Mechanical Design and Fabrication of Compact, Portable Nuclear Particle Detectors

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Abstract — **Over the past decade there has been an increased interest in compact, portable particle detectors for a variety of applications - nonproliferation, nuclear waste management, fundamental physics research, etc. As a result, many institutions are now designing and building various radiation detectors that can be transported by two or fewer persons or a small vehicle. Historically, neutrino (e.g., Super-Kamiokande experiment in Japan) and neutron detectors have been very large and immobile. These large, static detectors have a substantial volume of passive scintillator, and in the case of neutrino detectors, are buried far beneath the ground surface, minimizing the effects of background radiation. The transition to a compact, portable detector has introduced several challenges in various focus areas. Less scintillator volume means a lower interaction rate requiring more efficient detection techniques and more powerful digitization capabilities. For these reasons, readout components with very high quantum efficiency per unit area and compact, fast-timing electronics with a high-channel count are desirable. The reduction of passive scintillator volume also requires other physical aspects of the detector be cleverly designed and precisely fabricated. Furthermore, these compactness and portability requirements introduce challenges with regard to power and thermal management as well as background radiation discrimination. This paper examines on the mechanical design and fabrication process of compact detector components intended to optimize the optical characteristics of a neutron detector. It focuses on our current optically segmented neutron double scatter camera design, but also reviews lessons learned from our previous compact detector designs, including miniTimeCube and NuLat.**

I. INTRODUCTION

As the saying goes, "the devil is in the details." This holds especially true for compact instruments with multiple interconnected components. A particle detector, for instance, requires scintillating or light propagating material, readout components such as photomultipliers, digitizers (i.e., the electronics hardware), a power supply, supports and an enclosure. All of these items must work together to allow for particle interactions to be observed and transmitted into useful information. However, several mechanical challenges arise when transitioning from design space to physical tests which prevent useful data from being collected. Sometimes patchwork can be performed in the firmware or software, but ideally the physical design, fabrication and assembly of the device is such that minimal software fixes are required.

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Detailed experiences with constructing compact detectors and a review the lessons learned is discussed herein. Material selections and fabrication processes are examined and summarized to optimize future compact detector development.

II. The miniTimeCube Experience

Members of our team developed and assembled one of the first compact, portable neutrino detectors, the miniTimeCube (mTC) [1], in 2012. The mTC consisted of a 13 cm cube of boron doped plastic scintillator with all 6 faces covered by 24 micro-channel plate photomultiplier tubes (MCP-PMTs). Coupling the MCP-PMTs to the plastic cube was achieved using optical grease, which due to an unexpected suction force, created semi-permanent connections. It was very difficult to remove the PMTs without damaging them. Removing and replacing PMTs would have been beneficial in improving the performance of the instrument. For example, it was believed that air bubbles trapped in optical grease caused some erroneous results, but this could not be verified and was never resolved.

Custom electronics developed at the University of Hawaii were connected to the back of each PMT directly, without cables, to maximize compactness and improve signal integrity. These components (scintillator cube, MCP-PMTs and electronics) made up the central core of the detector and performed the main functions with regard to neutrino signal readout and digitization. Figure 1 depicts the mTC detector components.

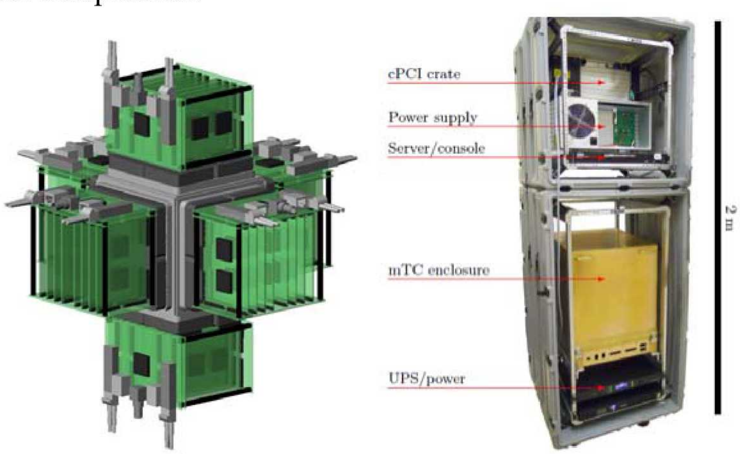

Figure 1. (Left) Rendering of the central core of components for the mTC detector – custom electronics, MCP-PMTs and a cube of plastic scintillator (hidden from view); (Right) stacked configuration of mTC and auxiliary components (active cooling system and external cabling and tubing not shown) [1].

As the detector assembly and testing progressed, difficulties with heat dissipation and component communication caused the detector prototype to evolve into a very complicated network of systems – e.g., an active cooling system was required, a Raspberry Pi was installed and a Weiner electronics module was added, resulting in a rat's nest of cabling and tubing, as seen in Figure 2. Assembly, supporting and housing all components proved to be a challenging task. A quick solution of metal poles, connecting clasps and zip ties were instrumented to support everything. A brass enclosure ("The Gold Box") was built using a computer numerical control (CNC) machine and welding to contain everything and provide a light tight enclosure. This setup was sufficient for operating the various detector systems, but did not allow for easy disassembly, maintenance and reassembly. Labeling each and every component was crucial in knowing which channel, system or segment of the detector was which.

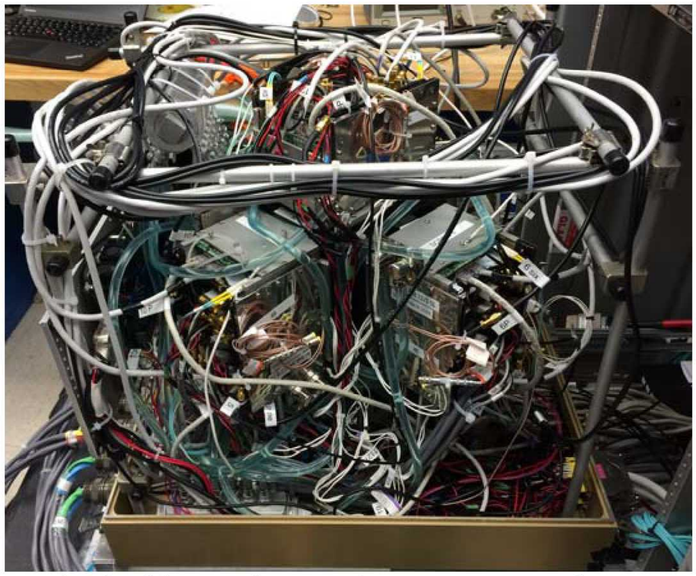

Figure 2. Complex network of cabling, tubing and wiring surrounding core of mTC.

The custom electronics, containing application specific integrated circuits (ASICs), could reach temperatures exceeding 80° C, which compromises the integrity of the material used to create a vacuum seal within the PMTs. Due to the susceptibility of the mTC detector components being damaged from overheating or leaking, failsafe measures were implemented. Temperature, humidity and leak sensors were installed and programmed to send out warning texts and then shut down all systems if a reading limit was surpassed. These systems were tested and worked well except for one critical instance.

During testing in a laboratory at the National Institute of Standards and Technology (NIST), the temperature failsafe malfunctioned and the cooling system coincidentally shut down causing temperatures to rise over the 80° C limit. This situation went undiscovered for about one hour before the system was manually shut down. One PMT was determined to be nonresponsive immediately after this incident. Over the course of several months, 8 additional PMTs failed one by one. It was never confirmed that the overheating incident was the cause of all 9 failed PMTs, but the evidence suggested that was the case.

In addition to the mechanical complications of the mTC, performing physics analysis to accurately reconstruct neutrino (neutron or gamma) events was also very challenging. Because the detector was a monolithic solid cube of scintillator surrounded by 4 PMTs on each side, each interaction would be read out by multiple PMTs on multiple sides of the detector. This configuration resulted in background radiation frequently mimicking the target signal and prevented the readout components and data analysis from deciphering neutrino signals from gamma interactions, for example.

As a result of the complications experienced during testing and operating the mTC, alternative configurations were employed in future detectors developed by members of the mTC team and our collaborators.

III. Neutrino Lattice (NuLat) Demonstrator

mTC developers also participate in the NuLat neutrino detector project initiated by Virginia Polytechnic and State University (Virginia Tech) [2]. As the name suggests, the NuLat design was based on a 3D lattice arrangement of 3375 small plastic scintillator cubes (6.3 cm) separated by small reflective spacers. The NuLat design is very similar to the Raghavan Optical Lattice (ROL) demonstrator shown in Figure 3.

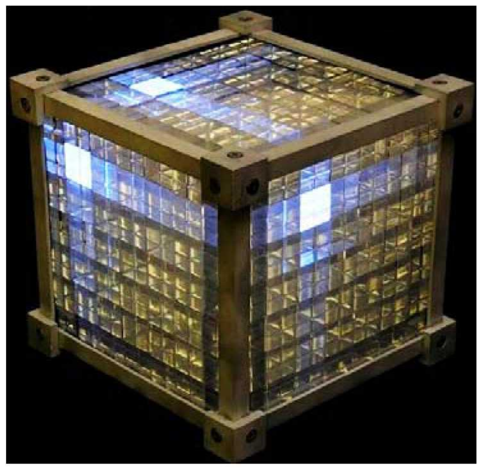

Figure 3. Photo of a solid Raghavan Optical Lattice (ROL) demonstrator constructed at Virginia Tech. prior to NuLat [2]

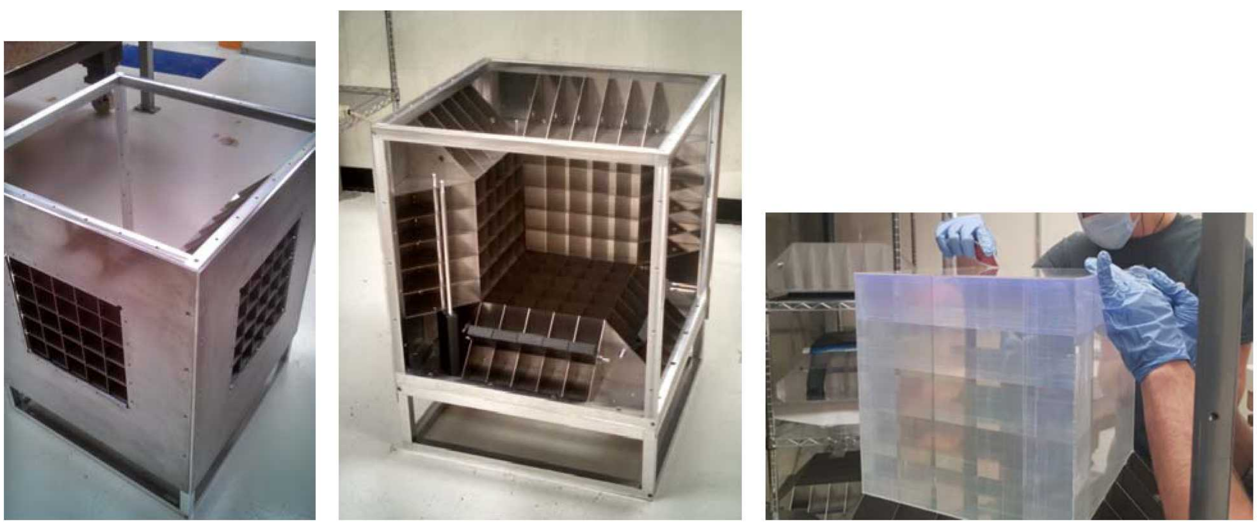

Figure 3. (Left & Middle) Steel support structure and enclosure for the NuLat detector, (Right) assembly of acrylic box surrounding scintillating cubes

This lattice design offers a theoretical improvement to its monolithic counterpart in neutrino interaction location precision since light propagation is contained within the perpendicular rows and columns associated with the cube where the initial and subsequent particle interactions occurred. However, segmenting the scintillator volume introduces many mechanical design challenges, especially considering the full scale prototype (15x15x15 scintillating cubes) would have 1350 round PMTs reading out particle interaction signals. In the small scale prototype (5x5x5 scintillating cubes) currently in production, these PMTs were coupled to the outer scintillator cubes using acrylic light guides (square surface transitioning to a round surface, Figure 4). Both optical grease and optical interface pads were used to create the optical connection between light guides and the PMTs. To eliminate air bubbles in the optical grease that may have been trapped in this interface, these coupled components were placed in a vacuum chamber overnight. Designing supports to keep all the scintillator cubes, PMTs, and light guides aligned and fixed was a very challenging endeavor. These details are described in a thesis paper written by Xinjian Ding [3].

Figure 4. PMT sitting on a custom acrylic light guide [3]

Collaborating with the Virginia Tech team on the development of the NuLat detector prototype has provided invaluable insight on various mechanical techniques, material selection and other component configuration resolutions.

IV. Optically Segmented (OS) Single Volume Scatter Camera (SVSC)

The authors of this paper currently collaborate in the Single Volume Scatter Camera (SVSC) program managed by Sandia National Laboratories in Livermore, California. This program focuses on neutron detection using the kinematics of neutron double scattering. The relevant theory suggests a neutron source (e.g., spent reactor fuel or weapons grade plutonium) can be located and/or imaged by computing the trajectory of incoming, emitted neutrons via energy and timing measurements of primary and secondary neutron scatters. Figure 5 illustrates one possible safeguards application of a soldier scanning shipping containers at a shipyard or similar storage facility. This illustration also shows the compactness and portability that our team is considering when selecting various detector components and configurations.

Figure 5. Rendering of a potential application of a mature OS SVSC used at a shipyard.

The OS SVSC design employs 64 narrow bars of plastic scintillator which channel light propagation to silicon photomultipliers (SiPMs) used to read out the neutron interaction signals. This design deviation from the mTC is intended to improve the signal to noise ratio and simplify the analysis required to reconstruct events. However, the OS detector prototype has repurposed the same custom electronics used for the mTC. Although these electronics have notable issues, we have them on hand with many of the firmware and software packages completed. Furthermore, one electronics module reads out 128 channels – the total channel count of the OS prototype.

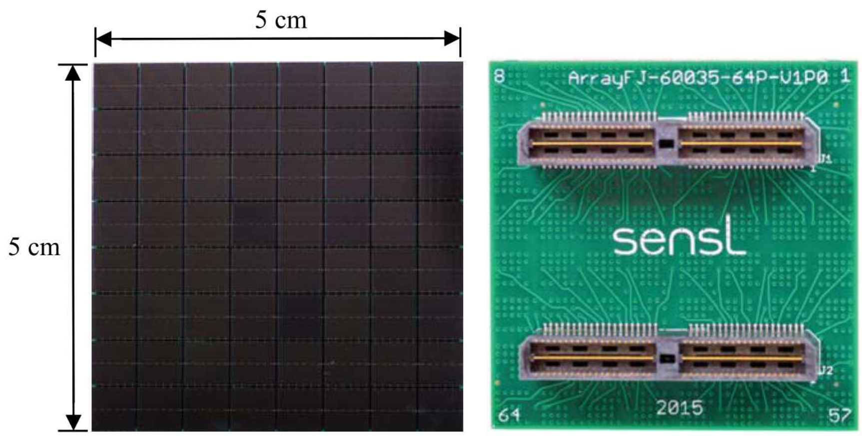

Figure 6. Front and back of a 64 6 mm x 6 mm pixel J-series SiPM array from SensL

Each end of a 5mm square cross-section scintillator bar couples to a 6mm square SiPM. Our design is currently driven by the off-the-shelf SiPM arrays provided by SensL Technologies, Ltd., as shown in Figure 6. Therefore, an array of 64 scintillator bars is used as the passive detection volume of the detector. Figure 7 illustrates the configuration of components inside the compact neutron detector currently being developed and tested by the SVSC collaboration.

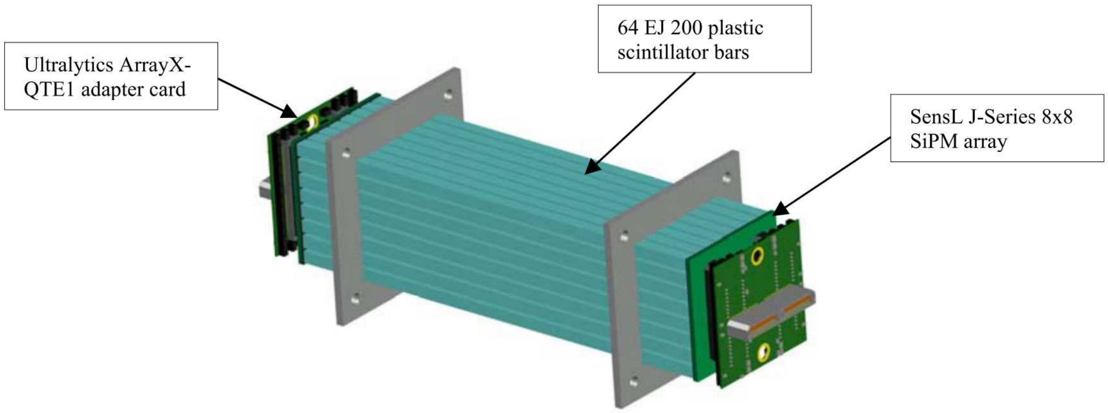

Figure 7. Rendering of OS SVSC internals.

Mechanical components are manufactured in-house using rapid prototyping methods (e.g., the lattice bar and SiPM array supports in Figure 8 are 3D printed with polylactic acid (PLA) filament, while the outer enclosure walls are milled from aluminum plate using a CNC machine to achieve a high degree of precision). As seen in the photo (Figure 8), the scintillator bars are wrapped in Teflon tape to improve light retention, since it acts as a reflector. The optimal bar type and wrapper were studied by testing individual bars and comparing the position resolution results. The results of these studies can be found in Ref. [4]. Threaded rods were used to align the support components and allow for wrapped bars to be passed through both lattice supports. This was an extremely tedious process and we are exploring design improvements to make assembly less complicated. Not shown in Figure 8 are silicon rubber optical interface sheets termed "cookies." These cookies provide an interface for the photons to travel from the ends of the bars to the SiPMs. Eventually, as used with the mTC and NuLat detectors, optical grease will be applied for more advanced testing, but to minimize cleaning between disassembly and reassembly, cookies will be used for the interim. The suction force that caused issues with the mTC is reduced for the plastic bars due to less surface area, but the SiPM arrays must be slid transversely, instead of pulled laterally, off the ends of the bars to avoid damage.

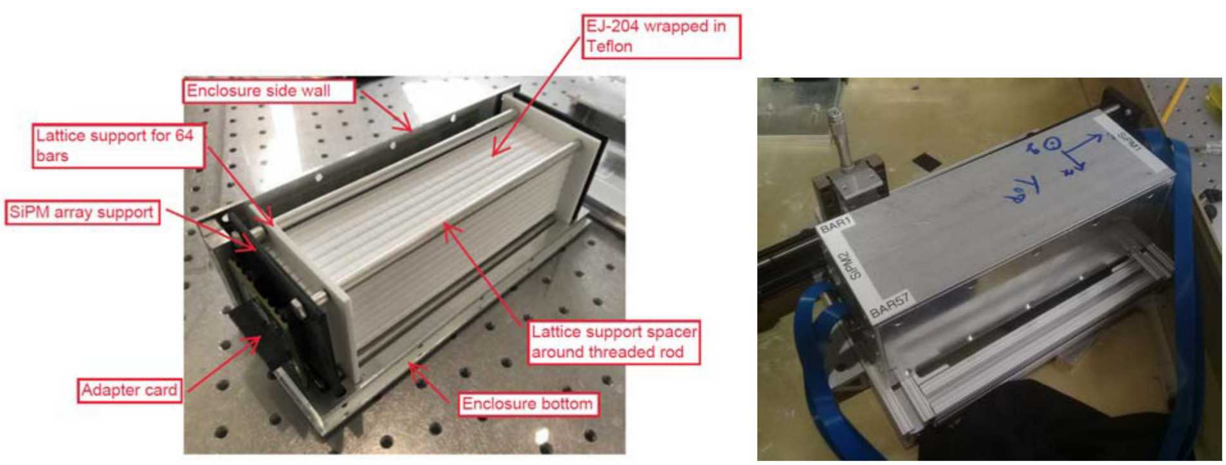

Figure 8. (Left) Photo of Phase 1 prototype enclosure and internals for OS SVSC. (Right) Phase 1 prototype of the OS SVSC in a test setup. Data is transferred to digitizers (not shown) using blue Samtec cables.

To minimize light leakage, all enclosure screw holes are tapped such that they are ultimately blind, and there are only two thru-holes in the end walls for the adapter card connectors. The digitizer electronics and power supply will reside outside the prototype enclosure. Figure 8 shows the assembled prototype setup for testing within the repurposed Gold Box. During the fit check of the internal components in the enclosure, a SiPM was damaged due to excessive force applied to its surface from a bar end. A lattice support also cracked during this procedure.

Testing of the 64-bar prototype is ongoing, but many useful results have been determined and design improvement opportunities have been identified. The test results, which will be summarized in future paper(s), have determined a need to reduce both optical and electrical cross-talk. The design improvements planned thus far consist of 1) modifying the SiPM and bar spacing, 2) modifying the SiPM and bar cross-section size, 3) reducing the cable length or eliminating the cables that carry data from the adapter cards to the digitizers and 4) redesigning the adapter cards. Further improvements are also being considered, such as changing the enclosure material from aluminum to a more optimal material that shields unwanted particles, but allows neutrons to pass through. Furthermore, more efficient scintillating (or similar) material and more reliable electronics are being investigated as part of a long-term development.

V. Conclusion

Our collaboration has gained a strong understanding of various materials and techniques used to detect and located radiation sources. We leverage this knowledge to rapidly advance our current prototype detector shown in Figures 7 and 8. New prototype versions will continued to be developed and tested since it is relatively inexpensive and each development advances our understanding and the effectiveness of the device.

Simulations are being prepared to identify the optimal configuration of the SiPM array, bar size and component spacing. We aim to assemble a custom SiPM array in house as part of a future OS prototype phase. This redesign will require all new support and enclosure components, but these changes are motivated by the indication that nearly all cross-talk can be eliminated. Physics results from testing new prototype OS SVSC detectors will hopefully be published by early 2020.

References

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