

# ARGONAUT: A ROBOTIC SYSTEM FOR CRYOGENIC ENVIRONMENTS\*

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## Abstract

Fermilab and the HEP community invest significant resources into liquid argon detectors. The largest and most expensive of these detectors will be located in the Deep Underground Neutrino Experiment (DUNE). However, recent experiences have shown that there are limited avenues of monitoring, intervention, and interaction in the internal liquid environment. This proposal shows a technological path that could provide a valuable tool to ensure or at least improve management of these HEP detectors. The development of a robotic system named Argonaut will demonstrate several technologies including:

1. demonstration of suitable mobility of a small robotic device at liquid argon temperatures,
2. demonstration of wireless communication,
3. demonstration of improved diagnostics capabilities, such as tunable optics with motion control,
4. demonstration of interconnectivity of a robotic system with hardware residing within the detector.

This initial research will be a seed for extended development in cold robotics and associated technologies. This work will allow FNAL to contribute a significant technology capability to recent efforts to cryogenic detector operations.

## SIGNIFICANCE

The Deep Underground Neutrino Experiment (DUNE) will use large detectors consisting of modules with a fiducial mass of 10 ktons of liquid argon (LAr) [1]. As part of the development of LAr detector technologies, much has been learned from years of design efforts and detector operations on smaller systems. Significant effort is required in preparing and testing of planned hardware for the reliability and expected performance requirements for systems. These systems must last longer than anything the HEP community has ever built before without the option of access to the inside of the detector for diagnosing or repairing problems.

Lessons learned from recent experiences working with LAr detectors have highlighted shortcomings in both diagnostics and accessibility. We propose Argonaut, a robotic system that resides inside of a LAr detector. The first goal for this robotic system is to improve the diagnostics capabilities such as the monitoring of temperatures, electronics, high voltage systems, and assisting in assembly, filling, and any required maintenance. The next goal is to show Argonaut's repair capability which is not an option in existing LAr detectors or currently planned for DUNE. A final goal

is to improve the operations of the LAr detectors by showing the feasibility of a robotic system to assist in calibrating the detector.

## CAPABILITIES

This work has many possible research avenues and benefits and we expect this LDRD to act as a seed for extended development in cold robotics and associated technologies.

### Diagnostics



Figure 1: Birdseye view top view port (left) and a View Port Camera System (right).

The ProtoDUNE detector illustrates the shortcomings in diagnostic capabilities of current LAr detectors. The dual phase ProtoDune detector had a LAr mass of 0.3 kt [2]. ProtoDune had cameras strategically placed to monitor all the necessary areas. Alternate camera systems, shown in Fig. 1, stage the camera on a enclosure that penetrates the top of the detector vessel. However, ProtoDune experienced bubbles which formed in areas not seen by the cameras. The experiment was left theorizing the bubble formation location because the cameras were not mobile. Even had a camera been fortunate to be pointing at the location, a firm analysis may not have been possible because the cameras could not autofocus. Argonaut would take advantage of the latest camera technology by using complementary metal-oxide semiconductor (CMOS) cameras to monitor inside the LAr detectors. The use of CMOS cameras at cryogenic temperatures within LAr has made significant progress and continues to be developed. Argonaut can provide the mobile platform to bring the CMOS camera(s) to investigate any problems. Argonaut can help with monitoring the drift voltage in the high voltage area of the LAr detector's Time Projection Chamber (TPC). CMOS cameras with isolated power sources such as power over fiber (PoF) offer the possibility of use near high voltage.

For instance, the drift field required for DUNE is  $500 \text{ Vcm}^{-1}$ , implying a nominal drift voltage as high as approximately -200 kV. This may be high enough for HV breakdown. Having Argonaut bring a camera to the TPC in a detector as large as DUNE can aid in monitoring its drift voltage. Additoanlly, an electric field monitor that

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records the electric field within the robotic region as well as the electrostatic potential could be achievable (similar to satellite E-filed monitoring).

### Calibration

The calibration of these large detectors is critical to ensure physics performance. A variety of calibration systems are required to perform operational systems checks for all aspects of the detectors. Two calibration systems require the use of external lasers to create either ionization tracks inside the active detector region or a photon shower. The coverage should be complete enough to allow an accurate mapping of the detector response parameters. These external systems rely upon preplace components with limited options. A submersed robotic system could provide for extended coverage and backup capability. Argonaut demonstration plan will include a movable mirror with 180 degrees in x and 90 degrees in y motion capability. Additionally, using piezo deflectors, we hope to demonstrate sub degree control.

As already mentioned, electrical-field calibration may be possible although initial plans are to demonstrate near ground plane membrane measurements.

Photo detector calibration may be enhanced with a movable emitter system. Argonaut could generate any number of light pulses in areas not easily accessible. This could act as a primary or as a backup capability.

### Repairs

As previously noted, a failed HV support on ProtoDune could not be repaired without significant downtime and costs. Loss of electronic components were expected and did occur but with no option for repair. If the DUNE detectors are designed with a robotic system in mind, field cage circuit boards and SiPMs PoF systems could be made to be exchangeable. We propose that Argonaut have small armature(s) with specific grip technologies. Recent success at CERN has shown that clippers and graspers are good candidates, but others need to be examined. The ability to house a set of accessible arm appendages would allow a robotic system to change from one tool to another as needed. Power limitations and weight are likely to drive the design and capability of the appendage(s).

## MECHANICAL DESIGN

Argonaut technology R&D can be divided up into three overlapping areas: Diagnostics capabilities, electrical (cold electronics and power), and mechanical. The mechanical aspects are what will determine the success of the robotic system. The difficult environment of LAr (87 degrees K) will be very challenging for a variety of reasons [3]. Initial safety requirements include that the system does not contaminate, does not generate a significant amount of bubbles, and does not pose a threat to the detector operation when operating or in a failed state. Off-the-shelf solutions and material selection will consider its sustainability within the cold environments over long periods of time.

### Material Selection

In the past Fermilab has created small, movable camera systems using vessels made of stainless steel in conjunction with aluminium bronze for motion components. The leak-tight vessels, as shown in Fig. 2, serve to protect the electronics of the off-the-shelf camera when the vessel is immersed in LAr. Each assembly includes a viewport for the camera lens. For a robotic system with a limited power budget that needs to move over a large area, the weight of a stainless vessel is problematic. The Argonaut project will attempt to use PEEK, G10, and other plastics for the camera vessel to keep system weight a minimum. Using plastics instead of metals in this low-pressure environment will help reduce power consumption, simplify mechanical support design, and open the door to additional manufacturing processes. To speed up the development phase the Argonaut project is currently investigating using 3D printed PEEK components with or without post processing to create non-machinable, leak-tight geometries.

Figure 2: Stainless Steel Camera Vessel at FNAL.



### Motion

Motion on the argonaut project can be broken into two distinct categories. The first category is motion that occurs inside the system itself, isolated from the cryogen. In this scenario there is no risk of grease or bearing material debris contaminating the LAr. Small resistive-heating circuits inside the system could also be employed to keep the motion components operating within a suitable temperature range. When possible, motion components such as motors will be kept outside of the vessel using off the shelf feedthroughs to minimize the number of bearing surfaces in LAr.

The second category of motion, movement which requires motion components in the cryogen, provides a much larger challenge. For the range of motion required to inspect large detectors it will be nearly impossible to locate all motion components such as motors, guide rails, bearings, and locomotion systems outside the cryogen. As such, contamination due to material wear may become a considerable problem. To help minimize debris from material wear, keeping the mechanical loads on the motion system low and careful material selection will be required. Piezo-electric motors have been shown to work in liquid helium

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temperatures and show some promise for small movements [4]. Consideration must be given to finding long-lasting solutions that do not require maintenance, or a method to access the motor for repair or replacement over the lifetime of the detector.

For moving the motion of the robotic system over a large area several methods of locomotion are being considered. A stainless-steel acme screw and aluminium-bronze nut with PEEK guide bushings is a common solution for single axis motion in cryogenic systems. For a two or three degree-of-freedom system, complications begin to arise as the drive motors or power transfer components for one or more axes become challenging to isolate from the cryogen. One possible alternative well suited to a two-axis range of motion would be to use a cable driven system as shown in Fig. 3. By using a three-cable arrangement all drive motors can be kept out of the cryogen, and only a single bearing on the lower pulley is immersed in LAr. While movement range is somewhat limited, this system lends itself to a simple mechanical design and a low number of moving components. Another option could be to forgo a mechanical drive system entirely, and instead use superheated jets of argon gas to propel the system. By locally heating areas of the cryogen and carefully redirecting the produced gas, it may be possible to propel the vessel slowly along guide rails provided the vessel has neutral buoyancy.

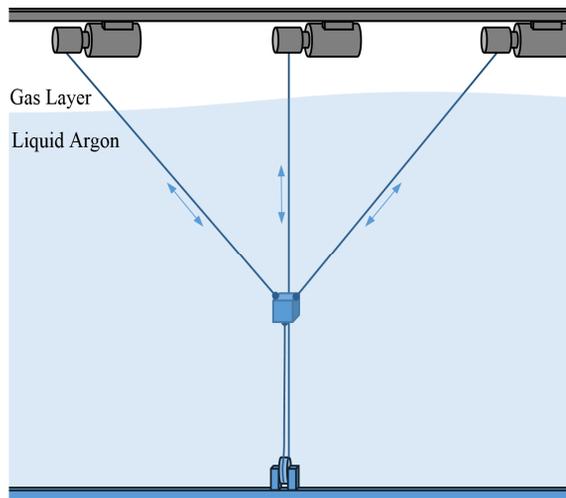


Figure 3: 3-Motor cable drive system.

### Appendages

In addition to diagnostic capabilities, a robotic system within a LAr detector may be able to directly interact with the detector to simplify calibration and repair. A mirror mounted to the exterior of the camera vessel may be used to allow precise calibration from within the vessel without the use of external viewports. Additionally, small grippers or single degree-of-freedom actuators could allow the robotic system to perform simple mechanical repairs on the detector in-situ. The mobile platform could also include sensor packages with additional degrees of freedom to get localized temperature data as needed.

## ELECTRICAL DESIGN

The electronics considerations include finding components that can operate as required for the lifetime of the detector, power limited – efficiency will be critical, and motor power systems. Argonaut will utilize recent cold electronics but focus on components that meet efficiency demands of a closed isolated system with PoF as the only source. The power systems have been divided into several functional areas. However, general discrete component use and testing will follow work previously done for cold detectors, NASA applications and quantum [4-6].

### Communication Power

The difficult environment will be very challenging for a variety of reasons. Initial safety requirements include that the system does not contaminate and does not pose a threat to the detector operation when operating or in a failed state.

### Motors/Motion Power

We have planned motion control for a mirror, camera, and demonstration of an external arm. This first Argonaut will have limited area coverage due to test stand limitation. These systems will have a several watt power budget. This will result in slow motion with limited torque.

### Diagnostics Power

There are several planned diagnostics components to be tested. As previously mentioned, a camera and lighting system is a priority. An initial investigation of the requirements and possible available devices has provided a short list of suitable CMOS high resolution cameras. The ideal candidate will provide several mm resolutions, adjustable focal length (to be determined), sensitive to wavelengths from approximately 350 – 1050 nm, low noise (0.7 e<sup>-</sup>), and low power.

A temperature probe will be included with resolution of better than 1 degree. The temperature probe will be a simple two wire device and connect to a planned mother board circuit.

A e-field probe is being investigated. This will use a two-bulb differential probe to measure the flux density. The sensitivity required to be useful is estimated to be about 3%. Initially, the static field testing will be in one plane perpendicular to the grounded detector membrane.

All the above-mentioned diagnostic hardware will be connected to a mother board. The data pipeline may be transmitted via optical fiber or wirelessly via Bluetooth or Wi-Fi. Both options are planned to be investigated.

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