Automating a Cryogenic Transport System for Measuring Quantum Materials

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Abstract:

Collection of resistivity-temperature data is necessary for the determination of the residual resistance ratio (RRR) of samples, and is further useful for observing other material characteristics, including the Curie temperature of superconducting materials. Two current measurement methods are utilized: a cryogenic transport measurement system and the physical property measurement system (PPMS). This report will detail the mechanization and automation of the former, with the intent of creating an upgradable, semi-modular, automated system with improved reliability and reduced operator involvement.

Summary of Research:

Design Considerations. The current cryogenic transport measurement system measures resistivity temperature data by immersing a sample attached to a four-point terminal sensor into a dewar of liquid helium. The sensor itself is attached to a 1.5 meter long rod, with a connection box on the opposing end. The temperature is controlled by the physical positioning of the probe within the dewar, with the probe being slowly lowered until it reaches the surface of the liquid helium. The rate of change in temperature is controlled via operator feedback, with users adjusting the depth of the probe to maintain the approximate desired rate. This process on a whole takes 1-1.5 hours to complete, and is significantly faster than the PPMS system, which takes 6-7 hours. However the process requires the operator to be present for the entirety of its duration, and with the throughput of upwards of 70 samples a month, the time spent operating the system is nontrivial.

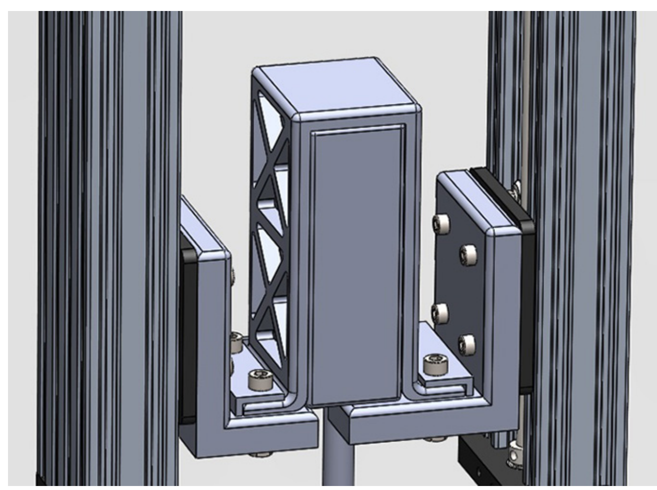

Figure 1: Mounting bracket within SolidWorks CAD software.

Other motivating factors for changes to the existing system include improving the mechanical reliability of the system. At maximum excursion, the probe connection box is lifted close to three meters off the ground. Because the center of gravity is located at this height without additional support, the rod has warped over its lifespan, leading to occasional mechanical stoppage and increased difficulty in the lowering and raising process. Likewise, variation in measurement methods has also led to incorrect usage of the system.

The current system could therefore be improved by adding a hardware layer involving mechanization and automation. In addition to improving mechanical robustness, mechanization would allow for set usage of the system and further reduce potential operator error.

Hardware Design. To replace the manual mode of raising and lowering the probe, mechanized linear actuation was required. Of equal consideration was the significant travel distance necessitated for the process (one meter). The chosen option involved the implementation of a lead-screw linear actuator. This was favored over a ball-screw design because the latter would have necessitated the use of braking mechanisms and was generally less suited for vertical application. Belt-driven actuation is suited for high-speed travel but is otherwise inferior for the planned use case, suffering from slippage and poorer actuation control. A worm-screw system would require a significant re-design of the system, which was beyond the scope of the project.

To drive the linear actuators, two NEMA-23 style motors with 345 oz-in of torque were chosen. While the load imposed by the probe itself is minimal, the friction created by the o-ring seal was not. Furthermore, microstepping the motors to increase resolution would also have led to a corresponding decrease in torque. These factors necessitated the selection of higher torque motors. The mounting bracket to hold the probe was designed in SolidWorks and underwent several rapid prototyping iterations using the various 3D printers available through the ECE Makerspace and RPL. This allowed for several versions of the bracket to be developed within the span of two weeks, each with iterative improvements.

Software Design. To interface between the aforementioned hardware and the existing LabView environment used for data-taking, an Arduino microcontroller with the LabView interface for Arduino (LIFA) package was utilized. LIFA provides serial communications with the Arduino microcontroller via the LabView virtual instrument software architecture (VISA), and allows for programming of the microcontroller within the LabView environment. This enables firmware changes to be made without the need to enter a dedicated low-level programming environment, which should increase program serviceability and usability.

Software is built on state machine architecture, which is suited for the automation required by the project. The architecture further enforces a set number of "states" for the machine to exist in, and should also help to standardize measurement methods between various operators of the system. The original data-taking software has since been added as a sub-VI into the integrated motion control and measurement system.

Current Status and Future Work:

Currently, the proposed dipper system has been assembled, with electronics fully integrated. The system has completed initial trial runs, which have proven the functionality of the linear actuation method. Planned short-term improvements include designing further hardware fail-safes into the system, improving the user interface for the software, and adding z-axis distance sensing for the actuators. Longer-term work will include the integration of a new version of the probe, as well as development of PID controls for actuation.

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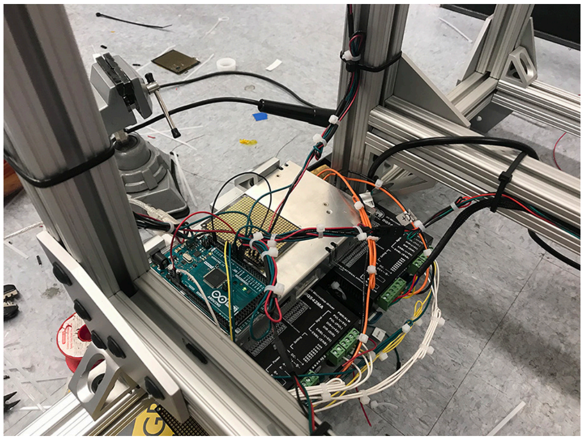

Figure 2: Integrated electronics bay for system.

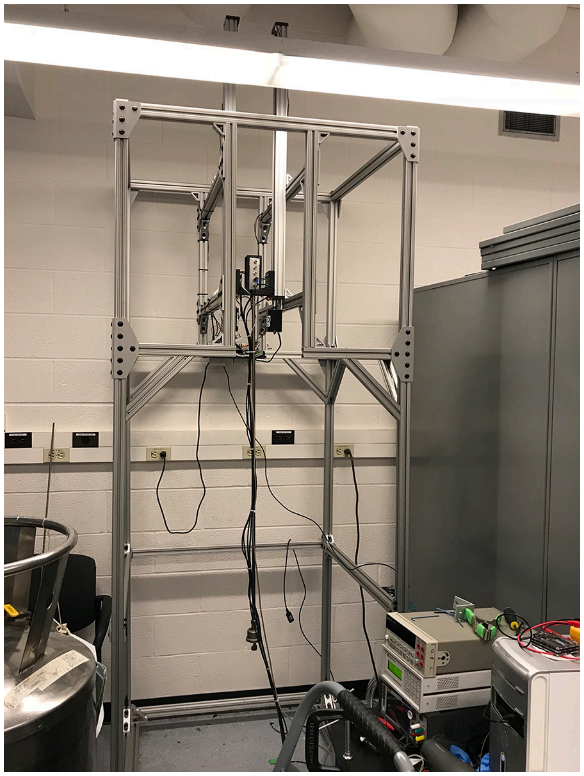

Figure 3: Completed system in unloaded position.