Robotic Integrated Mobile System for Material Inspection and Handling – 25077

Margaret Fontaine[1], Adam Garsha[1], Hersch Nathan[1], Robert Schloen[1], Javier Ruiz[1], and Beth Boardman[1]
[1]Los Alamos National Laboratory

ABSTRACT

The mission of Los Alamos National Laboratory (LANL) is to ensure national security through deterrence. In the course of meeting LANL's mission, workers handle hazardous materials which can have safety concerns. Improving worker safety requires advancing the use of automation and robotics technology at LANL. This project aims to adapt two commercial-off-the-shelf (COTS) robots for material handling. Specifically, this project implements two different types of COTS robots: the Clearpath Ridgeback mobile platform robot and the Universal Robots UR5 six-axis robotic arm. First, this paper describes the mechanical and electrical integration of both robots as well as software integration using the Robot Operating System (ROS). The UR5 arm is mounted on top of and toward the front of the Ridgeback. Simulation of the integrated system is done in ROS Visualization for testing prior to physical deployment. Then, a material handling demonstration is used to show how automation can improve processes. The premise of the demonstration is for the robot to explore an environment, locate spheres, and sort them. For exploration, LiDAR and computer vision are used. The cameras are used to locate AprilTags which marked the location of interaction. The spheres are sorted using AI/ML to classify the spheres. The efforts of this project show that the integrated Ridgeback with UR5 can navigate and interact with the environment successfully. Mobile material handling and inspection can be done autonomously which will reduce worker hazards.

INTRODUCTION

The Los Alamos National Laboratory's (LANL) mission is to ensure national security through deterrence. In achieving this mission, workers must handle hazardous materials with various safety concerns. Therefore, improving workplace safety necessitates the implementation and advancement of automation and robotics. One approach to implementation is to adapt robotic systems previously developed for commercial use to suit the custom applications and environments found at LANL.

This adaptation of commercial systems is exhibited by the modification and integration of two distinct commercial systems for material handling and inspection. Notably, Universal Robotics®,[1] UR5 Robotic Arm (UR5) and ©[2] Clearpath Robotics, Inc.'s Ridgeback™,[3] Mobile Platform (Ridgeback™) each provide a unique set of industrial capabilities. The combination of these systems allows these capabilities to complement one another and develops an overall system that can be modified to fit a large range of applications.

Principally, the UR5 and Ridgeback™ can be combined to automate the handling, inspection, and final placement of materials that are hazardous to workers. This application relies on the merged capabilities of both systems and the development of new capabilities only possible due to integration. In the project demonstration, the Ridgeback™ and UR5 robots are integrated together with mechanical and electrical modifications. After integration, the Ridgeback™ with UR5 searches for metal spheres in an unknown environment. These spheres, representing hazardous material, are inspected for damage and then sorted. Once sorting is complete, the material is placed in a specified location and exploration for hazardous materials resumes. Holistically, the automation of this process illustrates how commercial systems can be adapted to LANL's unique environments and how the implementation of automation allows for safer working conditions.

---

[1] Universal Robotics® is a registered trademark of Universal Robotics A/S

[2] © Clearpath Robotics, Inc., a Rockwell Automation Company. All rights reserved

[3] Ridgeback™ is a trademark of Clearpath Robotics

Mechanical

The UR5 arm and Ridgeback™ platform perform different types of industrial tasks. Consequently, the mechanical capabilities and limitations of these systems should be understood separately. Figure 1 shows a model of the Ridgeback™ with mounted UR5.

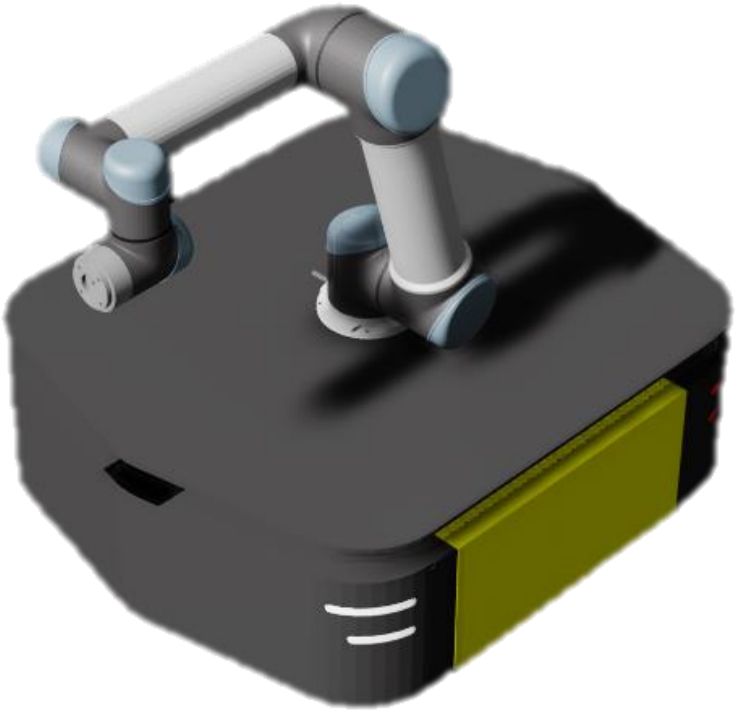

Figure 1. Model of the Ridgeback™ with UR5 system.

The UR5 robotic arm has six degrees of freedom. Each degree of freedom, or joint, has 360 degrees of rotation with 0.00011 inch (0.0028 mm) repeatability. Through these joints, a pose can be created as a specified position of the entire arm system. The sixth joint, referred to as the wrist, includes a tool flange with mounting holes to attach various tools or end effectors. Subsequently, the UR5 capabilities are expanded upon and customized to specific tasks. Furthermore, beyond the physical capabilities of the arm, the robot is designed to be stationary at a single mounting point and does not measure any environmental information (sensors, vision systems, etc.). Whilst end effectors can be used to add vision systems and sensors, these features are built to only provide information about the environment immediately surrounding the wrist joint.

For this particular application, the tool used is the OnRobot®,[4] VGC10 Vacuum end effector. This tool is fitted to the UR5 through the adapter plate and utilizes 1.18 in (30 mm) vacuum cups on extension pipe mounting. The VCG10, mounted to the UR5, can be seen in Figure 2 picking up a metal sphere.

The UR5 arm is mounted to the Ridgeback™ which is a system designed to navigate through an unknown environment. This exploration is done with four omnidirectional wheels and two LiDAR sensors. The LiDAR and wheels enable the Ridgeback™ to detect an obstacle and move around it accordingly. The result of this movement is that anything mounted to the Ridgeback's™ platform is moved through an environment.

---

[4] OnRobot® is a registered trademark of OnRobot A/S

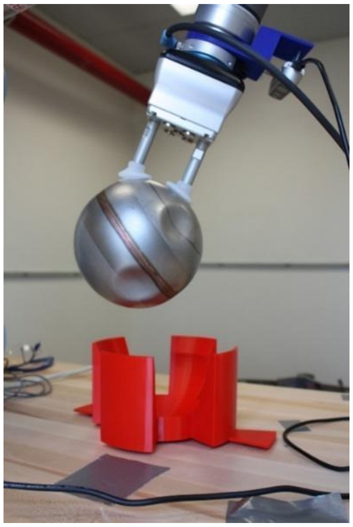

Figure 2. Image of the VGC10 gripping a metal sphere.

By mounting the UR5 arm to the Ridgeback™, the limitations of the arm can be overcome. This allows for the UR5 to move to different points in an environment and alter its behavior given the LiDAR's information. Furthermore, in this project the weaknesses of the robotics system are further supplemented by the implementation of the Intel RealSense™,[5] D435i Camera. The mounting system of the VGC10 is altered with 3D printing to place the D435i camera between the end effector and UR5 wrist.

Electrical

Each electro-mechanical system has three main electrical components: power, communications, and safety systems. Both robotic subsystems have these components.

The Ridgeback™ is powered by a pair of marine grade 12 volt batteries in series providing 24 volts with enough capacity to last an entire workday. That power is routed through a set of fuses and converters which power the motors, microcontroller (MCU), sensors, integrated computer, and user power. An integrated battery charger allows for safe charging of the batteries as needed. In the stock configuration there is a second computer that runs Clearpath Robotics's™,[6] proprietary software IndoorNav for indoor navigation. User control of the system is handled through Robotic Operating System (ROS™,[7]), discussed in the Software Section. ROS™ runs on top of a standard local area network (LAN) connection inside the robot to communicate with a node on the integrated computer. That computer sends commands through the LAN to the MCU to tell the system how to move. The integrated computer receives sensor information over ROS™ on the LAN. The MCU communicates with the motors via serial bus communication. The communication connections are shown in Figure 3.

Any autonomous system, especially those that may be in close proximity to humans, must have emergency stop capabilities. The Ridgeback™ has four emergency stop mushroom buttons, one on each of the four corners of the Ridgeback™, see Figure 4.

---

[5] Intel RealSense™ is a trademark of Intel Corporation or its subsidiaries

[6] Clearpath Robotics is a trademark of Clearpath Robotics, Inc

[7] ROS is a trademark of Open Source Robotics Foundation, Inc. ("OSRF" or "Open Robotics").

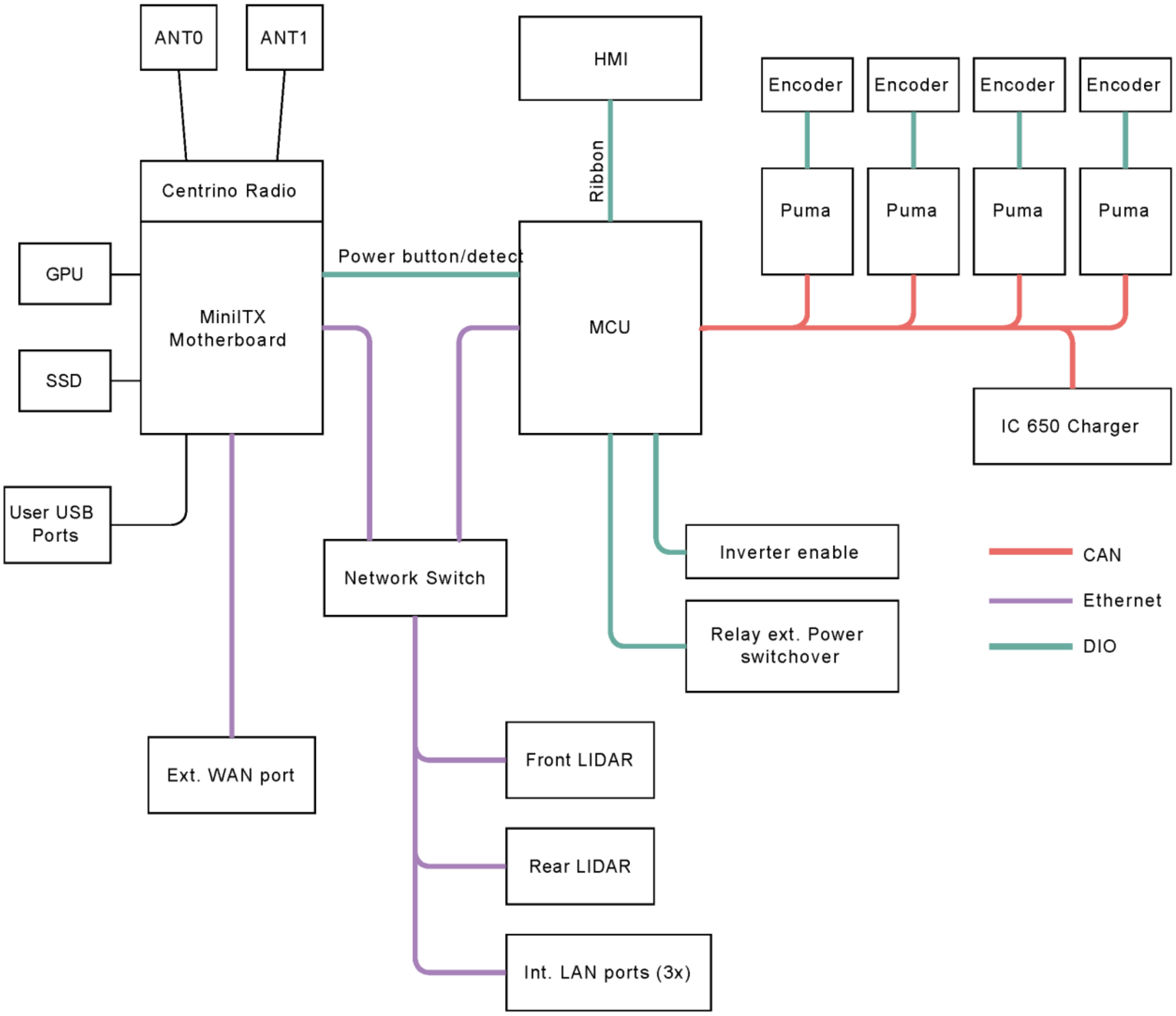

Figure 3. Diagram of the Ridgeback's™ communication connections, [1].

Figure 4. E-stop on one corner of the Ridgeback™.

The UR5 is controlled by a Universal Robots® CB3. The CB3 is powered via 120 V AC that is converted to 48 V DC and 12 V DC. The 12 V power is used to power the safety control board, motherboard, and teach pendant, which runs PolyScope. The 48 V DC is solely used to power the joints on the arm itself. Communication to the CB3 happens via a LAN connection or the digital inputs. The UR5 communicates between the safety control board and the motherboard using the same LAN. To command the arm itself to move, serial commands are sent to the actuators. The CB3 features a PLC like I/O module that includes safety input and output in addition to an emergency stop on the Teach Pendant.

The VGC10 Vacuum end effector is operated by the OnRobot® compute box. The OnRobot® compute box is powered by a 120 V AC to 24 V DC wall adapter and provides the 24 V power to the end effector. It communicates via a LAN and talks to the end effector with a custom cable.

Software

A variety of means exist for controlling autonomous robotic systems. In particular, ROS™ is a popular framework for controlling such systems. ROS™ is commonly used in research and development settings [2] to analyze and control robots. Furthermore, it was used specifically for material handling systems by Harsh and Dhami [3].

ROS™ operates using packages that contain nodes. Nodes communicate with each other using messages passed via topics, following a publish/subscribe model. Nodes can also communicate using services, in which one node sends a directional request to another node, analogous to an HTTP request. ROS™ provides tools, such as ROS™ Qt-based GUI Framework (RQT), that facilitate debugging and understanding of communication between nodes. The source code for nodes can be written in Python®,[8] or C++™,[9], but exchange of information between nodes is agnostic to the language used, allowing package development in either language. Figure 5 shows the RQT graph for the V-REP package used to simulate robot motion.

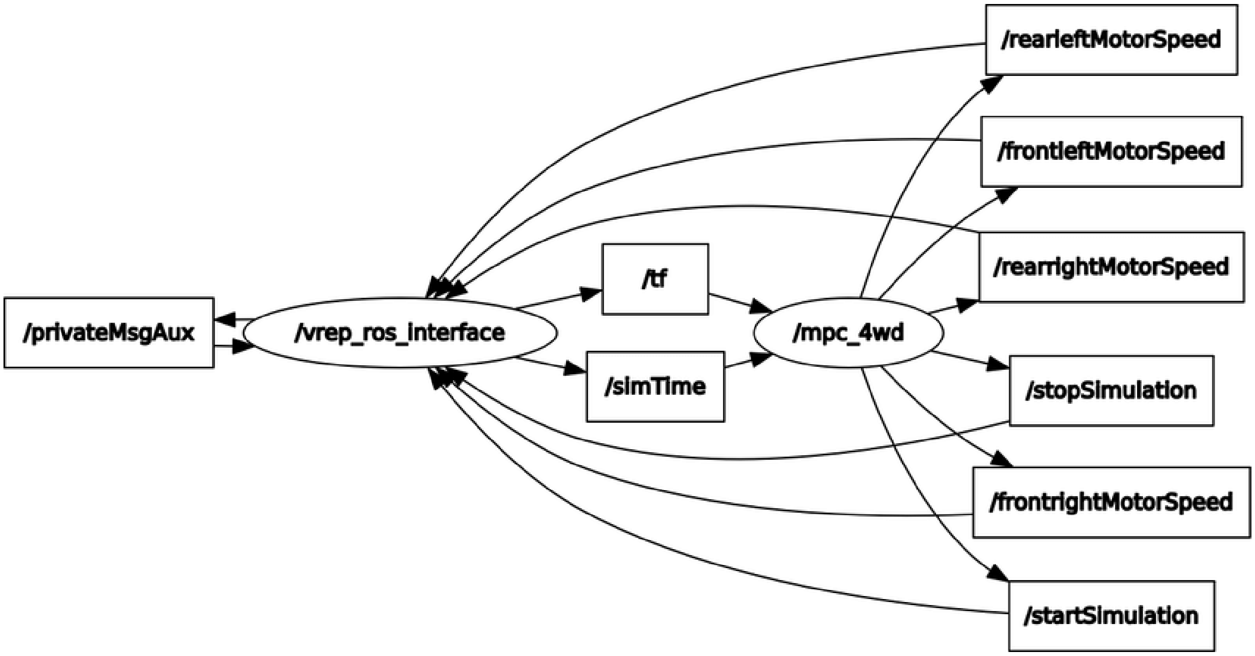

Figure 5. RQT graph showing the communication between nodes in the V-REP package, [4].

---

[8] Python® is a registered trademark of the Python Software Foundation (PSF)
[9] C++™ is a trademark of the Standard C++ Foundation

ROS™ packages exist for a variety of tasks. Robot control, visualization, sensor measurement, and simulation capabilities can be implemented with the appropriate packages. When a ROS™ launch file is run, nodes within specified packages are started and they begin communicating with each other.

For the system described within this paper, software was required to control the UR5, Ridgeback™, OnRobot VGC10 gripper, and other auxiliary systems including a speaker and D435i camera. Fortunately, ROS™ or Python® support exists for each of these devices, as listed in Table 1.

Table 1. A list of the ROS™ packages used for each device.

Device	ROS™ Packages and Tutorials	Link
UR5	Getting Started with a Universal Robot™ and ROS™-Industrial	http://wiki.ros.org/universal_robot/Tutorials/Getting%20Started%20with%20a%20Universal%20Robot%20and%20ROS-Industrial
Ridgeback™	Ridgeback™ Tutorials	https://docs.clearpathrobotics.com/docs/ros1noetic/robots/indoor_robots/ridgeback/tutorials_ridgeback/#simulating-ridgeback
VCG10	OnRobot®	http://wiki.ros.org/onrobot
VCG10	Onrobot-vg	https://github.com/takuya-ki/onrobot-vg
D435i	RealSense™	http://wiki.ros.org/RealSense

ROS™ packages controlled movement for the UR5 arm and Ridgeback™ platform, and allowed for D435i camera data to be analyzed. A custom ROS™ package was created to control the gripper. D435i camera data was also used to create octomap visualizations, which are 3D collision maps created by the D435i camera's depth sensor. Additionally, sounds could be played out of the speaker using a sound play package.

For the arm in particular, ROS™ was also able to control PolyScope which is the default software enabled on the UR5 arm. Using ROS™ external control, pose and joint goals can be sent directly to the robot without needing to use PolyScope for motion planning. This facilitated a ROS™-centered control system with material inspection and handling abilities.

SYSTEM DESCRIPTION

Navigation Capabilities

The Ridgeback™ has two SICK®,[10] Inc. LiDAR LMS111 sensors that provide a 360-degree 2D map of the area immediately surrounding the robot. Furthermore, using ROS™ mapping packages, the Ridgeback™ can save mapping information about regions it has visited and update in real time based on new LiDAR data.

In addition to LiDAR sensors, the UR5 arm has been modified to support an D435i camera. The D435i camera has both depth-sensing and standard imaging capabilities. The D435i camera aids in navigation by recognizing AprilTags, which are 2D pixelated images that store information similarly to a QR code, as shown in Figure 6. The AprilTags are placed at points of interest (POIs), so the robotic system recognizes an area and performs a task. The LiDAR capabilities of the Ridgeback™, coupled with the identification of POIs via an attached D435i camera, allows the combined UR5-Ridgeback™ system to navigate both known and unknown environments.

One of the add-on options for the Ridgeback™ is the IndoorNav Autonomy Software which is a modified version of the OTTO®,[11] Autonomy software. It provides a simple navigational kit for the Ridgeback™, however it was not used for this project because it did not provide advantages over the built in ROS™ packages and could not control the UR5 arm.

---

[10] SICK is a registered trademark of Sick AG

[11] OTTO is a registered trademark of OTTO Motors by Rockwell Automation

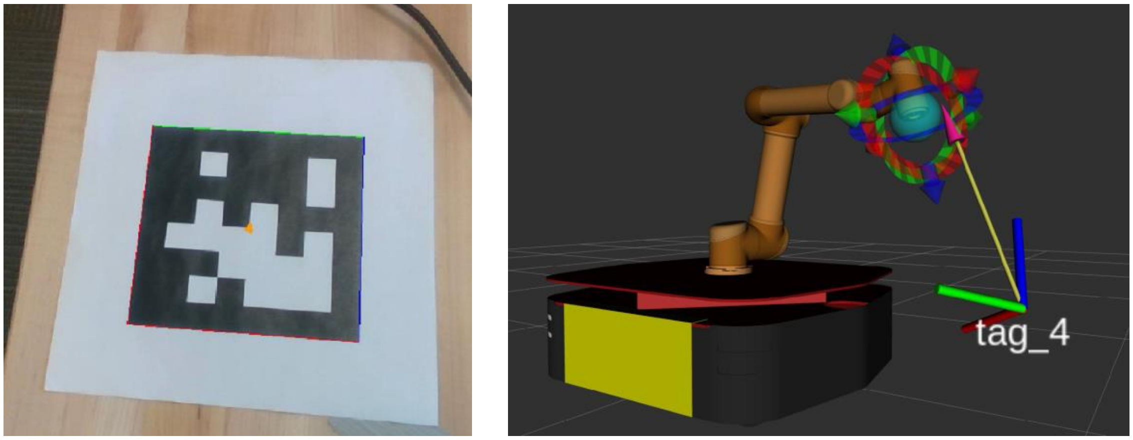

Figure 6. An AprilTag and ROS™ Visualization (Rviz) simulation of UR5 recognizing an AprilTag.

Inspection Capabilities

A core aspect of the combined UR5-Ridgeback™ system is its capacity to approach, inspect, and handle objects. For the purposes of this particular demonstration, metal spheres were sorted based on how damaged they were.

To facilitate inspection, the D435i camera detects AprilTags placed on fixtures holding the metal spheres. These spheres were differentiated by the presence of dents and other deformations indicating damage. Half of them were damaged, while the other half were kept in their original condition. To show the adaptability of material handling capabilities, 5 and 6 inch diameter spheres were used which weighted 0.98 and 1.375 lbs (444.52 and 623.69 g) respectively. Figure 7 shows the different sized spheres and one of the containers used for holding the spheres.

Figure 7. Image of the metal spheres and a container.

After detecting the AprilTag, the UR5-Ridgeback™ system approaches the sphere fixture, collects the sphere, and sorts it into the corresponding damaged or undamaged container. This is accomplished by utilizing the depth and color data from the D435i camera to search for dents and scratches. As shown in Figure 8, first, the depth point cloud data is converted to a 2D topographical map which is used to create a mask around the sphere. That mask is applied to the color image before sending it to a classification model that sorts spheres into damaged and undamaged categories. Transfer learning was used to retrain the last layer of a RESNET-18 neural network model to create this classification model.

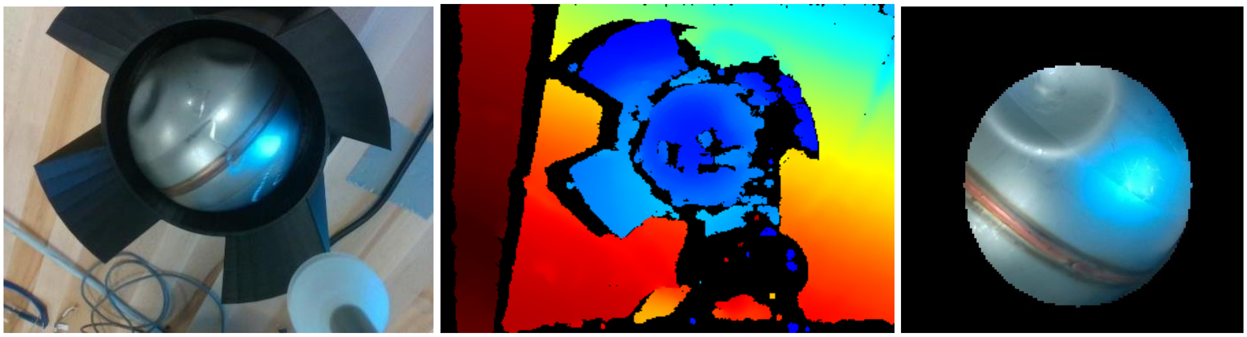

Figure 8. Images showing the sphere identification process.

While the above procedure applies to one particular type of inspection, the UR5-Ridgeback™ system could be adapted for other inspection tasks. This is discussed further in the Conclusion Section.

Hardware & Electrical Modifications

As previously discussed, the IndoorNav software and hardware was not useful for this application, and it was removed from the Ridgeback™. This opened up one of the cavities on the base of the robot to integrate other electronics into.

The UR5's CB3 was modified to be powered off a 24 V DC battery. The two AC to DC power supplies were replaced with brand equivalent 24 V DC to 48 V DC and 12 V DC power supplies. An additional relay was placed in between the positive side of the 24 V DC input on the 48 V DC power supply to control the state. The CB3 only enables 48V power to unlock and move the arm. Additionally, to protect the CB3 and upstream electronics a fuse was placed between the battery and the power supplies. The new electrical power diagram is in Figure 9.

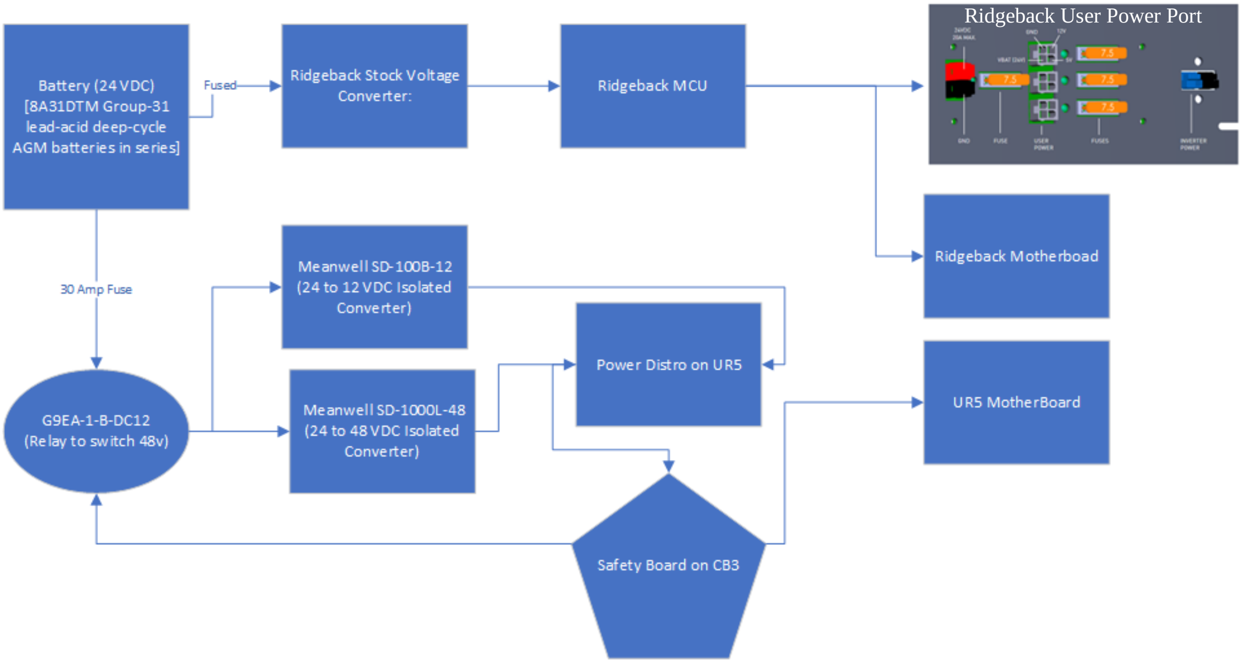

Figure 9. Overall system electrical power diagram.

In order to keep the Ridgeback™ platform clear for UR5 operation, the electronics were put into the empty cavity on the Ridgeback™. To do this we removed the CB3 from its stock box and developed custom mounting. This mounting, Figure 10, keeps the necessary CB3 components in place. Notably, all the mounting is a combination of press-fit, bolts, and hook and loop tape. All three of the circuit boards are bolted to small 3D printed plates which press-fit into protective green casings. The casings are epoxied together, and the combined casings are connected to the rest of the mounting system through hook and loop tape. The relay of this system is bolted to the overall mounting while the two power supplies are held in place through hook and loop tape and press-fitting. Finally, the overall mounting is secured to the cavity with hook and loop tape.

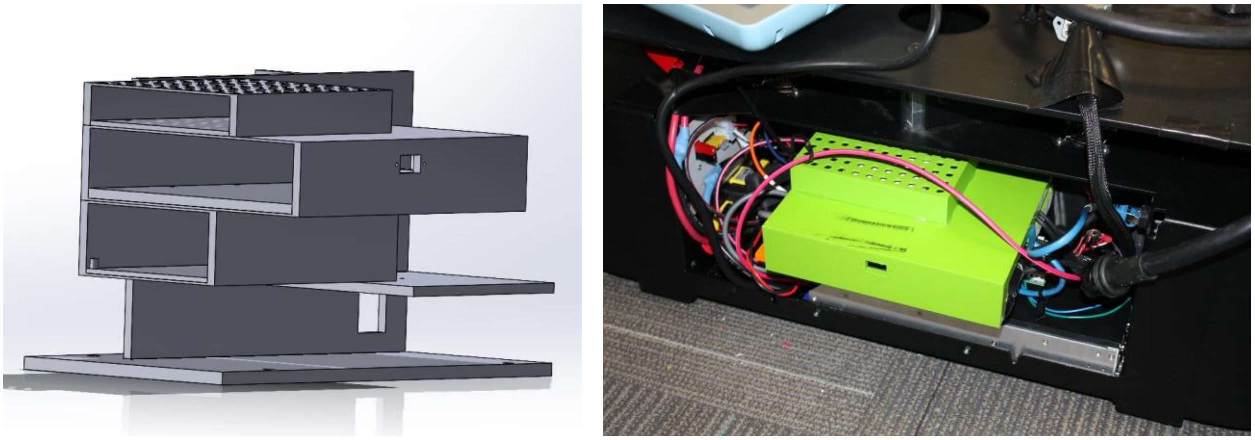

Figure 10. Left is the custom mounting model. Right is the actual mounting and components installed in the system.

Hardware Environment

To support the inspection tasks of these projects, particular environmental features were developed to hold the spheres. These fixtures, Figure 6, create set locations for the UR5 to move spheres to during inspection. Notably, the fixtures were 3D printed with PLA and have adhesive rubber to avoid slipping. These fixtures were intentionally designed to be easily moveable and placed in various locations. In other applications, these fixtures are analogous to known locations or conditions. For example, in a larger process where steps are automated by distinct systems, these fixtures could be known points of overlap. This could include one robotic system starting to process the hazardous material, placing it in the fixture, the UR5-Ridgeback™ moving it to another designated fixture, and a third automated system continuing to process the material. How a fixture, or its systematic equivalent, is used depends on the specific automation process; all that is required are several known features and conditions.

System Control

In order to control this system, it must first be activated, and all E-stops must be disabled. After ensuring proper safety protocols are followed, the ROS™ external control program must be started on the UR5 computer. Then, an external computer must Secure Shell (SSH) into the Ridgeback's™ main computer. This computer functions as the main ROS™ host and runs the Ridgeback's™ LiDAR mapping software.

Various ROS™ launch files provide robot control capabilities. In addition to robot control, the D435i camera, speakers, and other auxiliary systems can be started within these launch files.

In addition to controlling the physical robots, the system can also be simulated virtually by launching Rviz files. Simulations exist for the UR5 and Ridgeback™ individually and can be used to test autonomous code before execution on the real robots. Furthermore, combined simulations were developed to allow the arm to run simulations that avoid colliding with the Ridgeback™. This allows for rapid development without risking potential hardware damage.

For both the simulation and control launch files, various sensor readouts and panels provide information about the robot positions, visual data, and status of autonomous routines.

DISCUSSION

Results

The outcome of this project is a fully integrated UR5-Ridgeback™ robotic system, Figure 11, with the ability to navigate unknown areas and manipulate objects. While some aspects of the system are still candidates for improvement, the capabilities of the robots are detailed next.

The Ridgeback™ navigates through flat indoor areas while mapping using its LiDAR sensors. AprilTags are identified using the D435i camera mounted on the UR5 arm. Using AprilTags, metal spheres are found and analyzed by the D435i camera. These spheres are picked up using the VGC10 vacuum end effector and placed into containers. As the arm moves, an orientation constraint keeps the vacuum cups level so that the object remains in an upright position. While the damage identification software is not fully developed, the arm has shown its versatility in manipulating objects of different sizes and profiles.

Overall Integration

Integration into a single system involved work across mechanical, electrical, and software domains. The IndoorNav computer was removed from the Ridgeback™ and replaced by the CB3's electronics in a custom enclosure. The UR5 arm was mounted onto the plate on top of the Ridgeback™. Additionally, the standard end effector adaptor plate was customized with an additional stage for D435i camera mounting.

Figure 11. Photo of the final Ridgeback™ with UR5 system.

The CB3 was reassembled and connected to the new power supplies which were then connected to the Ridgeback's™ batteries. The CB3 was connected to the Ridgebacks'™ LAN. The control cable from the safety control board to the UR5 arm was connected. The wireless E-stop was wired to both the Ridgeback™

and the UR5. The VGC10 was connected to the OnRobot Compute Box which in turn was connected to the LAN. Regarding software, ROS™ packages were installed on the Ridgeback™ and an external computer to control the platform, UR5 arm, D435i camera, speakers, and VGC10 vacuum gripper.

CONCLUSION

In this project, dissimilar robotic systems were integrated to both improve overall performance and expand capabilities. Beyond the visual inspection task discussed here, the UR5 and Ridgeback™ system has numerous other capabilities. For example, the Ridgeback™ is capable of supporting far more weight than the UR5 and its 5 kg payload. Consequently, future applications consisting of moving large objects or storage units could be developed. Additionally, upon developing updated versions of the presented software, this system could be trained to identify different forms of damage across a wider array of objects. This expansion could be further enhanced by altering the sensor package of the system.

Some specific software changes that could be implemented include an improved AprilTag recognition system that can handle a variety of objects, not just sphere fixtures. Furthermore, the path planning algorithm used for the UR5 arm could be improved to handle manipulation of more types of objects. In addition, an improved octomap system could be developed using the D435i camera depth data to allow the UR5 arm to dynamically manipulate around walls, tables, and other obstacles, without relying solely on the Ridgeback™ LiDAR data.

Overall, the integration of these disparate systems illustrates how distinct needs can be met through a broader system. This particularly highlights how the limitations of individual systems currently developed can be overcome and customized to a variety of needs. Subsequently, it provides a new channel for problem-solving that allows projects to meet precise requirements while still utilizing the preexisting systems.

REFERENCES

1. Clearpath Robotics. Ridgeback User Manual, Melodic Development. (2023). Accessed: June 2023. [Online]. Available: https://github.com/ridgeback/ridgeback-user-manual
2. Linner, Thomas & Shrikathiresan, Alaguraj & Vetrenko, Maxim & Ellmann, Bernhard & Bock, Thomas. (2011). Modeling and Operating Robotic Environments Using Gazebo/ROS. 10.22260/ISARC2011/0177.
3. Anurag Harsh, S.S. Dhami, Development of mobile smart material-handling system, Materials Today: Proceedings, 2023, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.07.247.
4. Gomaa, Mahmoud & De Silva, Oscar & Mann, G.K.I. & Gosine, Ray & Hengeveld, Robert. (2020). ROS Based Real-Time Motion Control for Robotic Visual Arts Exhibit Using Decawave Local Positioning System *. 653-658. 10.23919/ACC45564.2020.9148022.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by Los Alamos National Laboratory and is approved for release under LA-UR-24-32404 Version 2.

This work was performed as part of an internship with LANL’s Automation, Robotics, and Controls group. We’d like to thank our mentors, Javier Ruiz, Robert Schloen, and Beth Boardman, for their support and guidance throughout the course of this project.