INTEGRATION OF THE SIMULATION ENVIRONMENT FOR AUTONOMOUS ROBOTS WITH ROBOTICS MIDDLEWARE

by

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ABSTRACT

ADAM CARLTON HARRIS. Integration of the simulation environment for autonomous robots with robotics middleware. (Under the direction of DR. JAMES M. CONRAD)

Robotic simulators have long been used to test code and designs before any actual hardware is tested to ensure safety and efficiency. Many current robotics simulators are either closed source (calling into question the fidelity of their simulations) or are very complicated to install and use. There is a need for software that provides good quality simulation as well as being easy to use. Another issue arises when moving code from the simulator to actual hardware. In many cases, the code must be changed drastically to accommodate the final hardware on the robot, which can possibly invalidate aspects of the simulation. This defense describes methods and techniques for developing high fidelity graphical and physical simulation of autonomous robotic vehicles that is simple to use as well as having minimal distinction between simulated hardware, and actual hardware. These techniques and methods were proven by the development of the Simulation Environment for Autonomous Robots (SEAR) described here.

SEAR is a 3-dimensional open source robotics simulator written by Adam Harris in Java that provides high fidelity graphical and physical simulations of user-designed vehicles running user-defined code in user-designed virtual terrain. Multiple simulated sensors are available and include a GPS, triple axis accelerometer, triple axis gyroscope, a compass with declination calculation, LIDAR, and a class of distance sensors that includes RADAR, SONAR, Ultrasonic and infrared. Several of these sensors have been validated against real-world sensors and other simulation software.

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Foremost, I would like to thank my wife and family whose support and encouragement has allowed me to come as far as I have and that has helped me surmount any obstacles that may lie in my way.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
API	Application programming interface
AUV	Autonomous underwater vehicles
BSD	Berkeley software distribution
CAD	Computer-aided design
COLLADA	Collaborative design activity
FLTK	Fast light toolkit
GPL	General public license
GPS	Global positioning system
GUI	Graphical user interface
HRI	Human-robot interaction
IDE	Integrated development environment
IMU	Inertial measurement unit
IPC	Inter-process communication
IR	Infrared
jFrame	Java frame
jME	jMonkeyEngine
jME3	jMonkeyEngine3
LabVIEW	Laboratory virtual instrument engineering workbench
LGPL	Lesser general public license
LIDAR	Light detection and ranging
Mac	Macintosh-based computer

MATLAB	Matrix laboratory
MEMS	Microelectromechanical systems
MRDS	Microsoft Robotics Developer Studio
MRL	MyRobotLab
MRPT	Mobile robot programming toolkit
NGA	National Geospatial-Intelligence Agency
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
ODE	Open dynamics engine
OpenCV	Open source computer vision
OpenGL	Open graphics library
OpenRAVE	Open robotics automation virtual environment
Orcos	Open robot control software
OSG	OpenScreenGraph
PAL	Physics abstraction layer
POJO	Plain old java object
POSIX	Portable operating system interface for Unix
PR2	Personal robot 2
RADAR	Radio detection and ranging
RF Modem	Radio frequency modem
RoBIOS	Robot BIOS
ROS	Robot operating system
SARGE	Search and rescue game engine

SEAR	Simulation Environment for Autonomous Robots
SLAM	Simultaneous localization and mapping
SONAR	Sound navigation and ranging
TCP	Transmission control protocol
UDP	User datagram protocol
UNIX	Uniplexed information and computing system
URBI	Universal robot body interface
USARSim	Unified system for automation and robotics simulation
UserCode	Code written by a user of SEAR
UT2004	Unreal Tournament 2004
VPL	Visual programming language
WiFi	Wireless fidelity
WMM	World magnetic model
XML	Extensible markup language
YARP	Yet another robot platform

CODE LISTINGS

CHAPTER 1: INTRODUCTION

The best way to determine whether or not a physical robotics project is feasible is to have a quick and easy way to simulate both the hardware and software that is planned to be implemented. Robotics simulators have been available for almost as long as robots. Until fairly recently, however, they have been either too complicated to be easily used or designed for a specific robot or line of robots. In the past two decades, more generalized simulators for robotic systems have been developed. Most of these simulators still pertain to specialized hardware or software and some have low quality graphical representations of the robots, their sensors, and the terrain in which they move. Overall, many of the simulations look simplistic and there are limitations with real-world maps and terrain simulations.

1.1 Motivation

Robotic simulators should help determine whether or not a particular physical robot design will be able to handle certain conditions. Currently, many of the available simulators and middleware have several limitations. Some, like Eyesim, are limited on the hardware available for simulation [1]. Others often supply and specify several particular (and generally expensive) robotics platforms with no easy method of adding other platforms such as Player. To add a new robotics platform (a particular set of hardware including a diving base and sensors, be they virtual or physical) to these, a large amount of effort is needed to import vehicle models and in some cases, custom code must be added to the simulator itself. New device drivers must be written to add new sensors, even ones that are similar to supported versions. Several simulators are also limited with respect to terrain. Real-world terrain and elevation maps cannot easily be integrated into some of these systems such as Eyesim, CoopDynSim[2], [3]. While technically possible for some other tools such as Gazebo and USARsim, it is a complicated and convoluted process [4], [5]. Gazebo, USARsim, Eyesim, CoopDynSim and others all use a text-based method for creating environments and robots as opposed to a more natural solution like robotBuilder which is a graphical application [6].

Some of the current systems also do not effectively simulate simple sensors and interfaces. For example, you cannot easily interface a Sharp IR sensor directly with Player middleware. Many tools like Player, SimRobot, USARsim, and SARGE choose a communication protocol (most commonly Transmission Control Protocol or “TCP”) for all the sensors to run on [7]–[10]. This requires more expensive hardware and leaves fewer options for easy integration of sensors. Other tools require that a specific hardware driver or “node” be written for a particular sensor (eg. ROS)[11]. A simple robot consisting of two distance sensors, two motor drivers, and a small 8-bit embedded system cannot easily be simulated in many of the current systems. However, a robot using a computer board running Linux that requires each distance sensor and motor driver to have its own 8-bit controller board running a TCP stack is easily simulated in the current systems. This shows a trade-off of hardware complexity and programming abstraction. The best general simulators today such as Webots or Microsoft Robotics Developer Studio seem to be both closed source and proprietary, which inhibits community participation in its development and their possible applications [12]–[14]. Some of these systems are detailed in Chapter 2.

1.2 Objective of This Work

The objectives of this work are to develop the methods and architecture for a modern robotics simulator. A better, simpler simulator than those previously described would be one that can simulate nearly any possible vehicle, using nearly any type and placement of sensors. The entire system would be customizable, from the design of a particular vehicle chassis to the filtering of sensor data. This system would also allow a user to simulate any terrain, with an emphasis on real-world elevation map data. All of the options available to the user must be easy to use and the interface must be intuitive. The simulator should be cross-platform, meaning that it will run on Windows, Linux/Unix, and Mac systems and integrate *easily* with all these systems. It should also be open source to allow community involvement and future development and the simulator should be free to anyone who wishes to use it.

An implementation of a simulator meeting the criteria above is described in this dissertation. A simulator system (SEAR or Simulation Environment for Autonomous Robots) has been developed to test the methods and architecture described here with the ability to load custom models of vehicles and terrain, provide basic simulations for certain types of sensors; three-axis accelerometer, three-axis gyroscope, odometer, GPS, magnetic compass with declination calculation based on the robot's current GPS reading, LIDAR unit, and a class of reflective-beam sensors to simulate ultrasonic, RADAR and infrared sensors. The simulator allows users to write and simulate custom code (referred to as “userCode”) and simulate robot motion and sensing using a realistic physics engine. Tools have also been developed to allow the user to create or import vehicle models.

Additionally, three custom “services” (or interfaces) were developed for the MyRobotLab middleware. These are: services for light detection and ranging (known as LIDAR), global positioning system (known as GPS) as well as a service for the simulator itself .

1.3 Contribution

The main contribution of this research is the creation of methods and techniques used to implement a new cross-platform robotics simulator that has high graphical and physical fidelity and can easily be used by users of any skill set. SEAR is this proposed simulator, created to validate these new processes and designs. SEAR targets a very broad user base. It is simple enough that beginners can use the tool to learn the basics of programming and accurate enough that it can be used for robotics research at the graduate level. It is cross-platform, meaning that it runs on a variety of common computer operating systems. It has the ability to interface with middleware, allowing users to utilize the same code for simulations as they will on actual hardware, without having to change the language or functions. It also provides the user the ability to create or import any environment they choose and allow for robotic vehicles to be built and imported in a simple way. A simulator of autonomous robots of this type does not currently exist.

1.4 Organization

This dissertation is divided into six chapters. Chapter 2 gives general descriptions of several currently available robot simulation software tools. Chapter 3 describes the concept of the software put forth in this thesis and the history of this research project. Chapter 4 introduces the software tools used for the creation of the simulator. Chapter 5 discusses the architecture of SEAR and its methods of communications with middleware as well as methods by which the different sensors are simulated. Chapter 6 summarizes the work done in this dissertation and plans a course for future innovation and development. While most of this dissertation deals with a developer's level of abstraction, Appendix A is a comprehensive user guide for SEAR. This guide provides sample code that shows how a user would interact with the simulator including examples of how to create environments and robots from scratch and how to interface with them utilizing custom user-written code to control the robot within the simulator. It is recommended that this section be read either along side Chapter 5 or after Chapter 6.

CHAPTER 2: REVIEW OF SIMILAR WORK

Use of robotics simulators has grown with the field of robotics. Since the beginning of the robotics revolution, engineers and scientists have known that a high quality simulations can save time and money [13]. Simulations are conducted in many cases to test safety protocols, to determine calibration techniques, and to test new sensors or equipment. In the past robotics simulators have been generally written specifically for a company's own line of robots or for a specific purpose. In recent years, however, the improvements of physics engines and video game engines (as well as computer processing speed) have helped spur a new breed of simulators that combine physics calculations and accurate graphical representations of a robot in a simulation [15]. These simulators have the potential flexibility to simulate any type of robot. As the simulation algorithms and graphical capabilities of game engines become better and more efficient, simulations step out of the computer and become more realistic. Such engines can be applied to the creation of a simulator, and in the words of Craighead et al. "...it is no longer necessary to build a robotic simulator from the ground up" [15].

Robotics simulators are no longer in a software class of their own. To ensure code portability from the simulator to physical robotic platforms (as is generally the ultimate goal) specific middleware is often run on the platforms. Middleware allows for an abstraction of user-written code from physical or virtual hardware it is intended to control. The performance, function and internals of this middleware must be taken into account when comparing the simulators. All of these factors (and many more) affect the fidelity of the simulation. A second generation of robotics simulators based on game engines has emerged which utilize the frameworks and simulators of previous projects as their base [16], [17] Additionally, many established simulators are adding the capability to interface with different middleware and frameworks as they become available and prove useful [18], [19].

The ultimate goal of this chapter is to compare some of the most popular simulators and middleware currently available (both open source and commercial) in an attempt to find one that can easily be used to simulate low-level, simple custom robotic hardware with high graphical and physical accuracy. There is a lot of previous work in this field. This chapter adds to the work of Craighead, Murphy, Burke, and Goldiez [15], Elkady and Sobh [20], Castillo-Pizarro, Arredondo, and Torres-Torriti [21], Madden [22] as well as a previous publication of my own [23]. Of all the simulators available to users, the particular robotics simulators described and compared in this chapter are just a few that were chosen based on their wide use and specific feature sets. Each simulator being compared has one or more of the following qualities:

- Variety of hardware that can be simulated (both sensors and robots)
- Graphical accuracy capabilities including realistic terrains, obstacles, and robotics vehicles
- Physical simulation accuracy including capabilities to simulate gravity, collisions, inertia,
- Cross-platform capabilities: The ability to run on all common operating systems Windows, Mac, and Linux
- Openness of source code of the simulator, libraries, or middleware for future development and addition of new or custom simulations by the user)

2.1 Open Source Robotics Simulation Tools

There are many open source robotics simulators available currently on the internet. The specific simulators covered in this section are the most popular and are widely used, or they contain a feature that is of interest to the simulation methods or architecture of SEAR.

2.1.1 Player Project Simulators

Started in 1999 at the University of Southern California, the Player Project [24] is an open source (GPL or General Public License) three-component system involving a hardware network server (Player); a two-dimensional simulator of multiple robots, sensors or objects in a bit-mapped environment (Stage); and multi-robot simulator for simple 3D outdoor environments (Gazebo) [25]. Player is middleware that controls the simulators or physical hardware and is discussed in detail in Section 2.3.1.

Stage is a 2-dimensional robot simulator mainly designed for interior spaces. It can be used as a standalone application, as a C++ library, or as a plug-in for Player. The strength of Stage is that it focuses on being “efficient and configurable rather than highly accurate.” [7]. Stage was designed for simulating large groups or swarms of robots. As with other simulators that are designed to simulate swarm or multi-agent robotics systems like Roborobo [26], Stage is limited in graphical and physics simulation accuracy [7]. Sensors in Stage communicate exactly the same as real hardware (over a TCP network), allowing the exact same code to be used for simulation as the actual hardware [27]. This is no guarantee, however that the simulations have high physical simulation fidelity [7].

Gazebo is a 3D robotics simulator designed for smaller populations of robots (less than ten) and simulates with higher graphical and physical accuracy than Stage [28].

Gazebo was designed to model 3D outdoor as well as indoor environments [27]. The use of plug-ins expands the capabilities of Gazebo to include abilities such as dynamic loading of custom models and the use of stereo camera sensors [29]. The original implementation of Gazebo uses the Open Dynamics Engine (ODE) which provides high-fidelity physics simulation [8]. It also has the ability to use the Bullet Physics engine [30]. Gazebo has been utilized as the basis of other robotics simulators. These forks generally specialize in one type of simulation (as is the case with the quadrotor simulator in [17] and Kelpie, the water surface and aerial vehicle simulator [16]).

2.1.2 USARSim

Originally developed in 2002 at Carnegie Mellon University, USARSim (Unified System for Automation and Robotics Simulation) [31] is a free simulator based on the cross platform Unreal Engine 2.0. It was handed over to the National Institute of Standards and Technology (NIST) in 2005 and was released under the GPL license [32]. USARSim is actually a set of add-ons to the Unreal Engine, so users must own a copy of this software to be able to use the simulator [8]. A license for the Unreal game engine usually costs around $40 US [33]. Physics are simulated using the Karma physics engine which is built into the Unreal engine [34]. This provides basic physics simulations [15]. One strength of using the Unreal engine is the built-in networking capability. Because of this, virtual robots can be controlled by any language supporting TCP sockets [35].

While USARSim is based on a cross-platform engine, the user manual only fully explains how to install it on a Windows or Linux machine. A Mac OS installation procedure is not described. The installation requires Unreal Tournament 2004 (UT2004) as well as a patch. After this base is installed, USARSim components can be installed.

On both Windows and Linux platforms, the installation is rather complicated and requires many files and directories to be moved or deleted by hand. The USARSim wiki has installation instructions [36]. Linux instructions were found on the USARSim forum at sourceforge.net [37]. Since it is an add-on to the Unreal tournament package, the overall size of the installation is several gigabytes.

USARSim comes with several detailed models of robots available for use in simulations [38], however it is possible to create custom robot components in external 3D modeling software and specify physical attributes of the components once they are loaded into the simulator [39]. An incomplete tutorial on how to create and import a model from 3D Studio Max is included in the source download. Once virtual robots are created and loaded, they can be programmed using TCP sockets [40]. Several simulation environments are also available. Environments can be created or modified by using tools that are part of the Unreal Engine [39].

There have been a multitude of studies designing methods for validating the physics and sensor simulations of USARSim. Pepper et al. [41] identified methods that would help bring the physics simulations closer to real-world robotic platforms by creating multiple test environments in the simulator as well as in the lab and testing real robotic platforms against the simulations. The physics of the simulations were then modified and tested repeatedly until more accurate simulations resulted. Balaguer and Carpin built on the previous work of validating simulated components by testing virtual sensors against real-world sensors. A method for creating and testing a virtual Global Positioning System (GPS) sensor that much more closely simulates a real GPS sensor was created [42]. Wireless inter-robot communication and vision systems have been designed and validated as well [38]. USARSim has even been validated to simulate aspects of other worlds. Birk et al. used USARSim with algorithms already shown to work in the real world as well as real-world data from Mars exploration missions to validate a robot simulation of another planet [43].

2.1.3 SARGE

SARGE (Search and Rescue Game Engine) [44], shown in Figure 2.1.3, is a simulator designed to train law enforcement in using robotics in search and rescue operations [45]. It is released under the Apache License V2.0. The developers of SARGE provide evidence that a valid robotics simulator could be written entirely in a game engine [15]. Unity was chosen as the game engine because it was more reliable than the Unreal engine and it provided a better option for physics simulations, PhysX. PhysX provides a higher level of fidelity in physics simulation of collisions and gravity [8]. SARGE currently only supports Windows and Mac platforms, although it is still under active development. Currently, a web player version of the simulator is available on the website http://www.sargegames.com.

FPS: 29.83
SARGE
The Search & Rescue Game Environment
USF UNIVERSITY OF SOUTH FLORIDA
SPLATSOSOFT
POWERED BY UNITY
PnL
PnD
PnR
Rev
Figure 2.1.3 SARGE screenshot

It is possible for SARGE users to create their own robots and terrains with the use of external 3D modeling software. Sensors are limited to LIDAR (Light Detection and Ranging), 3D camera, compass, GPS, odometer, inertial measuring unit (IMU), and a standard camera [45]. Only the GPS, LIDAR, compass and IMU are discussed in the user manual [46]. The GPS system requires an initial offset of the simulated terrain provided by Google Earth. The terrains can be generated independently in the Unity development environment by manually placing 3D models of buildings and other structures on images of real terrain from Google Earth [45]. Once a point in the virtual terrain is referenced to a GPS coordinate from Google Earth, the GPS sensor can be used [8]. This shows that while terrains and robots can be created in SARGE itself, external programs may be needed to set up a full simulation.

2.1.4 UberSim

UberSim [47] is an open source (under GPL license) simulator based on the ODE physics engine and uses OpenGL for screen graphics [48]. It was created in 2000 at Carnegie Mellon University specifically with a focus on small robots in a robot soccer simulation. The early focus of the simulator was the CMDragons RoboCup teams; however the ultimate goal was to develop a simulator for many types and sizes of robotics platforms [49]. Since 2007, it no longer seems to be under active development.

2.1.5 EyeSim

EyeSim began as a two-dimensional simulator for the EyeBot robotics platform in 2000 [1]. The EyeBot platform uses RoBIOS (Robot BIOS) library of functions. These functions are simulated in the EyeSim simulator. Test environments could be created easily by loading text files with one of two formats, either Wall format or Maze format. Wall format simply uses four values to represent the starting and stopping point of a wall in X,Y coordinates (i.e. x1 y1 x2 y2). Maze format is a format in which a maze is literally drawn in a text file by using the pipe and underscore (i.e. | and _) as well as other characters [50].

In 2002, the EyeSim simulator had graduated to a 3D simulator that uses OpenGL for rendering and loads OpenInventor files for robot models. The GUI (Graphical User Interface) was written using FLTK [2]. Test environments were still described by a set of two dimensional points as they have no width and have equal heights [50].

Simulating the EyeBot robot is the extent of EyeSim. While different 3D models of robots can be imported, and different drive-types (such as omni-directional wheels and Ackermann steering) can be selected, the controller will always be based on the EyeBot controller and use RoBIOS libraries [2]. This means simulated robots will always be coded in C code. The dynamics simulation is very simple and does not use a physics engine. Only basic rigid body calculations are used [50].

2.1.6 SubSim

SubSim [51] is a simulator for Autonomous Underwater Vehicles (AUVs) developed using the EyeBot controller. It was developed in 2004 for the University of Western Australia in Perth [52]. SubSim uses the Newton Dynamics physics engine as well as Physics Abstraction Layer (PAL) to calculate the physics of being underwater [15].

Models of different robotic vehicles are can be imported from Milkshape3D files [52]. Programming of the robot is done by using either C or C++ for lower-level programming, or a language plug-in. Currently the only language plug-in is the EyeBot plug-in. More plug-ins are planned but have yet to materialize [52].

2.1.7 CoopDynSim

CoopDynSim [3] is a multi-robot simulator built on the Newton Game Dynamics physics engine and OpenGL. It has the ability to playback simulations and even change the rate of time for a simulation. It uses YARP middleware which uses a socket-enabled interface. A benefit of this simulator is that each robot spawns its own thread. CoopDynSim was designed specifically for the hardware available in the author's lab at the Department of Industrial Electronics at the University of Minoh in Portugal.

2.1.8 OpenRAVE

OpenRAVE [53] (Open Robotics and Animation Virtual Environment) is an open source (LGPL) software architecture developed at Carnegie Mellon University [54]. It is mainly used for planning and simulations of grasping and grasper manipulations as well as humanoid robots. It is used to provide planning and simulation capabilities to other robotics frameworks such as Player and ROS. Support for OpenRAVE was an early objective for the ROS team due to its planning capabilities and openness of code [55].

One advantage to using OpenRAVE is its plug-in system. Everything connects to OpenRAVE by plug-ins, whether it is a controller, a planner, external simulation engines and even actual robotic hardware. The plug-ins are loaded dynamically. Several scripting languages are supported such as Python and MATLAB/Octave [53].

2.1.9 lpzrobots

lpzrobots [60] is a GPL licensed package of robotics simulation tools available for Linux and Mac OS. The main simulator of this project that corresponds with others in this survey is ode_robots which is a 3D simulator that used the ODE and OSG (OpenScreenGraph) engines.

2.1.10 SimRobot

Figure 2.1.10 shows a screen shot of SimRobot [61] is a free, open source completely cross-platform robotics simulator started in 1994. It uses the ODE for physics simulations and OpenGL for graphics [62]. It is mainly used for RoboCup simulations, but it is not limited to this purpose.

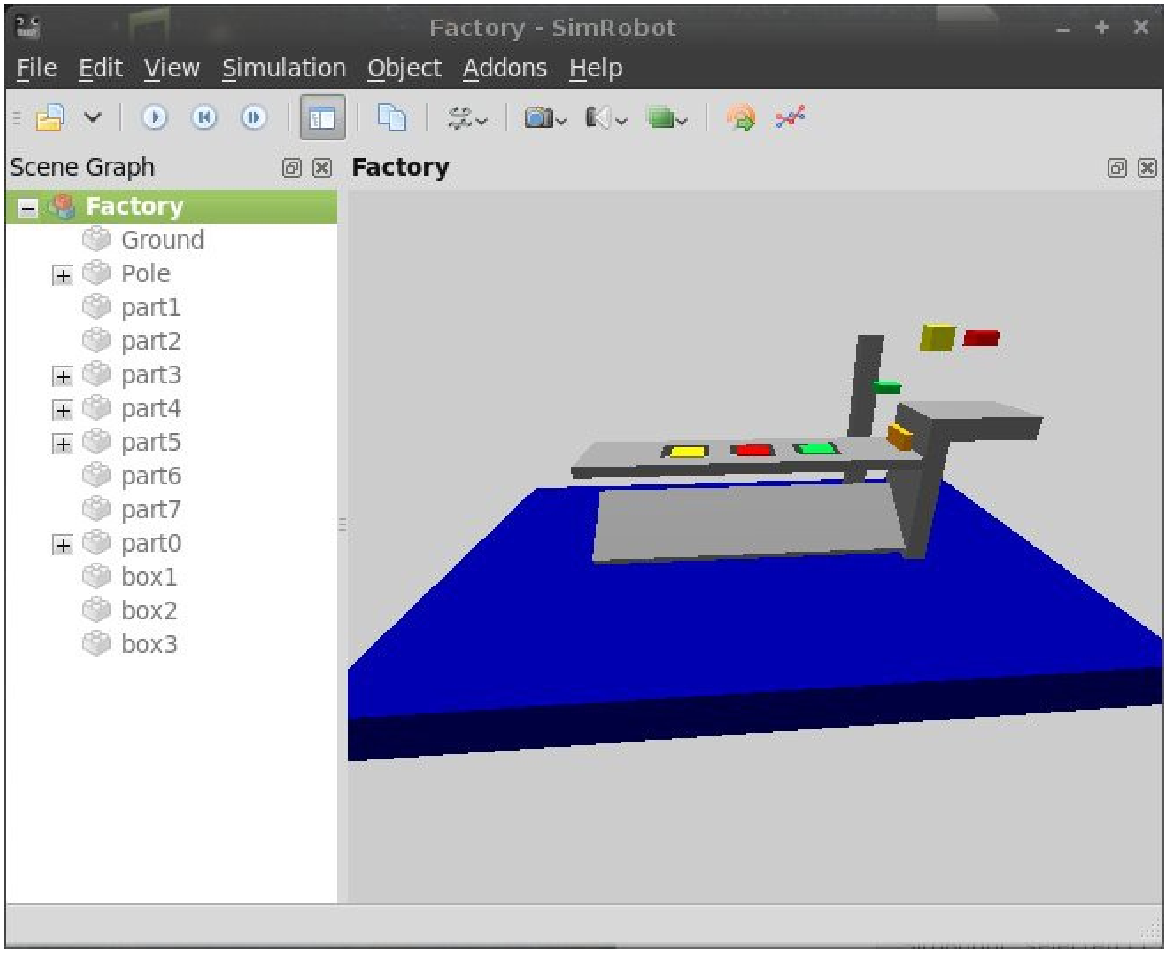


Figure 2.1.10 SimRobot screenshot

A simple and intuitive drag and drop interface allows custom items to be added to scenes. Custom robots can be created and added as well [10]. Unlike many of the other robotics simulators, SimRobot is not designed around client/server interaction. This allows simulations to be paused or stepped through which is a great help when debugging [10].

SimRobot does not simulate specific sensors as many of the other simulators do; rather it only provides generic sensors that users can customize. These include a camera, distance senor (not specific on a type), a "bumper" for simulating a touch sensor, and "actuator state" which returns angles of joints and velocities of motors [10].

Laue and Rofer admit that there is a "reality gap" in which simulations differ from real-world situations [62]. They note that code developed in the simulator may not translate to real robots due to distortion and noise in the real-world sensors. They also note, however, that code that works in the real world may completely fail when entered into the simulation because it may rely on that distortion and noise. This was specifically noted with the camera sensor and they suggested several methods to compensate for this difference [62].

2.1.11 Moby

Moby [63] is an open source (GPL 2.0 license) rigid body simulation library written in C++. It supports Linux and Mac OS X only. There is little documentation for this simulation library.

2.1.12 Comparison of Open Source Simulation Tools

Table 2.1.13 shows the relative advantages and disadvantages of the simulators covered in this section [64].

Table 2.1.13. Comparison of open source simulators

Simulator	***Advantages***	***Disadvantages***
Stage/Gazebo	• Open Source (GPL) • Cross Platform • Active Community of Users and Developers • Uses ODE Physics Engine for High Fidelity Simulations • Uses TCP Sockets • Can be Programmed in Many Different Language	
USARSim	• Open Source (GPL) • Supports both Windows and Linux • Users Have Ability to Make Custom Robots and Terrain with Moderate Ease • Uses TCP Sockets • Can be Programmed in Many Different Language	• Hard to Install • Must have Unreal Engine to use (Costs about $40) • Uses Karma Physics Engine

Table 2.1.13 Continued

Simulator	***Advantages***	***Disadvantages***
SARGE	• Open Source (Apache License V2.0) • Uses PhysX Physics Engine for High Fidelity Simulations • Supports both Windows and Mac • Users Have Ability to Make Custom Robots and Terrain with Moderate Ease • Uses TCP Sockets • Can be Programmed in Many Different Languages	• Designed for Training, not Full Robot Simulations
UberSim	• Open Source (GPL) • Uses ODE Physics Engine for High Fidelity Simulations	• No Longer Developed
EyeSim	• Can Import Different Vehicles	• Only Supports EyeBot Controller
SubSim	• Can Import Different Vehicles • Can be programmed in C or C++ as well as using plug-ins for other languages	
CoopDynSim	• Multi-Robot system • Multithreaded • Uses YARP to interface via TCP sockets	
OpenRAVE	• Open Source (Lesser GPL) • Everything Connects using plug-Ins • Can be used with Other Systems (like ROS and Player) • Can be Programmed in Several Scripting Languages	
lpzrobots	• Open Source (GPL) • Uses ODE Physics Engine for High Fidelity Simulations	• Linux and Mac only
SimRobot	• Open Source • Users Have Ability to Make Custom Robots and Terrain	
Moby	• Open Source (GPL 32.0) • Written in C++	• Supports Linux and Mac only • Very little documentation

2.2 Commercial Simulators

There are many commercial robotics simulators available. The commercial simulators described and compared in this paper will be focused on research and education.

As with any commercial application, one downfall of all of these applications is that they typically are not open source. Commercial programs that do not release source code can tie the hands of the researcher, forcing them in some cases to choose the less than optimal answer to various research questions. When problems occur with proprietary software, there is no way for the researcher to fix it. This problem alone was actually the impetus for the Player Project [65].

2.2.1 Microsoft Robotics Developer Studio

Microsoft Robotics Developer Studio (MRDS) [14] uses Phys X physics engine which is one of the highest fidelity physics engines available [15]. A screen shot can be seen in Figure 2.2.1. MRDS robots can be programmed in .NET languages as well as others. The majority of tutorials available online mention the use of C# as well as a Visual Programming Language (VPL) Microsoft developed. Programs written in VPL can be converted into C# [66]. The graphics are high fidelity. There is a good variety of robotics platforms as well as sensors to choose from.

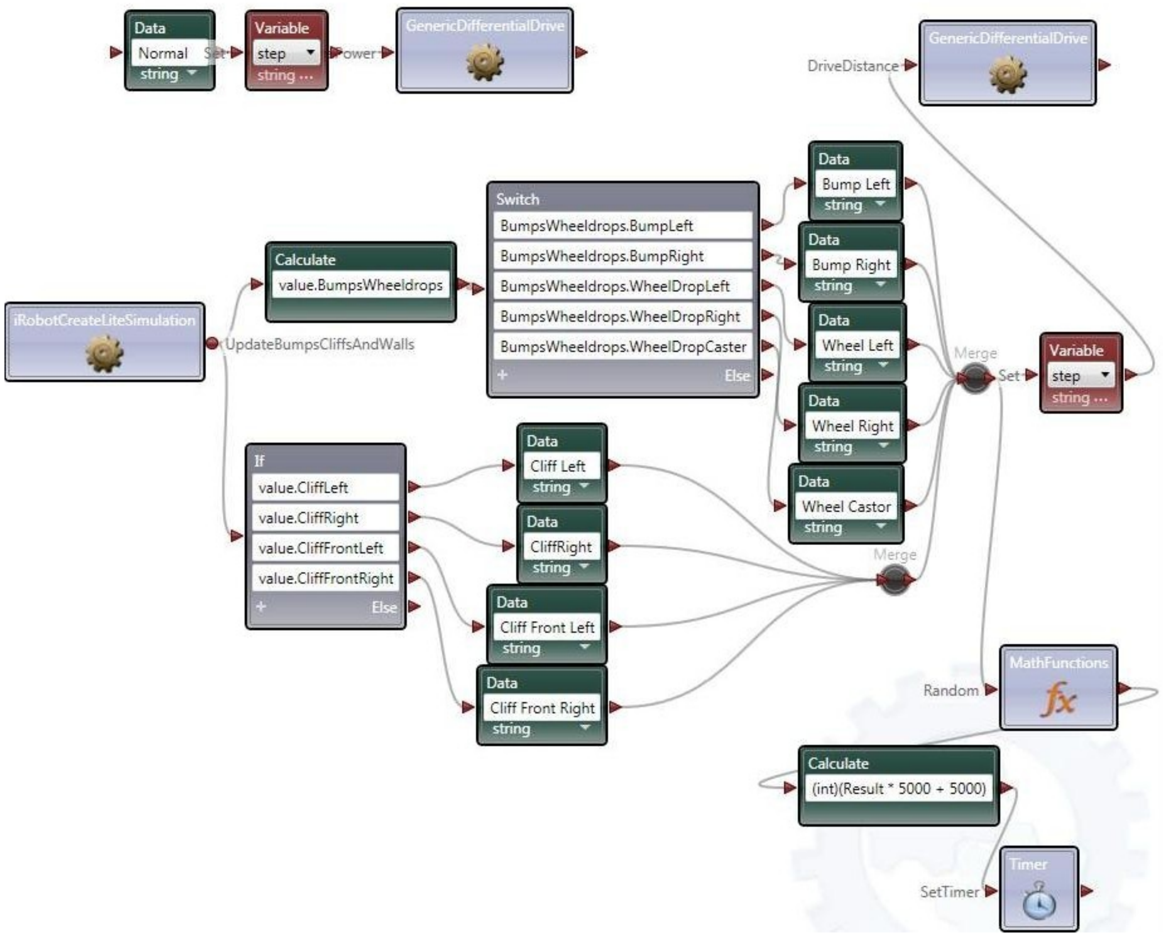
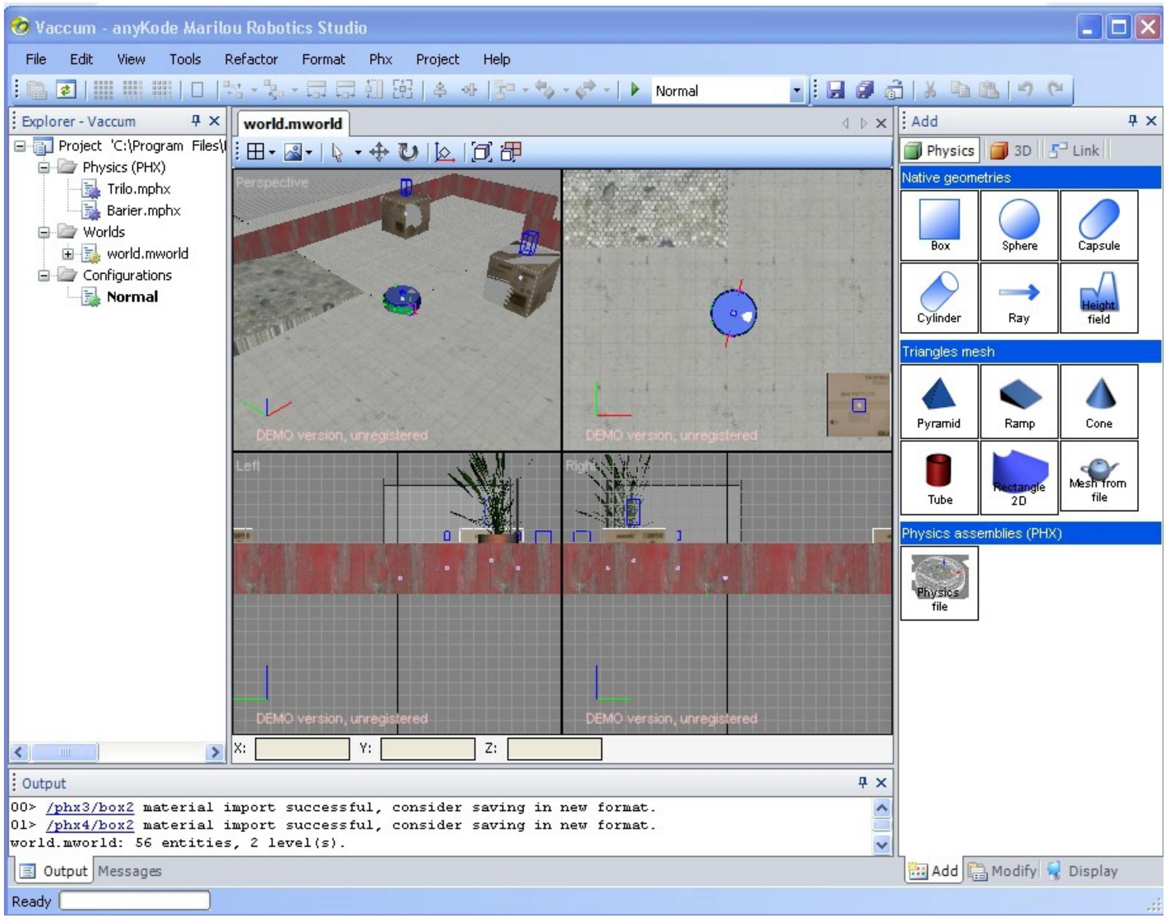


Figure 2.2.1 Microsoft Robotics Developer Studio screenshot

Only computers running Windows 7 are supported in the latest release of MRDS, however, it can be used to program robotic platforms which may run other operating systems by the use of serial or wireless communication (Bluetooth, WiFi, or RF Modem) with the robot [67].

2.2.2 Marilou

Figure 2.2.2 shows a screen shot of Marilou by anyKode [68]. Marilou is a full robotics simulation suite. It includes a built in modeler program so users can build their own robots using basic shapes. The modeler has an intuitive CAD-like interface. The physics engine simulates rigid bodies, joints, and terrains. It includes several types of available geometries [69]. Sensors used on robots are customizable, allowing for specific aspects of a particular physical sensor to be modeled and simulated. Devices can be modified using a simple wizard interface.



```
00> /phx3/box2 material import successful, consider saving in new format.
01> /phx4/box2 material import successful, consider saving in new format.
world.mworld: 56 entities, 2 level(s).
```

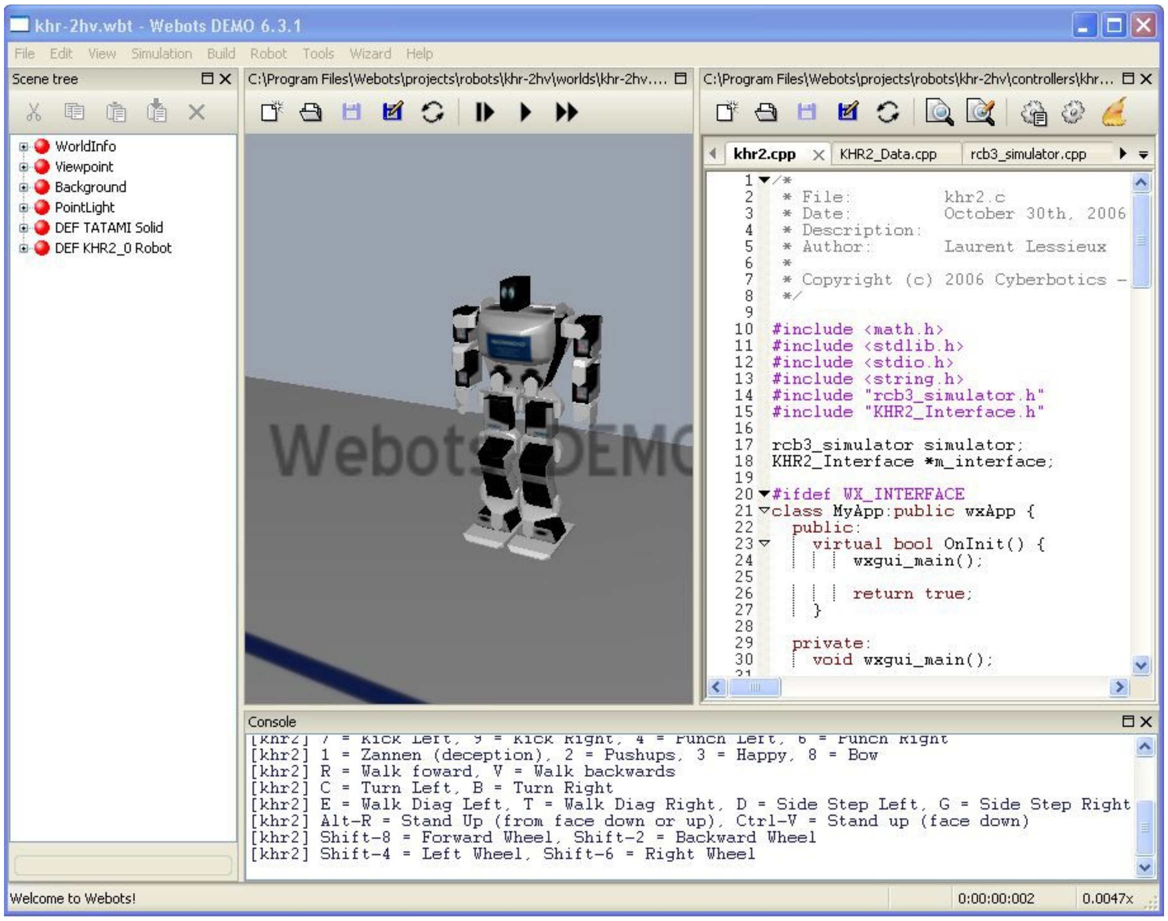
Figure 2.2.2 anykode Marilou screenshot

Robots can be programmed in many languages from Windows and Linux machines, but the editor and simulator are Windows only. Marilou offers programming wizards that help set up projects settings and source code for based on which language and compiler is selected by the user [70].

Marilou is not open source or free. While there is a free home version, it is meant for hobbyists with no intention of commercialization. The results and other associated information are not compatible with the professional or educational versions. Prices for these versions range from $360 to $2,663 [71].

2.2.3 Webots

The Cyberbotics simulator Webots [72] (shown in Figure 2.2.3) is a true multiplatform 3D robotics simulator that is one of the most developed of all the simulators surveyed [13]. Webots was originally developed as an open source project called Khepera Simulator as it initially only simulated the Khepera robot platform. The name of the project changed to Webots in 1998 [73]. Its capabilities have since expanded to include more than 15 different robotics platforms [12].


khr-2hv.wbt - Webots DEMO 6.3.1
File Edit View Simulation Build Robot Tools Wizard Help
Scene tree
WorldInfo
Viewpoint
Background
PointLight
DEF TATAMI Solid
DEF KHR2_0 Robot
C:\Program Files\Webots\projects\robots\khr-2hv\worlds\khr-2hv....
Webots DEMO
C:\Program Files\Webots\projects\robots\khr-2hv\controllers\khr...
khr2.cpp
KHR2_Data.cpp
rcb3_simulator.cpp
Console
Welcome to Webots!
0:00:00:002
0.0047x

```
/*
 * File:          khr2.c
 * Date:          October 30th, 2006
 * Description:
 * Author:        Laurent Lessieux
 *
 * Copyright (c) 2006 Cyberbotics -
 */

#include <math.h>
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include "rcb3_simulator.h"
#include "KHR2_Interface.h"

rcb3_simulator simulator;
KHR2_Interface *m_interface;

#ifdef WX_INTERFACE
class MyApp:public wxApp {
  public:
    virtual bool OnInit() {
      wxgui_main();

      return true;
    }

  private:
    void wxgui_main();
```

```
[khr2] 7 = Kick Left, 9 = Kick Right, 4 = Punch Left, 6 = Punch Right
[khr2] 1 = Zannen (deception), 2 = Pushups, 3 = Happy, 8 = Bow
[khr2] R = Walk foward, V = Walk backwards
[khr2] C = Turn Left, B = Turn Right
[khr2] E = Walk Diag Left, T = Walk Diag Right, D = Side Step Left, G = Side Step Right
[khr2] Alt-R = Stand Up (from face down or up), Ctrl-V = Stand up (face down)
[khr2] Shift-8 = Forward Wheel, Shift-2 = Backward Wheel
[khr2] Shift-4 = Left Wheel, Shift-6 = Right Wheel
```

Figure 2.2.3 Webots screenshot

Webots uses the Open Dynamics Engine (ODE) physics engine and, contrary to the criticisms of Zaratti, Fratarcangeli, and Iocchi [40], Webots has realistic rendering of both robots and environments. It also allows multiple robots to run at once. Webots can execute controls written in C/C++, Java, URBI, Python, ROS, and MATLAB languages [74]. This simulator also allows the creation of custom robotics platforms; allowing the user to completely design a new vehicle, choose sensors, place sensors where they wish, and simulate code on the vehicle.

Webots has a demonstration example showing many of the different robotics systems it can simulate, including an amphibious multi-jointed robot, the Mars Sojourner rover, robotic soccer teams, humanoids, multiple robotic arms on an assembly line, a robotic blimp, and several others. The physics and graphics are very impressive and the software is easy to use.

Webots has a free demonstration version available (with the ability to save world files crippled) for all platforms, and even has a free 30 day trial of the professional version. The price for a full version ranges from $320 to $4312 [75].

2.2.4 robotSim Pro/robotBuilder

robotBuilder [72] is a software package from Cogmation Robotics that allows users to configure robots models and sensors. Users import the models of the robots, import and position available sensors onto the robots, and link these sensors to the robot's controller. Users can create and build new robot models piece by piece or robotBuilder can import robot models created in other 3D CAD (Computer-Aided Design) programs such as the free version of Google Sketchup. The process involves exporting the Sketchup file as a COLLADA or 3DS file, then importing this into robotBuilder [73].

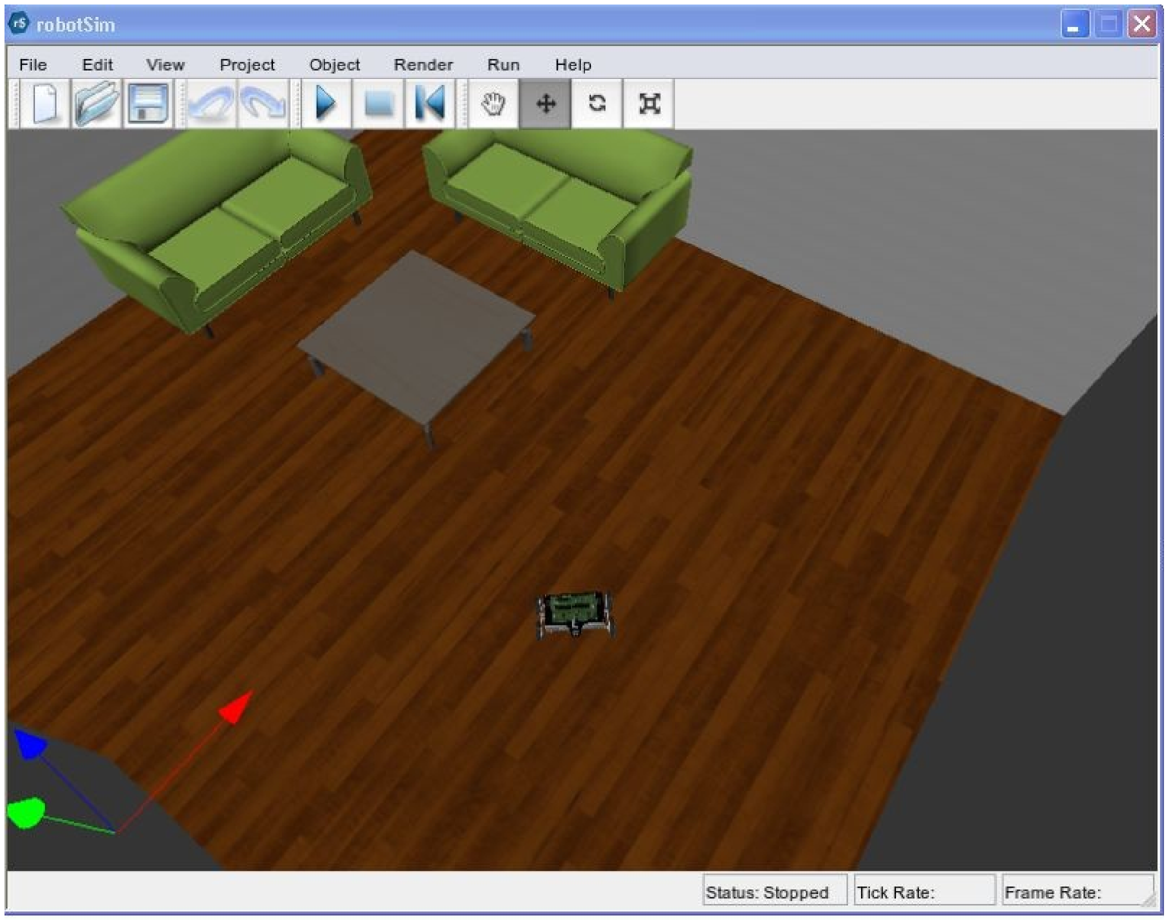


Figure 2.2.4 robotSim Pro screenshot

robotSim Pro (seen in Figure 2.2.4) is an advanced 3D robotics simulator that uses a physics engine to simulate forces and collisions [76]. Since this software is commercial and closed source, the actual physics engine used could not be determined. robotSim allows multiple robots to simulate at one time. Of all of the simulators in this survey, robotSim has some of the most realistic graphics. The physics of all objects within a simulation environment can be modified to make them simulate more realistically [76]. Test environments can be easily created in robotSim by simply choosing objects to be placed in the simulation world, and manipulating their positions with the computer mouse. Robot models created in the robotBuilder program can be loaded into the test environments. Virtual robots can be controlled by one of three methods; the Cogmation

C++ API, LabVIEW, or any socket-enabled programming language [77].

robotSim is available for $499 or as a bundle with robotBuilder for $750. Cogmation offers a 90-day free trial as well as a discounted academic license.

2.2.5 Comparison of Commercial Simulators

Table 2.2.5 is a comparison of the relative advantages and disadvantages of the specific commercial simulators mentioned in this survey.

Table 2.2.5. Comparison of commercial robotics simulators

Simulator	***Advantages***	***Disadvantages***
Microsoft Robotics Developer Studio	• Visual Programming Language • Uses PhysX Physics Engine for High Fidelity Simulations • Free	• Installs on Windows Machines only • Not Open Source
Marilou	• Users Have Ability to Make Custom Robots and Terrain Using Built-in Modeler • Provides Programming Wizards • Robots Can be Programmed in Windows or Linux • Free Home Version Available	• Installs on Windows Machines only • Not Open Source • License Costs Range between $260 and $2663
Webots	• Uses ODE Physics Engine for High Fidelity Simulations • Can be Programmed in Many Different Languages • Free Demonstration Version Available	• Not Open Source • License Costs Between $320 and $4312
robotSim /robotBuilder	• Users Have Ability to Make Custom Robots and Terrain Using Built-in Modeler • Uses TCP Sockets • Can be Programmed in Many Different Languages • 90-day Free Trial and Discounted Academic License Available	• Not Open Source • License Costs Between $499 and $750

2.3 Middleware

Middleware is software that sits between the user-written control code and the target hardware such as a robot (whether it be simulated or real hardware). The reason middleware exists is to allow for highly abstracted interactions between multiple types of hardware and software. For instance, in many cases the user doesn't have to change their code if they move from a simulator to a real robot, or even between different types of robotic vehicles. Middleware also allows for access to third-party software libraries for advanced features such as path planning, localization, mapping, computer vision, etc. It can act as a kind of “switch-board” to direct messages to and from different libraries and hardware. Several types of middleware were considered during this survey.

2.3.1 Player Project Middleware

Player is a TCP socket enabled middleware that is installed on the robotic platform [20]. This middleware creates an abstraction layer on top of the hardware of the platform, allowing portability of code [65]. Being socketed allows the use of many programming languages [27]. While this may ease programming portability between platforms it adds several layers of complexity to any robot hardware design.

To support the socketed protocol, drivers and interfaces must be written to interact with each piece of hardware or algorithm. Each type of sensor has a specific protocol called an interface which defines how it must communicate to the driver [78]. A driver must be written for Player to be able to connect to the sensor using file abstraction methods similar to POSIX systems. The robotic platform itself must be capable of running a small POSIX operating system to support the hardware server application [25]. This is overkill for many introductory robotics projects, and its focus is more on higher level aspects of robotic control and users with a larger budgets. The creators of Player admit that it is not fitting for all robot designs [27].

Player currently supports more than 10 robots as well as 25 different hardware sensors. Custom drivers and interfaces can be developed for new sensors and hardware. The current array of robots and sensor hardware available for Player can be seen on the Player project' s supported hardware web page [24].

2.3.2 ROS (Robot Operating System)

ROS [79] is currently one of the most popular robotics middleware systems. Only UNIX-based platforms are officially supported (including Mac OS X) but the company Robotics Equipment Corporation has ported it to Windows [80]. ROS is fully open source and uses the BSD license [11]. This allows users to take part in the development of the system, which is why it has gained wide use. In its meteoric rise in popularity, over the last three years it has added over 1643 packages and 52 code repositories since it was released [81].

One of the strengths of ROS is that it interfaces with other robotics simulators and middleware. It has been successfully used with Player, YARP, Orcos, URBI, OpenRAVE, and IPC [82]. Another strength of ROS is that it can incorporate many commonly used libraries for specific tasks instead of having to have its own custom libraries [11]. For instance, the ability to easily incorporate OpenCV has helped make ROS a better option than some other tools. Many libraries from the Player project are also being used in certain aspects of ROS [65]. An additional example of ROS working well with other frameworks is the use of the Gazebo simulator.

ROS is designed to be a partially real-time system. This is due to the fact that the robotics platforms it is designed to be used, like the PR2, will be in situations involving more human-computer interaction in real time than many current commercial research robotics platforms. One of the main platforms used for the development of ROS is the

PR2 robot from Willow Garage. The aim of using ROS's real-time framework with this robot is to help guide safe Human-Robot Interaction (HRI). Previous frameworks such as Player were rarely designed with this aspect in mind.

ROS is made up of many separate parts, namely the ROScore and ROSnodes. The ROScore is like a switchboard. It routes messages between other ROSnodes. "ROSnode" is a term used to describe other applications that either send or receive ROS messages. Figure 2.3.2 shows an example ROS project.

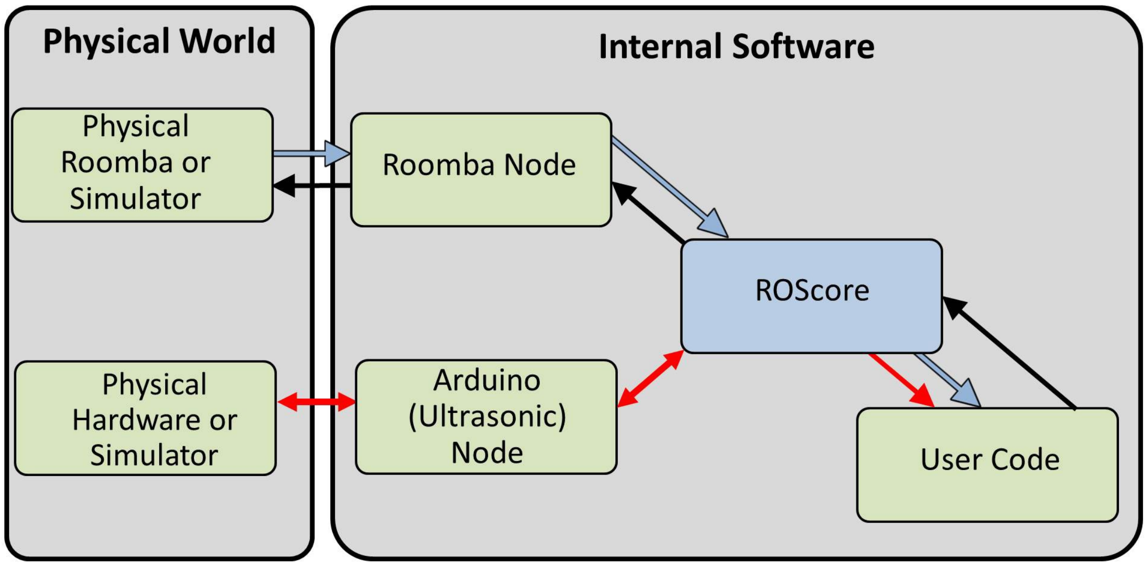
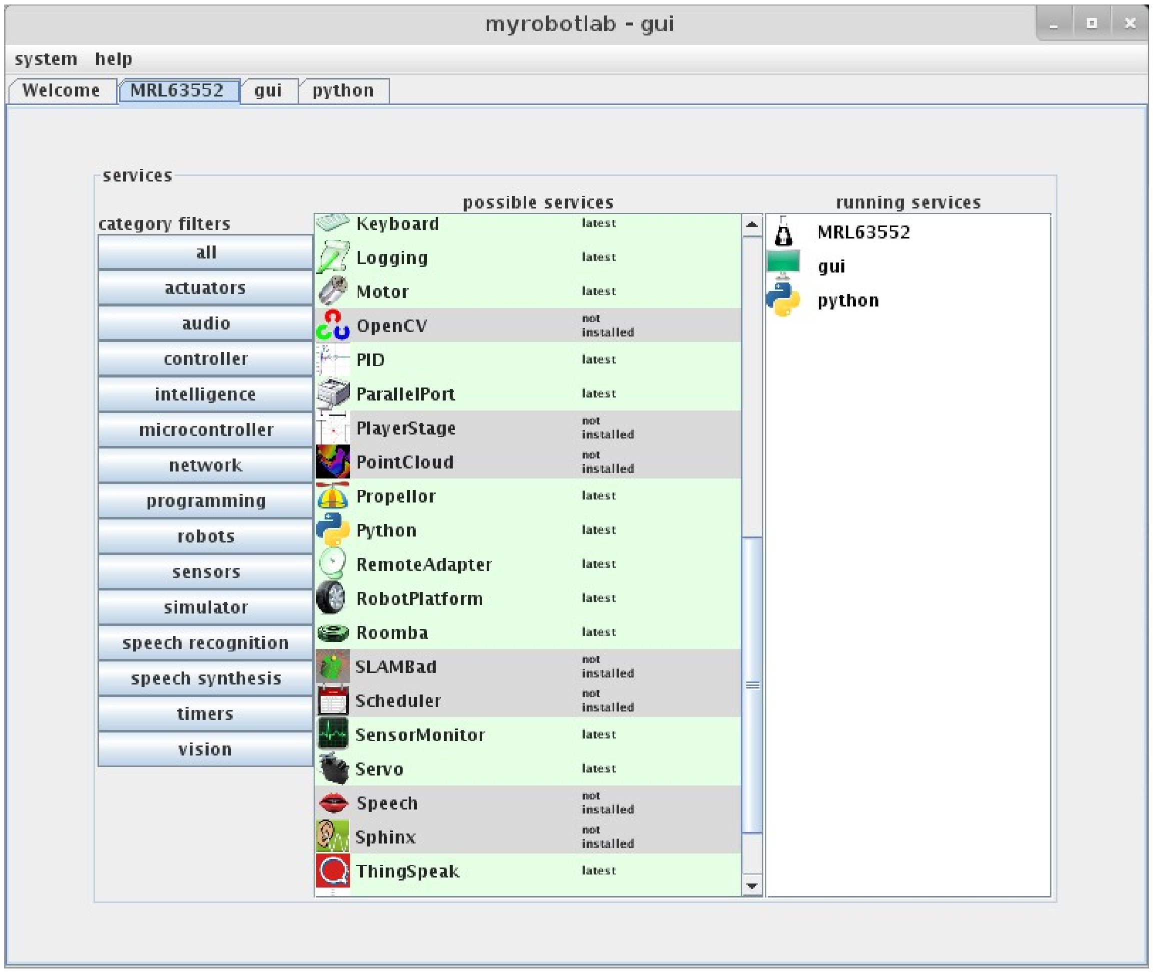

Physical World
Internal Software
Physical Roomba or Simulator
Roomba Node
ROScore
Physical Hardware or Simulator
Arduino (Ultrasonic) Node
User Code

Figure 2.3.2 Simplified ROS application

In the example shown in Figure 2.3.2, all of the bubbles attached to the ROScore directly are ROSnodes. The code that the user writes must implement a ROSnode to be able to send messages to the ROScore. The Roomba and arduino nodes can be thought of as device drivers and have two interfaces. One side interfaces with ROScore and sends and receives ROS-standard message types. The other side connects via serial ports to either physical hardware, or a simulator depending on how the user has configured the project. The Roomba node converts ROS-standard "drive" message-types (a "twist" message) into Roomba protocol commands and sends them to a physical Roomba robot. The arduino node converts ultrasonic sensor values into the ROS-standard “range” message-type when gets forwarded to the user's code. The user's code can be written in one of several different ROS-supported languages. It receives sensor information from the Roomba and arduino nodes via the ROScore (shown in Figure 2.3.2 by the red and blue arrows). The code then processes the sensor data to derive an appropriate drive command. This drive command is a standard ROS message-type called a “twist” (the black arrow in Figure 2.3.2). It is then sent to the ROScore and routed to the RoombaNode. The Roomba node converts the twist message into the standard Roomba protocol command and sends it to the actual Roomba hardware via serial connection. The hardware abstraction layer in Figure 2.3.2 can be replaced by a simulator, and the rest of the software would not “know” the difference.

2.3.3 MRL (MyRobotLab)

MRL (seen in Figure 2.3.3.1) is a Java middleware that includes many third-party libraries and hardware interfaces [83]. It is written as a service-based architecture that includes both graphical and textual control of the services and their interconnections. A python interpreter gives the user complete access to all public classes in all the services of MRL. This allows for users to design complex systems in a single python script file. Recently, a Java service has been implemented in MRL which will also become useful for users once it is more mature. MRL is actively developed, and the developer is generally available for consultation through the MRL website.



possible services	
Keyboard	latest
Logging	latest
Motor	latest
OpenCV	not installed
PID	latest
ParallelPort	latest
PlayerStage	not installed
PointCloud	not installed
Propellor	latest
Python	latest
RemoteAdapter	latest
RobotPlatform	latest
Roomba	latest
SLAMBad	not installed
Scheduler	not installed
SensorMonitor	latest
Servo	latest
Speech	not installed
Sphinx	not installed
ThingSpeak	latest

Figure 2.3.3.1 A screenshot of the main MRL window displaying several important services that are available to the user.

Figure 2.3.3.2 shows a typical project in MRL using an actual Roomba vehicle. The user's code is written in MRL's python interpreter. MRL uses the open source RoombaComm Java library to communicate to Roomba hardware. The user can initiate a RoombaComm service either manually using the MRL GUI or in the python interpreting service. This service then connects to an actual Roomba using a serial port. Sensor and drive messages are defined in the Roomba's native protocol (as defined in [84]).

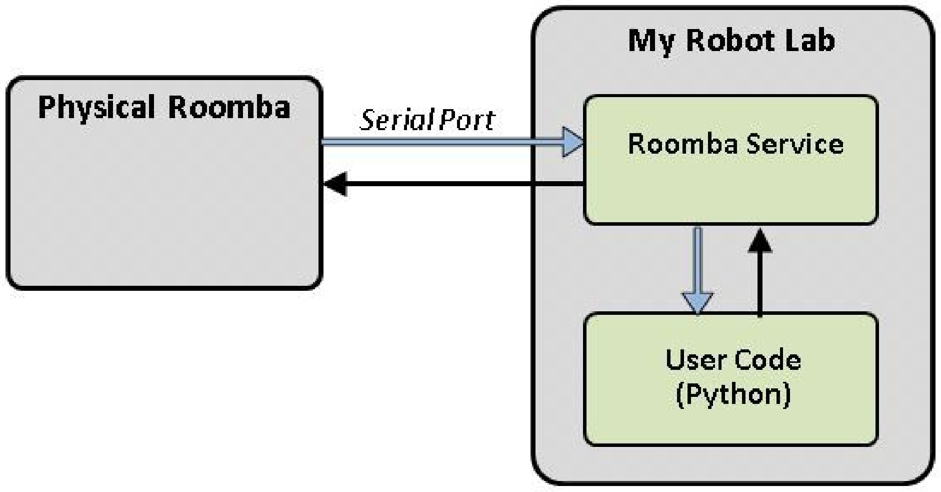


Figure 2.3.3.2 A typical project in MRL using an actual Roomba vehicle.

2.3.4 RT Middleware

RT Middleware [85] is set of standards used to describe a robotics framework. The implementation of these standards is OpenRTM-aist, which is similar to ROS. This is released under the Eclipse Public License (EPL) [86]. Currently it is available for Linux and Windows machines and can be programmed using C++, Python and Java [85]. The first version of OpenRTM-aist (version 0.2) was released in 2005 and since then its popularity has grown. Version 1.0 of the framework was released in 2010.

OpenRTM-aist is popular in Japan, where a lot of research related to robotics takes place. While it does not provide a simulator of its own, work has been done to allow compatibility with parts of the Player project [87].

2.3.5 Comparison of Middleware

Table 2.3.5 compares the relative advantages and disadvantages of the open source middleware discussed in this survey.

Table 2.3.5. Comparison of open source middleware

Simulator	***Advantages***	***Disadvantages***
Player	• Open Source (GPL) • Cross Platform • Active Community of Users and Developers • Uses TCP Sockets • Can be Programmed in Many Different Language	• Every physical hardware device must use TCP protocol
ROS	• Open Source (BSD License) • Supports Linux, Mac, and Windows* • Very Active Community of Users and Developers • Works with Other Simulators and Middleware	• Very complicated to learn and to use
MRL (MyRobotLab)	• Open source • Completely Java based, making it able to run on Linux, Windows, Mac, Android and even in web browsers • Very easy to learn and use • Active community of developers • Interfaces with a multitude of common third-party libraries, software, and hardware • Very easy to customize	
RT-Middlware	• Open Source (EPL) • Based on a Set of Standards that are Unlikely to Change Dramatically • Works with Player Project • Can be Programmed in Several Different Languages	

2.4 Conclusion

While this is certainly not an exhaustive list of robotics simulators and tools, this is a simple comparison of several of the leading simulator packages available today.

Most of the simulators in this survey are designed for specific robotics platforms and sensors which are quite expensive and not very useful for simpler, cheaper systems. The costs and complexities of these systems often prevent them from being an option for projects with smaller budgets. The code developed in many of these simulators requires expensive hardware when porting to real robotics systems. The middleware that is required to run on actual hardware is often too taxing for smaller, cheaper systems. There simply isn't a very good 3D robotics simulator for custom robotic systems designed on a tight budget. Many times a user only needs to simulate simple sensor interactions, such as simple analog sensors, with high fidelity. In these cases, there is no need for such processor intensive, high abstraction simulators.

CHAPTER 3: HISTORY OF SEAR

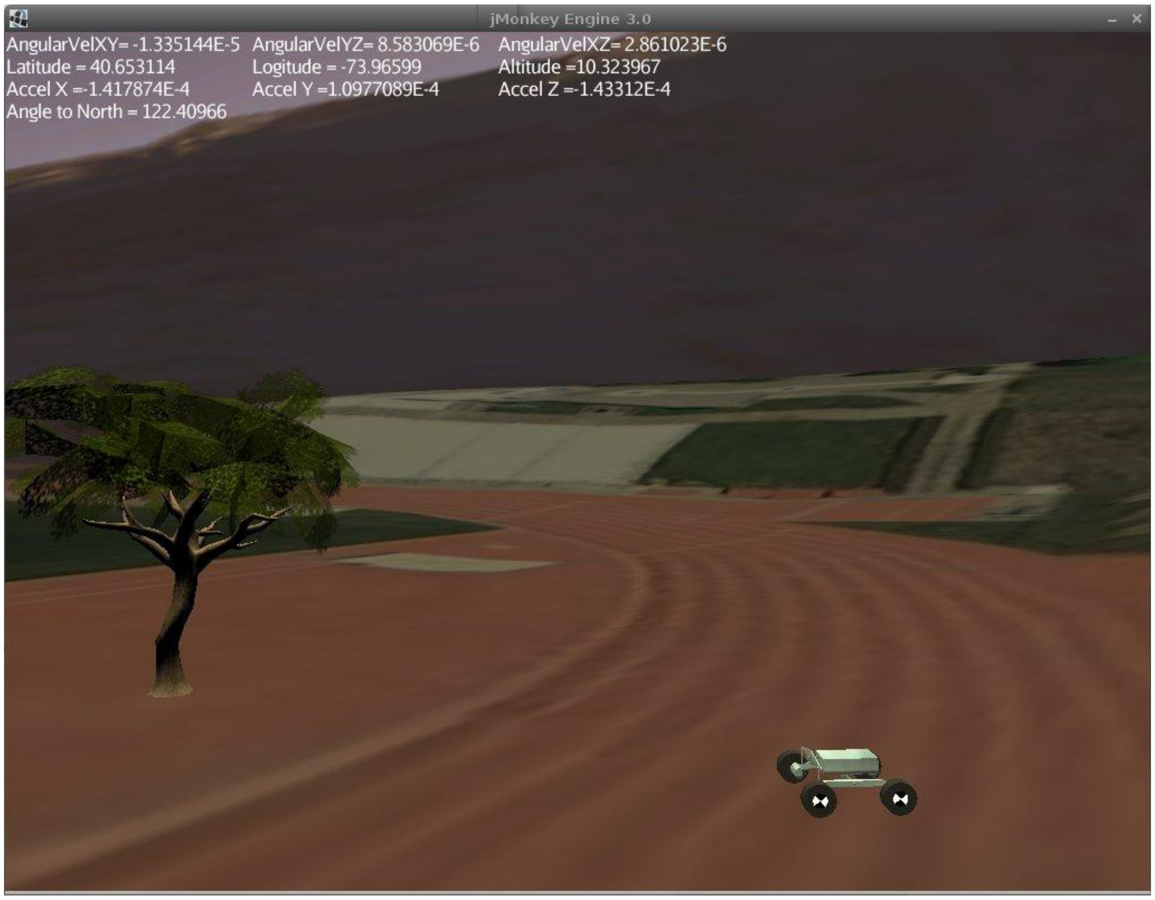
3.1 Overview of SEAR Concept

The concept of SEAR was conceived as a free (completely open source), cross platform, and 3D graphically and physically accurate robotics simulator. The proposed simulator is able to import 3D, user-created vehicle models and real-world terrain data. The SEAR simulator is easy to setup and use on any system. The source code is freely available which entices collaboration from the open source community. The simulator is flexible for the user and is intuitive to use for both the novice and the expert.

SEAR began as a thesis project which laid the groundwork for a tool that matched the concept requirements [64]. Since its inception, SEAR has gone through multiple iterations as features were either added or removed and as sensors were validated.

3.2 Initial Design

In the initial design of SEAR, the models of robotic vehicles were imported into the simulator in Ogre mesh format. These models were created using one of the many 3D modeling CAD software programs. Terrain models could be created either externally in CAD and imported into the simulator, or coded directly in jME. One method for creating real-world terrains is by importing from Google Earth. This model can then be used as the basis for a fully simulated terrain as can be seen in Figure 3.2.



```
AngularVelXY= -1.335144E-5  AngularVelYZ= 8.583069E-6  AngularVelXZ= 2.861023E-6
Latitude = 40.653114        Logitude = -73.96599       Altitude =10.323967
Accel X =-1.417874E-4       Accel Y =1.0977089E-4      Accel Z =-1.43312E-4
Angle to North = 122.40966
```

Figure 3.2 The main SEAR Simulator window showing gyroscope, accelerometer, GPS and compass values as well as the robot vehicle model and a tree obstacle. The terrain is from Google Earth of the varsity sports track at the University of North Carolina at Charlotte.

Settings for the overall SEAR project were entered in a Project Settings Window. This recorded which models would be used for terrain, robot body and robot wheels. The robot vehicle dynamics were also set in this window to allow user-described values to be used in the physics simulations. User code files were selected in this window as well. The user had the option of selecting a custom userCode file, creating a new userCode file template or creating a new Java file template in their chosen working directory. All of the project settings were saved to a file.

The user was able to use a template for a “User Code File” which helped simplify the coding process of coding by allowing only three methods to be used; a method in which users can declare variables, an initialization method and a main loop method. This was designed to reduce confusion for novice users and makes prototyping a quick and easy process. Additionally, the user could choose to code from a direct Java template of the simulator itself. This would be a preferred method for more advanced simulations.

Upon starting a simulation, the values recoded in the project settings file (.prj) created in the Project Settings Window and the userCode file (.ucf) were used to create the simulator Java file by copying and pasting the user code to the appropriate sections of the simulator Java template. This file was then compiled and the resulting application was run to perform the simulation. Every time the simulator ran, it had to be completely recompiled. Though this was hidden from the user, it proved to be a complicated and messy implementation. There was no error console, so if the user code caused an error, there was no feedback from the compiler to explain why the compilation failed.

3.3 Intermediate Designs (Graduate Work)

SEAR has gone through many intermediate designs, including interfacing with multiple middleware suites as well as testing multiple communication protocols to validate which would be best to utilize. Concurrently, previously created sensors were improved, new classes of sensors were added and validated against actual hardware.

3.3.1 Early ROS Middleware Integration

A new class of sensors, “visual sensors,” was added which included ultrasonic sensors. The creation and validation of the technique used for simulating this new class of sensors meant that SEAR would have to change drastically. The new sensors were validated (proven to act similarly to physical sensors in a similar physical environment) against both real world sensors and another simulator (Stage). In order to keep as many variables in the testing of the SEAR sensor as consistent as possible with the physical experiment as well as in the Stage simulation experiment a middleware, ROS, was selected to interface with each system. This allowed the same robot control code to be used on all three platforms: SEAR, real-world hardware, and Stage. Additionally, the Roomba robot was chosen as the vehicle because the iRobot Roomba is nearly universally supported by many robotics simulators and middleware. Only indoor environments were used for testing to reduce the number of variables introduced. The odometer sensor was created to allow for a second measure in the validation of the visual sensor class.

Since the focus of SEAR changed to the validation of sensors, many of the previous features had to be removed. The model-loading for terrain was no longer needed as it was simpler to build the environments within jME3 by hand. Similarly, the ability to load custom robotic vehicles was removed. Hard-coded environments and vehicles reduced the time between simulations and reduced the number of files associated with a given project. The removed features were later added back into SEAR.

User-code integration was completely removed and in its place, a separate ROS communications thread was used. This allowed SEAR to send and receive standard ROS message-types. Because of this simplification, there was no need to dynamically create and compile the SEAR simulation each time it ran.

Simulation no longer required the project settings GUI since all the settings were hard-coded. The sensor wizard XML files were also no longer required. The distance sensor class was validated in SEAR utilizing only the main simulation class, the sensor simulator classes, and the ROS communications thread.

3.3.2 Early MRL Integration

After the sensors were validated, the focus was moved toward integration with a simpler middleware called MyRobotLab (MRL). The main reason for this change is the immaturity of the Java-based implementation of ROS. ROSJava, as it was called, changed so rapidly that the code used in the validation was completely deprecated by the time the validation was finished. Instead of starting from scratch on ROS integration, the change to MRL allowed for a more stable development platform over time.

The first integration with MRL used a client library called the MRLClient. It began as a UDP messaging service that communicated with a running instance of MRL. Shortly after implementation, the protocol was changed to TCP to reduce the amount of packet loss between the two programs. This was still not an ideal solution as it was slow and often times had errors. Eventually, SEAR was incorporated directly with MRL with the creation of a SEAR service inside MRL. This allowed for communication between MRL services to be very easy.

During the same time as the MRL integration, the LIDAR simulator was implemented and then verified against actual hardware. Once all of the sensors were finished, they were combined into a single Java package that could interact together in the same simulation. The simulators were moved to execute in the physics thread of jME rather than the simpleUpdate() method. This increased the speed of simulations.

The creation of environments (models of terrain and obstacles) inside SEAR was added to the MRL SEAR service. This involved the creation of many new classes of environment object-types such as Box, Cylinder and Cone objects. These objects can be created in python code inside MRL and are stored in the main SEAR project folder as

XML files. This development meant that environments were no longer hard-coded into SEAR; they could be changed easily.

SEAR currently supports "robot objects" which communicate using the iRobot Roomba Create Open protocol [84]. This protocol was chosen because the Roomba protocol is widely used and very simple to implement on practically any hardware. In fact, the drive commands from the iRobot protocol use a common interface that Eyesim authors refer to as "omega-v" which specifies both the linear and angular velocity the robot should obtain [1], [2]. Custom protocols could also be used with SEAR, however the user would have to write a "customController" SEAR object script to handle communications and drive the virtual robot.

3.4 Conclusion

As shown in this section, the growth of SEAR allowed for experimentation of each important aspect previously defined for a good modern simulator. Middleware integration was explored by interfacing with ROS and later with MRL. Different methods of communication were explored as well. Simulations of sensors were improved and validated against physical hardware to prove the simulated outputs closely matched the results of the actual sensors they were modeled on. The final iteration of SEAR is described in detail in the following chapters.

CHAPTER 4: SUPPORTING DESIGN TOOLS

This research relied on several software tools for development. The required software ranged from integrated development environments (IDEs) to 3D modeling CAD software. Netbeans 6.9 was used for coding Java for the project. The game engine used was jMonkeyEngine3 (jME3). A survey of different modeling software was performed to show the variety available to the user [64].

4.1 Language Selection

Using previous surveys of current robotics simulators [15], [21], [23] it was shown that several of the current systems claim to be cross platform. While this may technically be true, it is often so complicated to implement these systems on different platforms that most people would rather switch platforms than spend the time and effort trying to setup the simulators on their native systems. Most of the currently available open source simulator projects are based on C and C++. While many of these are considered also cross-platform, getting them running correctly requires so many work-arounds and special configurations that it is often more efficient to change the development hardware to match the recommended hardware of the simulators.

To make a simulator easy to use as well as to simplify further development, Java was selected as the language to code the simulator. Java runs in a virtual machine on a computer. This abstraction prevents the Java code from having to directly interface with any hardware, allowing the Java code to be unchanged regardless of what hardware it is run on. The development platform used was NetBeans 6.9.

4.2 Game Engine Concepts

The jME3 game engine consists of two major parts, each with their own “spaces” that must be considered for any simulation. The first is a “graphics world space” (called the “scene graph”) which is controlled by the rendering engine and displays all of the screen graphics. The scene graph is created by jMonkeyEngine in this project.

The second space, the “physics world space,” is controlled by the physics engine which can simulate rigid body dynamics, fluid dynamics, or other dynamic systems. Currently in SEAR, only rigid body dynamics are being used. The physics engine calculates interactions between objects in the “physics space” such as collisions, as well as variations in mass and gravity.

A developer must think about both the graphics and physics spaces concurrently as each runs in its own thread. It is possible for objects to exist in only one of these spaces which can lead to simulation errors. Once an object is made in the graphics space, it must be attached to a model in the physics space in order to react with the other objects in the physics space. For instance, an obstacle created in only the graphics space will show up on the screen during a simulation, however, the robot can drive directly through the obstacle without being affected by it. Conversely, the obstacle can exist only in the physics space. A robot in this instance would bounce off of an invisible object in a simulation. Another issue would be to have an obstacle created in both spaces, but not in the same place. This would lead to problems such as the robot driving though the visible obstacle, and running into its invisible physics model a few meters behind the obstacle. Attention must be paid to attach both the graphics objects and physics objects correctly.

The game engine creates a 3D space or "world." In each direction (X, Y and Z) the units are marked as "world units." The Bullet physics engine (the one implemented in jME3) treats one world unit as one meter [88]. Certain model exporters will have a scale factor; however that can be used to change the units of the model upon export. Additionally, any object can also be scaled inside the game engine.

4.3 JmonkeyEngine Game Engine

The game engine selected for this project was jMonkeyEngine3 (jME3) since it is a high performance, truly cross platform Java game engine. The basic template for a simple game in jME3 is shown in the code snippet below:

```
public class BasicGame extends SimpleApplication {

    public static void main(String[] args){
     //create an instance of this class
        BasicGame app = new BasicGame();
        app.start();//Start the game
    }

    @Override
    public void simpleInitApp() {
    //Initialization of all objects required for the game.
    //This generally loads models and sets up floors.
    }

    @Override
    public void simpleUpdate(float tpf) {
    //Main Event Loop
    } //end of Class
```

The superclass *SimpleApplication* handles all of the graphics and physics involved. Because this class is extended, local overrides must be included. The *simpleInitApp* method is used to initialize the world and the objects within it.

The *simpleInitApp* method calls methods for loading models of the robotic vehicle, loading the terrain models, setting up groups of collision objects, and any other tasks that must be performed before the main event loop begins. *simpleInitApp* then sets up all the internal state variables of the game and loads the scene graph [89]. The *simpleUpdate* method is the main event loop. This method is an infinite loop and is executed as quickly as possible. This is where important functions of the simulator reside. Additionally, other methods from the *simpleBulletApplication* may be overridden such as *onPreUpdate* and *onPostUpdate*, though these were not used specifically in this project.

jME3 uses the JBullet physics engine for physics calculations. JBullet is a one-hundred percent Java port of the Bullet Physics Library which was originally written in C++. There is a method in *SimpleApplication* specifically for handling the physics called "*physicsTick*()". This is the method in which the sensors of SEAR are simulated. jME3 allows the physics to be handled in a separate thread from the graphics.

Objects in jME3 must be represented both graphically as well as physically to work in a simulation. Simulating sensors in SEAR also requires utilizing both the graphics and physics threads almost simultaneously. Data must be passed between the threads to calculate graphical representations of sensor components as well as the virtual robot's position within the virtual environment. This is similar to the CoopDynSim simulator [3]. Figure 4.3 is a representation of roughly how the threads communicate.

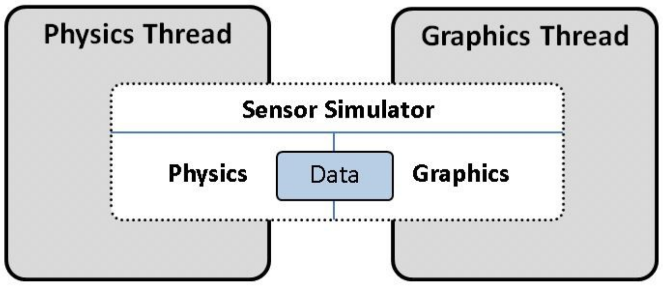
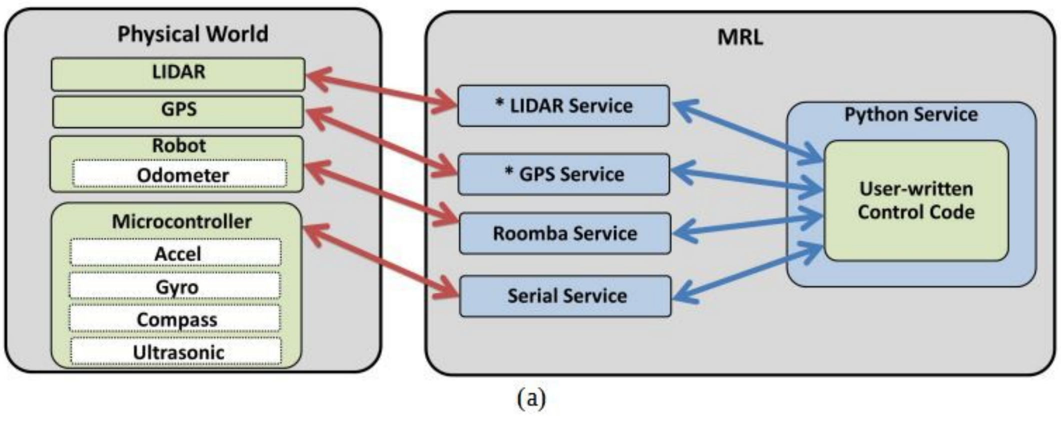


Figure 4.3 Data for each sensor simulator is shared between graphics and physics threads in SEAR

CHAPTER 5: ARCHITECTURE AND METHODS OF IMPLEMENTATION UTILIZED TO CREATE SEAR

This section describes the implementation of the virtual sensors within SEAR, the architecture of SEAR, communication between SEAR and middleware (MRL), and the organization of a end-user's files related to a single simulation project from the perspective of a developer of SEAR. Typical end-user interactions can be found in Appendix A which has example code listings for how to create and use every environment object (terrain and obstacles) as well as robot components (boxes, cylinders, wheels, robot dynamics settings, and sensors).

For perspective, it is useful to understand where each of the components of SEAR fit in an example of a typical user project. In this example, the user will utilize MRL's python service to control a virtual robot and communicate with sensors. One of each sensor will be used. As a comparison the same project is shown twice; one implemented with physical hardware (shown in Figure 5a), and then again using the SEAR simulator (shown in Figure 5b). The portions that were created by the author of this dissertation for the SEAR simulator are shown by the text being preceded by an asterisk (*).



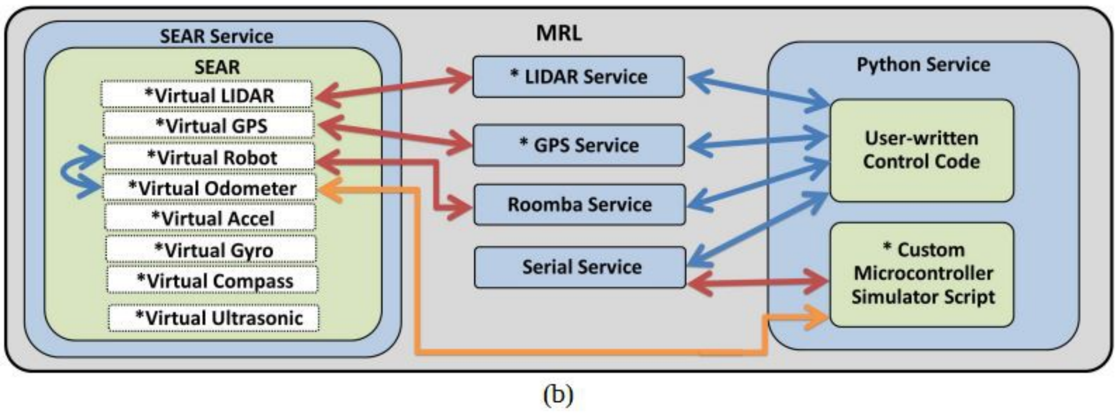


Figure 5.0 (a) A typical project using MRL to control a physical robot. (b) The same project interfacing instead with SEAR. The blue arrows are MRL system messages, the Red arrows are serial or virtual serial ports and the orange arrow is a direct JAVA method call from MRL to SEAR. The items with an asterisk (*) denote modules written by the author of this dissertation.

5.1 The SEARproject

The concept of a "SEARproject" was devised to allow users to contain all the files of a single project together. It is similar in structure to how word processor documents save text, formatting and associated files to a computer hard drive. This structure will allow users to share aspects of their projects, be it code, entire environments, or entire robot models (complete with sensor specifics).

The SEARproject is created when the user creates objects using a custom library. This creates a folder within MRL"s operating environment called "SEARproject."

Environment objects are stored in a subfolder named “environment,” robot components are stored in a subfolder named “robot,” and all the files associated with user-created CAD files of objects or any images the user selects to wrap around SEAR-native objects are located in a folder named “assets.” Users' Python or Java code can be stored in the SEARproject folder.

When the user is ready to save the SEARproject, this folder is compressed in ZIP format, and renamed with the file extension “.sear” to designate it as a sear project. This can then be opened at a later time from the MRL SEAR service GUI window, or shared with other users. Figure 5.1 illustrates the file structure inside a .sear file.

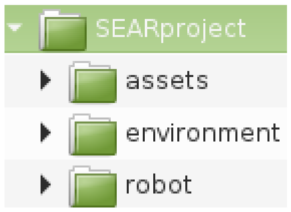


Figure 5.1 Folder tree showing the layout of a SEARproject

MRL's SEAR service has options to save and open .sear files. Projects are stored in MRL's working directory in a folder named “SEARproject” until they are saved. When the user saves a file, the SEAR service zips SEARproject folder and saves it as a .sear file at the given path and file name the user enters.

5.2 Custom MRL Services

Several MRL services were created to allow SEAR and its virtual robots and sensor objects to communicate with MRL. Additionally, MRL did not support several standard sensor types for physical sensors. Custom services were written to add LIDAR and GPS sensors to MRL, as well as a service used to interface MRL with the SEAR simulator. These services can interface with actual hardware or simulated hardware [90].

5.2.1 MRL'S LIDAR Service

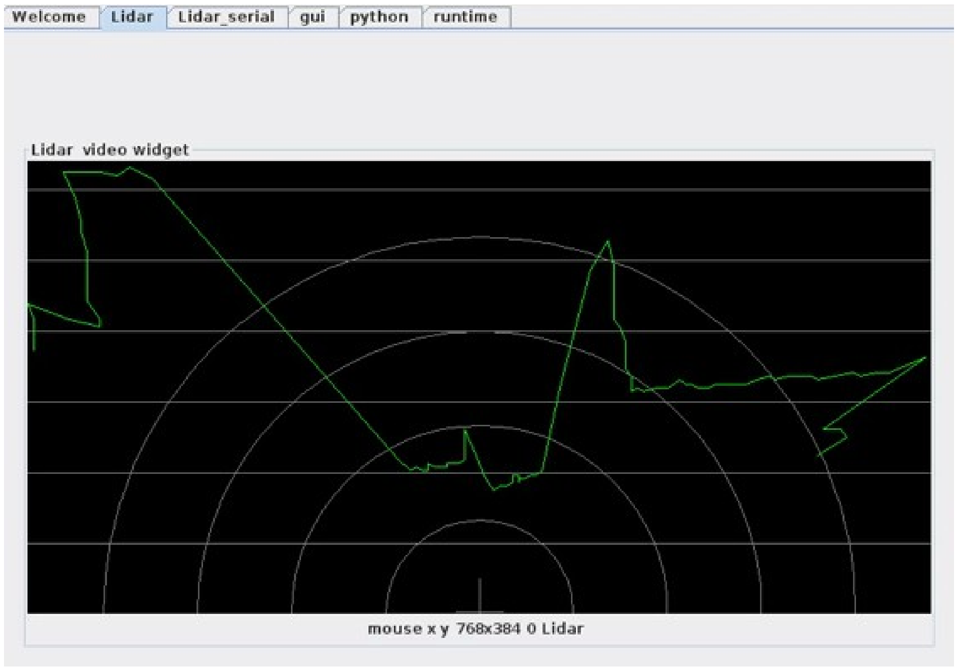


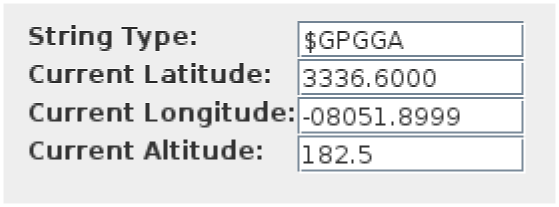
Figure 5.2.1 The LIDAR service GUI panel showing the output of an actual SICK LMS-200 scan

MRL did not have a service for interfacing with LIDAR devices at the time of this research, so one was created. The service currently handles SICK LMS-200 devices and can be used to set up and receive scan data [91]. Once a scan is performed, the resulting values are parsed and displayed on the LIDAR service GUI panel in MRL in polar form (with the senor location being at the center of the bottom of the display). Figure 5.2.1 shows a resulting LIDAR scan. This service was first tested with an actual SICK LMS-200 LIDAR unit to verify functionality. LIDAR messages are called “telegrams” in the SICK documentation [91]. Many telegrams are currently supported with the exception of the “streaming” scan mode. Users can get similar functionality by putting the single scan function call within a loop to perform multiple scans. The user has the ability to change the resolution of the scans and the speed of the serial communications using standard

LMS-200 telegrams [92]. All functions are currently only available to the user if they use the Python or Java MRL services.

5.2.2 MRL's GPS Service

MRL did not have a GPS service at the time of this research, so one was created. The service utilized other portions of MRL's serial service to parse values from a GPS NMEA string. Currently, only GPGGA strings in the format used by the San Jose FV-M8 are supported as they are the most useful for the SEAR simulator at this time and the only physical hardware available to test [93]. The MRL GPS service parses the GPGGA string and displays the values in the GPS service GUI panel, and allows the user to access this data directly from the GPS service via Python or Java code. Figure 5.2.2 shows the GPS GUI.



String Type:	$GPGGA
Current Latitude:	3336.6000
Current Longitude:	-08051.8999
Current Altitude:	182.5

Figure 5.2.2 The GPS panel of MRL's GPS service GUI showing values from a simulated GPS device

5.3 MRL'S SEAR Service

The SEAR service has a GUI portion that allows users to open or save SEAR project files, and start a SEAR simulation. Most of its functionality is not available on the GUI window. The SEAR service orchestrates all the serial communications between the software serial ports (*virtualSerialPort* services within MRL).

5.4 SEAR's Object Grammar

A custom grammar was created to allow users to design environments, obstacles and robot components using SEAR-native objects. This is accomplished by the

SEAR.POJO library that was added to MRL. The user must import the “SEAR.POJOs” library within MRL's Python or Java service in order to create these objects. A POJO is a “Plain Old Java Object” which is a Java object that is devoid of methods and simply holds information. It can be thought of as similar to a “structure” in C language. By default, when the user creates these POJO objects, they are immediately serialized as XML files.

SEAR objects include graphical and physical representations of boxes, cylinders, and cones as well as components specific to a robot such as dynamics, sensors and wheels. Sensor objects are used to set up the specific settings of a particular sensor type such as communication settings, resolution, and type. Tables 5.4.1 and 5.4.2 list the different types of objects supported by the POJO library.

Table 5.4.1. Physical objects in the SEAR POJOs library

Objects	***Description***
Box	A rectangular prism with a default image of a cardboard box
Cone	A cone shape with a default image of a traffic cone
Floor	A rectangular prism that can be ignored by distance and LIDAR sensors
Cylinder	A cylinder with a default image of a recycling bin
Model	A 3d model the user created outside of MRL and SEAR usually in OGRE mesh format. This can include custom images and textures. Additionally, Blender .blend files can be used.
Wheel	A special cylinder object that is specifically used as a robot component. The user can select whether this wheel is connected to the motor or if it is an idler.

Table 5.4.2. Sensor objects in the SEAR simulator POJOs library

Objects	***Description***
SEARrobot	This is an object that represents a "robot" entity. Other physical and sensor objects are added to this entity to create the physical representation as well as the sensor payload of the robot.
3-axis Accelerometer	Measures acceleration in 3 dimensions relative to the robot's body
Compass Sensor	Measures angle to "north" which defaults to 1000km in the X axis unless magnetic declination is selected (automatically calculated based on the robot's GPS coordinates)
Distance	This sensor is highly configurable and can simulate SONAR, RADAR, Infrared, simple laser reflectors and ultrasonic sensors with a multitude of resolutions
Robot Dynamics	This allows the user to make a serial connection to the microprocessor on-board the robot. It uses roomba command protocol. The user also sets up physical aspects of the robot here such as suspension characteristics.
GPS	Simulates a rough GPS coordinate system in the simulated environment
3-axis Gyroscope	Measures angular velocity in 3 dimensions relative to the robot's body
LIDAR	Simulates Laser ranging devices, named the SICK LMS200
Odometer	Measures distance traveled Default is to simulate a roomba's odometer which resets after every 32,767 millimeters or -32,768mm

5.4.1 Environment Objects

SEAR's object grammar is utilized from within MRL's Python or Java services allowing users to instantiate and manipulate objects in a simulation. The SEAR-native environment objects are Box, Cone, Cylinder, and Model. The user can create these objects very easily, then scale them, translate their locations, or rotate them in the environment as they wish. Users can even select custom images to be wrapped around the objects so a Box object can be made to look like a cardboard box, a metal shipping container, or even a brick wall. All of these items are native to SEAR except the "model" object. The user can create models in external CAD software such as Blender and export the model's files into the “assets” folder of a SEARproject and create a model object POJO object. The POJO will be automatically serialized to an XML file stored in the “environment” folder of the SEARproject when the python is executed.

5.4.2 Terrain

Users can create and modify a simulation's terrain in one of two ways. They can create a “floor object” XML file using the SEAR POJO library, which gives the option to make the floor invisible to the sensors. This can be useful for interior environments. The second method for setting up terrain in SEAR is to load a OGRE mesh or Blender model. Again, users can select to have the terrain invisible to the sensors if needed. This can help reduce spurious sensor signals, especially on uneven terrains. When a terrain is loaded, the center of the terrain becomes the origin in the 3-dimensional world within the SEAR simulator. This is important as some terrains can be loaded from Google Maps, and have an associated GPS coordinate that is also referenced as the center of the terrain model. In the SEAR simulator, the GPS sensor relies on this “world center” value to calculate the GPS coordinates of the robotic vehicle.

5.4.3 Obstacles

Obstacles are added to the environment either by hand (manually creating and saving the appropriately formatted XML files in the “environments” folder) or by using the SEAR.POJO library in MRL's Python service. The user can create a variety of “SEAR-native” objects which include boxes, cylinders, and cones. Each obstacle has its own overloaded methods in the POJOs library which can require as little or as much specific information as the user desires. For instance, to create a box the user can specify as few as five options; the object name, the length, width, height, and mass of the box.

Additionally, the objects can be translated and rotated in each axis giving the user complete control when designing a custom environment. If the mass value is set to 0, the object ignores the influence of gravity in the simulator and does not fall to the ground but rather it stays in the exact translation and rotation the user specifies, completely ignoring gravity in the simulator. This can be useful when simulating walls or other large immovable structures. It can even be used to design environments with objects that hang down from the ceiling. User-created CAD models can also exist as objects within the simulation environment. Once the simulator begins, it will load the model's XML file, and then search for the associated files in the “assets” folder.

When entering values for an objects location and rotation, it is important to note that translation values represent meters and are referenced from the center (0,0,0) of the jME3 world. Similarly, the rotation refers to the roll, pith and yaw of the object within the jME3 world and is measured in degrees.

5.4.4 Virtual Robotic Vehicles

Virtual robots can be created several ways in SEAR. The simplest method is to build a robot from SEAR-native components. Objects will be created the same way as for obstacles, however, a special “robot” object must be created. The “robot” object has no visual or physical representation of its own. Parts must be added to the robot object as components. For example, the body of a virtual robot could be a cylinder. The user would first create a SEAR-native cylinder, create a new robot object, then add this cylinder to the robot object. SEAR will automatically move the cylinder's XML file to the “robot” folder within the SEARproject. Similarly, if a model is utilized as a component of the robot, the XML file for the model will be moved to the robots folder of the SEARproject, though the actual model meshes and images will remain in the “assets” folder.

Objects that are added as components to a robot object change their translation and rotation reference from the jME3 world frame to the robot body frame. This means that an object with a translation of (1,0,0) would be located 1 meter along the X-axis of the robot body. Similarly, an object with a rotation of (0,45,0) will point 45 degrees counterclockwise of the front of the robot.

5.5 Manual Control

There is still the need for manual control of the simulation in some cases. This can be useful for debugging. The camera angles can be manually controlled. By default, the flycam in SEAR is disabled. This means the default action of the camera is to follow the robot automatically. By pressing the space bar on the keyboard during a simulation, the flycam can be toggled on or off. This will then allow the user to control the camera angle using the Q, W, A, S, D, and Z keys on the keyboard. Additionally for current debugging purposes, the H,K,U,J, and ; (colon) keys will allow the user to manually drive the robot when there is no user code being used. The Enter button will reset the robot to the beginning location and rotation, and reset the odometer; therefore, effectively starting the simulation over again. Table 5.5 shows the binding of each key.

Table 5.5 Keyboard controls of the Simulator Window

Key	***Action***
H	Spin Vehicle Left
K	Spin Vehicle Right
U	Accelerate Vehicle
J	Reverse Vehicle
; (colon)	Stop Vehicle
Enter	Reset Robot Position
Space Bar	Toggle Flycam
Q	Pan Camera Up (requires Flycam)
W	Pan Camera Forward (requires Flycam)
A	Pan Camera Left (requires Flycam)
S	Pan Camera Backward (requires Flycam)
D	Pan Camera Right (requires Flycam)
Z	Pan Camera Down (requires Flycam)

5.6 Sesnor Simulation in SEAR

Moving into the developer-level abstraction layer (as opposed to the user-level abstraction layer), sensors in the SEAR simulator consist of two separate types which are referred to as “physical” and “visual.” Simulators that rely directly on values from the physics engine in jME3 such as positional sensors (GPS, compass, etc) are referred to as “physical” sensors. These sensors don't require any visual representation to work. They assume a position of the 0,0,0 point in the vehicle (robot's) body reference frame.

5.6.1 Position-Related Sensor Simulation(“Physical” Sensors)

Autonomous robotic vehicles rely very heavily on knowledge of their locations in 3D space. Without this information, autonomous control of the vehicle is impossible. For this reason, the class of positional sensor simulators was created.

5.6.1.1 GPS

GPS simulation is not a new concept as shown by Balaguer and Carpin [42]. Though Balaguer and Carpin, as well as Durst and Goodin [94] describe and test advanced GPS simulation algorithms, it is sufficient to simulate GPS with only basic functionality. To simplify GPS simulations, satellite tracking is not simulated in SEAR and as such, no atmospheric anomalies are simulated either. Basic functionality of GPS is simulated to provide only the latitude, longitude and altitude measurements of the vehicle's current position. To further simplify the simulation, GPS is simulated as a roughly flat projection of the terrain. This is similar to the simple version of the GarminGPS sensor in early Gazebo simulations [95]. Developments will improve or replace this implementation, but it is important to have a simple and basic version of this sensor for initial tests of the simulator.

There are several important settings that the user must enter before using the GPS sensor in a simulation. The first set of values represents the latitude, longitude and altitude values of the center point of the terrain map being used. These values are then converted from a string to complete decimal format and will be used as an offset which helps calculate the updated latitude, longitude and altitude of the robotic vehicle during simulated movement.

Since the Earth is not a perfect sphere, the length of a longitude degree varies from 111,320 meters per degree at 0 degrees latitude (the equator) to 0 meters per degree at 90 degrees latitude (the poles) [96]. Calculating this value on a constant basis can prove rather costly on computing resources. To simplify the changes in longitudinal distances, a look up table based on the Zerr's table is used to simulate distance per degree latitude [96]. The value entered by the user of the starting position of the robot vehicle will be used in this look up table to find the closest matching latitude.

Since it is impractical that a simulation will require a vehicle to travel more than five latitudinal degrees, the value of the length of a degree is never recalculated during the simulation.

To find the distance per degree longitude in this simulator, a simple distance formula (shown in 5.6.1.1.1) is used [97].

$$\begin{gathered}\textit{Length of a degree of Longitude}\\ = \textit{Radius of Earth at the Equator} \times \cos\left(\textit{Latitude}\right)\end{gathered} \tag{5.6.1.1.1}$$

Distance of a degree of longitude at the equator = 111320.3411 meters as shown by Zerr. The final formula is shown in Formula (5.6.1.1.2).

$$\begin{gathered}\textit{Length of one degree of Longitude}\\ = 111320.3411\,\textit{meters} \times \cos\left(\textit{Latitude}\right)\end{gathered} \tag{5.6.1.1.2}$$

Since this formula is a fast calculation, it can be calculated each time the GPS simulator is polled (about 60 times a second) without a large determent to the speed of the overall simulation.

When the GPS simulator is polled, it finds the distance in three dimensions of the vehicle from the center of the world space from the current position of the vehicle. These values are returned in world units and are treated as meters (in this simulator, one world unit equals one meter). Knowing the offset in three dimensions (in meters) from the center point of the map as well as the values of the center of the map, the latitude, longitude, and altitude of the vehicle can be calculated. The current vehicle position on the X-axis in meters of the vehicle is converted to latitude using the values from Zerr's table [96]. The latitude of the vehicle is then known and can be used in Formula 5.6.1.1.2

to find the length per degree longitude. The current vehicle position in the Z-axis (in meters) is then divided by this value to find the current longitude of the vehicle. The current vehicle offset in the Y-axis is added to the value of the altitude of the center of the terrain map. This gives the actual vehicle altitude in relation to the original center value. The GPS simulator is accessible through a virtual serial port within MRL. It streams GPGGA NMEA strings formatted to match the San Jose MTK-3301 GPS receiver series (specifically the FV-M8) [93].

5.6.1.2 Compass

The compass simulator is single-axis and simple. A Vector3f object is used to store the position of North. For example, the default location of North is located at x, y, z ordinates (100000, 0, 0). Since one world unit equals one meter in this simulator, this means the North Pole is located at 100km on the X-axis of any simulation. Of course, this value can be changed by the user to a more accurate estimation of actual pole distance when the latitude and longitude of the terrain are considered. For an accurate calculation, users can select to enable a magnetic declination calculation. This will use the current GPS location of the robot to calculate the location of magnetic North relative to the robot. This calculation uses the NOAA (National Oceanic and Atmospheric Administration) National Geospatial-Intelligence Agency (NGA) World Magnetic Model (WMM) for the years of 2010-2015 [98]. The declination is calculated using "GeomagneticField.Java" from the Android Project [99], [100]. These values are stored in a table and can be updated by the developer as newer models are released.

The simulator calculates the angle of the robot to north by getting the values of the forward direction of the robotic vehicle using the getForwardVector() method. The values of this vector of the X and the Z directions represent the forward facing direction in the X-Z plane. These values are compared to the X and Z values of "North." The angle between these two values is the angle between the forward-facing direction of the robotic vehicle and North. This angle is represented in +/-180 degrees (or +/- PI radians).

When importing terrains from Google Maps, it is important to note that the location of North in the Google Maps terrain corresponds to the X direction when the terrain is exported correctly (with North facing upward). This automatically sets North in the terrain model to the X direction in the simulator when models are loaded from Google Maps into Sketchup.

The user's code must poll the compass to obtain a current value using code such as int *currentHeading = sear.getCompassResult("comp1")* where "*comp1*" is the compass's name given by the user. This will return a float value between +/- 180 degrees. The user can scale and format this data any way they might need to simulate actual hardware. This sensor doesn't have its own serial port (in many cases in actual hardware as well) so for a user to communicate with the simulated sensor in the same way as they would with actual hardware, the user can write a custom controller script which will accept serial commands, poll the simulator for sensor values, format and scale the data, and return the data over the virtual serial port.

5.6.1.3 Three-Axis Accelerometer

The use of MEMS (Microelectromechanical Systems) accelerometers is becoming very common in robotics. Accelerations can be used in dead-reckoning systems as well as force calculations.

Simulations of accelerations are made simpler because of several methods built into jME3. jME3 provides a *getLinearVelocity()* method which will return the current linear velocity of a VehicleControl object in all three dimensions. To get accelerations from this method, a simple integration of these values over time is taken. To get an accurate time, the timer class was used. The timer class provides two important methods used in this integration, *getResolution()* and *getTime()*. *getResolution()* returns the number of "ticks" per second and *getTime()* returns the time in "ticks." These two values together are used to find time in seconds.

The accelerometer method is called from the physicsTick loop in the simulator code. This allows it to function continuously during the simulation. The accelerometer simulator must not take too much time to execute; otherwise it will slow down the entire simulation. To make sure the main event loop executes quickly, the accelerometer method does not stall for the given time between measurements, rather it stores a starting time and calculates the time that has passed every time the main event executes. The elapsed time is compared to the number of ticks between readings calculated from the bandwidth.

On the first run of a single reading, the first linear velocity is returned from the *getLinearVelocity()* method and saved, then the *getTime()* method saves the current time (in "ticks") and a flag is set to prevent this from happening again until the next reading. Every time the *physicsTick()* loop runs, it calls the accelerometer method which now compares the elapsed time from the first reading with the number of ticks between readings calculated from the bandwidth. When this time has finally elapsed the second linear velocity is taken and immediately an ending time is saved. The total number of seconds passed between readings is found by subtracting the number of ticks that have elapsed during the measurement, and dividing this difference by the resolution of the timer from the *getResoultion()* method. The acceleration is equal to the second velocity minus the first velocity divided by the elapsed time in seconds as shown in Formula 5.6.1.3. Once a single reading is finished, the flag for reading the first velocity and starting time is reset.

$$\frac{\left(Velocity_2 - Velocity_1\right)}{\left(\text{Elapsed Time in Seconds}\right)} \qquad (5.6.1.3)$$

These readings are for all three axes. Additional error could be simulated by manipulating these data before it is sent to the user, however, the decision was made not to handicap the user by forcing them to use a particular error calculation [94]. The user is free to model high-quality or low-quality accelerometer hardware. The resulting raw values from all three axes are returned every time the accelerometer is simulated to simplify coding. If a user is only interested in one axis, the others can be ignored. The user must poll the accelerometer from their userCode. They first need to start a SEAR MRL service, then access the simulator from within that service by making a function call directly to SEAR such as accelerations = sear.getAccelResult("accel") where “accel” is the name of the sensor given by the user. This sensor does not have its own serial port. To access the virtual accelerometers in the same way as an actual hardware distance sensor, a user can write a “custom controller” script which accepts serial messages, polls the simulator for sensor values, formats and scales the data, then returns the data over the virtual serial port.

5.6.1.4 Three-Axis Gyroscope

Gyroscopes often accompany accelerometers in the design of inertial measuring systems. They can be used to help correct offsets and errors given by real-world accelerometers. There is no error in the simulated accelerometers in this simulator, but the results are often “jittery” due to the way the physics engine simulates both accelerating and braking of the vehicle. Users may still want to use the gyroscope in the standard way to improve their filtering algorithms. Real-world MEMS gyroscopes often have a large output drift. This drift isn't currently simulated.

jME3 has a method to return angular velocity, however, it does not return values in radians per second. In fact, it could not be determined exactly what units it returned even with the help of the developer's forum. A custom method for finding actual angular velocity was created that is very similar to the accelerometer simulator.

Again, jME's timer class was used to find timer resolution (in “ticks” per second) and elapsed time, in ticks. To find the angle traveled over an elapsed time, the getForwardVector() method was used. This method returns the 3D normal vector of the forward direction of the VehicleControl object. For the first run of a sensor reading, the first forward direction vector and start time are recorded then a flag is set to prevent this from happening again until the next reading. The current time is compared with the expected elapsed time until it is reached. At this point the second forward direction vector is recorded as well as the stop time. Since the Vector3f class has no methods for comparing the angle between the components, both of the forward vectors are projected on each of the three original planes; XY, YZ and XZ. Each of these values are stored in a Vector2f. Using the angleBetween() method in the Vector2f class, the angle between each projected portion of the forward directions are calculated. For example, XY1 are the X and Y components of the first forward vector and XY2 are the X and Y components of the second forward vector. XY1.angleBetween(XY2) returns the angle between these components. This would describe a rotation about the Z-axis (yaw). Once the angle traveled in each axis is found the elapsed time is used to find the angular velocity. The angular velocity is then returned to the user. As with the accelerometer, all three axes are always simulated regardless of how many axes the user is measuring and the resulting values are without error. The user can choose to model error for any particular gyroscope they plan to use. A very good scheme for modeling error for a MEMS gyroscope can be found in [94].

To access the gyroscope readings, a user must follow the same method as with the accelerometer. (I.e. start a SEAR service within MRL, then poll the simulator for the gyro values). The function call would be GyroReadings = sear.getGyroResult("gyroscope") where “gyroscope” is the name of the sensor given by the user. This sensor does not have its own serial port. To access the virtual distance sensor in the same fashion as an actual hardware gyroscope sensor, a user can write a “custom controller” script which accepts serial messages, polls the simulator for sensor values, formats and scales the data, then returns the data over the virtual serial port.

5.6.1.5 Odometer

Odometry is a very useful metric used in positioning calculations for vehicles. The odometer sensor tracks the distance the robot has moved in both the forward and reverse directions. As with the other “physical” sensors, the odometer assumes it is located at the center of the robot's body. There is a minimum threshold that must be met in any linear direction before distances will be logged. This is due to the way jBullet simulates vehicle objects. When the robot (a type of vehicle object) is stopped, the brakes are constantly “fighting” with the acceleration setting, causing the vehicle to shake ever so slightly. Without the threshold value mentioned above, these vibrations would accrue to a very large error in odometer readings over time.

The way users can access this sensor is different from any of the others because the odometer sensor is a component of a “robot” object by default in SEAR. This means that a user can measure this sensor by sending a message to the robot object's virtual serial port in Roomba protocol format. SEAR will return the data on the virtual serial port in the same format as an actual Roomba would. Like an actual Roomba, SEAR stores the value of the distance as a 16-bit signed value (between -32,768 and +32,767) and sends the data as high-byte then low-byte when it is requested. Once the value has been requested by the user it is reset to 0, again, the same as with an actual Roomba [84].

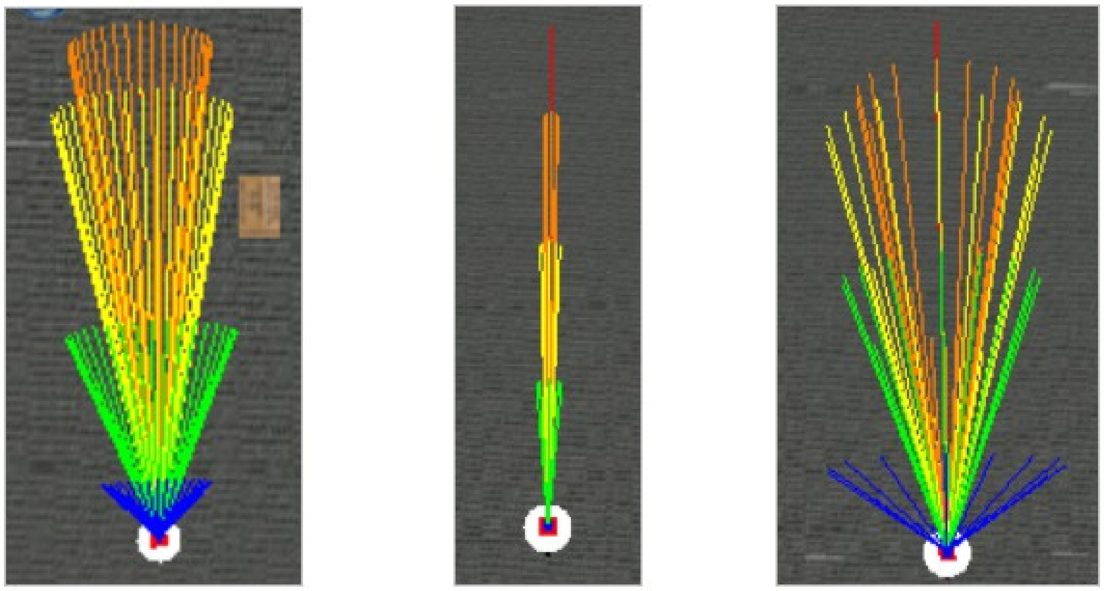
5.6.2 Reflective Beam Simulation (“Visual” Sensors)

Beam reflection sensors are arguably the most common sensors used in robotics. This sensor class includes sensors such as Infrared (IR), RADAR, SONAR, LIDAR, and Ultrasonic sensors. Though the technologies behind these types of sensor differ, they operate on the same principles. In the real world, this type of sensor works by sending a signal out into the environment and measuring the time it takes for that signal to reflect back to the sensor. SEAR uses ray casting to simulate this class of sensors. The reason these sensors are referred to as “visual” sensors in this dissertation is that the rays are cast along graphical lines drawn in the environment. These lines help users determine exactly what objects are being detected by the simulated sensors. Many simulators use ray casting as a method for finding intersections with triangle meshes of objects in a virtual environment [101].

5.6.2.1 Ultrasonic, Infrared, RADAR and SONAR Distance Sensors

The distance sensor class is used to simulate reflective sensors such as ultrasonic, infrared, RADAR and SONAR. The concept of these sensors is simple, though their implementation is quite complicated. To match specific sensors, actual hardware was designed and tested at specific distances and spread angles. Currently a “PING)))” ultrasonic sensor is the only one that has been validated against actual hardware measurements in this way. Distance sensors are implemented by having nested cone-shaped arrays of graphical lines. This group of lines may be attached at any given point on the robot, and rotated to point in any direction [64], [102], [103].

Each nested cone of lines has a slightly different angle from the X-axis of the ray's reference frame. Each nested cone also has a different length and color. The angles and length correspond better to the actual lobes of the ultrasonic sensor. The number of lines in each particular cone and the total number of cones define the sensor's resolution. During simulation, a list of “distance sensor” objects is used to iteratively cast rays along each line of each sensor. For a given sensor, only the closest collision distance and collision point can be returned. The collision point is used to display a red sphere at the actual point of impact on whatever object the sensor happens to detect. This helps the user debug their robotics projects by visually representing the point that is being detected by the sensor. If no objects are detected within range of the sensor, then the maximum sensing distance is returned by the sensor.



(a) (b) (c)

Figure 5.6.2.1.1 The distance sensor beam pattern is adjustable in SEAR. (a) Shows the beam pattern of a PING))) brand sensor which was experimentally acquired. (b) Shows an example of an infrared sensor beam. (c) Shows an example of the side lobes of the beam pattern being simulated

The angles, ranges, and resolution of the sensors are adjustable by end users (as well as developers) of SEAR as shown in Figure 5.6.2.1.1 and 5.6.2.1.2. This allows for a wide range of sensors and sensor types to be simulated by this particular simulator. IR and Ultrasonic beams can have a variety of different shapes depending on the applications they are used for. Sensors in the Sharp family of IR sensors generally have an ovate or “football” shape. They have much more narrow beams and are less prone to errors due to collision with angled objects while the MaxBotix EZ series ultrasonic sensors have more of a teardrop beam pattern [104]–[106]. All of this can be simulated as long as the developer knows the particular beam pattern of the sensor to be simulated. It is recommended to measure these values experimentally since datasheets often use different methods for determining values listed in the given charts and graphs which may not be useful for the particular environment in which the sensor will be used. The nested cone implementation also allows for side lobe as well as main lobe beam patterns, which are best mapped experimentally.

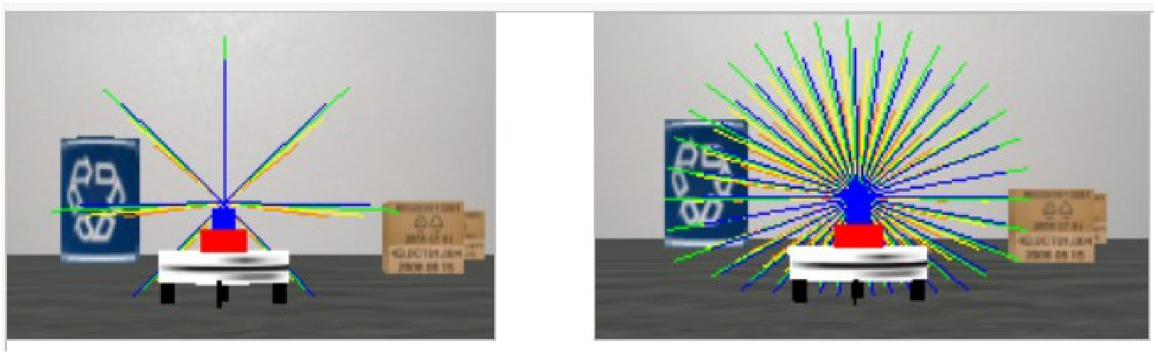
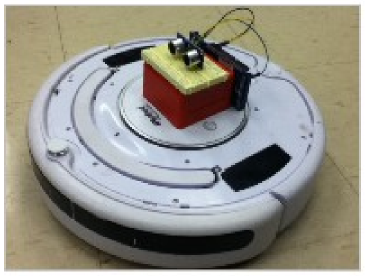

(a) (b)

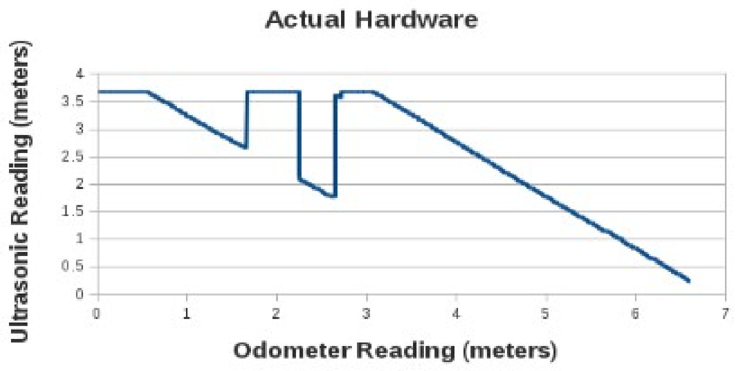
Figure 5.6.2.1.2 The distance sensor resolution is adjustable in SEAR. (a) shows a sensor with only eight lines used to simulation the nested cones. (b) shows a sensor that uses 36 lines to simulate each nested cone.

For Maxbotics sensors, a one inch diameter pipe was moved in front of the beam and the resulting measurements were used to give a rough estimate of the beam pattern of the sensor for the datasheets [106]. The method used to validate SEAR's PING))) sensor relied on a similar method, except the diameter of the sensor was 0.457 meters. It has been shown that this particular method for simulating ultrasonic sensor results in higher fidelity simulations than some standard robotics simulators [102].

The resolution of the reflective beam sensors can be modified by the developer by increasing the number of lines that are used to define each of the nested cones of a given sensor. The higher the number of lines used to define a particular cone, the smaller the angle created between each line. This decreases the chances of an object being missed by the sensor if it is within range.

For validation of the PING))) sensor, an actual Roomba robot was used as a mobile platform carrying a PING))) brand sensor. It was placed in a specific environment that contained several obstacles. ROS was used to interpret userCode which only drove the Roomba forward at a specified speed and recorded values from the Roomba's odometer and the PING))) to a file. The test robot and its validation test results can be seen in Figure 5.6.2.1.3.

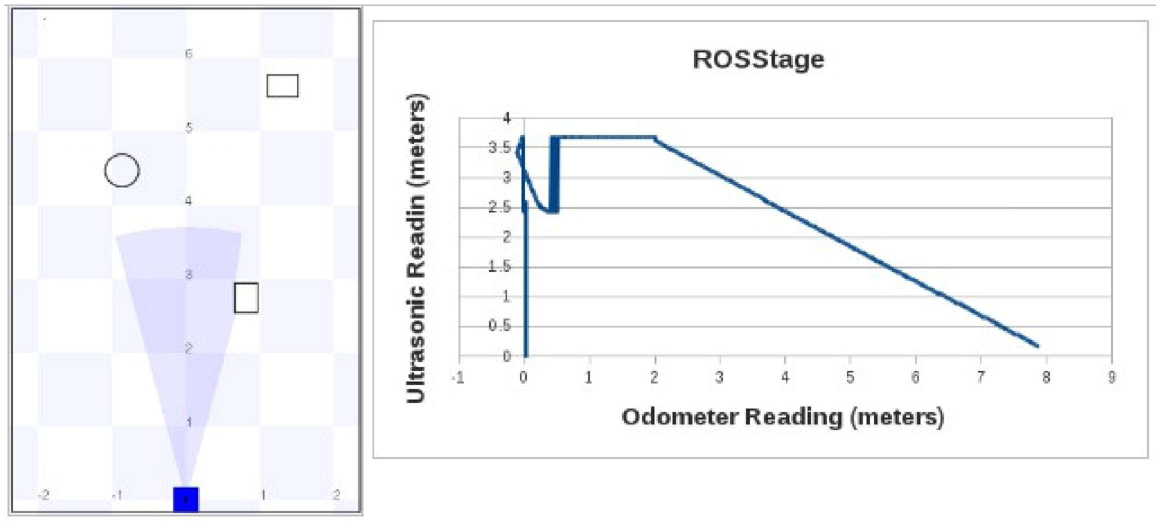




(a) (b)

Figure 5.6.2.1.3 (a) The actual Roomba robot with ultrasonic sensor payload on top. (b) The resulting graph of the odometer reading versus the Ultrasonic reading as the robot drove through the test environment.

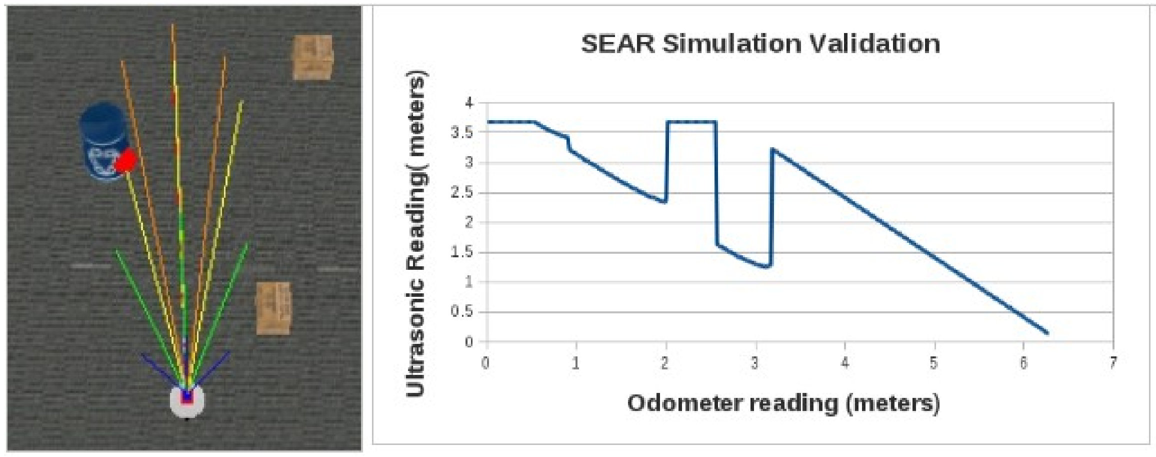
The same environment was designed for the ROSStage simulator. A similar robot was designed for the simulator and the exact same code was tested. The resulting odometer and ultrasonic sensor values were saved to a file. It should be noted that Stage does not simulate the correct beam-pattern of the sensor, rather it only simulates a section of a circle. The Stage simulation and its test results can be seen in Figure 5.6.2.1.4.



(a) (b)

Figure 5.6.2.1.4 (a) The ROSStage simulation showing the ultrasonic sensor beam pattern used. (b) The resulting graph of the odometer reading versus the Ultrasonic reading as the robot drove through the test environment.

Again, the same environment was designed inside SEAR. A similar robot was also designed. The same userCode was again tested, this time on the SEAR simulator's robot. The odometer and ultrasonic sensor values were recorded to a file. The SEAR simulation and its results can be seen in Figure 5.6.2.1.5. It is clearly shown that the SEAR implementation of a PING))) sensor is very close to the readings from the physical PING))) sensor, thereby validating the method used in SEAR.



(a) (b)

Figure 5.6.2.1.5 (a) The SEAR Roomba simulation showing the ultrasonic sensor beam pattern used. (b) The resulting graph of the odometer reading versus the Ultrasonic reading as the robot drove through the test environment.

The user can attach multiple distance sensors to their robot any at attachment point they choose and orient the sensors in any way they choose (Figure 5.6.2.1.6 shows an example of this). Each sensor must have a custom name so SEAR will know from which one to acquire data. To interface with these sensors in SEAR, the user must first start an instance of a SEARservice, then make a function call to the simulator from the SEARservice. The user must pass to the function the name of the sensor they wish to poll such as distance = sear.getDistanceResult("Ping1") where Ping1 is the name the user gave the sensor when creating the robot. The resulting value is returned in meters. The user can scale and format this as needed. This sensor does not have its own serial port. To access the virtual distance sensor in the same way as an actual hardware distance sensor, a user can write a “custom controller” script which accepts serial messages, polls the simulator for sensor values, formats and scales the data, then returns the data over the virtual serial port.

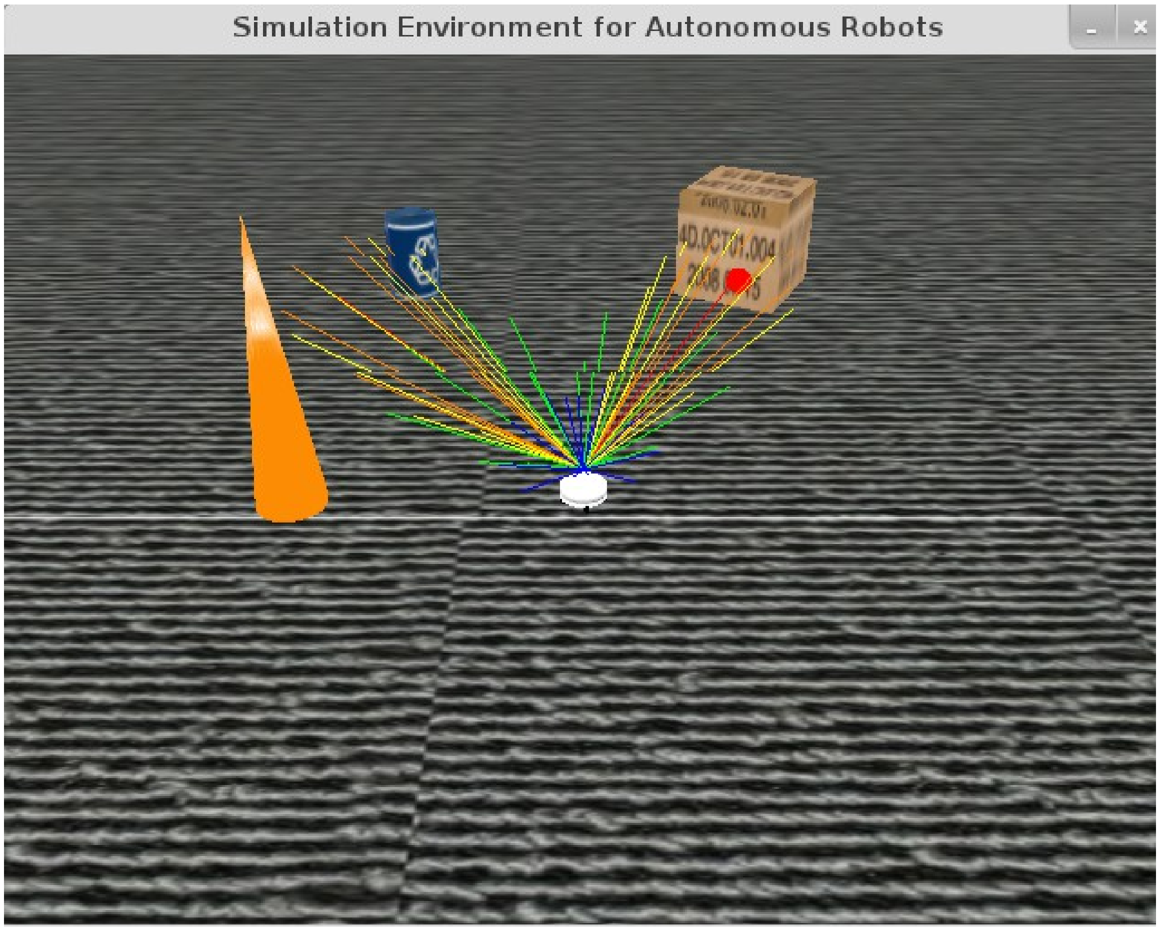


Figure 5.6.2.1.6 Two ultrasonic sensors attached to a Roomba in an indoor environment.

5.6.2.2 LIDAR Sensors

LIDAR (or Light Detection And Ranging) is a method of sensing in which a laser on the sensor directs a beam at an object and uses the time it takes the reflection of the laser to return to the sensor to calculate the distance to that object [92]. LIDAR units can scan the laser 90, 180, 300 and even 360 degrees [91], [107]. This scan results in the distances of all objects the laser encounters in a plane. Figure 5.6.2.2.1 shows a robot scanning the virtual environment with a virtual LIDAR.

LIDAR was simulated in this project using a simplified version of the distance sensor class, that is by ray casting. This is a typical method used for simulating LIDAR sensors [101]. Instead of multiple nested cones of lines and rays as in the distance sensors, a single flat plane of graphical lines are drawn on the screen originating from the location of the sensor (as given by the user). The lines have a length equal to the maximum range of the LIDAR sensor. The length of the visual line determines the maximum range of the ray cast along that line. This value is given in the LIDAR's datasheet and can be set by the user.

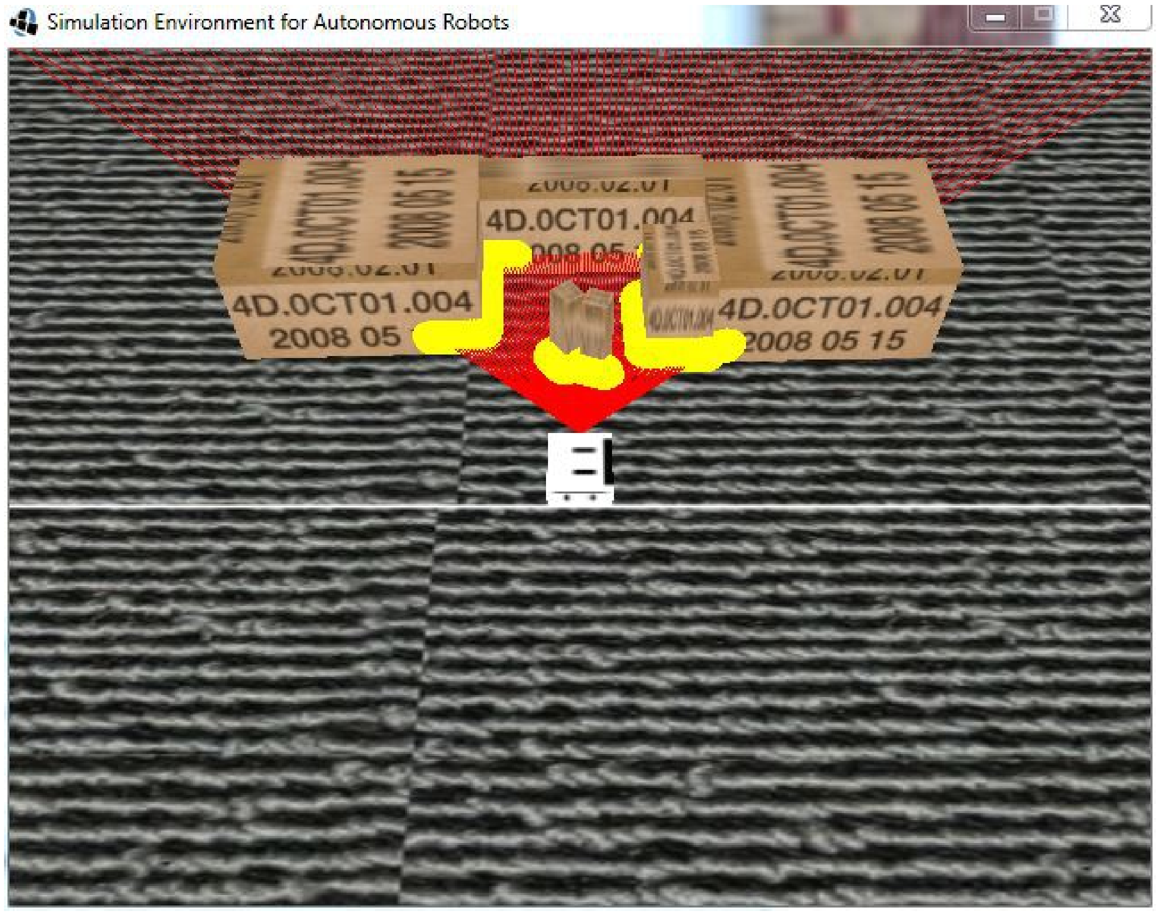
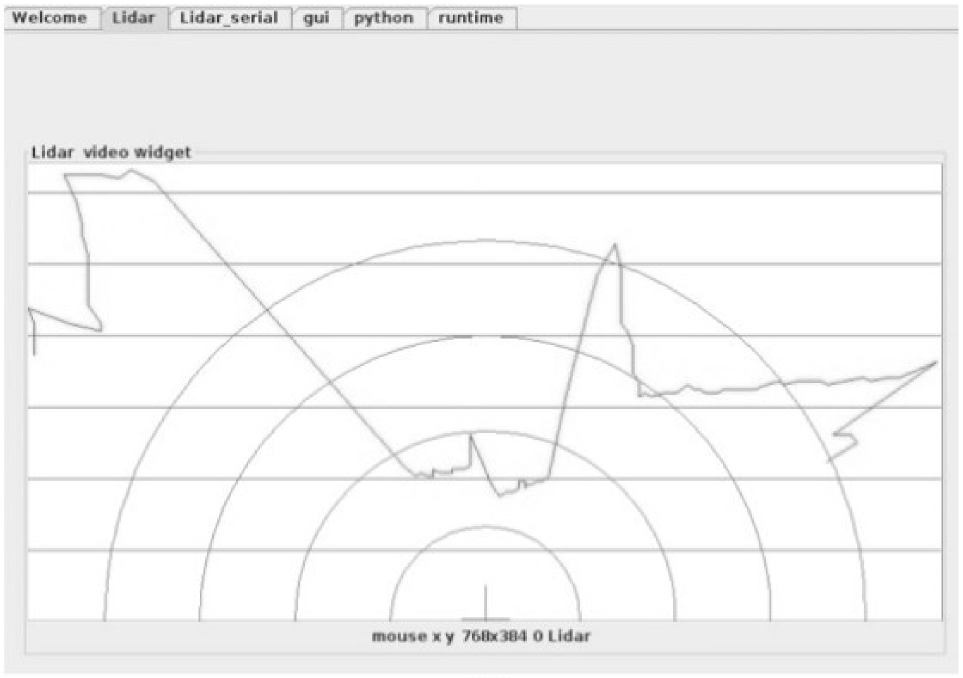
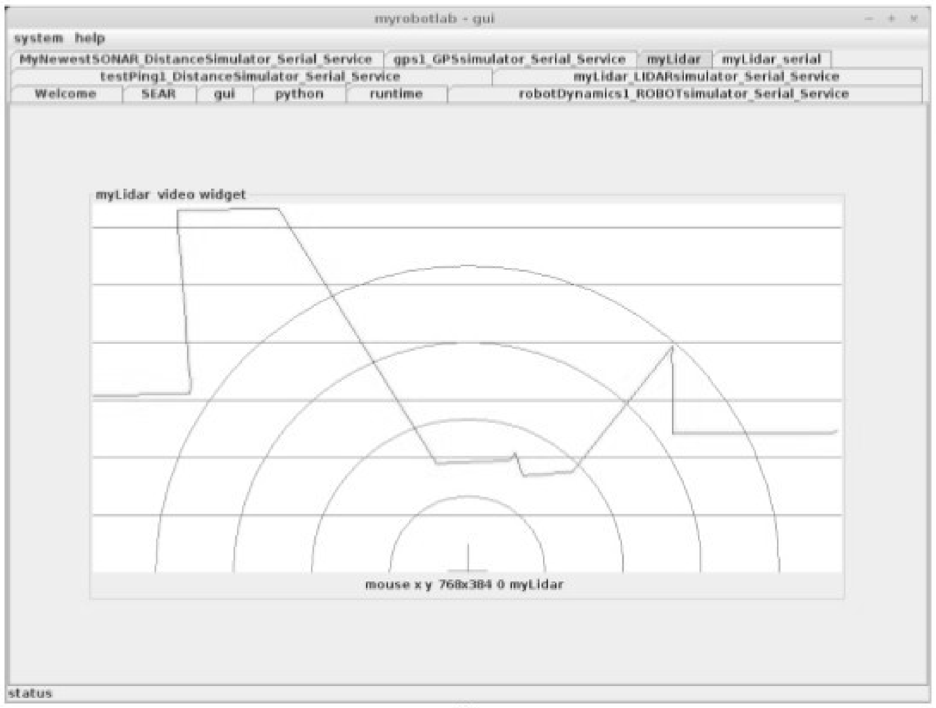


Figure 5.6.2.2.1 A single scan from the LIDAR simulator on a test environment. The red lines show where the rays are cast and the yellow spheres shows where the rays collide with the box objects. The results of this simulation can be seen in Figure 5.6.2.2.2b

Inside the SEAR simulator itself, the SICK LMS200 LIDAR was modeled and simulated. The sensor interfaces through a virtualSearialPort object within MRL and is accessible from userCode in the same way as actual hardware. This requires the user to start a LIDAR service within MRL, and passing it the path of the virtualSerialPort object as the port for the service to connect. Figure 5.6.2.2.2 shows a comparison of an actual SICK LMS200 scan of the lab environment versus a scan of the equivalent environment in the simulator (the environment shown in Figure 5.6.2.2.1). The major differences that can be seen between the two scans are mainly due to the fact that the simulated LIDAR does not calculate the scattering or absorption of the laser beam once it hits an object. Otherwise it is very easy to identify the edges and sides of the boxes that were scanned.



(a)


myrobotlab - gui
system
help
MyNewestSONAR_DistanceSimulator_Serial_Service
gps1_GPSsimulator_Serial_Service
myLidar
myLidar_serial
testPing1_DistanceSimulator_Serial_Service
myLidar_LIDARsimulator_Serial_Service
Welcome
SEAR
gui
python
runtime
robotDynamics1_ROBOTsimulator_Serial_Service
myLidar video widget
mouse x y 768x384 0 myLidar
status

(b)

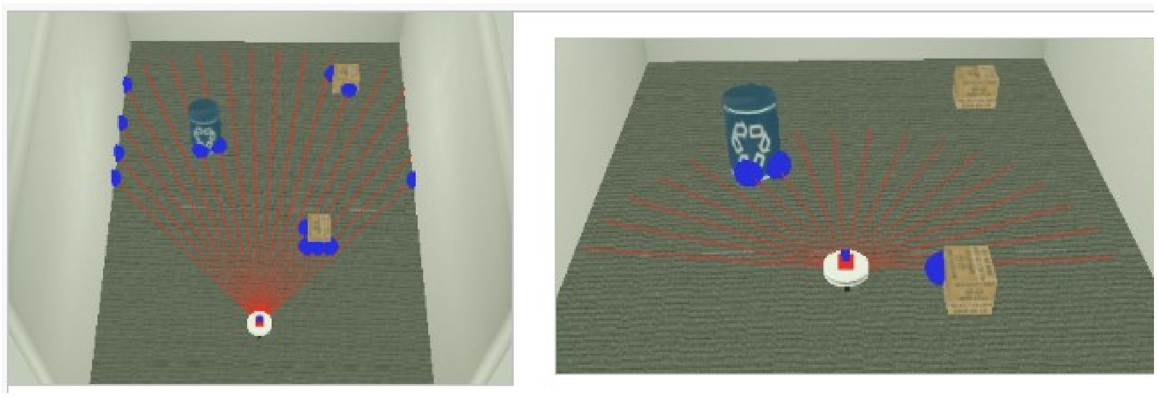
Figure 5.6.2.2.2 (a) The readings from an actual SICK LMS200 (b) the readings from the SEAR simulated LIDAR in a similar environment. These readings provide a top-down view of an environment in which there are two larger boxes at the left and right extremes and two smaller boxes in the front center of a wall in front of the LIDAR sensor.

The algorithm for simulating the scan involves finding the current 3D translation and rotation of the LIDAR sensor. The sensor is placed on the robot's body by the user when designing the robot. As the robot moves within the world, the position of the LIDAR sensor updates. The graphical lines of the LIDAR are updated automatically (since they are part of the robot's Node object). During the physicTick() loop, in which all of the physics are calculated in jME, rays are cast along each graphical line. The resulting collision points with any other object in the physics space are returned. If no collision is detected within the distance of the maximum range, then the value of the maximum range is returned. The simulation results are a set of distances. Each distance corresponds to a particular line.

An example scan with a maximum degree spread equal to 180 degrees and an angle step of 0.5 degrees per step would include 361 readings; one each at the following angles:

$$0^o, 0.5^o, 1^o, 1.5^o, 2^o \;\ldots\; 178^o, 178.5^o, 179^o, 179.5^o, 180^o$$

The result of the measurements is an array of floating point decimal numbers representing distances to collisions in world-units. Just as with actual LIDAR systems, this information is packaged with a header and checksum value. Figure 5.6.2.2.2 shows two examples of LIDAR sensors with different properties.



(a) (b)

Figure 5.6.2.2.2 The LIDAR sensor is highly configurable. (a) shows a narrow spread and long range LIDAR, where (b) shows a wide spread LIDAR with a short range. The blue spheres show the locations of any collisions of the lines.

5.7 Serial Communication Between MRL and SEAR

At the developer level, serial communications between MRL and SEAR's simulated sensors works in a non-intuitive way. First, when an instance of the SEAR simulator runs, it creates a HashMap containing the information about all the sensors related to that SEARproject and passes it to the SEARservice within MRL. This SEAR-service then registers callback methods with each serial port using Java reflection. Meanwhile, within the SEAR simulator, each sensor creates two "virtualSerialPort" objects using an MRL library. These objects look and act like hardware serial ports, but they do not exist anywhere but inside MRL's service structure. Each sensor's XML file contains the UARTport and userPort addresses associated with a given sensor. These two ports are nulled together such that data coming from one is sent out the other. Also, a "Serial" object is created and set to the "UARTport" address. Data generated by the sensor can be sent out via this SerialPort object back to MRL.

Sending commands or data to a particular simulated sensor is more complicated because the actual SEAR simulator is not registered as a part of MRL, it instead communicates to MRL via the *SEARservice*. When data is sent from userCode to a particular SEAR virtual sensor, it cannot travel directly on the sensor's serial port service like data coming the other direction. Instead, it triggers a set of events within the MRL *SEARservice*. First, the type of sensor is acquired by looking at the message being sent. Then everything except the sensor's name is stripped from the message. For instance: "*myLidar_LIDARsimulator_Serial_Service*" becomes "*myLidar*". Once the sensor's type and name are known, the *SEARservice* can then send the userData to that instance of the sensor. Figure 5.7 shows a graphical representation of the dataflow when userCode sends a message to a LIDAR to acquire data, and how that sensor sends data back to the userCode. The steps described in the figure are:

1. User code running within a python service sends a message to the LIDAR serial service requesting a scan (this is the same as with actual hardware).
2. The LIDAR service sends the serial data to the LIDAR simulator's serial port, but the message is processed by the SEARservice.
3. The SEARservice invokes the particular LIDAR simulator instance within the SEAR simulator.
4. The SEAR simulator makes a method call to the particular LIDAR simulator instance.
5. The LIDAR scans the simulated environment, formats the data and sends it to its Serial service.
6. The LIDAR's serial service sends the data back to the LIDAR service.
7. The LIDAR service sends the data to the userCode running within the Python service.

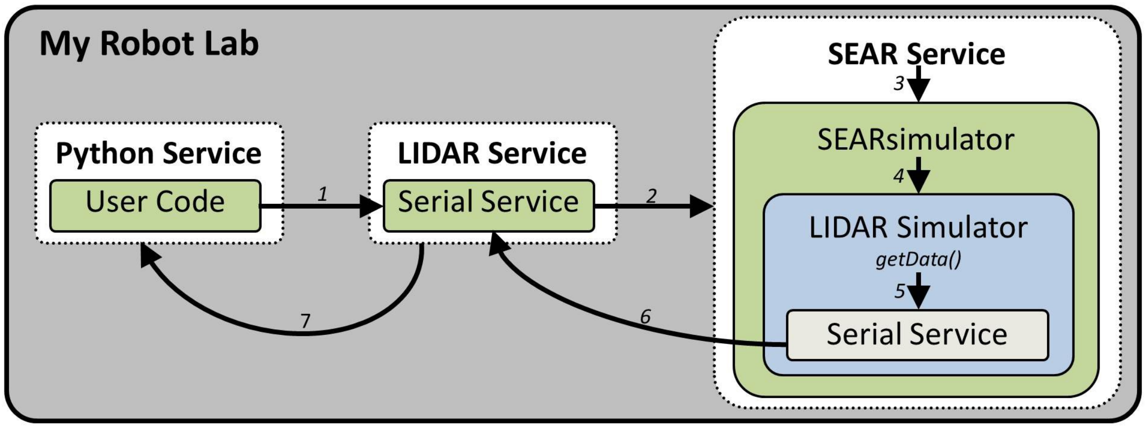


Figure 5.7 The data flow diagram of serial messages between userCode in MRL's Python service and SEAR simulated sensors.

All of this action occurs to abstract the userCode so users will interface with the simulated LIDAR the same way they would as with an actual LIDAR, by a method call in the LIDARservice. To the user, all of these other communications are hidden. The only difference the user will notice is the serial port name of the simulated LIDAR doesn't appear anywhere outside of MRL. If they check the device manger in windows or run a directory listing in /dev/ on UNIX or LINUX-based machines, the serial port will not be listed.

CHAPTER 6: CONCLUSIONS AND FURTHER WORK

This research developed the methods and techniques for the design of a tool that can be used for a variety of academic uses, from teaching introductory programming concepts to performing accurate graduate-level robotics research. This design was demonstrated by the development of the Simulation Environment for Autonomous Robots. Most of the accomplishments planned for this research have been met. These include the following:

- Identification of features and a working architecture for a modern robotics simulator:

  As defined in this work, a modern robotics simulator, SEAR, is available to users on any major platform (Windows, Mac and Linux). It also is open source meaning the source code is freely distributed, allowing a community of developers can improve it over time. One of the most important aspects of a successful modern robotics simulator is the ability to interface with at least one of the many middleware applications that are currently available. This greatly increases the usability of the simulator and extends the capability of the user by allowing them to use third-party libraries and software easily.

- The creation of methods for simulating different types of sensors in a virtual 3D environment:

  Common sensors (a 3D accelerometer, a 3D gyroscope, a magnetic compass, an odometer, a GPS, a LIDAR, and a class of reflective distance sensors including ultrasonic and infrared) used in autonomous robotics projects have been developed and several have been validated against actual hardware. The method of simulation of some of these sensors is novel. For example, the distance sensors are simulated in such a way that beam patterns of these sensors can be adjusted by the user.

- The addition of new sensor types to SEAR and improvement of current sensors:

  The odometer sensor was added to keep track of the overall distance the robotic vehicle traverses. Also, the new class of "visual" sensors which includes Ultrasonic, SONAR, RADAR and infrared sensors as well as a user-definable LIDAR sensor were added.

  Users can define custom beam shapes for the distance sensor class such that they can include all makes and models of sensors of this class. The compass sensor class was made more efficient by the addition of a new declination calculation method.

- Implementation of an interface with common robotics middleware:

  The same user-defined code can be used on actual hardware or the SEAR simulator with little to no modification.

- The implementation of a method for users to import or create models:

  Custom terrains can now be designed by the user using SEAR's POJO library. Models of terrains can also be imported from external CAD software. The resulting terrains and obstacles are saved as XML files that are dynamically injected into SEAR at start up. These files can be created and manipulated by hand if needed and transferred from one user to another easily.

Robots can be built component by component using the SEAR POJO library. Components of robots can be imported from external CAD software. The suspension characteristics of the robot are completely accessible to the user including mass, damping, compression, wheel rest length, stiffness and maximum suspension force.

- The implementation of a simple file extension for SEAR projects:

  Settings of entire *SEARprojects* are stored as a single zip file which contains all the user's code, models, and files for robots and terrains.

6.1 Virtual Serial Ports and ROS Integration

All of the goals set for this research were met or exceeded with the exception of interfacing with ROS middleware using virtual serial ports. Previous iterations of SEAR had interfaced with ROS directly (as it now does with MRL). This proved hazardous for development as the infrastructure of ROS changed multiple times, completely invalidating the deprecated method used. The most effective way to interface with ROS was determined to be at the highest abstraction level, away from the internal changes within the ROS project. For SEAR, it was determined that only serial communication to specific ROSnodes (such as the Brown University Roomba driver, or the Arduino serial driver) would protect SEAR from the constant code revisions. The method for connecting two serial was to use pseudoterminals as virtual serial ports. This method was expected to provide a relatively clean connection between ROS and SEAR, while keeping one of the main concepts of SEAR intact; interfacing with SEAR simulated hardware should be the same as interfacing with actual hardware. The pseudoterminals are configured in such a way to pass inputs from one pseudoterminal to the output of the other and vice versa. If this method had worked, a single implementation of SEAR could be used to communicate with both MRL and ROS.

Through many investigations, if was determined that the use of pseudoterminals does not work for piping ROS data through to MRL and subsequently SEAR. By adding a secondary hardware serial port in parallel with the an actual Roomba connected to ROS, it was shown that ROS sends different commands to an actual Roomba than it sends when connected to a pseudoterminal. This makes it impossible to implement a serial interface with ROS using the ROS Roomba node via pseudoterminals.

There are two possible solutions to this, and neither of which were determined to be suitable for the needs of most users. The first method requires nulling together two actual serial ports on the host machine that ROS and SEAR are running on. This is a physical implementation of how the pseudoterminals work.

The second way to allow ROS to communicate to MRL, and thereafter SEAR, would be to use a package called ROSbridge that converts ROS commands to TCP protocol. This would require MRL to implement a TCP protocol as well which does not conform to the goals set out in this research; to interface with SEAR exactly the same way as with actual hardware. As such, this method was not investigated any further.

6.2 Further Work

There are many opportunities for improvement of the SEAR simulator. Additional sensor types could extend the capability of SEAR. Some good candidates for new sensors include visual cameras, infrared cameras, and 3D depth cameras (such as an XBOX kinect). More models of the currently supported sensors could be added as well. For instance the GPS and LIDAR simulators are each based on only one actual sensor brand

and model respectively. The addition of new beam shapes for the infrared is also possible, though this ability is already available to the end user as they can use one of the overloaded constructors in the POJOs library to define their own beam shapes. It would be simple to add in different beam shapes based on names so that when a user names a sensor “MaxBotics EZ1” SEAR will automatically use the beam pattern built in to simulator that particular sensor.

Moving each sensor simulation into their own threads would also increase the ability of SEAR by reducing lag time when large amounts of data are being collected. Each sensor could be encapsulated in its own thread. This would also allow for an expansion of SEAR from simulating a single robot, to the ability to simulate multiple robots. Since there is a large amount of graduate-level research in these areas this ability would increase the usage of SEAR.

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APPENDIX A: SEAR USER INTERACTIONS

There is a need to describe a typical user interaction with SEAR and MRL using the highest level of abstraction, the “User Space”. To this end, this user case can serve as both a clear example of user interaction and as a guide for users of SEAR.

A.1 Creation of Environments and Objects

In MRL, a python service must be started. In this example, the python service is also named “python.” From this service, a user can import the SEAR.POJOs library and create the environment using SEAR-native objects. These objects will be stored in a folder titled “SEARproject” inside the main MRL working directory. Code Listing 1 shows the creation of an environment with an example of each SEAR-native element.

Code Listing 1: Python script that can create the XML files for a simulation environment.

```python
from org.SEAR.POJOs import Cylinder
from org.SEAR.POJOs import Box
from org.SEAR.POJOs import Cone
from org.SEAR.POJOs import model

floor = Floor("floor", 50, 50)    #create floor

 #create some obstacles
box = Box("Box1_name", 0.25, 0.25, 0.25, 0)
box.move(-1.5, 1.25, 0)
box.rotate(45, 0, 0)

cyl = Cylinder("trash Can", 0.25, 0.75, 10)
cyl.move(-3, 0, -3.5)
cyl.rotate(0, 30, 30)

coneA = Cone("Traffic Cone", 0.25, 2, 10)
coneA.move(-2, 0, 0)
coneA.rotate(0, 0, 45)

tree = Model("Tree1_name","models/Tree/Tree.mesh.xml")
tree.move(0, 0, -3)

print "Done creating Environment"
```

A.2 Creation of a Virtual Robot in SEAR

Virtual robotic vehicles are created in a similar fashion as environments. The difference is that the objects are then added as components to a “robot” object. Code Listing 2 shows example code for the creation of a robot with sensors.

Code Listing 2: The creation of a simple Roomba-like robot

```
from org.SEAR.POJOs import Cylinder
from org.SEAR.POJOs import Box
from org.SEAR.POJOs import Cone
from org.SEAR.POJOs import Wheel
from org.SEAR.POJOs import SEARrobot
from org.SEAR.POJOs import Gyroscope
from org.SEAR.POJOs import Accelerometer
from org.SEAR.POJOs import GPS
from org.SEAR.POJOs import Compass
from org.SEAR.POJOs import Odometer
from org.SEAR.POJOs import Distance
from org.SEAR.POJOs import LIDAR
from org.SEAR.POJOs import Dynamics

robot = SEARrobot("myRoomba");#create a “robotObject” entity

#setup suspension and communications ports
dyna = Dynamics("robotDynamics1", 400, 60, 0.3, 0.4, 10000, 0.1,
0, 0.1, 0, 0, 0, 180)
dyna.setPorts("/dev/my_Robot01", "/dev/SEAR_Robot_01")
robot.addComponent(dyna)

#create a cylinder for the body of the Roomba and apply a custom
image to it
body = Cylinder("Roomba Body",  0.1666875, 0.0762, 400,
"./textures/roomba.jpg")
robot.addComponent(body)

#create and add the wheels to the robot object
cyl1 = Wheel("frontWheel", 0.0381, 0.03, 0)
cyl1.move(0, 0, 0.16)
robot.addWheel( cyl1);

#adding wheels saves wheel specs in the robot XML
cyl2 = Wheel("rightWheel", 0.0381, 0.03, 1)
cyl2.move(-0.16, 0, 0)
robot.addWheel( cyl2)

cyl3 = Wheel("leftWheel", 0.0381, 0.03, 1)
cyl3.move(0.16, 0, 0)
robot.addWheel( cyl3)

cyl4 = Wheel("backWheel", 0.0381, 0.03, 0)
cyl4.move(0, 0, -0.16)
robot.addWheel( cyl4);
```

A.3 Controlling a Virtual Robot in SEAR

Once both the environment and robot have been created, the user can write the code to control the robot and read sensors. To drive the robot within SEAR, the user must write code which starts a SEAR simulation which will load this robot from the XML files, then connects to the robot's virtual serial port to communicate with the robot. An example of this can be seen in Code Listing 3. Notice that first, a Roomba MRL service is created. This is because the robot dynamics in SEAR expects to use the Roomba protocol to receive drive commands, and to return sensor data. The Roomba protocol is very simple to understand, easy to implement on other robotics platforms and almost universally supported by many other software applications (including other robotics middleware).

Code Listing 3: Example userCode that drives a robot in SEAR.

```python
from time import sleep
from org.myrobotlab.service import Roomba

sear = Runtime.createAndStart("SEAR","SEAR")
sear.startSimulation();          #start SEAR simulation

roomba = Runtime.create("robot_Dynamics1","Roomba")
roomba.connect( "/dev/SEAR_Robot_01" )
roomba.startService()
roomba.startup()
roomba.control()
roomba.goForward()
roomba.sleep( 1000 )
roomba.goBackward()
```

A.4 Creating and Communicating with a Virtual LIDAR in SEAR

The user must first create the XML file for a LIDAR sensor in the robots folder of the SEARProject. This is done easily by using a python script or Java class written within MRL. The creation of the XML file will be done automatically in Code Listing 4. This snippet should be added to the script that creates the virtual robot (Code Listing 2).

Code Listing 4: The creation of a virtual LIDAR sensor

```
from org.SEAR.POJOs import LIDAR

lidar1 = LIDAR ("myLidar")#creates LIDAR object named "myLidar"
lidar1.setRange(8.191)
lidar1.setSpread(180)
lidar1.setResolution(1.0)

#sets UART port, then the port the user will communicate with
lidar1.setPorts("/dev/my_Lidar01", "/dev/SEAR_LIDAR_01")
lidar1.setBaud(9600)
lidar1.move(0,0.15,0.2)  #move the physical location of this
sensor on the robot's body
lidar1.LMS(1)
robot.addComponent(lidar1) #add as a component of the robot
```

Access to this sensor during a simulation is simple. First, an instance of SEAR must be created and started either by manually starting a SEAR service in MRL or programmatically as shown in Code Listing 5, then a LIDAR service should be started in MRL just as if an actual physical LIDAR device was being used. The communications options (LIDAR name, UARTport, and userPort) should be the same as those set in the XML description of the LIDAR sensor.

Code Listing 5: Starting a LIDAR MRL service

```
from time import sleep
sear = Runtime.createAndStart("SEAR","SEAR")
sear.startSimulation(); #start SEAR simulation
sleep (2); # Give some time for things to fall into their natural
place.

#These lines are initialization of the LIDAR
lidar = Runtime.createAndStart("myLidar", "LIDAR")  # creates
LIDAR service named "myLidar"
lidar.startService()
print "connect LIDAR service to /dev/SEAR_LIDAR_01"
lidar.connect("/dev/SEAR_LIDAR_01")
#have python listening to lidar
print "adding the LIDAR service listener"
lidar.addListener("publishLidarData", python.name, "input")
# set scan mode for 100 degree spread with a reading every 1
degree
print "setting scan mode"
lidar.setScanMode(100, 1)

print "Ready to receive LIDAR data... "
while 1:        # infinite loop
        lidar.singleScan()  #get a single scan
        sleep(2)        #wait two seconds and repeat
```

While the simulation is running, the LIDAR data can be viewed in the LIDAR service tab named "myLidar" in MRL. This will update once each time the LIDAR scans. To access the data of the LIDAR within the userCode script, a listener must be added to the LIDAR service's publishLdarData method. This will call a userCode method each time the LIDAR service receives a valid message. In Code Listing 6, the listener calls the userCode method "input" each time the LIDAR service publishes data. There are several examples (commented out) of how to use the raw LIDAR data. The example that is not commented in this method will print the results out in the python console window of MRL's python service as Cartesian coordinates of collisions using the placement of the LIDAR in the simulated world as the reference (0,0).

Code Listing 6: Example code for accessing the raw LIDAR data

```
from time import sleep
import Java.lang.String
import math
 # This script only uses the LIDAR sensor on the simulated robot, the user is expected to drive the robot using the i,j,k,l,and ; keys

def input():
  startingAngle = 0
  code = msg_myLidar_publishLidarData.data[0]
  length = len(code)
  print "received " + str(length) +"readings:"
  if length==101 or length==201 or length==401:
        startingAngle = 40
  else:
        startingAngle = 0

  for i in range(0, length):
#       print hex(code[i])      #print result in hexadecimal
#       print (code[i])         #print results (without units)
#       print (code[i]/float(100))      #Print results in centimeters (if LIDAR was in CM mode)

#       print ((code[i]/100)/2.54)      #Print results in inches (if LIDAR was in CM mode)

#       print str(i)+"\t"+str((code[i]))  #print polar Coordinates (without units)
#convert polar to Cartesian
        x = (code[i])*math.cos(((i*100/length)+startingAngle)*(3.14159 / 180))
```

Code Listing 6 Continued:

```
 26          y =(code[i])*math.sin(((i*100/length)+startingAngle)*
       (3.14159 / 180))
 27          print str(x) +"\t"+str(y)
 28
 29      # create and start the SEAR simulator instance
 30      sear = Runtime.createAndStart("SEAR","SEAR")
 31      sear.startSimulation(); #start SEAR simulation
 32      sleep (2); # Give some time for things to fall into their natural
       place.
 33
 34      print "Attempting to create the LIDAR service..."
 35
 36       #These lines are initialization of the LIDAR
 37      lidar = Runtime.createAndStart("myLidar", "LIDAR")
 38      lidar.startService()
 39      print "connect LIDAR service to /dev/SEAR_LIDAR_01"
 40      lidar.connect("/dev/SEAR_LIDAR_01")
 41
 42       #have python listening to lidar
 43      print "adding the LIDAR service listener"
 44      lidar.addListener("publishLidarData", python.name, "input")
 45
 46       # sets scan mode for 100 degree spread with a reading every 1
       degree
 47      print "setting scan mode"
 48      lidar.setScanMode(100, 1)
 49
 50      print "Ready to receive LIDAR data... "
 51      while 1:        # infinite loop
 52              lidar.singleScan()  #get a single scan
 53              sleep(2)        #wait two seconds and repeat
```

Note that in Code Listing 6, line 6 is the function that the userCode uses to access the raw LIDAR service data. This line has to be constructed carefully to ensure it will acquire the correct data. In this line, the variable getting loaded is called “code”. The raw LIDAR data is stored in a variable which follows the format *msg_<LIDAR service name>_pubishLidatData[0]*. The “*<LIDAR service Name>*” should be replaced with the name of the LIDAR service created in this code. This can be seen in line 8: code = *msg_**myLidar**_publishLidarData.data[0]*, where “***myLidar***” is the name given to the LIDAR sensor in line 37: *lidar = Runtime.createAndStart("**myLidar**", "LIDAR")*. It is important to note that this variable will return as an array. Each element of this array will contain the result of a LIDAR reading. The length of the array is determined by the settings of a particular LIDAR scan.

A.5 Creating and Communicating with a Virtual GPS in SEAR

The user must first create the XML file for a GPS sensor in the robots folder of the SEARProject. This is done easily by using a python script or Java class written within MRL. The creation of the XML file will be done automatically in Code Listing 7. Notice that the user must provide a starting GPS coordinate. This represents the starting point of the robot and the center of the world.

Code Listing 7: Creation of a GPS sensor XML file for SEAR. This snippet should be added to Code Listing 2.

```
from org.SEAR.POJOs import GPS
 # create a new GPS object (myGPS) with the name "gpsUnit1"
myGPS = GPS("gpsUnit1", 33.61, 182.5, -80.865)
myGPS.setPorts("/dev/my_GPS_01","/dev/SEAR_GPS_01")
robot.addComponent(myGPS)
```

There are two methods for users to access this sensor during a simulation. Firstly, the user can see the results from GPGGA NMEA strings by initializing a GPS service in MRL. This can be performed either manually (using the MRL GUI) or programmatically using MRL's python or Java service. Figure 5.1.2 shows a screenshot of the GPS service GUI printing data. To access the GPS data inside the userCode, the user can start a GPS service in python or Java, then add a listener to that service. Code Listing 8 shows an example that simply prints the resulting GPS values to the terminal. Note that the name of the GPS agrees with the XML file. This is especially important in the lines that get the GPS data.

Code Listing 8: Example code to access raw GPS data.

```
from time import sleep

 # This script only uses the GPS sensor on the simulated robot,
the user is expected to drive the robot using the i,j,k,l, and ;
keys

sear = Runtime.createAndStart("SEAR","SEAR")
sear.startSimulation(); #start SEAR simulation
```

Code Listing 8 continued

```
initialized = 0

gps1 = Runtime.createAndStart("gpsUnit1", "GPS")
gps1.startService()
gps1.connect("/dev/SEAR_GPS_01")
sleep(1)
def input():
  startingAngle = 0
  Latitude = msg_gpsUnit1_publishGGAData.data[0][2]
  Longitude =  msg_gpsUnit1_publishGGAData.data[0][4]
  altitude = msg_gpsUnit1_publishGGAData.data[0][9]
  print "Lat: " + Latitude
  print "Long: " + Longitude
  print "Alt: " + altitude + "\n"

 #have python listening to GPS
gps1.addListener("publishGGAData", python.name, "input")

print "Ready to receive Data from GPS..."
```

A.6 Simple Sensors

Simple sensors are those which do not contain their own serial connection which users can communicate with. This includes accelerometers, gyroscopes, compass sensors, and the distance sensors. These sensors can be accessed in two ways; a very simple method call to directly the simulator, or a by simulating a custom microelectronic that handles the sensors and serial communications. This section describes the former case.

Simple sensors can be accessed directly from userCode using method calls to the simulator within the SEARservice. This interface is straightforward and can easily be understood by users with little skill or knowledge of programming. The concept with this implementation was to make it easy for users with little skill to access the sensors. The aspiration is that SEAR would be used to help teach programming concepts such as conditionals and loops. By having a simple method for accessing sensor data, the focus of lessons could be on the overall programming concept rather than the specifics of SEAR or MRL.

A.7 Custom Controller for Simple Sensors

For user who wish to more accurately emulate actual hardware, interfacing with simple sensors (accelerometers, gyroscopes, compasses and distance sensors) happens by proxy. In reality, the user would connect these sensors to a microcontroller which can handle serial communications with userCode in MRL, and performs the actions required to request and format data from these sensors. The processes of this microcontroller can be simulated using a template python script provided with SEAR.

The communications protocol used by the template is based on the Roomba serial protocol and is very simple to implement both in a simulation as well as with actual hardware. The last “sensor command” in the Roomba protocol requests data from sensor message number 42 [84]. SEAR’s custom controller accepts the same “sensor request message” as the Roomba protocol, except it begins with number 43. Given that this is an 8-bit number, the user can add more than 200 additional commands.

The virtual controller handles the serial communications, parses the serial commands, and selects the appropriate function to perform based on the command. Just as would be required of actual hardware, functions must be supplied by the user. If the command is received to “read the left ultrasonic sensor” then the user must insert code to perform this action within the SEAR simulator. This simply consists of a call to SEAR's ultrasonic sensor simulator class. Data is returned to this custom controller template which then writes the data back on the serial port. When in use during a simulation, abstraction allows this to be a black box to which a user issues commands and receives data in return. This implementation is exactly the same as would be required to connect to physical hardware. The pseudo-code in Table A.7 compares the code of a SEAR virtual controller and a physical microcontroller.

Table A.7: Comparison of communications between userCode and physical hardware versus userCode and SEAR virtual hardware

Physical Microcontroller	***SEAR's Virtual Controller***

User sends command via serial connection to the physical microcontroller to get a reading from the compass module. Usercode snippet:
`Serial.writeByte(42)   # send sensor request`
`Serial.writeByte(30)   # sensor "address"`
	User sends command via serial connection to the simulated controller object to get a reading from the compass module. Usercode snippet:
	`Serial.writeByte(42)   # send sensor request`
	`Serial.writeByte(30)   # sensor "address"`

Command is sent via serial connection to the physical microcontroller	Command is sent via serial connection to the virtual controller object.
Microcontroller on the robot parses the command and calls the function to read the compass module's current value: (Microcontroller code snippet:) `int heading = getCompassValue(); #Assuming a function performs this for the user.`	Simulated controller object parses the command and calls the function to read the compass module's current value: (virtual controller code snippet:) `int heading = sear.getCompassResult("comp1") #The name of this sensor on the robot is in quotes to identify it from other sonar sensors that the robot might have.`
Microcontroller on the robot sends data back to the user over the same serial port: `Serial.writeInteger(heading)`	Custom controller sends data back to the user over the same serial port: `Serial.writeInteger(heading)`

The suggested method of using the custom controller is to send a request to the controller's serial port from the user's code. The user should know the size of the message the controller will return (this will be known since the user would have written that code as well). The custom controller receives the message, parses it, performs the selected action (such as taking the reading from the front-left ultrasonic sensor) then returning the resulting data to the user's code over its serial connection.

The custom controller code uses code written in a Python or Java file by the user previous to running the simulation. The controller code simply utilizes MRL's virtualSerialPort objects to communicate to the main userCode (controlling the overall simulation). The messages from this serial connection get parsed and a set of if statements help select which action to perform. The user can choose to write custom code for each if statement based on the needs and design of the robot.

To access SEAR's simulated sensors the user will use methods from the SEAR service. For the ultrasonic example above, the user would use code like *sear.getDistanceResult("leftFrontPing")* which will return the distance in centimeters to the nearest object that is within the range of that specific sensor. The name of the sensor, *leftFrontPing* must match the name of the sensor in its XML file within the SEARproject/robot folder. Once this value is acquired, it is sent back over the virtual serial port to the user's overall simulation code.

To simplify the process of creating a custom controller in SEAR, a template is provided that listens for serial events on the virtual ports. There is also a list of empty "if" statements with commented examples for each type of sensor. This template also has a function to send the acquired data back to the main simulator. The suggested method of using the custom controller is to send a request to the controller's serial port from the user's code. The user should know the size of the message the controller will return (this will be known since the user would have written that code as well). The custom controller receives the message, parses it, performs the selected action (such as taking the reading from the front-left ultrasonic sensor) then returning the resulting data to the user's code over its serial connection.

The custom controller code uses code written in a Python or Java file by the user previous to running the simulation. The controller code simply utilizes MRL's virtualSerialPort objects to communicate to the main userCode (controlling the overall simulation). The messages from this serial connection get parsed and a set of if statements help select which action to perform. The user can choose to write custom code for each if statement based on the needs and design of the robot.

The custom controller is implemented in a second python script (controller.py) in addition to the user's code. Inside this script, there are functions for listening to a specified virtual serial port, parsing the serial data, making the appropriate method calls in SEAR simulator, and then a method for returning the data back over the virtual serial port. The user must execute this file from a method call in the main userCode. Code Listing 9 is an example for a custom controller that access multiple sensors. Users can modify this template to match the specific sensor names used in their simulation and desired sensor number (between 43 and 255, extended from the Roomba protocol sensor data request commands).

This process becomes complicated when the controller attempts to send data back to the userCode. The userCode must "listen" to its serial port "publishByte" command to catch incoming messages from the controller. This "listener" method acts like an interrupt that is triggered each time it receives a byte. The userCode must wait until all of the bytes arrive before processing the data. A simple method for performing this action is used in the pair of code listings for the simulated controller and userCode examples in Code Listings 9 and 10 respectively. In this case, the user sets the expected size of the message that will be returned, and clears the message buffers before sending the request to the simulated controller. The userCode then runs a blocking method that compares the current size of the received message with the expected size. When these values are equal, the blocking method returns back to the main function. This is only one simple example of how this may be accomplished. The userCode in listing 9 is only expecting data in big endian two-byte format, though the user is free to change this to any format they wish. Users are strongly encouraged to use the userCode and simulated controller code in listings 9 and 10 respectively as templates for their custom implementations.

Debugging and testing of the simulated controller is simplest when the user appends the current file name to the print statements used within the code, making it easier to see which "thread" is printing at what time and in what order. Additionally, it was found that for many data manipulation techniques used in this type of implementation it was simpler to test the techniques in their own python scripts in MRL. For example, for combining high byte and low byte of a two-byte array.

Code listings 9 and 10 contain the simulated virtual controller code and the userCode that communicates with it respectively.

Code Listing 9: Example controller code named userCode.py

```
from time import sleep
import sys

print "\n \n executing serial send"
python.execFile("controllerTest.py") #execute the simulated
controller's code
sleep(2)

currentLength = 0
messageLength = 2
msgBuffer = list()
msgResults = list()


def sendControllerData(message):
#write a series of bytes to the serial port
        serial.write(0x8E) #0x8E = 142 decimal which is the
"Sensor request" roomba opcode
        serial.write(message)
from org.SEAR.POJOs import Cylinder
from org.SEAR.POJOs import Box
```

Code Listing 9 Continued:

```
from org.SEAR.POJOs import Cone
from org.SEAR.POJOs import model

floor = Floor("floor", 50, 50)    #create floor

#create some obstacles
box = Box("Box1_name", 0.25, 0.25, 0.25, 0)
box.move(-1.5, 1.25, 0)
box.rotate(45, 0, 0)

cyl = Cylinder("trash Can", 0.25, 0.75, 10)
cyl.move(-3, 0, -3.5)
cyl.rotate(0, 30, 30)

coneA = Cone("Traffic Cone", 0.25, 2, 10)
coneA.move(-2, 0, 0)
coneA.rotate(0, 0, 45)

tree = Model("Tree1_name","models/Tree/Tree.mesh.xml")
tree.move(0, 0, -3)

print "Done creating Environment"

def receiveMessage():

        global msgBuffer
        global messageLeng--Add “Code Listing 1 Continued” headings where required
        global currentLength
        global msgResults

        data = msg_serial_publishByte.data[0] & 0xff
        if (currentLength < messageLength): # if not the full message, then store this in our buffer
                msgBuffer.insert(currentLength, data) # fill the message buffer full of bytes.
                currentLength +=1 #increment index value

        if (currentLength == messageLength):  #otherwise, we are at the last byte in the message, clear everything and parse into short ints 10
                for i in range (0, messageLength, 2):   # for i in range(start, finish, step)

                        if msgBuffer[i] >0 :
                                msgResults.insert(i/2, (msgBuffer [i]<<8) + msgBuffer[i+1])
                        elif msgBuffer[i] <0 :
                                msgResults.insert(i/2, 256+ (msgBuffer [i]<<8) + msgBuffer[i+1])

                        else:
                                msgResults.insert(i/2, 0x00ff & msgBuffer[i+1])

```

Code Listing 9 Continued:

```
        messageLength = 0  # reset this value to 0 so the user knows when to check msgResults for values
        currentLength = 0


def waitForReply():  #this just constantly checks messageLength to see if it is 0, indicating the data has been received completely.
    global messageLength
    while(messageLength != 0):
        pass


def  clear():
    global currentLength
    global msgBuffer
    global msgResults
    msgBuffer = [0,0,0,0,0,0,0]
    msgResults = [0,0,0,0,0,0,0]
    currentLength = 0


#The below is the main function and actually calls the functions above:
sear = Runtime.createAndStart("SEAR","SEAR")

sear.startSimulation(); #start SEAR simulation
sleep(1)
roomba = Runtime.createAndStart("robot_Dynamics1","Roomba")
roomba.connect( "/dev/SEAR_Robot_01" )
roomba.startup()
roomba.control()
sleep(1)

#create a Serial service named serial
serial = Runtime.createAndStart("serial","Serial")
#connect to a serial port COM4 57600 bitrate 8 data bits 1 stop bit 0 parity
serial.connect("/dev/user_CONTROLLER_01", 9600, 8, 1, 0)

serial.addListener("publishByte", python.name, "receiveMessage")
print "listening to: "+serial.name



sleep(1)
print "Main: Requesting Sonar 1"
messageLength = 2       # set the number of bytes I expect the controller to return (1 16-bit U-ints)
sendControllerData(0x2B) # get SONAR 1 reading
waitForReply()
print "\nBack in Main, Sonar 1 value received = " + str(msgResults[0])


print "Main: Requesting Sonar 2"
```

Code Listing 9 Continued:

```
clear()
messageLength = 2       # set the number of bytes I expect the controller to return (1 16-bit U-ints)
sendControllerData(0x2C) # get SONAR 1 reading
waitForReply()
print "\nBack in Main, Sonar 2 value received = " + str(msgResults[0])


print "Main Requesting Accel"
clear()
messageLength = 6       # set the number of bytes I expect the controller to return (3 16-bit U-ints)
sendControllerData(0x2D) # get Accel readings (x, y, z)
waitForReply()
print "Back in Main, AccelX = " + str(msgResults[0]) +" AccelY = " + str(msgResults[1]) +" AccelZ = " + str(msgResults[2])


print "Main Requesting Gyro"
clear()
messageLength = 6       # set the number of bytes I expect the controller to return (3 16-bit U-ints)
sendControllerData(0x2E) # get Accel readings (x, y, z)
waitForReply()
print "Back in Main, GyroX = " + str(msgResults[0]) +" GyroY = " + str(msgResults[1]) +" GyroZ = " + str(msgResults[2])


print "Main Requesting Compass"
messageLength = 2       # set the number of bytes I expect the controller to return (3 16-bit U-ints)
sendControllerData(0x2F) # get Compass reading
waitForReply()
# The compass sensor modeled here is the simple HMC6352 in "heading" mode which will return a single value from 0-360.0 degrees in tenths of a degree (in steps of 0.5 degrees).
#Now we must divide by 10 because the HMC6352 outputs are from 0-3599 [https://www.sparkfun.com/datasheets/Components/HMC6352.pdf ]
print "Back in Main, Compass heading (out of 360 degrees) = " + str(float(msgResults[0])/10)
```

Code Listing 10: Example controller code named controller.py

```
from org.myrobotlab.serial import SerialDeviceFactory;
from org.myrobotlab.serial import VirtualSerialPort;
from org.myrobotlab.service import Serial;
import Java.lang.String;
import struct
import math

previousCodeValue=0


# this function sends int data back to the userCode over the serial connection.
def sendInt(message):
        lowByte =(message & 0x0000ff)
        highByte = ((message& 0x00ff00) >>8)
        print "Sending HighByte:" + hex(highByte)#highByte, highByte.encode('hex') #http://stackoverflow.com/questions/12214801/python-print-a-string-as-hex-bytes
        SEAR_CONTROLLER_Serial.write(highByte)
        print "Sending LowByte: " + hex(lowByte) #lowByte, lowByte.encode('hex')
        SEAR_CONTROLLER_Serial.write(lowByte)


def input():
  global previousCodeValue
  currentCodeValue =  ord(struct.pack('B', msg_serialController_publishByte.data[0])) #pack into an unsigned byte
  if currentCodeValue == 0x8E and previousCodeValue != 0x8E : #142 in decimal is the Roomba opcode for "get sensor value"
#It should be followed by a single byte stating which sensor to get the value of
#since Roomba reserves 0-42, our first sensor will start at 43 decimal and move up from there.
#this gives us a possibility of 255-42 = 213 possible different commands (sensors)
#The user must know how many bytes to expect back (how big the result of the sensor will be)
        previousCodeValue = 0x8E

  if currentCodeValue == 0x2B and  previousCodeValue == 0x8E: # 0x2B = 43 decimal which is our first sensor number.
#In here, you could request any sensor data from the SEAR simulator (specifically from
#sensors that don't have their own serial ports. For now let's try to get the PING sensor value.
#The PING sensor will return a Java float
        distance1 = sear.getDistanceResult("testPing1") #The name of this sensor on the robot is in quotes to identify it from other sonar sensors that the robot might have.
# convert the distance to cm and send as an int back over serial:
        numCentimeters =int(distance1*100)
```

Code Listing 10 Continued:

```
sendInt(int(distance1*100))

if currentCodeValue == 0x2C and  previousCodeValue == 0x8E:# 0x2C = 44 decimal which is our second sensor number.
distance2 = sear.getDistanceResult("MyNewestSONAR") #The name of this sensor on the robot is in quotes to identify it from other sonar sensors that the robot might have.
# convert the distance to cm and send as an int back over serial.
    numCentimeters =int(distance2*100)
    sendInt(int(distance2*100))


 if currentCodeValue == 0x2D and  previousCodeValue == 0x8E: # 0x2D = 45 decimal which is our third sensor number.
    accelerations = sear.getAccelResult("accel") #This results in a comma separated String containing X, Y and z respectively. We can simply parse the string to send the results.

# convert each accel axis reading to a single int and send over serial.
# SEAR's accelerometers output floats in meters/second^2. In the ADXL330 for instance, each axis responds based on a measurements of "g-forces". We can assume that on the actual hardware, the microcontroller would handle converting the analog input from the accelerometers to meters/second^2 before it sends the values back as 3 ints:  x, y, then z.
#In the ADXL330 though, 0Gs is at the midpoint of the analog output (if Vcc=3v, midpoint = 1.5volts)  This will correspond to 10-bit resolution (in an Arduino for example) of about 512.  So when an axis = 0G, the numeric value expected should be in the center of that range.
# the ADXL330 also has a 300mV/G resolution, so all of this information should be taken into account when formatting the data
    tokens = accelerations.split(',')   # Split my CSV string into individual number-strings
#from meters/sec^2 to #Gs
#number of Gs to mV/G, Make sure not to go higher than the range of the ADXL330 +-3.6Gs
#from Gs to volts (range must be shifted so 1.5volts = 0Gs)
#from volts (what the ADXL330 outputs) to ADC steps
#(an arduino with  3.3v AREF using 10-bit ADC) = 310.30303 ADC steps/volt
#send this ADC value back to MRL (userCode), so it can handle converting it to useful values for a robot or filter it, etc.

    integerAccelX = int((float(tokens[0]) /-9.8 * 0.3 + 1.5)* 310.30303)
    if integerAccelX >1023:
            integerAccelX = 1023
    #integerAccelX = int(float(tokens[0]))

    integerAccelY = int((float(tokens[1]) /-9.8 * 0.3 + 1.5)* 310.30303)


```

Code Listing 10 Continued:

```
if integerAccelY >1023:
            integerAccelY= 1023
    integerAccelZ = int((float(tokens[2]) /-9.8 * 0.3 + 1.5)* 310.30303)
    if integerAccelZ >1023:
            integerAccelZ = 1023
    print "accel ints =  "+ str(integerAccelX)+",  "+ str(integerAccelY)+",  "+ str(integerAccelZ)
    print "hex accel ints =  "+ hex(integerAccelX)+",  "+ hex(integerAccelY)+",  "+ hex(integerAccelZ)
    sendInt(integerAccelX)  # Sending X acceleration value
    sendInt(integerAccelY)  # Sending Y acceleration value
    sendInt(integerAccelZ)  # Sending Z acceleration value


 if currentCodeValue == 0x2E and  previousCodeValue == 0x8E: # 0x2E = 46 decimal which is our fourth sensor number.
    gyroReadings = sear.getGyroResult("gyro1") #SEAR's Gyro returns a CSV string of angular velocities (in radians)  Let's convert these into the nearest integer value of rad/sec
    tokens = gyroReadings.split(',')   # Split the CSV string into individual number-strings


# SEAR's Gyroscope returns values in radians / second.
# In this example, we will mimic the IDG500 (which normally has 2 axis, but we will scale all 3 the same.
#the IDG500 returns values on an analog output.  Its datasheet values are for a VCC of 3.0 volts (not 3.3)
# The value is scaled 2mv / (degree/second)  and the output at 0 = 1.35v. There are 57.2957795 degrees per radian
# If we are using an arduino with a AREF of 3.3v, that = 310.30303 ADC steps / volt

    integerGyroX = int(((float(tokens[0])*57.2957795 * 0.002)+ 1.35)*310.30303)
    integerGyroY = int(((float(tokens[1])*57.2957795 * 0.002)+ 1.35)*310.30303)
    integerGyroZ = int(((float(tokens[2])*57.2957795 * 0.002)+ 1.35)*310.30303)
    sendInt(integerGyroX)   # Sending X Gyro value
    sendInt(integerGyroY)   # Sending Y Gyro value
    sendInt(integerGyroZ)   # Sending Z Gyro value


 if currentCodeValue == 0x2F and  previousCodeValue == 0x8E: # 0x2F = 47 decimal which is our fifth sensor number.
    rawHeading = sear.getCompassResult("comp1") #The name of this sensor on the robot is in quotes to identify it from other sonar sensors that the robot might have.
#Note that SEAR returns +-180 degrees, so we must make this 0-360:
    if rawHeading < 0:
        rawHeading = rawHeading + 360


```

Code Listing 10 Continued:

```
# The compass sensor modeled here is the simple HMC6352 in "heading" mode which will return a single value from 0-360.0 degrees in tenths of a degree (in steps of 0.5 degrees). The simulated SEARcompass returns a float from 0-360.
        #We must convert the SERAcompass value to mimic the output of the HMC6352.  So we will first round to the nearest 0.5 degrees.  :
        heading = 0.5 * math.ceil(2.0 * rawHeading) #rounds to the nearest 0.5 http://stackoverflow.com/questions/9758513/how-can-i-round-up-numbers-to-the-next-half-integer
        #Now we must multiply by 10 because the HMC6352 outputs are from 0-3599 [https://www.sparkfun.com/datasheets/Components/HMC6352.pdf ]
        intHeading = int(heading*10)    #  convert this to an integer after it is multiplied, giving us a range of 0-3599
        sendInt(intHeading)      # Now send it back to the userCode on the virtual serial port


# main function code goes below here.
UARTport = "/dev/my_Controller01"
userPort = "/dev/user_CONTROLLER_01"


#Create two virtual ports for UART and user and null them together:
# create 2 virtual ports
vp0 =  VirtualSerialPort(UARTport);
vp1 =  VirtualSerialPort(userPort);

# make null modem cable ;)
VirtualSerialPort.makeNullModem(vp0, vp1);

# add virtual ports to the serial device factory
SerialDeviceFactory.add(vp0);
SerialDeviceFactory.add(vp1);

# create the UART serial service
SEAR_CONTROLLER_Serial = Runtime.createAndStart("serialController","Serial")
SEAR_CONTROLLER_Serial.connect(UARTport);

#have controller listening to userCode
SEAR_CONTROLLER_Serial.addListener("publishByte", python.name, "input")
print "user should connect to port named: "+userPort
```