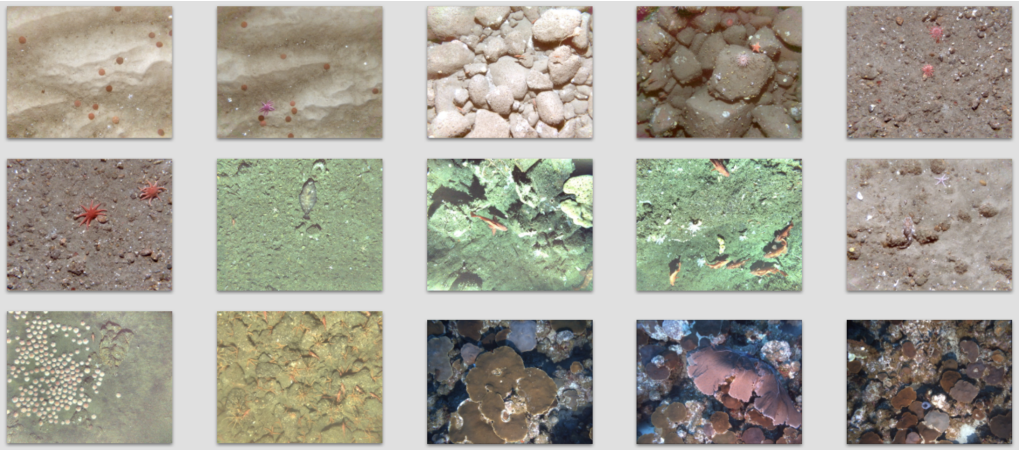

Figure 3, Habitat characterization may require a variety of multibeam and (as shown above) optical camera imagery to count and identify species, the background geology, as well as making measurements of chemical and environmental parameters.

Habitat characterization includes a variety of activities encompassing mapping and environmental characterization. Examples of such applications include the count and characterization of ecosystem populations and communities, environmental parameters including CTD, oxygen, methane, other chemical sensors, and the geology of the seafloor.

It is especially important to understand the scale of the target efforts and our ability to stratify by depth and other methodologies while conducting coastal, coast wide and extensive EEZ mapping.

3.0 Technology Drivers

3.1 Sensors

While examining the overall science drivers behind each of the major areas outlined above some common engineering themes dominated across all the areas. These include the requirements for better clocks, better orientation measurements, energy and power requirements, disposable housings with little or no impact on the environment, long endurance platforms on the ocean surface and underwater, the role of manipulation from underwater platforms, and the bandwidth issues with acoustic and optical communications underwater. While lower costs, more accuracy, lower power and smaller size seem to be obvious metrics to aspire towards, some of our colleagues in the engineering community were surprised that they could (in general) tradeoff other requirements that are required on land such as wide temperature stability.

There were also certain requirements which were less generic but just as important with a notable case being the need to transition from in-situ point measurements of chemical properties to high resolution flux measurements across fixed areas and within fixed volumes.

3.1.1 Clocks

The lack of GPS constrains not the navigation accuracy underwater but also just as importantly the ability to obtain high precision, low drift rate clocks for the variety of sensors that are required on the seafloor. These are critical for long term time series measurements from distributed sensors but also would be the basis of precise navigation for platforms on the seafloor.

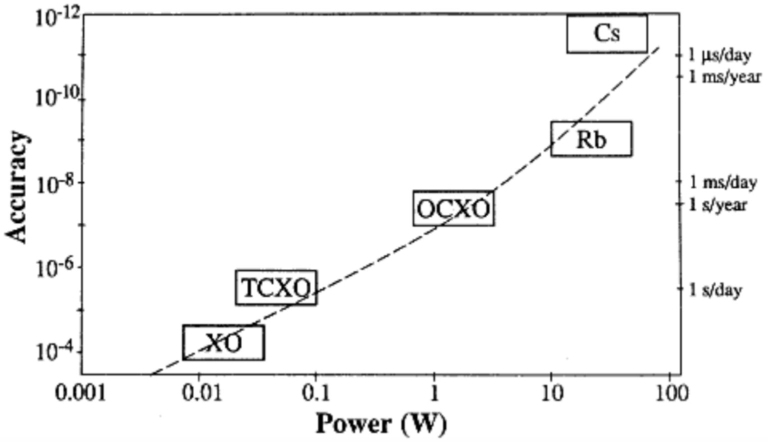

Figure 4. Clock accuracy versus power. The current generation of chip scale atomic clocks are an important breakthrough compared to the traditional clocks graphed above but are still not at the numbers that end users desire. Figure courtesy www.oscilient.com.

Current clocks have issues with precision, drift and power draw. Requirements from the seismology community are for a drift rate of less than 1ms over a period of one to five years. The current specifications for the chip scale atomic clocks are actually very close to the requirements in some regards (120mW power consumption, <17cm^3 volume, 35g weight, ±5.0E-11 accuracy at shipment, <1E^{-11} @1000s Short Term Stability). In practice, however, these devices have not lived up to expectation.

3.1.2 Orientation Sensors

Inexpensive orientation sensors are still a major stumbling block for seafloor science. Our current compasses have an accuracy of close to five degrees while the requirement is for a degree or less. Gyrocompasses which can easily meet this specification are too expensive from a cost, power and size viewpoint.

3.1.3 Housings

Deep water housings are a very mature technology with no active research into new materials and other design tradeoffs. Ceramics, carbon fiber all hold out promise but the market for deep sea deployments seems to be too small to sustain major research and testing efforts and such work needs to be encouraged. From just the perspective of being environmentally friendly, the half-life of the metals we use is extremely long and it would be nice to explore and identify options that are biodegradeable.

3.1.4 Batteries / Energy harvesting

Battery technology has been advancing significantly over the last few years these advances are driven primarily by the consumer market however requirements for underwater work are significantly different. Rechargeable batteries charging with an enclosed purchase sphere is a significant issue hope wondering batteries podcast he is still challenging.

The good news is that our instrumentation has very little current draw although at this stage it is still a few orders of magnitude greater than what is available through energy harvesting. The academic research community continues to make strides in terms of small devices capable of energy harvesting. The challenge for our community is to enable the routine use off energy harvesting and either eliminate or supplement our needs for primary and secondary battery storage.

Inductive power transfer has also seen giant strides on land for a variety of consumer applications. These technologies can be transitioned to use underwater and the concept of inductive power transfer coupled with acoustic or optical based data transfer may enable the next generation of standalone sensor networks that can be serviced from shore by long endurance underwater platforms.

3.1.5 Chemical ADCP

The fundamental issue here is to move away from making point measurements to we couple chemistry and physics to get mass fluxes. At vent sites, for instance, measurement of fluxes requires faster sensors and perhaps an entire sensor array. The coherence between physics and chemistry holds out the promise for such measurements related to imaging techniques using optical, PIV, eddy covariance and scaling.

3.2 Technology Drivers: Communications

Science-driven seafloor operations rely on collection of physical samples, but also on the data that is gathered on-site and transmitted to the surface user. Data transmission can be accomplished through tethered links, by muling (physical transportation by AUVs), or by wireless communication links. Wireless transmission is desirable for obvious reasons (cables are heavy and restrict maneuverability) and is typically considered in two forms: optical, for short links with high bit-rate (e.g. data offload from a submerged instrument to an AUV), and acoustic, for longer links (anything in excess of about 100 meters) with lower bit rates. Currently available modem technology supplies transmission rates on the order of Megabits per second optically or a kilobits per second acoustically (e.g. the Woods Hole micro-modem, or the Benthos/Teledyne modems). While this technology may suffice for the present practice, much is to be desired for the future seafloor operations.

The benthic research group identified the need for wireless deep water communications (full ocean depth), as well communication between AUVs, be it point-to-point or within a group of autonomous agents that need to stay inter-connected during a mission. These two categories summarize the overarching needs fairly well, as neither deep water communications nor fleets of cooperating autonomous agents are in standard use today. While the first is challenged by propagation conditions that lead to effects such as shadow zones, the second is challenged by the development of network protocols that must orchestrate multiple communication links operating at the same time and in the same frequency band over a medium that entails potentially very long propagation delays.

The seismology group identified needs in data offload from seafloor sensors (possibly optical, to be muled by AUVs), direct bottom-to-surface acoustic links, and inter-connection to seafloor cables. This group also pointed out the need for accurate time keeping, which calls for measuring the salient clock drifts during deployment.

The fluid flow group identified the need for large-coverage sensor data collection (fluid properties at low flow rates), and search-and-map missions involving AUVs operating on multiple spatial scales. In terms of communications, these two requirements respectively imply static networks of a large number of nodes, and dynamic networks of fewer nodes but ones that integrate communication with navigation. Common to many of the above issues is also the question of on-board processing or edge computing: How much data should (and can) be compressed, how many decisions made on-board a sensor before a condensed message is sent over a band-limited underwater link?

With these questions in mind, it is clear that the scientific community is in dire need of a networking capability that can operate autonomously and in a robust manner under the ocean surface. To that end, three categories of science drivers were identified: point measurements, survey missions (mobile systems that need to operate on varying scales, ranging from local to regional), and multi-vehicle platforms. Within each category, three specific issues were found to need attention: (1) on-bard processing, (2) communication link (physical layer, i.e. modulation/signal detection), and (3) network design (multiple access, topology control, routing). We now look at these in turn.

3.2.1 On Board Processing

The needs for on-board processing systems change significantly as a function of requirements. Point measurement sensors might need compression, decision making and threshold detection, while multisensory array systems of type need more-sophisticated data fusion mechanisms. Networked systems need an additional dimension of on-board resource allocation including decisions on how much power to allocate to processing and how to allocate communications depending upon a node's proximity to neighbors.

3.2.2 Communications Link

In terms of the communication link, single sensors typically just need a direct link to the surface for periodic data offload. In contrast, multisensory arrays will need spectral agility for multiple range scales or operating situations. Finally, networks of platforms may require variable rate transmission with respect to quality-of-service and range requirements. At this time, vertical links have been demonstrated in the field. The community has also conducted conceptual studies of power and rate adaptation for acoustic communications system, but spectrum agility or rate adaptation have not been field deployed. The issue of communication system design is a major one that reaches beyond off-the-shelf technology and into the domain of its own research. A separately organized NSF workshop dedicated specifically to these issues was held in Washington D.C. in March 2018. That workshop identified a number of topics that should be addressed in the future, including the development of standardized channel models, modulation/detection methods beyond the commercially available ones (e.g. multi-carrier methods, software-defined scalable receiver architectures and network protocols for high latency operation.

3.3.3 Networking

Networking for the systems for fixed sensors is strictly speaking not required, but seafloor sensors, deployed for benthic point measurements could serve a dual use; namely, they could be outfitted to provide navigation aid ("underwater GPS") to other systems operating in the vicinity, such as isolated AUVs or fleets of AUVs. Multisensor systems bring up the issue of topology control, one that has been repeatedly mentioned, but not tested in practice. Scalability is a major issue in these systems: Can we design networking protocols that are equally applicable to a 1 km by 1km area and to a 100 km by 100 km area? Within the systems comprising moving platforms, networking brings up the issues of interference management, cooperation, network resource management and directive transmissions. Many of these issues depend upon the availability of feedback, by which one end of a link informs the other about the current propagation conditions. Acoustic feedback is a high-priority issue that will usher a new generation of acoustic communications that can adapt to the changing conditions thereby saving battery power, providing robustness, and increasing network capacity. So far, only a few isolated efforts have been mounted to demonstrate an adaptive acoustic link and much remains to be accomplished on this front.

3.3.4 Navigation

The introduction of precise clocks with acoustic networks has been already been demonstrated and the routine use of such technologies would enable a step change in our ability to navigate precisely (of the order of a meter) in the mid water column and the seafloor. However, as pointed out earlier, the requirement for an inexpensive heading sensor is still a major hurdle in terms of underwater navigation.

3.4 Technology Drivers: Platforms

3.4.1 Surface Platforms

The deep seafloor community has a rich history of using manned submersibles, remotely operated vehicles and autonomous vehicles for benthic, fluid flow and other applications. However these platforms all require ship support. The tradeoff between speed, area coverage, and the use of sensing modalities requiring significant power have limited deep sea floor platforms to operational scenarios that last from hours, to days to weeks and typically require a ship in reasonably close contact.

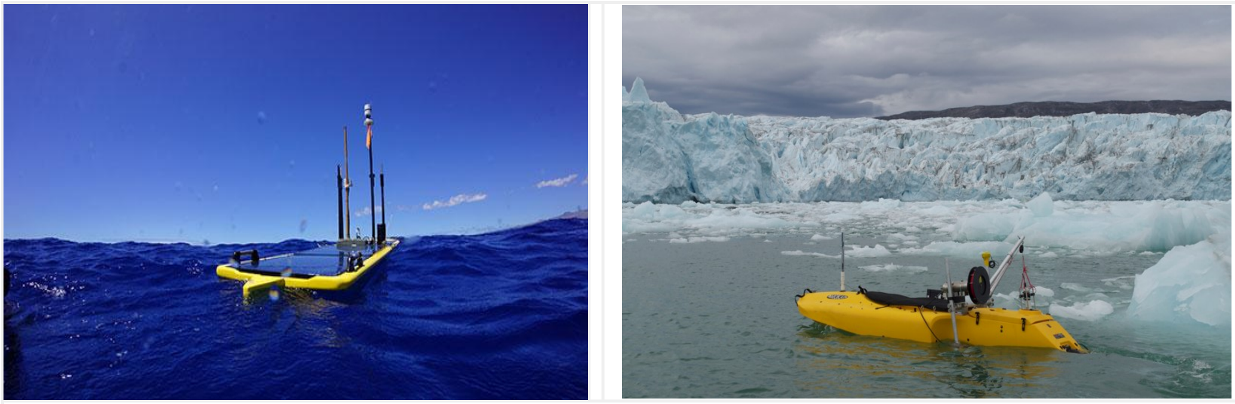

Figure 5. The Waveglider (left) and the Jetyak (right) ASVs represent two ends of the spectrum with respect to ASV capabilities. The Waveglider has extremely long endurance (measured in months) but moves very slowly as opposed to the Jetyak which is designed for speed but has limited (24 hour) endurance. The ability to combine these characteristics, that is travel 1000km at speed with significant payloads would represent a breakthrough for deploying and servicing seafloor instrumentation in the deep ocean.

For midwater column and surface measurements gliders and unmanned surface vehicles such as the wave glider and the saildrone have far longer legs but with limited sensor capacity and speed.

It is now technically feasible to build and deploy Autonomous Surface Vessels (ASVs) that are capable of 1000 km transects while carrying significant payloads. These systems hold the promise of saving significant ship time by acting as data mules to offload data from OBSs and other deep ocean instrumentation.

ASVs have also demonstrated an ability to ferry AUVs to remote locations for autonomous deployment and recovery. Such AUV deployments would further enhance our ability to turn service deep ocean instrumentation acting not just as data transfer mules but also serving as a mechanism to replenish power for deep sea nodes.

3.4.2 Manipulation

Manipulative capabilities on the seafloor continue to pose significant challenges. There is a strong need for developing control strategies for largely neutrally-buoyant platforms while grasping. The fundamental issue is how to deal with resultant forces imparted by a grasped object and the environment. This translates directly to our ability to provide significant force for push-cores and rock drilling, from smaller platforms.

There is also a strong need to provide haptic feedback for fine scale manipulative tasks such as collecting delicate biological samples.

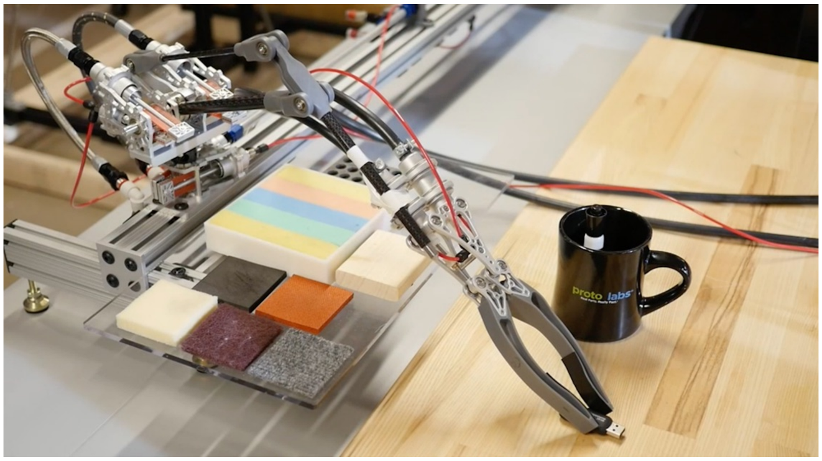

Figure 6. The development of manipulators that are lightweight, naturally haptic and preserve high-bandwidth force control and dexterity and their extension to the underwater environment holds out the promise of allowing small AUVs to conduct complex tasks autonomously in support of seafloor science. Image courtesy Prof Peter Whitney, Northeastern University

The ability to conduct autonomous manipulation in the unstructured deep sea floor environments is strongly highly desirable. On land there has been considerable progress in our ability to autonomously image and grasp object in cluttered environments but we need to translate this work to encompass the constraints unique to the underwater environment.

3.4.3 Systems Level Issues

While we have broken down the technical barriers into distinct categories it should be pointed out that individual progress in even some of these areas will see large dividends for the entire community as the individual parts come together into larger, more coherent systems. Solving the acoustic networking problem will considerably ease our ability to deploy underwater “GPS” system which in turn will positively impact our ability to deploy fleets of multiple vehicles.

4.0 Summary

While there are significant challenges facing the deep seafloor community, engagement with core engineering efforts holds out the promise that breakthroughs in the fields of IoT, and consumer product development can have a significant impact on seafloor science. While certain areas such as sensor development and robotics have strong land based efforts that can be modified and leveraged for applications related to seafloor science, there is also a strong need for basic research in other areas that are specific to the ocean environment.