Underwater Photometry System of the SNO+ Experiment

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Abstract.

The SNO+ experiment is a large-scale liquid scintillator-based experiment, adapting the Sudbury Neutrino Observatory (SNO) detector located at SNOLAB, Canada. The main physics goal is to investigate the Majorana nature of neutrinos through the search for the neutrinoless double-beta decay of $^{130}\text{Te}$. The camera system of SNO+ is designed to photograph calibration sources and triangulate their locations with an accuracy of a couple of centimeters. This will lead to better calibrations and more accurate physics measurements in SNO+. The camera system, when operated in a special mode with underwater lights turned on, also allows monitoring of the physical state of the detector. The optical calibration source was deployed in the water filled SNO+ detector in the summer of 2017. Pictures of the deployed source were taken using the camera system while the underwater lights were turned on. The triangulation analysis of the pictures gave us an opportunity to test the position accuracy of the deployed source in SNO+ using the camera system.

1. Introduction

The SNO+ experiment [1] uses infrastructure from its predecessor, SNO (Sudbury Neutrino Observatory) [2]. The detector is located 2 kilometers underground in Creighton Mine near Sudbury, Ontario, Canada. The existing acrylic vessel (AV) will be filled with 780 tons of liquid scintillator. The advantage of the transformation of SNO into a liquid scintillator detector is a boosted light yield and lower energy threshold of the detector. The acrylic vessel, 12 m in diameter, is surrounded by a photomultiplier (PMT) supprot structure (PSUP). The PSUP is a 17.8 m diameter geodesic steel frame, holding 9300 inward-facing PMTs coupled to reflectors that may increase the photocathode effective coverage up to approximately 54%. The AV and the PSUP are immersed in 7000 tonnes of ultra-pure water, which shields the scintillator volume from radioactivity in the PMTs and the surrounding rock. Additional shielding with thick urylon liner prevents diffusion of radon from the rock into the water volume, allowing for low background measurements at low energies.

The detector adapted from SNO has been upgraded with new calibration hardware as well as a new data acquisition and readout system. A rope net was also added to apply an even downward force on the AV to counteract the buoyancy of the liquid-scintillator filled AV. A camera system
Figure 1. Cameras are mounted on the PSUP around the SNO+ detector, looking inwards on the AV at six symmetrically-space locations, labelled as prototype(P) and camera numbers 1-5. Hoses containing camera electronics are shown in red, with the hold-down rope net shown in yellow. Two different orientations of the camera enclosure are shown in inset.

was installed on the PSUP to monitor the physical state of the detector, including the position of the rope net and the movement of the AV. The camera system can take photographs of a deployed calibration source and triangulate its location as a more accurate means of source localization. This will lead to better PMT calibrations and more accurate physics measurements from the SNO+ detector.

2. The Camera System
The camera system consists of six Nikon D5000 cameras mounted on the PSUP in symmetrically spaced locations looking inwards on the AV as illustrated in figure 1. Each camera has a wide view owing to its fish eye lens (Nikon AF-S DX 10.5mm F2.8G Lens) and is enclosed in watertight, stainless steel enclosures with clear acrylic dome-shaped viewports. The lens has a 180° picture angle allowing for wide-angle shots for each camera to view the entire AV. Each camera is connected to the control deck of the SNO+ experiment through a 25m long hose shown in red in figure 1. Each hose contains wires for power, RJ45 (ethernet) signal cable, and a plastic hose for a N\textsubscript{2} gas flush system to remove moisture from the enclosure. After reaching the surface, each group of three hoses reaches a control box that manages the electrical connections and monitors gas flow. From these boxes, the signal from each camera passes to an on-deck computer capable of remote and near-simultaneous operation of the cameras [3]. Two underwater lights (LEDs) are also installed as an external light source in the detector. They are mounted on the lower hemisphere of the PSUP beside two cameras so that the rope net is lit close to optimally. Figure 2 is shows two camera photographs viewing the AV from two different orientations. Shining underwater lights (LEDs) and their reflections on the AV surface are clearly visible in both photographs.
3. In situ camera calibration

In order to triangulate a calibration source position in the detector using multiple camera pictures, it is necessary to calibrate cameras individually by constructing a map of the source positions from a 3D global coordinate system to a 2D pixel space, \( f(X, Y, Z) \rightarrow (x_{\text{pixel}}, y_{\text{pixel}}) \) as depicted in figure 3. This is done following two steps: 1) transform the object in the global reference frame is transformed into the camera’s reference frame, in which the camera sits at the origin using Euler rotation \([3],[4]; \) and 2) transform the object from the camera’s reference frame to the pixel coordinate system, which projects the object into the imaging plane of the camera. Because, the fisheye lens is subject to considerable distortions, additional corrections are applied for the fisheye lens projection onto the 2D image plane \([4]\). Calibrating a camera requires consideration of more than 1000 PMT positions within the 3D coordinate system of the
Figure 4. A camera photograph [left photograph of figure 2] was adjusted using openCV libraries with varying adaptive thresholds so that most of the PMTs are foreground [upper left image]. Camera parameters are fit [bottom left image] using the known pixel positions of the visible PMTs and the contours of 3D PMT positions are overlaid on the photograph. Dots drawn at the centres of the contours are overlaid on the original colour image [right image].

Figure 4 shows the steps involved in in situ camera calibration. The first step is to adjust the contrast and brightness of the camera picture so that the individual PMT edges (of reflectors) are sharp and clear. The second step of the camera calibration involves the use of OpenCV libraries to vary the adaptive threshold constants to highlight most of the PMTs, making them white and foreground so that they can be detected with a contour fitter, as shown in upper left photograph of figure 4. In addition to the adaptive threshold in determining the brightness of all PMTs, the size of the threshold box and blurriness are optimized to even out the noise. The third step is to take this dataset and pass it through a contour fitter that determines the model parameters that best translate each point in 3D space into the 2D pixel frame. Ellipses are drawn over the contours found for PMTs by the fitter, shown in lower left photograph of the figure 4. In the fourth and last step of the camera calibration, the 3D PMT coordinates transformed into the 2D pixel space using the fitted camera parameters to generate a pixel map. The 2D pixel map is overlaid on the original image to confirm the accuracy of the fitted camera parameters, as shown in the right photograph of the figure 4.

4. Triangulation of the object position
Once the cameras are calibrated, they can be used to triangulate the 3D location of an object in the detector. To triangulate the location of a single point it is necessary to input its pixel location for each camera, as well as the set of the fitted parameters for each camera. The result of the minimization gives the coordinates \((X, Y, Z)\) that best translate into the pixel coordinates seen by each camera. The quantity being minimized is the residual between each calculated \((x_{\text{calc}}, y_{\text{calc}})\) pixel position using the fitted parameters and the observed \((x_{\text{pic}}, y_{\text{pic}})\) pixel position in the photograph, summed over all cameras involved.
5. Results
We have analyzed a photograph set where calibration source is clearly seen with two cameras only. To triangulate the center of the source, its pixel location for each camera and the set of fitted parameters of each camera were used. The result of the minimization gives the 3D coordinates of the deployed laserball position that best translates into the pixel coordinates seen by each camera. The camera picture triangulation analysis gives the deployed position of the calibration source in the detector coordinates as $(30.10, -2.58, 149.15)$ [mm], whereas the deployed position measured by the encoder used to deploy the source in the AV was $(0, 0, 108)$[mm].

The difference in the determined position of the calibration source using camera photographs and the position given by the encoder system is 51.05 mm, which is slightly worse than the expected accuracy by a couple of centimeters. Since the deployed laserball was visible only with two cameras, this likely impacted the minimization accuracy while triangulating the position of the source in the detector.

6. Conclusions
A camera system was installed in the SNO+ detector in order to accurately determine the position of deployed calibration sources in the detector and to monitor the rope net and AV during the experiment. Each camera in the camera system has now been calibrated in situ using the known position of the PMTs visible in the photographs taken by cameras. The accuracy of the triangulation method was tested using the photographs by two cameras of the optical ‘laserball’ calibration source during its first deployment in the detector. We expect the accuracy of the triangulation analysis to improve when a deployed source is visible by all cameras.

7. Acknowledgements
This work is funded by NSERC, CFI, DOE, ERC, NSF, STFC, FCT, CIFAR, EGI, GridPP, Compute Canada, Deutsche Forschungsgemeinschaft, Berkeley, ASRIP, Ontario MRI, FedNor, and Queen’s University. Kalpana Singh is supported by NSERC. We thank SNOLAB and Vale for valuable support.

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