TOC-WP-21-4560
STUDENT SUMMER INTERNSHIP TECHNICAL REPORT

Autonomous Navigation and Radiation Mapping Platform – Hardware Updates and Integration

DOE-FIU SCIENCE & TECHNOLOGY
WORKFORCE DEVELOPMENT PROGRAM

Date submitted:

December 10, 2021

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Submitted to:

U.S. Department of Energy
Office of Environmental Management
Under Cooperative Agreement # DE-EM0000598

ABSTRACT

Through the maturation of technologies, the Chief Technology Office (CTO) at Washington River Protection Solutions (WRPS) supports the Hanford Mission by heightening the levels of safety and efficiency in site workflows. Using off-the-shelf autonomous robotic platforms, such as the Clearpath Robotics® Husky™, as baselines for the development of automated workflows, the CTO studies robotic applications to tasks where a reduction of personnel entrances into key areas of the Hanford site are desired to reduce operational costs, decrease exposure risk, and obtain a higher flow of consistent data. One such task is the development of an automated system for general radiological mapping of an area – areas like tank farm perimeters. The Husky – or the Canary – was updated for the task and an upgraded sensor package was installed, alongside improved local networking and an auxiliary power system to support the new equipment. In conjunction with the existing equipment on the Canary, a more robust autonomous navigation capability was enabled and supported the development of an automated mapping workflow that can output a planar radiation map of a designated area.

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1. INTRODUCTION

The Chief Technology Office (CTO) at Washington River Protection Solutions (WRPS) supports the Hanford Mission by developing and maturing technologies that increase safety and efficiency. Off-the-shelf autonomous robotic platforms – such as the Clearpath Robotics® Husky^{TM} (also known as the Canary) – are a point of interest and development within CTO as they allow for autonomous workflows performed at a higher that require minimal supervision. This represents a benefit in operational cost reduction, decreased exposure risk, and a higher influx of more consistent data.

The market for off-the-shelf autonomous systems is steadily growing, with newer examples being closer to a ready-to-deploy solution than ever before. The Husky is an example of an off-the-shelf system that was slated for research and development, with a focus on providing a robust and open base for additional hardware and payload integration. By default, a Husky comes as a basic platform but can be optionally equipped with cameras, IMUs, arms, and other sensors and hardware.

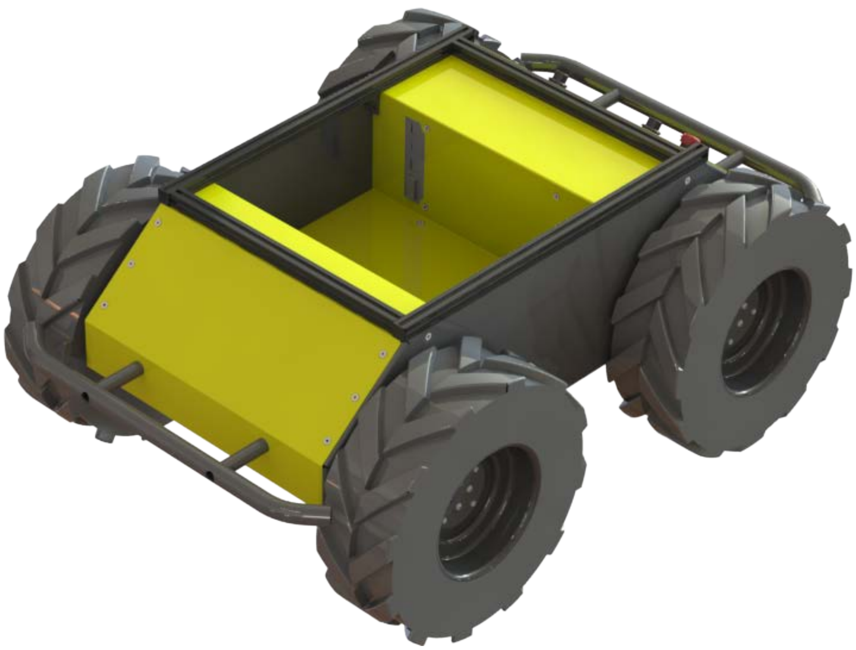

Figure 1: 3D render of Clearpath Robotics® Husky^{TM}.

The Canary – the Husky available at the CTO – came equipped with a suite of hardware that was best suited for primary teleoperation and mild autonomy. These capabilities were bolstered with initial hardware improvements that increased communication range and operational time between charges. With this setup as a baseline, the Canary was positioned to be a viable option for long-term operation in tasks that support the Hanford Mission – tasks such as autonomously producing a two-dimension (2D or planar) spatial radiological map to monitor general radiation levels of an area.

Although the Canary was already equipped for mild teleoperation, it was not fully outfitted for simultaneous localization and mapping (SLAM) or primarily hands-off operation. It was also not equipped to gather radiological data for use in the planar radiation mapping process. As part of the effort to develop an autonomous navigation and radiation mapping robot using the existing Canary, changes and additions to the hardware needed to be made to support the necessary functions for the task to be carried out.

Amongst the changes that were made to the original Canary are an updated operating system and software package, reworked network infrastructure, additional compute units, sensors to aid in navigation, localization and data, and an expanded auxiliary power system to support the additions. The end goal for the hardware adjustments was to develop the Canary on top of the already existing baseline to produce a robotic platform with the ability to autonomously conduct SLAM and gather radiological data with minimal input from the operator. The gathered data would then be used to generate the planar radiation map of a chosen area of interest.

Figure 2: Canary platform in baseline configuration.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2021, a DOE Fellow intern Jeff Natividad spent 12 weeks doing a summer internship at Washington River Protection Solutions under the supervision and guidance of Technology Integration Project Manager Alexander Pappas. The intern's project was initiated on May 17, 2021 and continued through August 5, 2021 with the objective of supporting the development of an autonomous radiation mapping robot by integrating an updated sensor package, reworking the on-board network, and producing an auxiliary power system for the existing Clearpath Robotics® Husky™.

3. RESEARCH DESCRIPTION

To bolster the autonomous navigation capabilities of the Canary, the onboard hardware was reviewed to evaluate the current limitations of the robot. Out of the box, the Canary featured a suite of hardware that was best suited for teleoperation and mild autonomy, which included a pan-tilt-zoom (PTZ) camera, a global positioning system (GPS) unit, a planar light detection and ranging (LIDAR) sensor, and an inertial measurement unit (IMU). This equipment suite was hooked up to the onboard computer, which is a small unit that is responsible for the robot's functionality such as movement and signal processing.

Additional hardware was initially added to the Canary to improve its communication range and operational time between charges. The original equipment lead-acid batteries were replaced with larger, lithium iron phosphate batteries which were mounted on the flat lid of the Canary. The charging system for these batteries was also installed on the Canary in the cavity that used to house the original batteries. This power equipment was initially strapped down to the Canary using ratcheting straps. As for communication, a long-range peer-to-peer antenna pair was installed to improve the operating range of the Canary. This effectively increases the maximum distance between the Canary's control laptop and the Canary itself.

With the former being considered the baseline configuration, the Canary was capable of long-range teleoperation using a controller connected to the control laptop and the live video feed from the pan-tilt-zoom camera. If placed outdoors, the GPS could be used in coordination with the LIDAR to perform basic autonomous point-to-point waypoint navigation with light collision avoidance. Generally, the operation of the Canary within an indoor environment depended on teleoperation while outdoor environments could allow a mix of teleoperation and autonomous navigation. For a general-use automated radiation mapping robot, this was not ideal.

Several hardware additions were necessitated to enhance the overall navigation capabilities of the Canary and enable simultaneous localization and mapping (SLAM) for the task of autonomous radiation mapping. To aid in navigation and localization, an upgraded sensor package was installed consisting of two LIDARs and three depth cameras. To process the massive influx of data from the new sensors, two additional single-board computers (SBCs) were installed. The on-board network system was then revisited to interlace the now three on-board computers, the long-range antenna – and the control laptop by proxy. To power all the additional and upgraded equipment, a new auxiliary power system had to be developed to allow for additional power connections and a higher load.

The integration of all these new and updated components involved a combination of modeling mounts on computer-aided-design (CAD) software for three-dimensional (3D) printing, soldering, managing wires and connectors for power and data, and developing network and power interfaces. The result was a single-button startup procedure for all the integrated systems on the Canary, which now had the potential to perform automated radiation mapping.

4. HARDWARE DETAILS AND INTEGRATION

4.1 The Upgraded Sensor Package

The first improvement made to the Canary's base configuration was the installation of several new sensors as part of an improved sensor package that would enable reliable and robust navigation capabilities that could surpass the limitations of the existing equipment. The upgraded sensor package includes depth cameras and LIDARs to cover both short- and long-range localization. As compared to the original capabilities of the Canary, the new package allows for autonomous navigation in not only tighter spaces, but also larger spaces

The bulk of the new package included three Intel® RealSense™ depth cameras – the D415, the D435, and the D455. These stereo image sensing devices allow for the generation of point cloud data that and three-dimensional imaging that help the Canary move forward in autonomous navigation by generating a detailed map of the environment ahead of it. Additionally, these three cameras were chosen to help improve the odometry and localization of the robot, which opened the Canary for use in tighter spaces. Each of the cameras can publish individual inertial measurement unit (IMU) data that can be used to improve the performance of the Canary's navigation through sensor fusion when the odometry frames are set up properly.

Two additional LIDARs were added to the system as well – the SLAMTEC® RPLIDAR A2 and the Intel® RealSense™ LIDAR Camera L515. The RPLIDAR was chosen due to its cost effectiveness and performance, which allows for the planar detection of objects at distances up to 12 meters away at an entry-level price. The L515, on the other hand, is a solid-state LIDAR that was chosen due to its minimal power use and production of high-resolution maps and images of its environment. These additional LIDARs were to be used in conjunction with the existing SICK® LMS-1XX 2D LIDAR to provide the Canary with a longer-range overview of the surrounding environment, as well as serve as collision sensors at different heights and orientations.

To handle the additional computing load and provide connectivity for the new sensors, two additional SBCs were added – an NVIDIA® Jetson Nano™ and an NVIDIA Jetson Xavier™ NX. Both of these small computers feature embedded graphics processors that allowed for efficient processing of the large influx of data from the sensors. The Xavier was designated to be used for managing the three forward-facing depth cameras and the RPLIDAR data streams, while the Nano would handle the rear-facing solid-state LIDAR. These two new computers were integrated into the robot operating system (ROS) network that also includes the control laptop and the primary on-board computer.

Lastly, a radiation sensor – the Type 5 Pocket Geiger Radiation Sensor from SparkFun Electronics® - was integrated via an Arduino® Nano connected through USB to the primary on-board computer. This sensor was designed to be used in conjunction with embedded systems and provides a basic reading after a 2-minute measurement time. The measurement range is between 0.05uSv/h to 10mSv/h at 0.01cpm to 300Kcpm. Although the data output was deemed to be basic, the error of measurement was also provided. With the radiation count and the error available, enough data was accessible to develop a model for a two-dimension radiation map.

4.1.1 Sensor Package Integration

To integrate these sensors onto the Canary, considerations had to be made for the placement of the different sensors. For the purposes of this task, forward navigation was emphasized, so the decision was made to have the three depth cameras facing forward. The largest of the three cameras, the D455 was to be mounted facing directly forward at the frontmost point on the Canary to provide the highest quality and range for the environment directly in front of the robot. The other two cameras would be mounted to the side of the Canary, but at a 45-degree angle to cover a wider area for the forward map. Meanwhile the L515 solid-state LIDAR would be mounted at the top of the Canary facing the rear. This decision was made to ensure detailed rearward vision for not only navigation and mapping, but also for obstacle avoidance. Meanwhile, the RPLIDAR would be mounted below the L515 and above the batteries to provide longer-distance coverage for obstacle avoidance.

New mounts had to be designed to accommodate for the decided mounting positions. Each mount was custom-designed via computer-aided-design (CAD) software and considered specific details from each sensor and the aluminum extrusions present form mounting on the Canary. Additionally, some of the parts were designed with a level of modularity in mind, such as the side camera mounts which feature additional camera mounting holes that allow for different angles to be used when mounting.

Figure 3: Examples of designed mounting pieces.

By using manufacturer documentation and previous design experience, each mounting piece was manufactured only once and required no additional iterations. The designed mounts were then sent for manufacturing. A Markforged® Onyx One was used to manufacture the designed parts via fused filament fabrication in their proprietary Onyx material. The Onyx carbon fiber filled nylon was ideal for the application due to its high strength and light weight.

4.2 Improved Networking Package

In the previous year, the network connectivity of the Canary was revamped to accommodate additional access points – both wired and wireless – for field testing at the time. Although this system was effective for handling the basic communications needed at the time between the on-board computer and the control laptop, it would not suffice for the additional components that were added with the upgraded sensor package. Additionally, a power component used for the peer-to-peer antenna connection was exhibiting signs of instability – so it was necessary to revisit the network system.

Previously, an on-board router was added to provide additional hard access points to the network, as well as a locally broadcasted wireless access point. However, this only allowed for two devices to be connected to the hard-lined local network due to a lack of ports. The router itself also required a decent amount of mounting space. So, the decision was made to switch to an on-board ethernet switch that would expand the number of wired access points, enhance network reliability, and simplify mounting and network management. This simplified network interface still featured an extra wired access point if a system outside of the ROS network needed to be connected in for maintenance purposes. Due to its compact nature when compared to the previously installed router, the ethernet switch was moved to the interior of the Canary to aid in cable management – essential for keeping the network cables neat and accessible.

Figure 4: On-board Ethernet switch in initial location.

As for the peer-to-peer antenna instability issues, the problem was traced to the installed power-over-ethernet (POE) injector that provided the required power to the ethernet cable for the peer-to-peer antenna. The antenna – a Ubiquiti® Bullet™ AC – required stable 24-volt power supplied via the network cable to work properly. However, the installed POE injector was failing to power on under normal start-up circumstances. For that injector to work, the antenna would have to be disconnected before powering on the Canary. Once the Canary was powered on, then the antenna could be reconnected. This was not ideal for field tasks where a one-button start-up (or simple wake-up) procedure was desired.

To remedy the instability issue, a replacement POE injector was installed to provide the power required to maintain a stable connection with the antenna. Not only did the new POE injector perform the same job as the previous injector, but the new unit was also smaller in size and aided in simplifying the interior of the Canary alongside the ethernet switch. The main difference in function between the old and new injectors is that the newer unit did not feature a built-in voltage regulator to accept common 24-volt inputs (22.6 to 25.6V). Instead, it injected the power it was provided directly into the cable. The proper 24V input for the injector, as well as the 12V input required for the ethernet switch was sourced from the newly installed auxiliary power system.

4.3 The Auxiliary Power System

Previously, the only way to power external equipment from the Canary's main power system was to access the interior power terminals of the robot – which was limited to a maximum current of 5 amperes by the fuses in each block (5, 12, and 24 volts). Some of these terminals were already populated and required a specific connector to interface with them. In preparation for a field task in the previous year, an automotive power inverter was initially installed to provide a high-capacity 120-volt interface with the batteries on the Canary. This was useful for powering larger components, such as an air compressor or data gathering equipment. However, the inverter system was imparting a parasitic draw on one of the batteries even when powered off, causing an uneven discharge condition that could potentially damage the battery cells. It was important to revisit the power system and produce an alternative auxiliary power system to support the equipment needed for the autonomous radiation mapping concept.

Figure 5: Initial integration of components on Canary without new power system.

The new auxiliary power system needed to power the primary new components – the two additional SBCs, new POE injector, and ethernet switch – and work in conjunction with the Canary's main power system for start-up and shut down. This was initially a complex idea since each of the components mentioned needed a different voltage, and a method of interfacing the auxiliary system with the existing power system was necessary. The new POE injector required 24 volts, the Xavier SBC needed 19 volts, the ethernet switch ran off 12 volts, and the Nano SBC was powered by a 5-volt source.

4.3.1 Addressing the Different Voltages

The Canary runs off a 24-volt system, source from a pair of robust lithium-ion phosphate batteries that provided 12 volts each on their own. For the new auxiliary system, it was desirable to first provide an efficient and neat means of accessing the power from the battery pair. To achieve this, screw terminal blocks were chosen to allow for easy access to the 24-volt level power coming directly from the batteries. Two blocks were used – one for the positive side of the power system, and the other for the ground side. Each block allowed up to four additional components to be connected cleanly while providing a simple means of connecting and disconnecting components for maintenance.

With access to the main battery power available, the work continued onto providing power at different voltages. To provide different voltages to the new components, automotive voltage regulators were used that could take the 24-volt input and step down to a variable output. This was ideal since the variable output would allow for the fine-tuning of the voltage to the required point for each component. This was particularly important in the case of the new POE injector, since it would provide the input power directly to the ethernet cable.

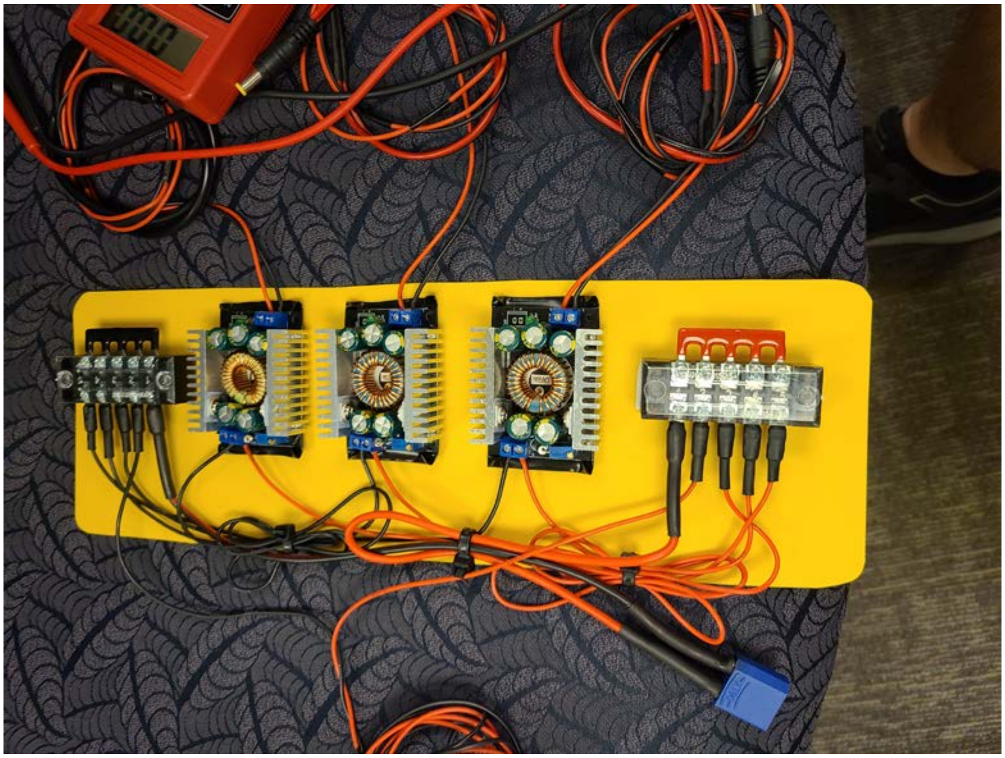

Figure 6: Initial layout of the auxiliary power system.

The complete auxiliary power system would then consist of the two terminal blocks and the four voltage regulators – one for each voltage that was required for the new components to run. It was of interest to test the system fully before integrating it on the robot, while at the same time making it available for use in the meantime for the development of the navigation stack. Each voltage regulator was installed on the auxiliary power system individually and a multimeter was used to dial-in the appropriate output voltage on each unit. Once the appropriate level was selected, only then was the component that needed power connected.

The components – such as the SBCs – were connected to the voltage regulators via silicone wire for reliable power delivery and workable management. On the voltage regulator side, the wires were installed via screw terminals that came with the regulators. On the component side, the wires terminated in barrel plugs for a direct plug-and-play interface. These barrel plugs also allowed for hot swap capabilities in the event that an SBC or component needed to be replaced or worked on individually from the Canary.

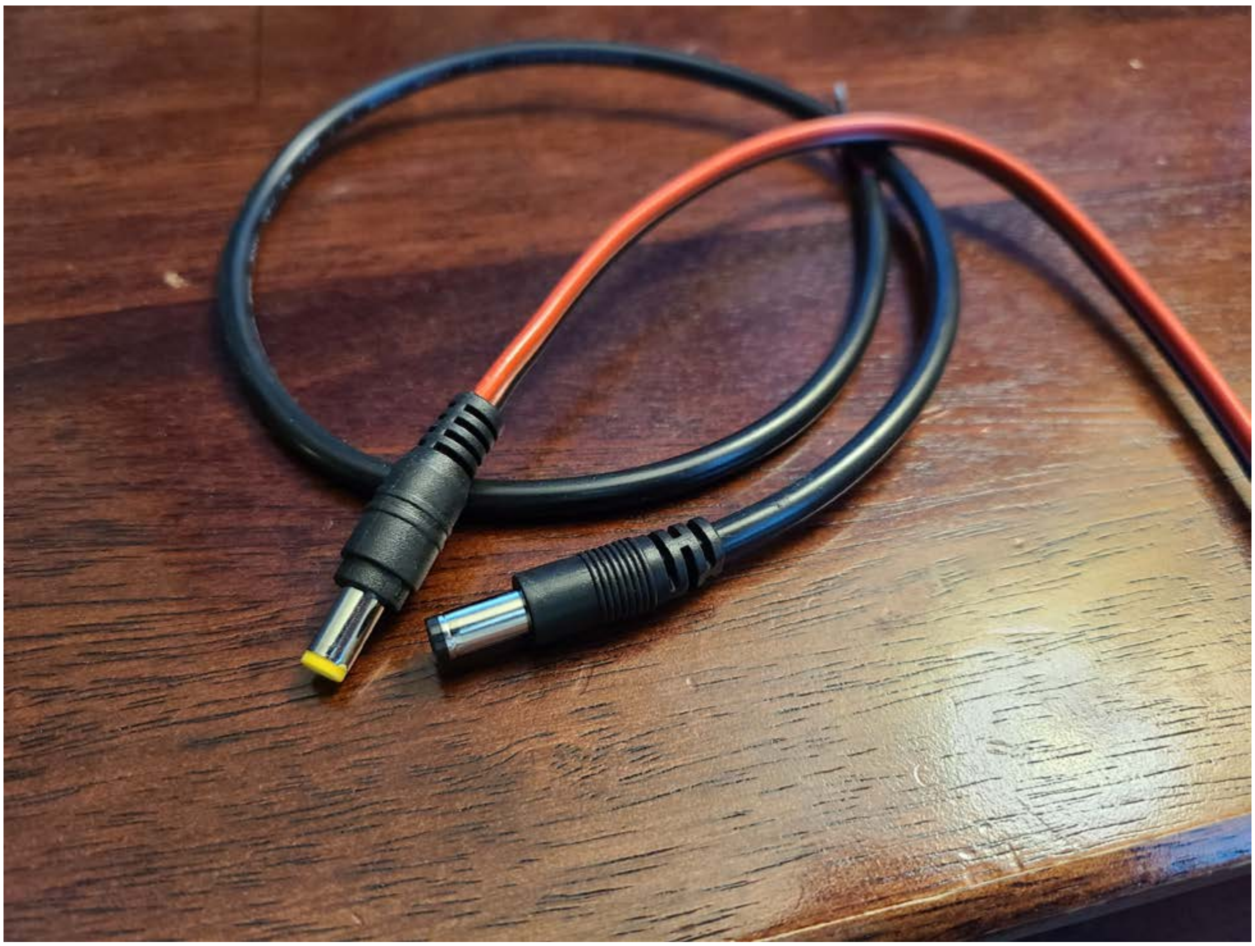

Figure 7: Barrel plugs used to connect components to the voltage regulators.

Since the system in that state could not power on and power down with the rest of the Canary, a quick-disconnect system using XT-90 connectors was implemented. This allowed for the system to be easily disconnected and reconnected from the battery. It also provided a means of interfacing the auxiliary system with the primary power system of the Canary.

4.3.2 Interfacing the Auxiliary with the Main Power System

The safest method of connecting two individual circuits together was with a relay. Yet another automotive piece, the relay would allow the main power system to act as a power-on or power-off signal for the auxiliary power system without directly connecting the two systems together. The chosen relay featured a harness socket for ease of replacement and was designed for 24-volt loads at up to 40 amperes.

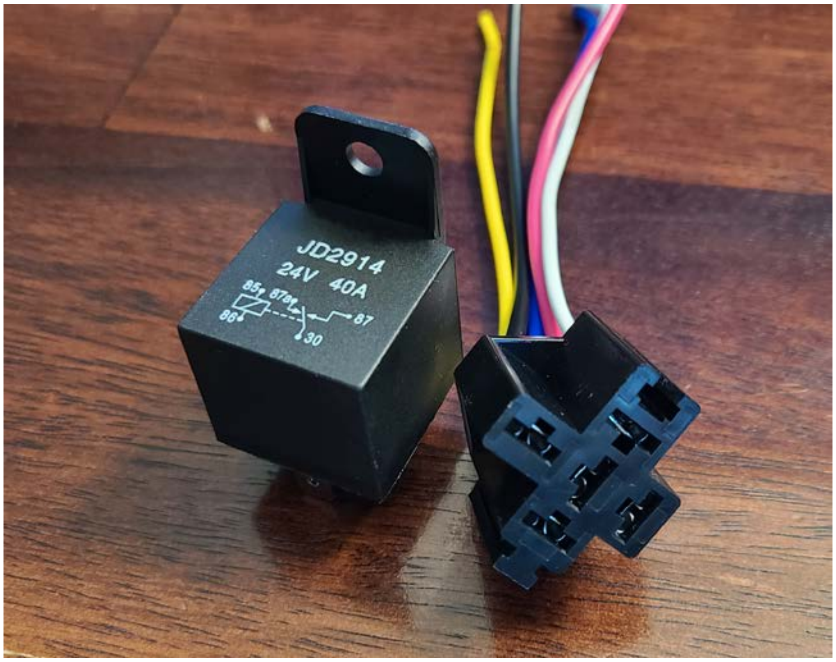

Figure 8: 24V relay and harness socket.

For the signal wire from the main power system, the line that powered the old POE injector was used. This line was open after the removal of the old injector and became live whenever the Canary was powered on. Meanwhile the normally open relay was placed in between the auxiliary system and the battery. XT-90 connections were also used for the relay, which allowed for easy integration into the system. In conjunction with the harness socket, the relay system that was installed is maintainable – either through total circuit replacement or relay replacement.

4.3.3 Housing the Power Components

After the initial layout, testing, and integration of the auxiliary power system was done and additional progress was made on the automated navigation stack of the Canary, a housing needed to be developed to encase all the components. Using the documentation available for the voltage regulators and terminal blocks, a housing was designed via CAD that was sent out to print in the same Onyx material as the sensor mounts.

Figure 9: CAD model of auxiliary power housing.

The housing featured mounting holes for the four voltage regulators and space for the installation of the terminal blocks. A divider wall split the housing into separate compartments for the terminal blocks and the regulators. A labeled lid covers each of the compartments for easy identification of the compartment itself as well as identifiers for the output voltage of each of the regulators in their respective compartment. These sliding lids also feature a system to secure them shut either via padlock or a bolt and nut combination for versatility. Vent holes and tie-downs for zip ties were also integrated into the sides of the housing.

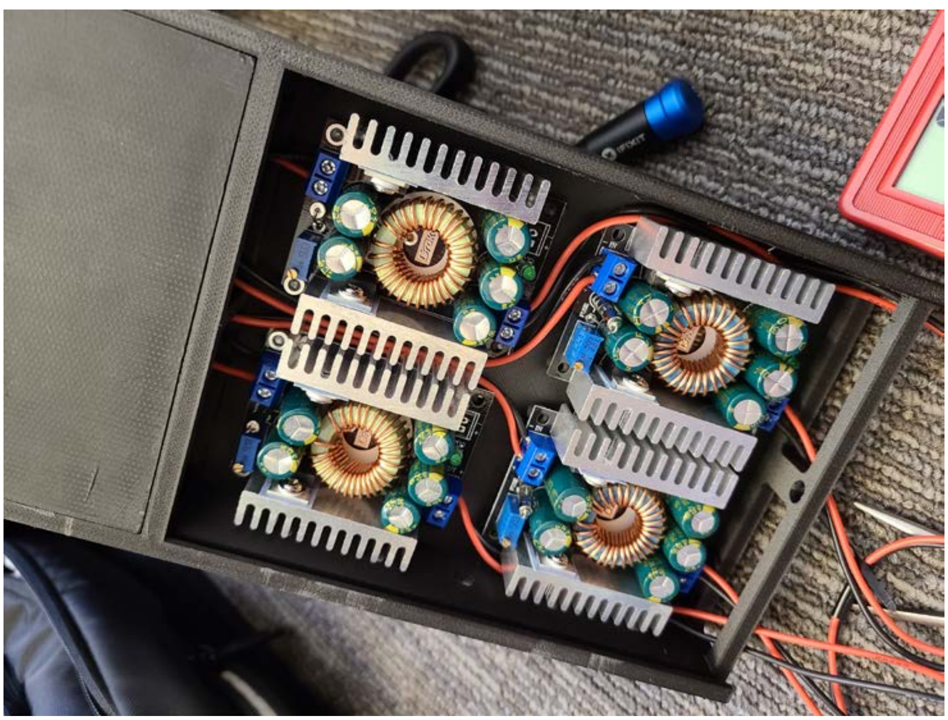

Figure 10: Voltage regulators installed into housing compartment.

Once all the auxiliary power system components were installed into the housing, the remaining space in the compartments were used for wire management. As a precaution, the barrel plug ends coming from each of the voltage regulators were labeled to reflect the output voltage – this was important due to some of the barrel plugs being compatible with multiple components. To keep the wires coming from the auxiliary power housing neat, the wires were run through a split wire loom spanning the length between the housing and the opening on the lid of the Canary's interior. The relay and socket were left easily accessible above the battery charging system that was mounted in the location formerly occupied by the Canary's original lead-acid batteries.

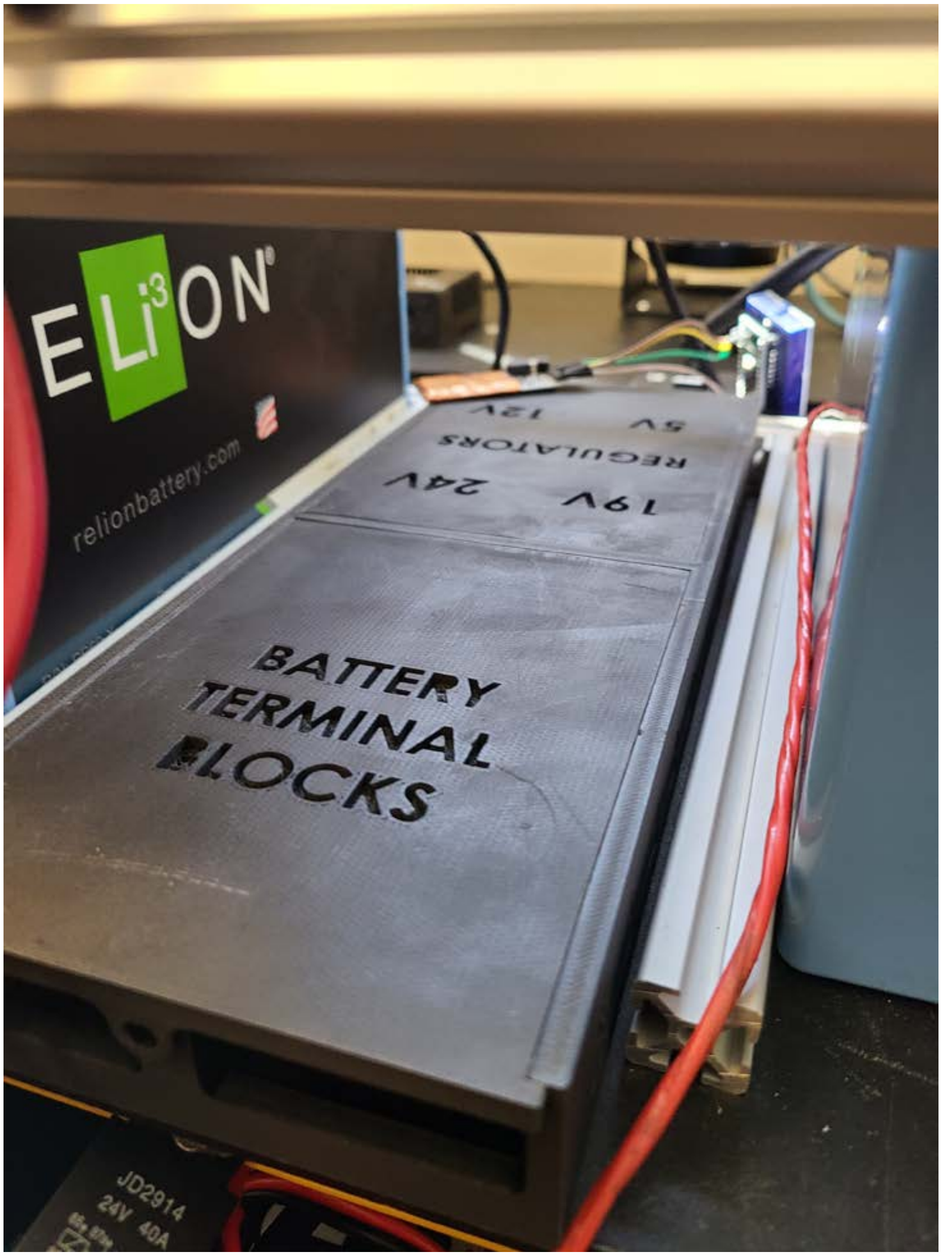

Figure 11: Auxiliary power housing installed on the Canary.

4.4 Additional Hardware Updates

After preliminary tests were performed with the new equipment and updated autonomous navigation stack, several additional changes were made to the Canary to address outdoor localization and radiation sensor implementation. Although the sensor package that was installed greatly improved the indoor navigation capabilities by bolstering close-range object detection, the localization was limited during outdoor testing of the system. After exploring GPS and IMU integration into the Canary's odometry to aid in outdoor navigation, it was decided to install an available Velodyne® VLP-16 three-dimensional LIDAR to significantly boost long-range detection capabilities. The VLP-16 was mounted onto the Canary using the original mount for the pan-tilt-zoom camera which was modified to accept the LIDAR and its quarter-inch thread mounting system. The LIDAR was then placed at the center of the Canary, on top of the upper mounting rail. Additionally, new terminals were added to support the required 12-volt supply for the LIDAR.

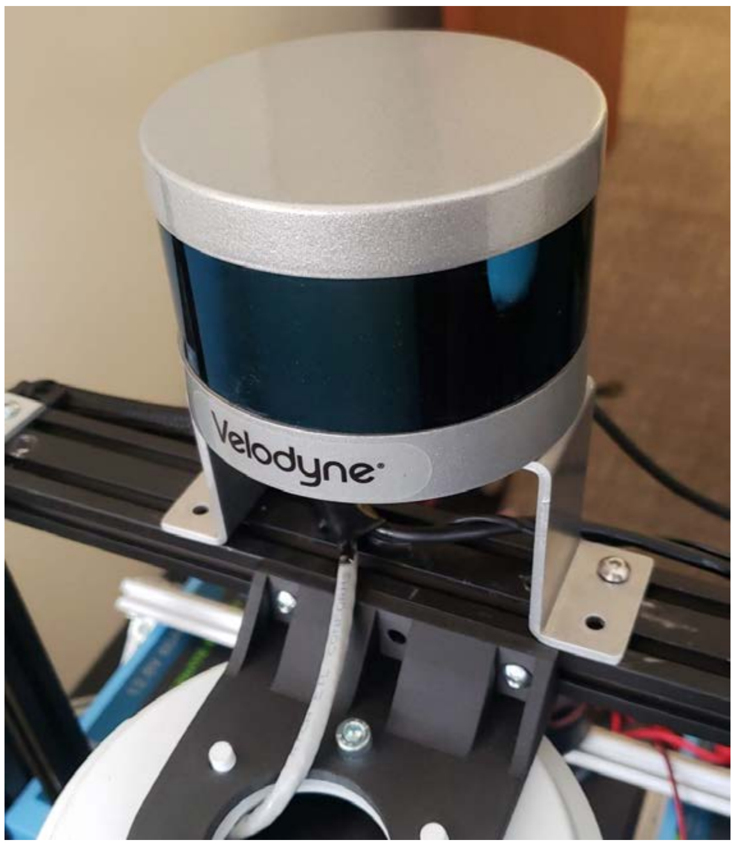

Figure 12: VLP-16 mounted on the Canary.

The final change made to the Canary was the replacement of the Jetson Nano with a Raspberry Pi 4 to support the integration of the radiation sensor into the ROS system. This addressed compatibility issues that were encountered between the sensor and the Jetson Nano and provided a simpler interface between the sensor and the rest of the system. The same 5-volt supply used on the Jetson Nano was applied to the Pi 4 using a barrel jack to USB type-C adapter. Likewise, the same network cable was also used to interface the Pi 4 with the network.

5. DISCUSSION AND CONCLUSION

With a wide array of robotic platforms available as research and development baselines, such as the Canary, modifications can be done to cater the robot to specific tasks that require a level of automation. In this case, it was of interest to develop an automated system that could produce a radiological map of an area with minimal operator input. The baseline configuration of the Canary – a Clearpath Robotics® Husky™ – was capable of efficient teleoperation due to the presence of a long-range peer-to-peer antenna and pan-tilt-zoom camera for remote operation via the control laptop. It was also capable of light autonomy due to the equipped planar LIDAR.

However, this level of equipment was not ideal for minimal interaction or higher-level autonomy – so additional hardware components were integrated onto the Canary. These additional components include three depth cameras, a planar LIDAR, a solid-state LIDAR, two single board computers for more processing power, a revisited network system, a new auxiliary power system, and a simple radiation sensor. In conjunction with the existing equipment and a rebuilt navigation stack, these adjustments enabled more robust autonomy on the Canary that improved object detection and avoidance and allowed for the development of a planar radiation map from data gathered from the integrated radiation sensor.

Throughout the development of the navigation stack, as well as the integration of the radiation sensor and its data into the network, the auxiliary power system has proven to be reliable and capable of providing power to the new devices. The three forward-facing depth cameras can produce a detailed environmental map for the Canary to use in navigation and visualization, while the LIDARs aid in object detection in ranges outside of the capabilities of the depth cameras. The simplified network has also streamlined connections between the three on-board computers and allowed for the distribution of computing requirements across the available units.

While the hardware integration was successful on the Canary, it is important to note that additional equipment had to be installed to support the automated radiation mapping task that was determined for it. This was due to the limitations of the baseline configuration of the Canary, but with an ever-increasing number of available off-the-shelf platforms, it is possible that there will be a system capable of performing the same mapping task with a lower threshold for necessary upgrades and additions. If defined as a percentage reflecting deployment readiness for the automated radiation mapping task, the Canary's baseline configuration could be viewed as 60% ready while newer platforms such as the Boston Dynamics® Spot® could be rated as 90 % ready.

Automated routines in the field at the Hanford site are steadily being realized, with new task ideas being made available and applicable to a robotic system. Using a robotic platform such as the Canary that has autonomy capabilities as a baseline, modifications can be made, and additional hardware can be integrated to cater the robot to these new tasks. For the use case of automated radiation mapping, the integration of an upgraded sensor package, improved networking, and auxiliary power system was successful and enabled the necessary capabilities for the task.