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Experiential Learning with Mobile Robots: Bridging Physical and Virtual Environments

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Abstract

This paper presents an ongoing experiential learning and research project initiated last summer (2023), aimed at fostering engineering education through the collaboration of undergraduate students at the University of Maryland Eastern Shore (UMES) and summer exchange students from neighboring universities in the state of Maryland, with high school students who participated in a remote setting. The project employed educational mobile robotic platforms, namely the LIMO, GoPiGo3, as well as, Sphero RVR and Bolt available at the UMES robotics lab. The emphasis was on the integration of a variety of sensors with the robotic platforms in a variety of scenarios including navigational challenges that may be encountered by lunar and Martian rovers.

Undergraduate students worked directly with the physical robots, gaining valuable hands-on experience. They were also introduced to state-of-the-art open-source simulation software platforms. The high school students engaged remotely with the undergraduate students while utilizing the same simulation platforms. Preliminary efforts were initiated in the summer to engage the participants with the Linux operating system to utilize the Robot Operating System (ROS) and Gazebo, a powerful 3D dynamic simulator. The use of Gazebo allowed for the creation of diverse virtual environments, simulating surfaces like earth soil and lunar regolith, similar to those encountered by robots in real-world scenarios. The paper will highlight the application of Gazebo in the realm of space exploration, drawing inspiration from NASA's utilization of Gazebo to simulate lunar and Martian environments for robotics-related simulation studies.

The hybrid approach adopted, effectively merged real and virtual learning experiences overcoming constraints related to transportation and other logistics, enabling a framework for contemporary education that provided valuable insights towards the integration of physical and virtual learning environments for aspiring roboticists.

Project leaders have engaged engineering and computer science students in the ongoing fall semester to continue with the efforts. This paper is largely based on the accomplishments of the students in the past summer and the ongoing fall semester.

1.0 Introduction

Since its inception, the summer exchange internship program (SEIP) has provided a platform for experiential learning and research for undergraduate STEM students at the affiliated institutions of the Maryland Space Grant Consortium (MDSGC- https://md.spacegrant.org/). Under the SEIP, the MDSGC lead institution provides support for exchange students to participate in project efforts ongoing at one of the affiliate universities other than their home institution under the supervision of a faculty member for 10 weeks in the summer, often working in a team setting with undergraduate and graduate students at the host institution. The exchange program culminates in a summer research symposium where the students present their work [1].

The “Autonomous Instrumented Robotic Sensory Platforms to Advance Creativity and Engage Students” (AIRSPACES) project led by the principal author at UMES leverages the SEIP platform and integrates its scope within its framework. The AIRSPACES project is also funded by MDSGC annually to engage UMES engineering and other STEM students in hands-on out-of-classroom multidisciplinary team projects throughout the year [2-4]. The UMES-UMD (University of Maryland College Park) collaborative project titled “DREAM: Developing Robotic Explorations using Agrobots and Moonbots” builds on the foundation provided by the AIRSPACES project and expands its scope to expose and engage student participants to robotics and other related efforts within the broad scope of NASA’s Artemis mission objectives. The DREAM project was funded by the NASA MSTAR program at the beginning of fall 2023 with the lead author as the principal investigator (PI). This paper will outline aspects of the AIRSPACES and DREAM project efforts undertaken during the summer and fall of 2023. A couple of high school students were very interested in participating in the AIRSPACES project efforts last summer but due to logistics constraints could not come to campus physically and participated in the project efforts remotely.

2.0 Soft Gripper and Sphero RVR

The Robotics, Automation, and Manufacturing (RAM) laboratory has initiated soft robotics-related efforts for the past couple of years to expose undergraduate engineering students to this growing field [5]. Efforts related to the integration of a commercial soft gripper with an industrial robotic arm and trials with Programmable-Air[6], elastomer grippers, and I Robot Create2[7] have been reported in reference 4. An exchange student in 2023 summer was assigned to familiarize himself with the newly acquired Sphero RVR[8] and Sphero Bolt robotic devices and adapt the elastomer-based soft gripper setup with the I Robot Create 2 and replace the Create 2 with the Sphero RVR.

Figure 1: Sphero RVR and Sphero Bolt

The RVR is a programmable four-wheeled educational robot from Sphero. It has many sensors including color (RGB) and infrared sensor, a magnetometer, and an Inertial Measurement Unit (IMU) that measures the accelerometer and gyroscope data in 3 axes (x,y, and z). It also has an ambient light sensor to measure the light intensity in lux.

The RVR also has integrated infrared transmitters and receivers to communicate with other RVR or Bolt robots and other robotic platforms. The Sphero Bolt is a programmable robot ball packed with several sensors including a compass, light sensor, gyroscope, accelerometer, motor encoders, and infrared communications, as well as an eye-catching and animated LED matrix. The RVR and Bolt can be programmed in Scratch, a block-based programming language originally developed at the MIT media lab (https://scratch.mit.edu/) as well as Java Script. RVR can also be interfaced with Raspberry Pi, the popular single-board computer, and programmed using Python. The emphasis for the 2023 summer internship efforts of the exchange student was on integrating a Raspberry Pi with the RVR and using the Python programming language. Some of the preliminary efforts undertaken by the exchange student included programming the RVR to move in a square, followed by sensing different colored paper placed on the corners of the square and turning the corresponding LED light on, on the body of the RVR, as well as moving the RVR on a specified path while emitting an infrared signal which was sensed by the Sphero-Bolt to follow it around (See Figure 2). During the initial phase, the student also demonstrated the capability of the Bolt for recording data on its position, distance, velocity, change of angle, acceleration, etc. as it moved on a specified path. The data could be easily exported to Excel Spread Sheet for graphing. The more challenging task undertaken by the exchange student involved integrating the RVR, Raspberry Pi, Programmable Air, and elastomer soft gripper, and performing simple pick and place operations with the setup. The Programmable-Air is an open-source hardware kit for controlling inflatable soft robots and grippers. It has two pumps and three valves that can be controlled using an embedded Arduino Nano microprocessor board that can activate the elastomer soft gripper by inflating and deflating the air chambers in the gripper body. The gripper was cured on molds 3-D printed in the RAM lab using CAD solid models earlier, but the exchange student was made familiar with the process. The exchange student successfully integrated all the components (see Figure 3) on the RVR platform and established communication between the Arduino Nano and Raspberry Pi so that the RVR could move to pre-designated spots under Raspberry Pi command using Python and activate the Nano to close and open the gripper to pick up and release the Bolt. Although the preliminary trial accomplished the desired objectives, it will be refined and improved in the future.

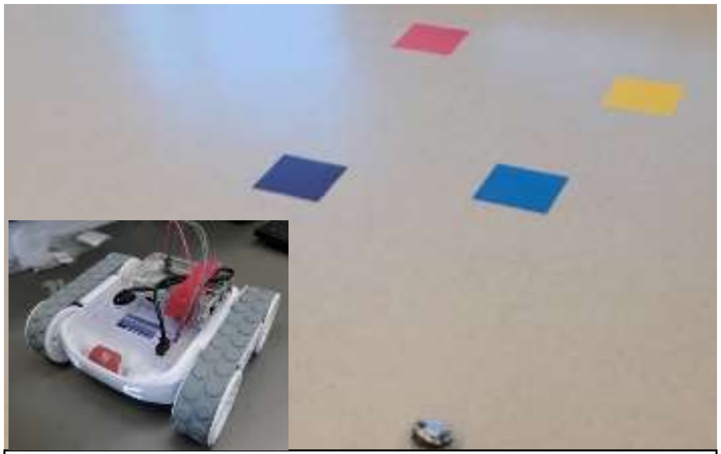


Figure 2: RVR with R-Pi, Bolt, & Colored Papers

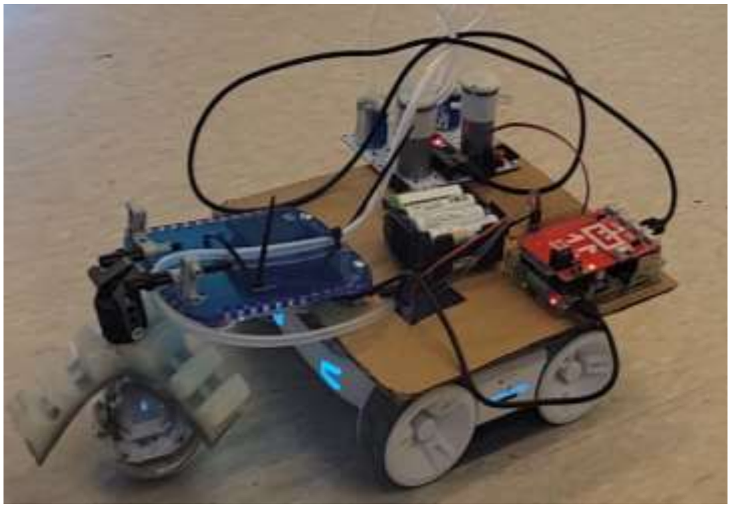


Figure 3: RVR, Programmable Air, and Soft Gripper

3.0 LIMO Trials in Physical and Virtual Settings

One Agilex LIMO robot was acquired by the project team in the summer of 2023 to provide student participants an introduction to AI-integrated advanced mobile robotics and exposure to the Linux operating system (Ubuntu), as well as ROS and GAZEBO software environments. The objective was to lay the foundations for the DREAM project proposal implementation efforts if funded. The Agilex LIMO mobile robot [9] is a ROS development and educational/research platform that has an embedded NVIDIA Jetson Nano computer with a LiDAR, stereo depth camera (RGB-D Red, Green, Blue, Depth), and a suite of other sensors. The platform is ideal for both education and research. One of the goals of the DREAM project is to provide students exposure to robotic exploration of the lunar surface using simulations and analog sites on campus. The initial efforts undertaken were broadly inspired by simulation efforts reported by NASA scientists and engineers [10] and the ongoing efforts at the NASA centers related to robot design for the VIPER project [11] integral to the broad goals of the ambitious Artemis mission objectives [12].

Figure 4. Agilex LIMO Robot

A virtual Gazebo simulation for the Agilex LIMO robot can be downloaded from the web ([https://github.com/agilexrobotics/ugv_gazebo_sim)](https://github.com/agilexrobotics/ugv_gazebo_sim) and can be launched into a user-created world environment with ROS. This provided a framework for the UMES and high school students to work together to initiate efforts using the virtual platform while the project team waited for the LIMO robot that was ordered towards the beginning of summer to arrive. Most students were working with ROS for the first time and had little to minimal exposure to the Linux/Ubuntu operating system. Moreover, since several versions of Ubuntu and ROS exist picking the best combination was a bit overwhelming at first. While one has the flexibility to use any compatible versions of Ubuntu and ROS in simulations, it was decided to use ROS Noetic with Ubuntu 20.04 for the simulations at the initial stages, although it was later realized that the physical robot could only run on ROS Melodic with Ubuntu 18.04 due to hardware constraints. Project participants also familiarized themselves with JPL/NASA's Moon Trek portal[13] which provided extensive data on the lunar surface. Participants could use texture and elevation data from selected regions of the moon to create a simulated lunar environment in the Gazebo world and launch the virtual LIMO into it. They could also navigate the virtual LIMO in the simulated lunar surface and activate

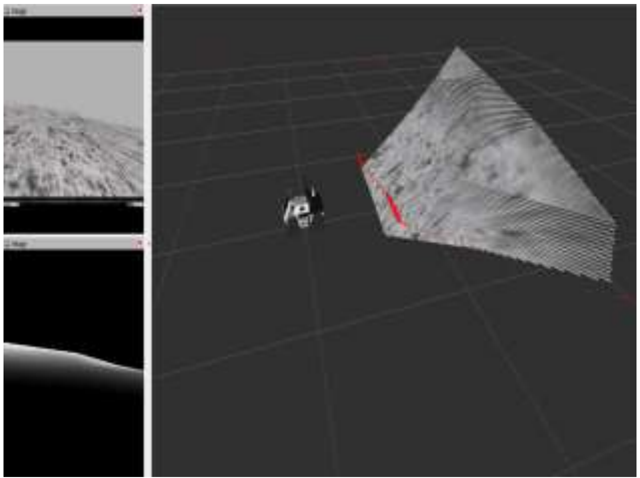


Figure 5a. RViz window of LIMO

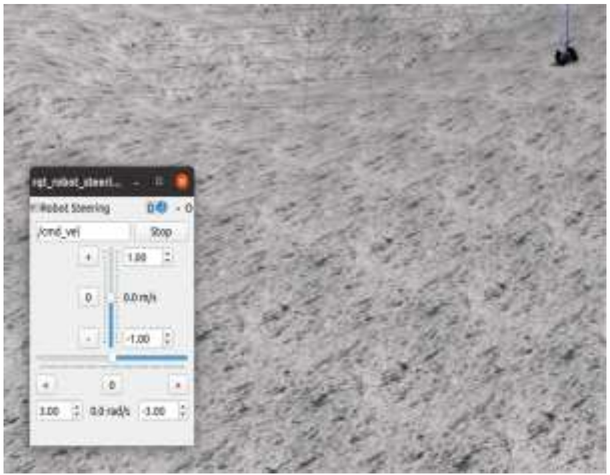
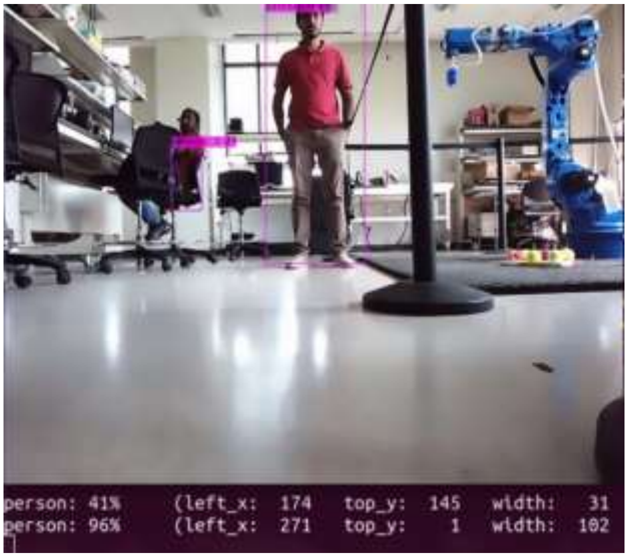


Figure 5b. Lunar terrain in Gazebo

the LiDAR integral to the virtual LIMO (See Figures 5a and 5b). Please note RViz ((https://wiki.ros.org/rviz, Figure 5a) is a 3D visualization tool for ROS that allows users to view the simulated robot model, log sensor information, and replay the logged sensor information.

Toward the end of the summer, the LIMO robot was delivered to the robotics laboratory on campus. Initial trials involved navigating the LIMO on the lab floor using the mobile app and exploring the AI capabilities built-in using the onboard RGB-D (red, green, blue - depth) camera and the LiDAR. The LIMO connects through Bluetooth at a maximum distance of 10m with a mobile phone. This multi-modal motion control gives the user control over the four-wheel differential mode. While it runs via Bluetooth, LIMO can also connect with Wi-Fi through the command control. Figure 6a is a view from the LIMO on the floor of the robotics laboratory as it is being navigated using the mobile app. In the image, the LIMO automatically identifies the student standing in front with 96% certainty and the student sitting in the chair with 41% certainty. Other built-in obstacle avoidance and image recognition capabilities are also built into the robot. Figure 6b demonstrates the Gmapping and navigation capabilities with 2-D LiDAR installed on the LIMO. The map of the robotics lab was made by driving the LIMO around with the GMapping (https://wiki.ros.org/gmapping) software running. The map is then given as a parameter for the move_base package, which is responsible for navigation. The map produced during the Gmapping phase consists of three colors: black line indicates what the LIMO understands are known stationary objects, gray indicates clear floor space, and red indicates what the LiDAR currently sees. The red and green axis marks are where the LIMO thinks it is, with red being forward. Once the map is passed as a parameter to the move_base package and the navigation begins, the obstacle avoidance calculations are initiated in a pre-determined radius around the robot. The black lines within this radius are converted to purple lines, and all detected objects are given a blue aura known as the inflation layer. The pink line is the path that the robot intends to follow to reach a set goal. The farther the robot must travel to reach a goal, and the closer it gets to an object's inflation



```
person: 41%     (left_x:  174   top_y:  145   width:   31
person: 96%     (left_x:  271   top_y:    1   width:  102
```

Figure 6a. LIMO – Person identification

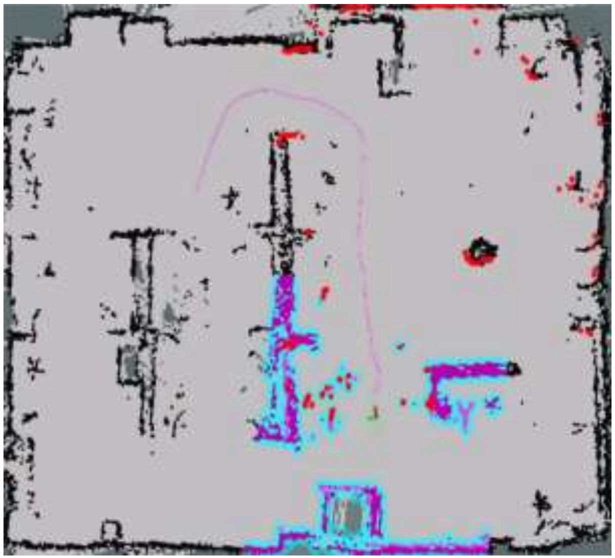


Figure 6b: Gmapping with LiDAR

radius, the more that path costs, and the robot will optimize these two variables to perform efficient path planning in real-time.

As mentioned earlier, the DREAM project proposal developed by the principal author in collaboration with faculty members of the partnering university was selected and awarded to the university by NASA in September 2023. After dealing with preliminary logistics and sub-award formalities, the UMD faculty collaborator selected a couple of his undergraduate students with significant experience in the design and development of planetary rovers as well as ROS and GAZEBO simulations in their campus to work with the UMES student participants by way of videoconferencing to get them up to speed with some of the software fundamentals through weekly tutorial sessions. Figure 7a is a screenshot taken during one of the video conferencing tutorial sessions among students of the partnering universities of the DREAM project. At the time of writing this paper, the students had collaborated on six such video tutorials. The topics covered included an overview of Linux and Ubuntu, setting up and navigating Ubuntu, basics and advanced usage of Git for version control, installing and configuring ROS (Noetic), Bash scripting, building and visualizing URDFs (Unified Robotics Description Format - an eXtensible Markup Language (XML) file type that contains physical description of a robot), Xacro use cases, and practical applications in Gazebo including robot control and integrating components like cameras and lasers. During these sessions, the students simulated a four-wheeled differential drive robot (they called it Boxxo) that had two programmable arms, each with 5 degrees of freedom with a camera attached at the end. Another camera was located on the upper surface of the square base of the robot to which the wheels were attached. In Figure 7b the virtual robot has been spawned on the Gazebo world on the Copernicus crater on the lunar surface with data gathered from the Moon Trek portal. The views from the robot base-mounted camera and the camera on one of the robotic arms, which is looking to the side, are also included in the Figure.

Figure 7a: Screenshot of Video Session

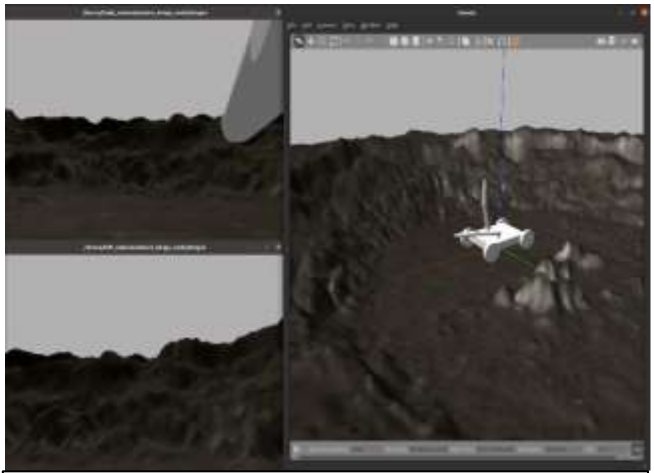


Figure 7b: Boxxo on the Copernicus Crater

Figure 8a:VERTEX (Umbilical Retracted)

Figure 8b:VERTEX (Umbilical Extended)

A physical rover designed and built by the UMD students will be tested on their campus and then it will be brought to the UMES campus for analog field trials in which the UMES students will also participate alongside UMD students as part of the initial phase of the project. The UMD rover is a dextrous autonomous robot (VERTEX) that works alongside astronauts and carries the primary life support system for the astronaut, including consumables, atmosphere revitalization systems (e.g., CO2 scrubbing, humidity, and temperature management, ventilation fan), power system (e.g., battery, power management and distribution), and thermal control system (e.g., water sublimator, cooling water pump), as well as umbilical lines to connect to the supported astronaut via the autonomous handling system (VERTEX/Biobot). The arrangement will not require the astronauts to carry a heavy load while performing tasks. Figures 8a and 8b are photographs taken during a recent field trial on the UMD campus with the umbilical lines retracted on the rover for navigation and extended and appropriately attached to the astronaut as he or she performs a specified task.

Figure 9a: LIMO navigating on bare soil

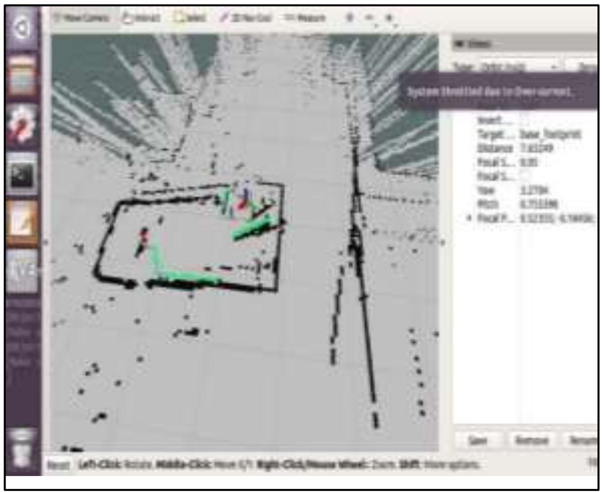


Figure 9b: LiDAR SLAM on bare soil

The students on the UMES campus continued activities to explore some of the capabilities of the Agilex LIMO robot in the fall. Students tested the LIMO robot in an outdoor setup on a raised bed. They used cardboard to set up the boundaries of the enclosure(Figure 9a) the LIMO navigated to perform a LiDAR SLAM (Simultaneous Localization and Mapping). The students navigated the LIMO on bare soil first (Figure 9b) then they also put cardboard on the floor and navigated the same enclosure. Subsequently, measurements were taken of the layout and a CAD model of it was developed. The CAD model was appropriately converted to the SDF (Simulation Description Format) format accepted by GAZEBO. The virtual LIMO was spawned in the CAD-based GAZEBO world (Figure 10a) and the LiDAR scan as it navigated the simulated enclosure was developed for comparison (Figure 10b).

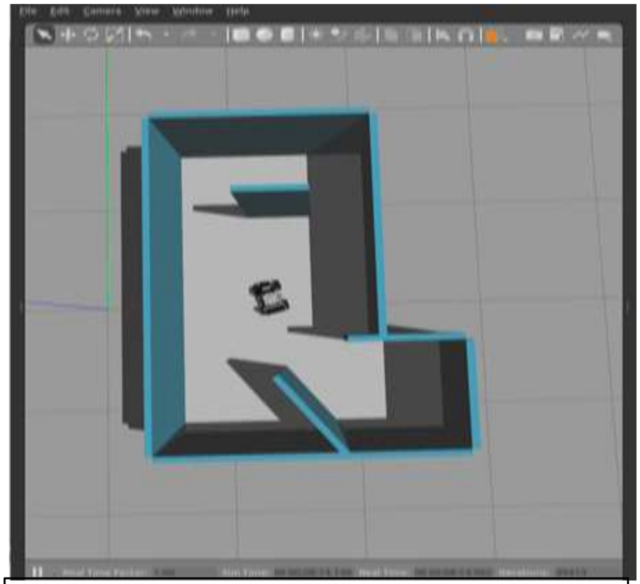


Figure 10a: CAD Gazebo world with LIMO

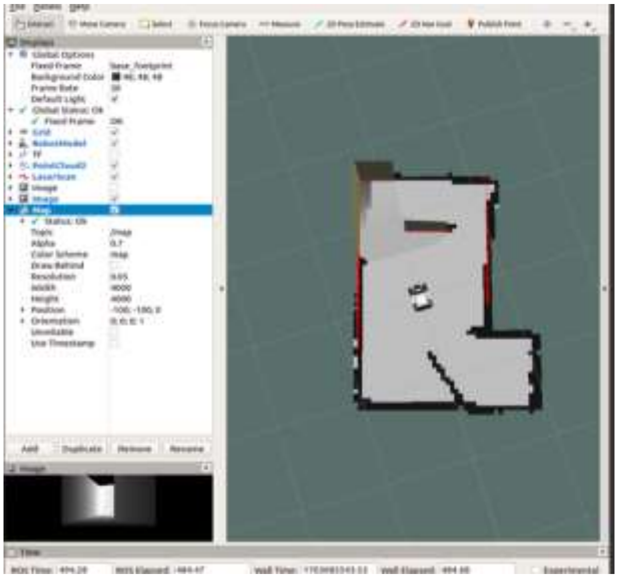


Figure 10b: LIMO LiDAR scan

The broader scope of the DREAM project also includes field trials to grow food crops using lunar regolith using automation under a controlled environment. A field experiment has been set up with varying levels of regolith and earth soil to test and compare the growth patterns of radish seeds. The experiment has been set up on an indoor FarmBot (https://farm.bot/)bed with grow lights. Efforts are underway to irrigate the set-up autonomously. The field trial setup and preliminary results are not included in this paper.

4.0 Accomplishments and Learning Outcomes

Projects such as the ones reported in this paper enhance university experiences for students and provide enriching learning engagements that address learning outcomes that are aligned with future professional work environments. The out-of-classroom involvements such as these are not limited to problem-solving from textbooks, structured laboratory studies, or even open-ended design projects that are constrained by compartmentalization of knowledge in academic disciplines, and as such allow integration of aspects of the real work environment that most students will join after completing their graduation requirements. Overall campus experiences of the students are enriched, although at times non-academic aspects of the fieldwork may appear to be of little educational relevance.

Learning can be categorized into developing skills in three broad domains - cognitive, affective, and psychomotor. Higher education typically focuses largely on the cognitive domain following Bloom's taxonomy – knowledge, comprehension, application, and evaluation [14]. ABET outcomes for engineering education integrate developing student abilities in both the affective and cognitive domains [15]. Integrating out-of-classroom active learning experiences for students such as those described in this paper provides rich learning outcomes that integrate academic, life skills, and civic responsibility outcomes that are difficult to address from within the classroom. Often the artificial silos limit the overall exposure for students if they limit their university engagement to just classroom education. The higher-order synthesizing skills of the students are brought to bear with the open-ended creative endeavors. The ABET learning outcomes related to teamwork, analyzing and interpreting data, and self-directed acquisition of new knowledge are facilitated by student-driven learning exercises and project efforts integral to the overall scope of the ongoing open-ended endeavors.

Sphero RVR mobile platform and associated soft robotics effort introduced students to popular microprocessor and microcomputer boards such as Arduino Nano and Raspberry Pi, structured programming with Python, C++, and Scratch, elastomer-based soft grippers, basics of mechanism design, CAD, and 3D printing. These efforts are largely driven by the AIRSPACES project; however, enhancement efforts are underway to explore synergistic avenues for integrating it with the overall scope of the DREAM project. The DREAM project has provided a fertile ground for students to engage in self-directed learning facilitated by student mentors at the collaborating university. One notable endeavor of the student team was the creation of a portable shell script (available on GitHub). This script facilitated the rapid configuration of new and factory-reset computers for ROS development, automatically detecting the Ubuntu distribution and installing the corresponding ROS distribution, essential packages, dependencies, and various software tools needed for ROS and robotic development. The approach streamlined and expedited the setup process, enabling a quicker transition from setup to active development. The students harnessed the power of state-of-the-art CAD/3D modeling software tools, particularly Blender and SolidWorks, to create Gazebo models and environments. These tools were used to convert publicly available MoonTrek data (MoonTrek) and 3D models from NASA (https://nasa3d.arc.nasa.gov/models) into Gazebo-ready SDFs. Additionally, the AgileX LIMO and Scout URDFs, sourced from AgileX's publicly available GitHub repository (https://github.com/agilexrobotics/ugv_gazebo_sim), were critical to simulation tests that integrated functionality of various virtual sensors like LiDAR and RGB-D camera on the simulated robotic platforms in the custom-created environments.

Additionally, students used the Gmapping software package to utilize LiDAR laser scan data to conduct SLAM (Simultaneous Localization and Mapping) for generating 2-D maps in RVIZ. This approach not only improved mapping accuracy but also enhanced student understanding, conceptualization, and comprehension of robot navigation and data interpretation.

A sample of the snippets for the Sphero RVR and LIMO robot codes are included in Appendix A for the interested reader.

6.0 Acknowledgment

Besides the authors, a few additional undergraduate STEM students and summer exchange students participated in the project efforts. Their contributions are acknowledged with thanks. Maryland Space Grant Consortium and the NASA MSTAR program have funded the synergistic AIRSPACES and DREAM project at UMES. Their support is gratefully acknowledged.

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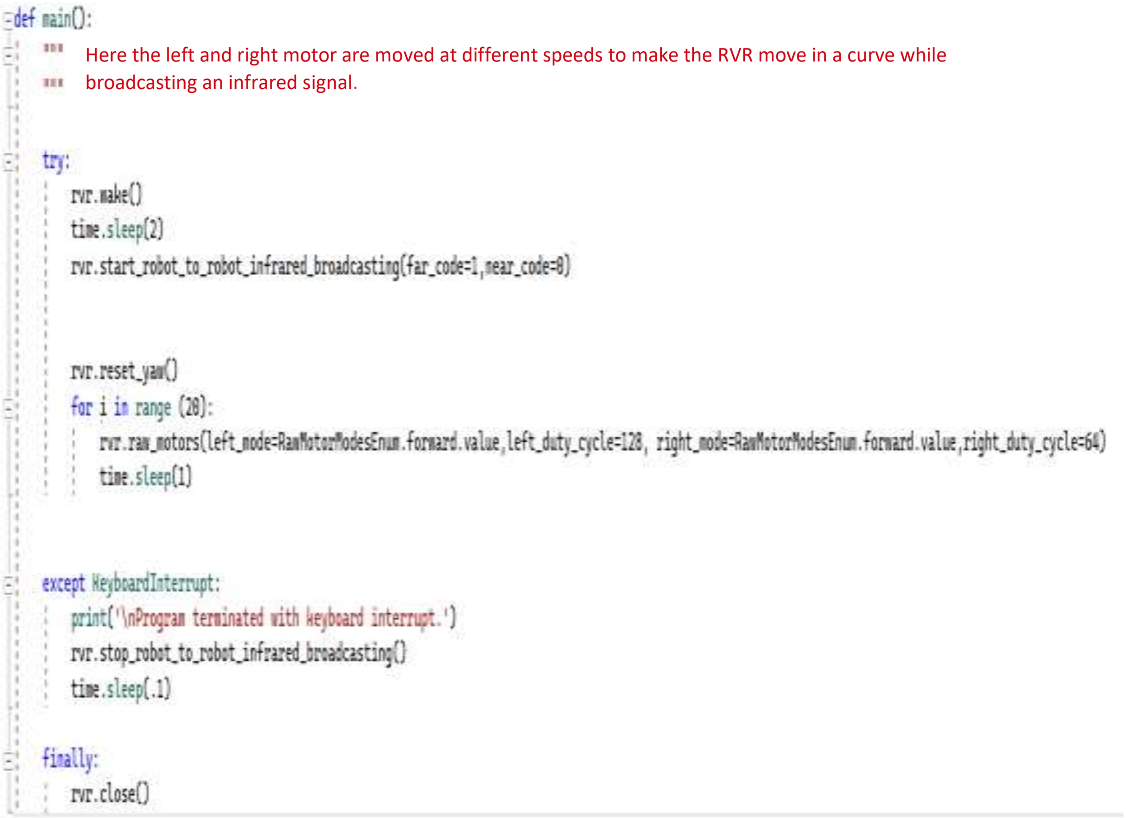
Appendix – A

One of the reviewers requested to include some code snippets in the paper. This Appendix provides a sampling of the codes for which the functionality has been described in the paper

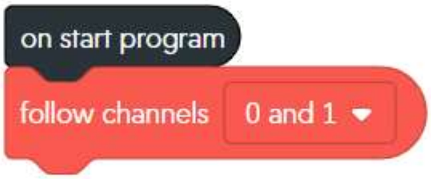
As outlined in the paper the Sphero Bolt was programmed (using Scratch Blocks) to sense the infrared signal from the Sphero RVR to follow it around. The Sphero RVR as described in the paper was interfaced with Raspberry PI and programmed in Python (refer to Figure 2 in the body of the paper)

RVR Python Code



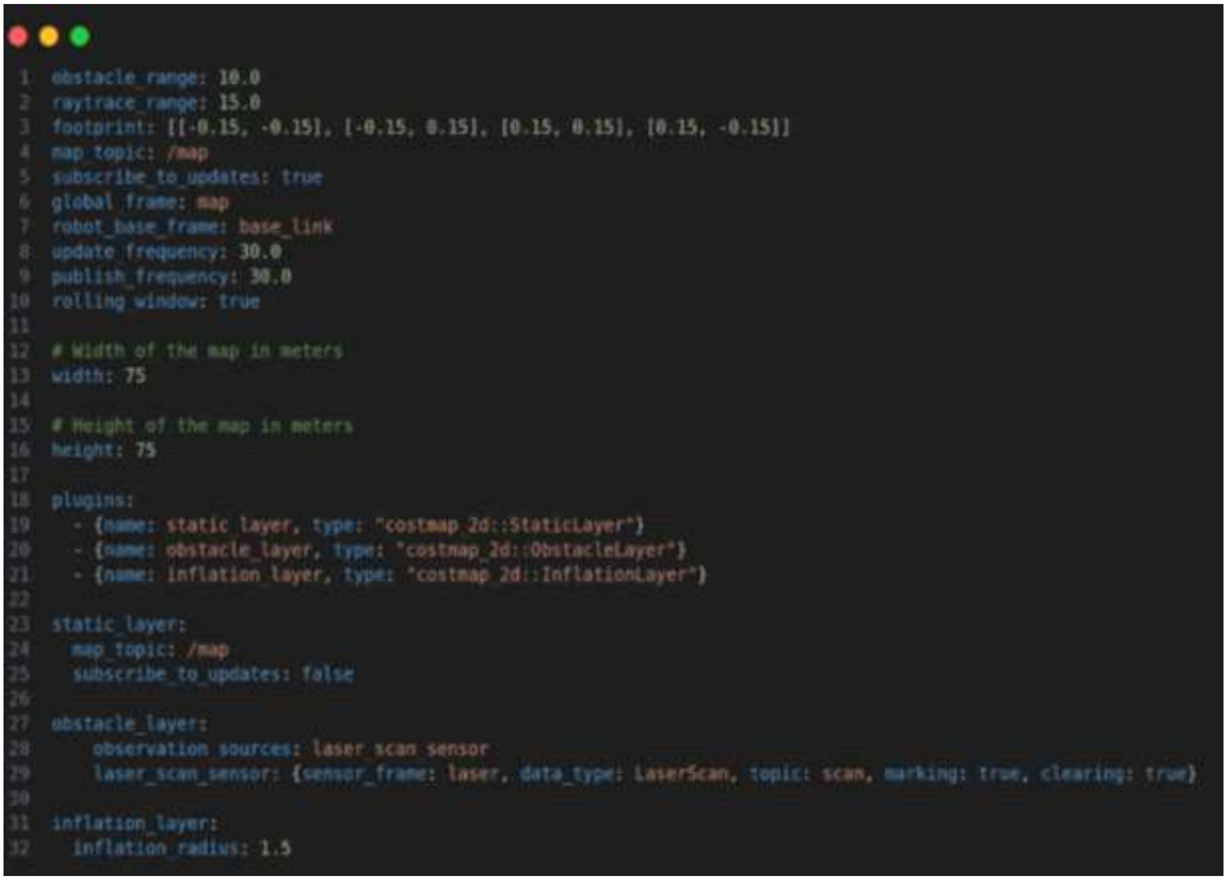
```python
def main():
    """ Here the left and right motor are moved at different speeds to make the RVR move in a curve while
    """ broadcasting an infrared signal.


    try:
        rvr.make()
        time.sleep(2)
        rvr.start_robot_to_robot_infrared_broadcasting(far_code=1,near_code=0)



        rvr.reset_yaw()
        for i in range (20):
            rvr.raw_motors(left_mode=RawMotorModesEnum.forward.value,left_duty_cycle=128, right_mode=RawMotorModesEnum.forward.value,right_duty_cycle=64)
            time.sleep(1)


    except KeyboardInterrupt:
        print('\nProgram terminated with keyboard interrupt.')
        rvr.stop_robot_to_robot_infrared_broadcasting()
        time.sleep(.1)

    finally:
        rvr.close()
```

Simple SCRATCH block code in BOLT to follow the RVR



```
on start program
follow channels 0 and 1
```

Sampling of LIMO Robot ROS CODE



```yaml
obstacle_range: 10.0
raytrace_range: 15.0
footprint: [[-0.15, -0.15], [-0.15, 0.15], [0.15, 0.15], [0.15, -0.15]]
map_topic: /map
subscribe_to_updates: true
global_frame: map
robot_base_frame: base_link
update_frequency: 30.0
publish_frequency: 30.0
rolling_window: true

# Width of the map in meters
width: 75

# Height of the map in meters
height: 75

plugins:
  - {name: static_layer, type: "costmap_2d::StaticLayer"}
  - {name: obstacle_layer, type: "costmap_2d::ObstacleLayer"}
  - {name: inflation_layer, type: "costmap_2d::InflationLayer"}

static_layer:
  map_topic: /map
  subscribe_to_updates: false

obstacle_layer:
    observation_sources: laser_scan_sensor
    laser_scan_sensor: {sensor_frame: laser, data_type: LaserScan, topic: scan, marking: true, clearing: true}

inflation_layer:
  inflation_radius: 1.5
```

The code above is the costmap_common_params.yaml – one of the most useful configuration files. This is where the Limo’s inscribed dimensions (used for obstacle avoidance calculations), important plugins, and the inflation radius of obstacles can be assigned so that Limo can avoid obstacles during autonomous navigation using move_base()

```cpp
void SlamGMapping::startLiveSlam()
{
  entropy_publisher_ = private_nh_.advertise<std_msgs::Float64>("entropy", 1, true);
  sst_ = node_.advertise<nav_msgs::OccupancyGrid>("map", 1, true);
  sstm_ = node_.advertise<nav_msgs::MapMetaData>("map_metadata", 1, true);
  ss_ = node_.advertiseService("dynamic_map", &SlamGMapping::mapCallback, this);
  scan_filter_sub_ = new message_filters::Subscriber<sensor_msgs::LaserScan>(node_, "scan", 5);
  scan_filter_ = new tf::MessageFilter<sensor_msgs::LaserScan>(*scan_filter_sub_, tf_, odom_frame_, 5)
  scan_filter_->registerCallback(boost::bind(&SlamGMapping::laserCallback, this, _1));

  transform_thread_ = new boost::thread(boost::bind(&SlamGMapping::publishLoop, this, transform_publis
}
```

The code snippet above is another important function located in the source code of the gmapping node @ gmapping/src/slam_gmapping.cpp. It is utilized to fill out the ‘Occupancy Grid’, a 2-D grid map in which each cell represents the probability from 0-100 of a cell being ‘occupied’ by an object – which determines whether or not a location is colored on the map as black (occupied) or gray (unoccupied, clear space) as seen in Figures 6b, 9b, & 10b in the body of the paper.