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14. ABSTRACT
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NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Alexander Kernbaum	0.25
Karen Koenig	0.25
Ian chen	0.25
Gordon Kirkwood	0.25
Julie Thomas	0.25
Cindy Ziker	0.25
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1 b. Open Source Robotics Foundation
170 S. Whisman Road
Mountain View CA 94041

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Gazebo Development

Sub Contract Award Date (f-1):

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Sub Contract Award Date (f-1):

Sub Contract Est Completion Date(f-2):

Inventions (DD882)

Scientific Progress

Overall, the workshops were successful in guiding users who had no prior experience with Gazebo in designing, simulating, and building a vehicle with customized wheel profiles for climbing over obstacles, within 11 hours of instruction time. Pre- and post-tests conducted by Georgia Tech showed marked improvement in the participants' knowledge of gear trains. They also showed an understanding of the subtleties of using simulation as a design tool. Nearly all participants remarked that the simulation results were similar but not identical to the real-world trials. The majority of participants agreed that they would use a simulator again to help complete a design task. The results from the multiple choice assessment at the conclusion of the MARMC 2 workshop indicate that most students showed an improvement in content knowledge, after participating in the course. The SiMPLE program has enabled the use of complex simulation tools such as Gazebo by people without a technical background, allowing them to engage in design processes and decisions in the field.

Technology Transfer

Additions and improvements to the simulation software Gazebo have all been incorporated in to the free open source supported version hosted by Open Source Robotics Foundation.

November 28, 2016
Final Report

SIMULATION FOR MANUFACTURING AND PROTOTYPING WITH A LEARNING ENVIRONMENT (SiMPLE)

DARPA's Manufacturing Experimentation and Outreach 2 (MENTOR2) Program

SRI Project # P22581
Contract W911NF-14-2-0062

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FOREWORD

This final report details the Simulation for Manufacturing and Prototyping with a Learning Environment (SiMPLE) project (July, 2014 – September, 2016). The overall goal of MENTOR2 is to improve defense readiness by giving students and deployed personnel tools to troubleshoot, repair, and adapt complex electromechanical systems. The SiMPLE team was tasked with developing simulation and analysis software, along with exemplary online courses and kits. The team developed a progressive series of interactive online courses that cover several design tasks that require students to approach problems by using multiple representations embedded in the system. These representations include full 3D simulation, schematic views, graph views, and the construction of a physical system. Findings from a pilot study with Navy and university personnel revealed a high degree of engagement and collaboration among participants, who successfully completed the coursework and met the design challenges. The SiMPLE program has enabled the use of complex simulation tools by people without a technical background, allowing them to potentially engage in design processes and decisions in the field.

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STATEMENT OF PROBLEM STUDIED

The ability to create effective solutions to technology and mechanical breakdowns is critical in both military and civilian contexts. One challenge often encountered by in-field personnel is the need to diagnose and repair physical electro-mechanical systems under conditions where time constraints and limited resources make efficiency a priority. Preparing for such situations requires hands-on training and instructional materials that promote the necessary knowledge and skills required to debug a complex system, determine part requirements, and make tradeoff decisions. Simulation software and rapid-prototyping tools can help users to minimize design errors and miscalculations, while efficiently testing and iterating solutions to technical problems. On-line training that blends simulation prototyping with instructional support for physical, hands-on prototyping can assist with meeting this challenge.

SUMMARY OF RESULTS

As part of the Mentor 2 collaborative efforts, SRI International (SRI) was tasked with developing simulation and analysis software along with exemplary online courses and kits relevant to the design and understanding of electromechanical systems. The SRI team, in partnership with the Open Source Robotics Foundation (OSRF), proposed to develop the Simulation for Manufacturing and Prototyping with a Learning Environment (SiMPLE) Project in an effort to enhance the rapid prototyping process. The goal of this project is to enable in-field personnel to understand how to quickly repair and build physical electro-mechanical systems through participation in a scalable Massive Open Online Course (MOOC) interface that integrates a 3D robotics simulation software package that supports rapid prototyping and iterative model enhancements (Koenig & Howard, 2004), with hands-on activities. The learning goals of the MOOC include developing proficiency using 3D simulation and other technologies (e.g., 3D printers, laser cutters, and robot kits) while promoting understanding of basic core systems.

The MOOC provides instruction on how to develop simulated designs that can be translated into prototypes of physical models. The MOOC course materials and simulation software feature embedded formative assessments, a Learning Companion tool that provides feedback on student performance, and a graphing utility designed to enhance diagnosis of design flaws.

The ultimate goal of the SiMPLE project was to support the design iteration process by enabling users and in-field personnel to understand, fix and build physical electro-mechanical systems. To accomplish this goal, SRI partnered with OSRF to enhance Gazebo software, which includes a collection of analysis and simulation tools. The SRI and OSRF team enhanced an assembly-level simulation tool called Gazebo, that makes it easy to rapidly iterate system design (select electromechanical components and specify linkage dimensions, mass, kinematics, etc.) and immediately observe the effects of design decisions and changes. Design iteration is both a learning tool and a critical part of the design process, where questions are resolved through brainstorming, analysis, experimentation and testing, leading to the next set of questions in a cyclic process. The initial vision for implementing Gazebo was to augment the user’s intuition by answering design questions (e.g., How far can it go? How fast will it go? How much will it lift?), prior to building or repairing physical models.

Existing simulation environments often require significant technical expertise and are not used as learning tools, but rather as specialized tools to extend the analysis capabilities of experienced engineers. The SiMPLE Gazebo simulation and analysis environment was designed to provide novices and experts with simple-to-use tools to explore a rich library of examples, simulate complex problems, and tinker with components and systems. The MOOC provides enough instructional guidance to allow students with limited prior knowledge to learn basic skills and more experienced students to experiment with more advanced or exploratory solutions, while facilitating the transition from virtual representations to physical models. Gazebo includes a graphical drag-and-drop interface for assembling components as well as a basic CAD modeling capability with intuitive interfaces to further support rapid design and testing at a more concrete level. This enables users to construct or modify a component in real time and receive instantaneous 3D visual feedback on how these changes affect the rest of the system.

As part of the SiMPLE project, SRI developed a series of five progressive, interactive online modules and design tasks that teach students how to troubleshoot, adapt, and modify complex systems to meet new demands. These modules are described in Table 1.

Table 1: SiMPLE MOOC course descriptions

Module Title	Course Description
SIM 101: Introduction to Simulation	Describes the elements of SiMPLE and how simulation fits into the overall engineering design process
SIM 102: Introduction to Modeling	Explores more features of Gazebo, reviews basic electrical concepts, and directs the construction of a simple electric circuit
SIM 103: Introduction to System Design	Provides both mechanical simulations and physical experiments related to the impact of weight distribution on a simple vehicle
SIM 104: Design Challenges	Engages learners to employ acquired knowledge and skills in competitions designed to exemplify the use of both simulation and physical prototyping
SIM 201: Customizing a Model	Explains how Gazebo interfaces with other tools, such as laser cutters, to provide a broad range of flexibility for developing physical models

A key feature of the SiMPLE course materials is the use of multiple representations to accelerate learning. These representations include: 1) a 3D world view to enable visualization of model dynamics and interactions within the simulated world environment, 2) a schematic view that allows for easy comparisons between disparate systems, 3) a model editor view that shows the kinematics of the model, 4) a physical representation that is created using a robot kit, and 5) a graphing utility tool that provides visual representations to enhance learner diagnosis of design flaws by plotting simulation properties over time, allowing users to quickly optimize simulations and make quantitative comparisons. Figure 1 illustrates these representations and their purposes.

Gazebo enables learners to collaborate and iterate designs using a novel Component Modeling Language (CML) that allows users to create system-level functional models through an intuitive drag-and-drop graphical user interface, and to iterate designs by testing them in a 3D simulation environment. The model editor allows learners to build and simulate their models. Using this tool, learners and field personnel can explore how components function, test their designs, and modify complex systems. Once the design has gone through several iterations within the Gazebo simulation environment, the user is then able to export data files that are compatible with the other prototyping technologies (e.g., software for laser cutters and 3D printers).

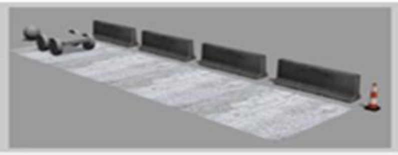
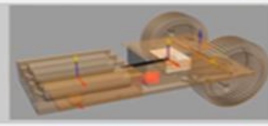
Representation Name	Image	Purpose
3D World View		• Enable visualization of model dynamics and interactions with the simulated world environment • Run the simulation in real time
Schematic View		• Present an abstract graph view of the links, components, and joint types • Allow for decomposition into subsystems • Allow for easy comparison between disparate systems
Model Editor View		• Show the kinematics of the model • Allow editing of link and joint properties
Physical System		• Experiment with the physical parts to test adequacy of simulated system • Develop hands-on manipulation skills
Graphing Utility		• Track variables over time • Optimize performance • Discover complex relationships

Figure 1. Multiple Representations used in SiMPLE.

MARMC Workshops

Two workshops were conducted at the Mid Atlantic Regional Maintenance Center (MARMC) facility in Norfolk, VA. The first workshop (MARMC 1) was held in fall of 2015 and included three 1.5 day long workshops with three groups of in-service personnel (see Project Quarterly Technical Report for October 15, 2015 for details about this event). Feedback and evaluation results provided by Georgia Tech were used to improve the workshop design, software, and MOOC content. The second workshop, MARMC 2, took place in April 2016 with adults from a variety of backgrounds (i.e., four in-service personnel, one undergraduate student, and two university faculty). Participants worked in teams of two or three to complete 20 hours of course work and design challenges, including designing wheels using laser cutters (see Figure 2). These workshops are described in detail below.

A subset of DARPA's Manufacturing Experimentation and Outreach 2(MENTOR 2) performers conducted demonstrations at the first MARMC workshop during the period of August 24th - 28th, 2015. These included SRI's SiMPLE project team, the Fab Foundation team, and the Georgia Tech team. The central objective of the demonstrations was to measure the applicability and efficiency of the innovative tools, technologies, and curriculum the performers were developing to improve the defense readiness of military personnel in troubleshooting, repairing, and adapting complex electromechanical systems in austere environmentsThe demonstrations were divided into three 12-hour-long sessions. Each session had three workshops running simultaneously by three performers. At the end of the three sessions, all participants had attended each of three performers' workshops.

Three SiMPLE team members traveled to Norfolk to deliver the three workshops. While formal study results were being collected and analyzed by the Georgia Tech evaluation team, the SiMPLE team was able to gather substantial feedback from users about the content of the courses, the usability of the kits, and their interactions with the Gazebo interface.

It was very important for the team to see first-hand how trainees interacted with the simulator. Gazebo has been developed for over 10 years as a tool for professional roboticists, most of whom have a programming background. MENTOR2 represents a new use of simulation (for understanding, debugging, and modifying electromechanical systems) and serves a new user group (military trainees with no background in simulation or robotics).

Overall, the MARMC 1 workshop was successful in guiding users who had no prior experience with Gazebo in designing, simulating, and building a vehicle with customized wheel profiles for climbing over obstacles, within 11 hours of instruction time. Feedback on the usability of the simulator varied from very positive ("This program is really user-friendly; it took me a month to learn MasterCam.") to very negative (without an undo function, a few users got so frustrated trying to position model parts together that they gave up). The SiMPLE team generated a comprehensive list of specific issues that were prioritized and added as ticketed issues to the formal development pipeline for Gazebo and the specialized MENTOR2 branch of Gazebo. Before each workshop began, pre-surveys with multiple-choice questions were distributed to measure the participants' knowledge specific to the workshop curriculum. The post-surveys distributed after the workshops had the same multiple-choice questions along with open-ended questions to collect participants' prior experience and feedback on the workshop. By comparing the answers to pre and post survey multiple-choice questions, the team drew conclusions about how effectively the workshops met their objectives.

Georgia Tech developed evaluation instruments, including a pre-post survey, to measure the success of the workshops. The answers to SRI, Georgia Tech, and Fab Foundation Pre/Post survey multiple-choice questions (Appendix B) show a trend of improvement in understanding the concepts after the workshop. Most of the SRI questions were focused on gear ratios. The open-ended pre and post questions for SRI are shown in Appendix C. The pre-survey answers revealed that about 60% of the participants had used some form of a simulator (Pre Q-8), so most of them had an idea of what a simulator does (Pre Q-9). Also, almost all of the participants had an idea of the types of components in an electric car (Pre Q-7). At the end of the workshop, participants were asked if the simulators always performed as expected (Post Q-15), and most of the participants pointed out that even though the results were close, there were some areas where results did not match the physics, especially for the inertial calculations.

When participants were asked which part of the simulator was most useful to them (Post Q-16), almost all agreed that figuring out appropriate gear ratios for the model was the most helpful function of the simulator, which is consistent with the improvement in gear-ratios related understanding, before and after workshops as measured by the multiple-choice surveys. When participants were asked which part of the simulator was least useful to them (Post Q-17), participants answered in terms of challenges they faced while using the simulator, which included difficulty in using the interface, "inability to make two moving models interact as desired." However, one participant said that rather than using the simulator, he preferred "narrowing down to least likely solution." Participants also gave some constructive suggestions on improvements to the Gazebo interface and physical assembly of the kit (Post – Q19 and Post Q-20 respectively).

The majority of the participants agreed that they would use simulator again to build a mechanism (Post – Q7). The reasons were varied; they suggested that simulation would help reduce overall cycle time, gain the understanding of the theoretical concepts, help identify and resolve the failures in a system, and economize the testing. Figure 2 shows selected results of a survey administered by Georgia Tech.

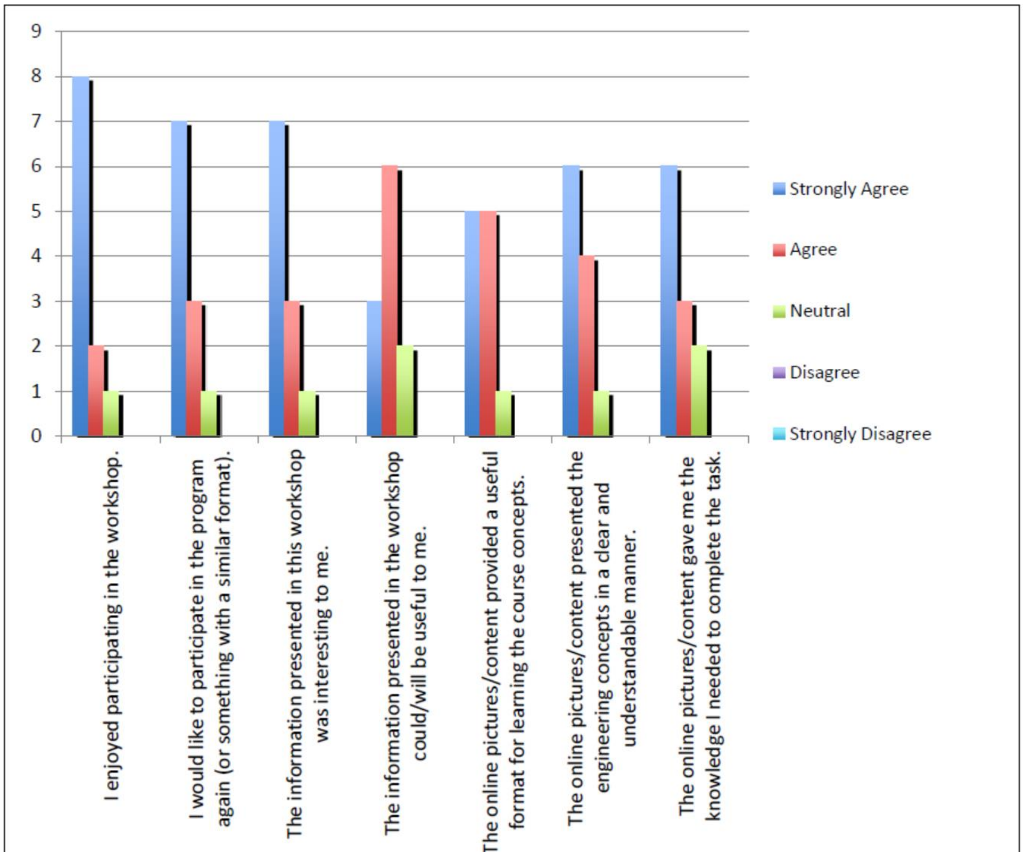


Figure 9:: SRI workshop Satisfaction Survey

Figure 2. Satisfaction survey taken by Georgia Tech (Figure from Georgia Tech's Evaluation Report, 9 October 2015).

In response to user feedback during internal testing at SRI and at the first MARMC workshop, several new Gazebo enhancements were implemented to make it easier for a user to create and edit models. The first of these enhancements was created to allow the user to easily delete wiring connections between electronic components in the Model Editor. While editing a model with electrical wiring connections, the user can now right-click on a connection and select a Delete option from a new context menu. The same gesture was added to Schematic View, as it is a logical place to view and edit electrical models. Wire deletions in either view are rendered correctly in the other view, as expected.

Another Gazebo feature was added to allow the user to select a density for a newly created model. While inspecting a model with the Link Inspector, the user is presented with a pull-down menu that contains selections for several commonly used materials (e.g., aluminum, plastic, Styrofoam, stainless steel, wood, etc.). Selecting a material from the list will automatically set the model's mass and inertial properties based on the density of the selected material. This user interface also allows for the entry of custom density values. Presets for simple shapes were also added to the Model Editor, allowing the user to select from several pre-defined shapes when creating a new model. The new common shapes include 1-cm, 10-cm, and 1-m cubes.

Improvements to Gazebo

Over the course of the MARMC 1 testing, we carefully tracked issues relating to the MOOC that made it difficult for the students to progress. Table 2 is a summary of the highest priority issues and how they have since been addressed.

Table 2: Summary of highest priority Gazebo improvements, as identified by MARMC testing

Priority	Title	Description
1	Reset	Make Reset World effective immediately. Support resetting model to previous states. Update Reset label in the time panel.
2	Align Tool	Redesign and merge functionality with the Snap tool.
3	Undo	Support Undo in simulation and Model Editor modes.
4	Wiring	Support deletion. Move Wire tool to toolbar.
5	Separate Modes	Update Model Editor visualization so that it is distinguishable from Simulation mode.
6	Presets	Add presets for simple shape sizes and link densities.
7	Units	Add gearbox efficiency unit and range.
8	Nested Models	Implement remaining GUI features. Support inserting database models in editor.

After MARMC 1 testing, the SiMPLE team initiated a validation study to quantify the correspondence between the simulated ground vehicle and the physical kit vehicle (see Appendix A and Project Quarterly Technical Report • 15 October 2015 Covering the period 5 June 2014 – 5 September 2015, pgs. 14-19). This study is intended to better inform the SiMPLE team, MENTOR2 program, and future users and trainees about the realism and reliability of this type of rapid simulation for testing design options. For example, is the gear ratio that enables the simulated car to reach the top of the ramp in Gazebo the same ratio that will work in real life? What assumptions are being made? How far can the simulation be trusted?

Trainees and engineers need a good understanding of the capabilities and limitations of any physical, analytical, or computer-based tool they use. For example, a hand calculation using the motor constants, gear ratio, battery size, and geometry of a wheel would allow you to figure out the amount of torque a car wheel will generate when the car is turned on. An experienced engineer or designer would be able to explain the limitations of this calculation: it does not account for friction in the construction of the mechanisms, time-varying electrical responses, heat, etc. So, if the physical car generated a measured torque that was 20% lower than the calculated value, it would not be surprising.

Engineers and designers also need to understand the range of parameters that apply to the model. For example, an experienced engineer would not use the same equation to calculate the size of the battery needed to generate 1000 Nm of torque with all other components remaining the same, because the equation would not account for the side effects of such a high current, such as melting the insulation on the motor coils.

Using a simulation tool to solve early-stage design problems and for training purposes provides two primary advantages.

1) The simulator can help calculate the value of parameters within the system (e.g., appropriate gear ratio).

   For this application, numerical correspondence is important, and our validation study aims to quantify how closely simulation results match reality. This validated correspondence verifies that the simulator is a reliable tool for evaluating design changes before implementation. This application benefits from working with somewhat fixed models of existing systems, which users can download and modify to validate proposed changes.

2) The simulator can illustrate and explain the relationship between a given parameter and a high-level system behavior (e.g., how a vehicle's ability to climb a ramp varies with gear ratio).

   This objective positions the simulator as a training tool for developing users' intuition about system behaviors. Rather than relying on an exact numerical correspondence between simulation results and real-world behaviors, this application requires a simulation model to support a large range of valid parameters so that users can see the relationships between specific parameter values and the resulting model behaviors.

   This application emphasizes the development of modeling tools that allow users to quickly and easily construct their own system models, while Charting and graphing tools allow for visualizing the relationships between parameters and system outcomes.

The validation study was inspired by one of the trainees at the MARMC 1 workshop. He was very intent on testing the car within Gazebo and documenting the results to optimize different parameters of the vehicle. While some students were content with any gear ratio value that got the car up the ramp, this student tested all the values and documented the time it took the model vehicle to reach the top of the ramp before he selected the optimal gear ratio, which yielded the fastest ascent while generating enough torque. He used a spreadsheet program on the laptop to document various simulation runs and generate performance curves (see Figure 3).

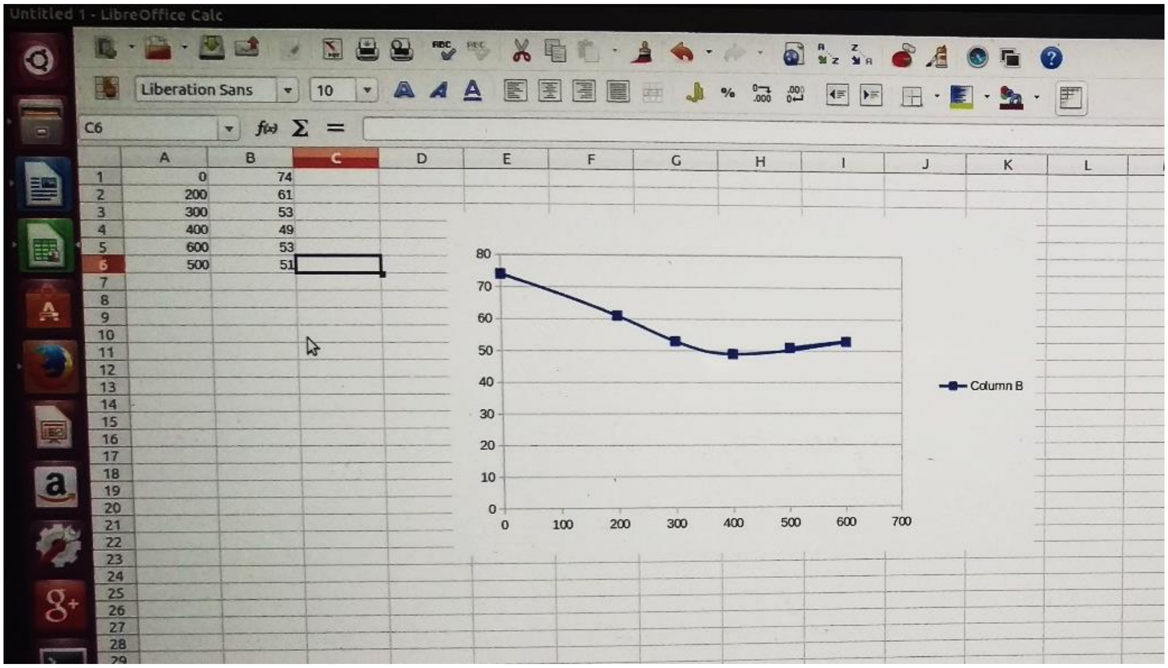


Figure 3. One participant took it upon himself to graph a parameter he wanted to optimize, such as the time it takes for the car to go up an incline, relative to the gear ratio.

Learning Companion Updates

At the time of the MARMC 1 workshop, the infrastructure of the Learning Companion (LC) was complete but its implementation was limited. The LC displayed information from Gazebo on our Canvas (online host) MOOC pages, but it did not change the content or provide critical information to the student. For the second MARMC workshop, new features were added to the Learning Companion to improve its effectiveness. These include features that support user monitoring and feedback such as, "You haven't used this feature yet, but it could be useful…" and "Maybe you should revisit this tutorial (reference)." Programming the Learning Companion can be a challenging problem. At its best, it involves deep learning of what students are attempting to do, and why they are not succeeding. This kind of solution would be a DARPA-hard program in its own right. Instead, we focused on a specific case to help the student gain a deeper understanding. The case of the hill-climbing robot generally poses two failure modes: the wheels slip, preventing the robot from climbing, or the wheels do not have enough torque to climb the hill. It may be hard for many students to detect what is happening, and how to differentiate these two similar failure modes. However, both of these conditions can be detected within Gazebo. Based on this, the Learning Companion can offer specific advice, and more importantly, teach the student the causes of these two failure modes and how they are connected.

One activity prompts students to choose a gear ratio and a weight distribution to optimize their vehicle's performance in a range of tasks, such as hill climbing and tug-of-war. In these cases, two common failure modes are sometimes difficult to distinguish: the vehicle may not have enough torque to get up the hill, or it has enough torque, but the wheels slip. In both cases, the vehicle stops moving forward. We built a module inside Gazebo that has access to detailed information about the state of the model. It can detect if the wheels are slipping or if the motor is stalled. This information is sent via the Learning Companion infrastructure to the MOOC, where it prompts the student to consider fixes. The response it provides depends on a range of variables, including how many times the student tries the experiment. For instance, a first response might be, “It looks like your car didn’t get up the hill. Can you use the graphing utility to see if the wheels are slipping?” After another try, it suggests, “It looks like your wheels are not slipping, but maybe you don’t have enough torque to move up the hill. You can revisit the course material to look at ways of addressing this.” The LC provides a link to specific content inside the MOOC.

Gazebo Development: Graphing Utility

Gazebo simulations provide rich, quantified data about how models are behaving in simulation. However, at our first MARMC trial, it was challenging to quickly access and analyze this data to help optimize a design. As noted above, in one instance, a participant at MARMC used a common spreadsheet program to graph the results of several simulations (Figure 2.1), clearly showing that the optimal gear ratio (X-axis) in this case is around 40:1 to minimize the time to complete the task (Y-axis).

We added a new real-time graphing utility to Gazebo that can perform this kind of analysis. The graphing utility allows the user to:

- Select useful numerical data and add them to a plot
- Save the plot and/or the data
- Compare different trials quickly to find trends
- Extract numerical data from plotted curves.

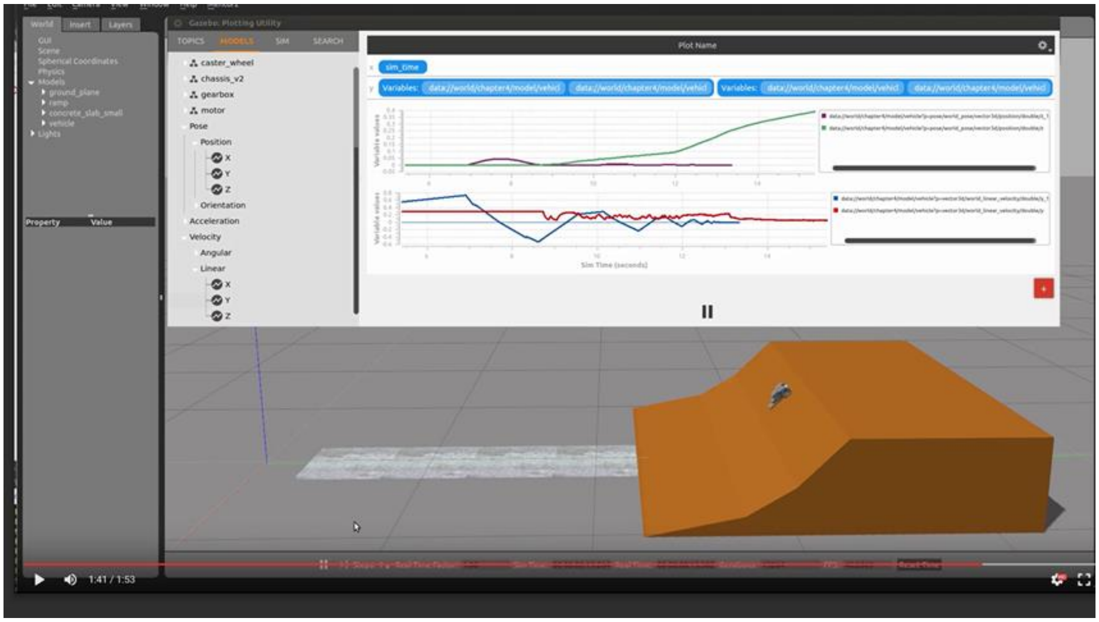


Figure 4. The new graphing utility plots multiple hill-climbing simulations for comparison. The green and red trial outperforms the previous trial (purple and blue). Comparing wheel rotation to forward motion can help diagnose wheel slip problems

Gazebo Development: Model Editor Undo/Redo

Undo/Redo are surprisingly complex commands in Gazebo. They must have different functions depending on how the user is interacting with the software. Broadly, these can be broken down into Simulation Undo/Redo and Model Builder Undo/Redo.

When running the simulation (i.e., dynamics are changing), users can now undo and redo the following types of user commands:

Move commands change the pose of models in simulation:

1. Translate
2. Rotate
3. Snap (snaps one model to another by aligning their faces)
4. Align (align by model bounding box)

Reset commands reset different aspects of the world to a previous state:

1. Reset world (reset entire state)
2. Reset model poses
3. Reset time

Apply Force Torque commands are associated with those that apply external force and/or torque to links via the Apply Force Torque Dialog.

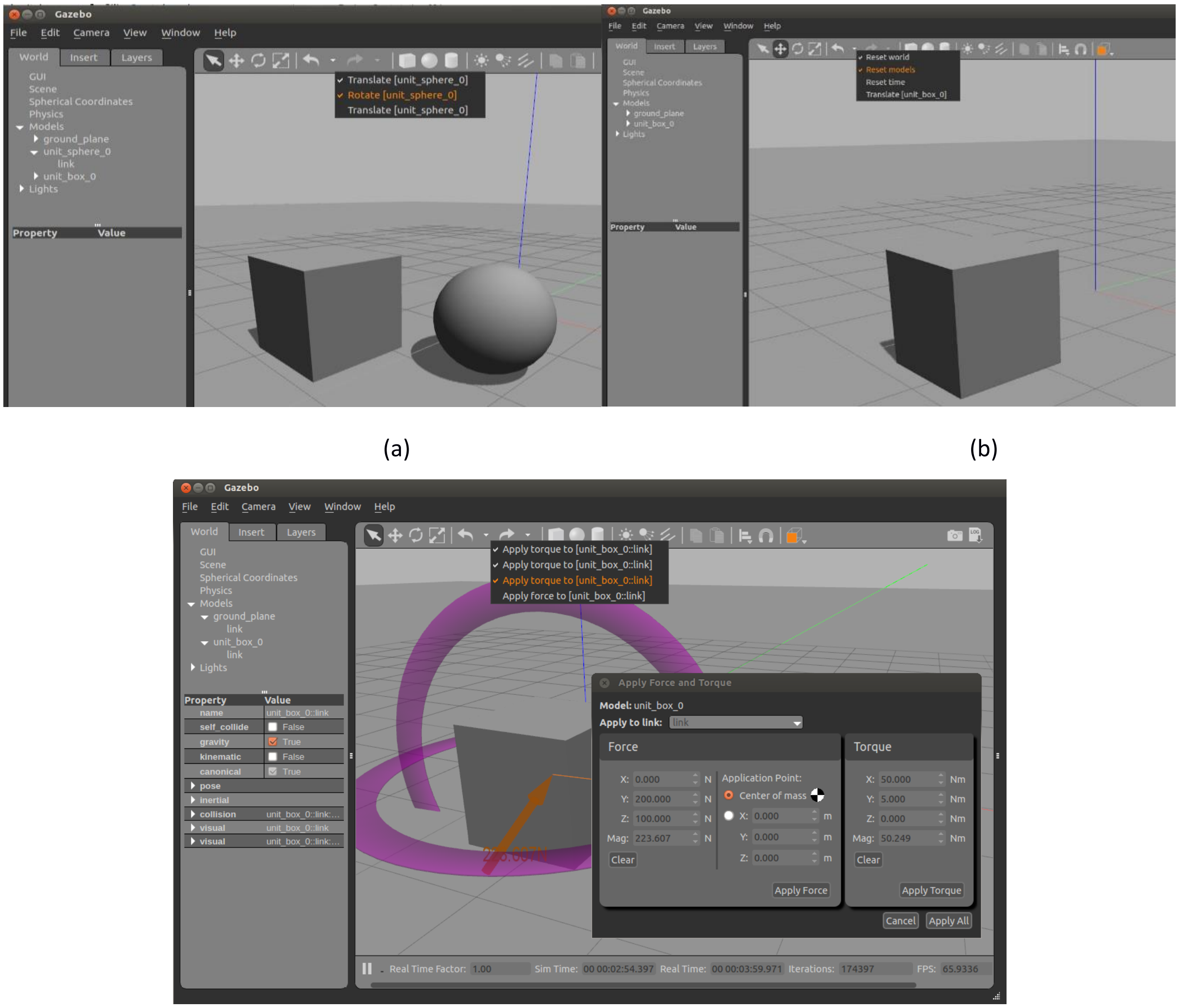
The Undo and Redo features in simulation take a key frame-based approach, where the state of the world is saved when a user action occurs. The server keeps a history of these undo commands in a stack that get popped off every time the user clicks on Undo. The commands that were undone are pushed to the Redo stack and become available as redo actions to the user. Since Undo works by restoring the world to a previous state, time is also rewound and the dynamic properties of bodies in the world are also reset, keeping everything consistent with the state they were in before.

The undo/redo implementation for the Model Editor differs in a number of ways compared to its counterpart in normal simulation mode. As the Model Editor is a client-only feature (no physics server is needed), the implementation does not involve communication with the server over the network. Instead of adopting a key frame-based approach for keeping track of simulation states, a local Model Editor Command manager stores every user command and the state of the entity the user is interacting with in the Model Editor. Whenever an undo or redo action is triggered, the manager executes an event that restores the state of the associated entity. Despite these differences, the user interaction is no different from undo/redo in normal simulation mode. The functionality is accessible in the toolbar and from the Edit menu.

The following user commands in the model editor can be undone/redone:

- Translation and rotation (nested models and links)
- Insertion / deletion (nested models, links, joints, and model plugins)
- Scale (links)
- Snap (nested models and links)
- Align (nested models and links)

Undo and Redo buttons were added to the Gazebo toolbar. Each button has its own sub-menu displaying a history of undo or redo commands. Figure 5 shows screenshots of Gazebo with the three different types of user commands described above.



(a) (b)

(c)

Figure 5. (a) Undo and Redo buttons in the Gazebo toolbar showing a sub-menu with entries for Move commands. (b) Undo menu with entries for Reset commands. (c) The Undo menu in the top toolbar lists a history of Apply Force/Torque commands that are sent by the Apply Force/Torque dialog on the bottom right.

New MOOC Content to Support New Tools

The Graphing Utility was a completely new tool for Gazebo. For students to be able to use it effectively, we incorporated new course content throughout the MOOC series. SIM 102 introduces the basic functionality by having the student graph the motion of a cylinder rolling down a ramp. The students learn how to select variable names from object properties and drag them to the graphing utility window. In SIM 103, the students learn how to extract data from graphs and compare multiple simulation trials to optimize the model vehicle to meet challenge goals. Students without a background in physics or mathematics can find it challenging to understand the basic principles of graphing, and concepts such as translation, velocity, and acceleration. We address all these concepts in the MOOC, and reinforce them with exercises and review quizzes. SIM 104 is less structured, and it builds on the skills and knowledge gained in the previous courses while suggesting using the Graphing Utility for model optimization and design.

SIM 201: In the first MARMC trials this course was in ‘beta.’ This revision includes detailed information about using third-party software (Inkscape and CorelDraw) to create custom shapes. Additional lessons allow students to integrate the custom drawings into Gazebo models for simulation. Further information discusses the preparation of a laser cutter to fabricate physical prototype components for testing.

Internal Review of all Course Material

In late May, SRI and OSRF conducted a full dry run of the workshop materials for MARMC. We recruited four students, employees of SRI with no previous experience with Gazebo. Two of the participants had previous experience with CAD software and two did not. Over the course of three days, they took the entire SiMPLE series while instructors took notes and provided assistance as needed. This realistic testing environment highlighted several areas of the MOOCs that needed clarification, and some lingering bugs in Gazebo relating to the new features. Updates to Gazebo and the MOOCs addressed most of these issues, prior to MARMC 2.

MARMC 2 included eleven participants, who worked in teams of two or three to complete 20 hours of course work and design challenges, including designing wheels using laser cutters (see Figure 5). The MOOC included embedded assessments that were completed by each team at the end of SIM 102 and SIM 103. The MOOC course materials and software include features designed to support learning of physical electromechanical systems through a Learning Companion tool that provides guidance based on user performance. SRI’s vision for this feature was to create an infrastructure through which information could be sent from Gazebo to the MOOC host (Canvas) where it would display diagnostic feedback to users. For example, in the case of the hill-climbing robot, there are generally two failure modes: the wheels slip, preventing the robot from climbing up, or the wheels do not have enough torque to climb the hill. It may be hard for many students to detect what is happening, and how to differentiate these two similar failure modes. However, both of these conditions can be detected internally within Gazebo easily. Based on this, the Learning Companion can offer specific advice by displaying feedback, and more importantly, teach the student the causes of these two failure modes and how they are connected.

The Graphing Utility we developed is a completely new tool for Gazebo. For students to be able to use it effectively, new course content was generated throughout the MOOC series. For example, in Sim 102 we introduced the basic functionality of the Graphing Utility by having students graph the motion of a cylinder rolling down a ramp. A video was included in the MOOC that shows students how to select variable names from object properties and drag them into the graphing utility window. In Sim 103, the instructional material was created to help students learn how to compare multiple simulation trials to optimize their vehicle for the task at hand.

For students without prior background in physics or mathematics, it can be challenging to understand basic principles of graphing and concepts such as translation, velocity, and acceleration. We addressed these concepts in the MOOC and reinforced them with exercises and embedded formative assessments. These “knowledge checks” were developed to provide auto-generated feedback and targeted key concepts that were presented during MOOC activities. The assessments were designed to be completed collaboratively, as the users worked in pairs during instruction. Results of the assessments were made available through the Canvas dashboard under the “Grades” tab.

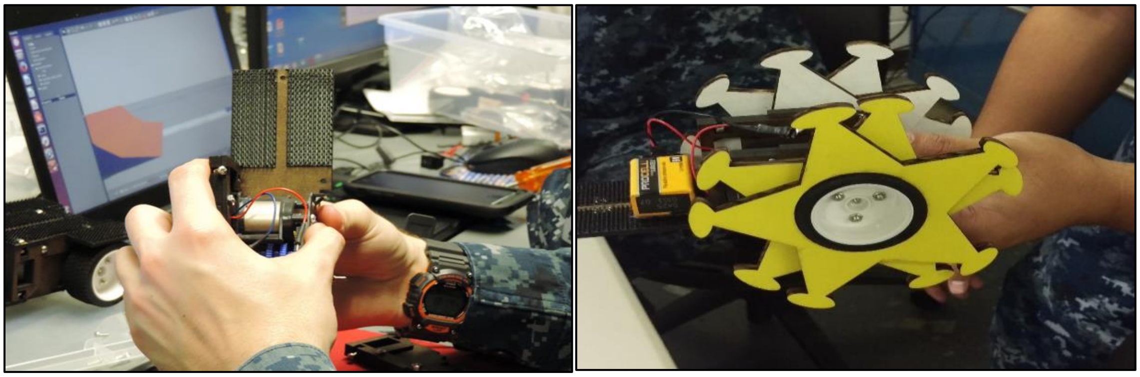


Figure 6. MARMC 2 Workshop Activities, April 2016.

All participants successfully completed the coursework, embedded assessments, and design challenges. Observations revealed a high degree of engagement and collaboration among participants. Feedback from participants was positive. Participants stated that the SRI workshop was very engaging and enjoyed the use of simulation during the design challenges. For example, one participant stated “Personally the SRI simulation workshop was the best learning experience for me.”

Results from a pre- and post-assessment of thirteen items related to course content that were completed by seven participants, revealed improvements in learner performance after completion of the course (see Figure 7). Similar to the MARMC1 testing, Georgia Tech collected extensive feedback and conducted comprehension tests. At the time of this publication, detailed feedback has not been provided by Georgia Tech to SRI. Please see Georgia Tech’s final Mentor2 report for this information.

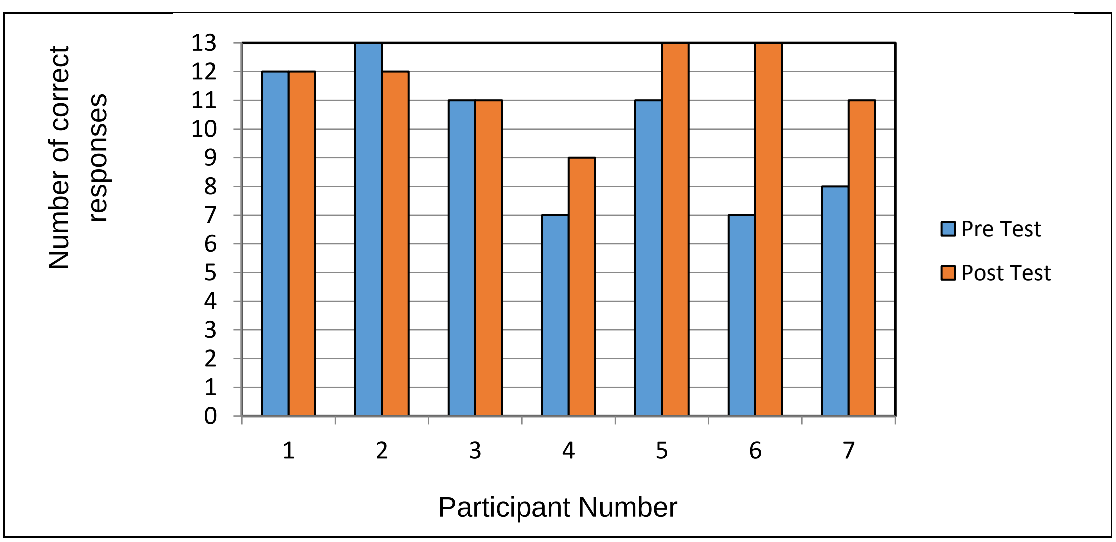


Figure 7. Pre- and post-assessment results from MARMC 2.

Demonstrations and Presentations

The SiMPLE project team participated in a DARPA Showcase on July 15, 2016, that included a demonstration of the simulation tools, the MOOC and the robots. Hands-on activities included interacting with the simulation software and testing the robotic rovers during design challenges. A presentation that included an overview of the project was presented on September 6th, 2016 in Paris, France at the 25th International Academic Conference of the International Institute of the Economic and Social Sciences (http://www.iises.net/proceedings/25th-international-academic-conference-oecd-paris/table-of-content/detail?article=intelligent-coaching-systems-in-higher-order-applications-lessons-from-automated-content-creation-bottlenecks). Features of the project and examples of the assessment tools will also appear in a publication to be published in 2017 by Springer entitled “Design Patterns for Assessing Model-Based Reasoning.”

CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

Overall, the workshops were successful in guiding users who had no prior experience with Gazebo in designing, simulating, and building a vehicle with customized wheel profiles for climbing over obstacles, within 11 hours of instruction time. Pre- and post-tests conducted by Georgia Tech showed marked improvement in the participants’ knowledge of gear trains. They also showed an understanding of the subtleties of using simulation as a design tool. Nearly all participants remarked that the simulation results were similar but not identical to the real-world trials. The majority of participants agreed that they would use a simulator again to help complete a design task. The results from the multiple choice assessment at the conclusion of the MARMC 2 workshop indicate that most students showed an improvement in content knowledge, after participating in the course. The SiMPLE program has enabled the use of complex simulation tools such as Gazebo by people without a technical background, allowing them to engage in design processes and decisions in the field.

The SiMPLE Team completed all tasks and submitted all deliverables (see Appendix D for a full list). Future efforts that will advance the work of the SiMPLE project include leveraging the Gazebo back-end to collect additional data on user behaviors; enhancing the learning companion tool; integrating with a cloud-based modeling and simulation environment to enable rapid deployment; and developing additional open-ended advanced courses that can extend learning in many professional settings.

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APPENDIX A: SIMULATION VALIDATION STUDY

In Gazebo, each component of a mechanical assembly has many physical properties that must be specified. For example, if a user creates a cube in Gazebo, the simulator needs to know the length of one side and the cube's material properties (mass, density, coefficients of static friction with other materials, coefficients of kinetic friction against other materials, and moments of inertia). A complex mechanical assembly consisting of many parts that interact with one another and with the environment includes thousands of properties, some of which need to be specified and others that are assumed. If any one of these variables deviates from the real-world model for any period of time during a simulation, the resulting simulated behavior will differ from the behavior that would occur in the real world.

In the initial vehicle validation study, we compared how long it took a physical car to travel five meters to a simulation model of that car traveling five meters. As shown in Figure A-1, differences in one or more properties of the physical car's motor, battery, gearbox, or wheels from the simulated vehicle properties cause the simulated time to travel five meters and the actual time to travel five meters to appear greater for the higher ratio physical gearbox. This difference may not be related to a property of the gearbox at all; it could be a discrepancy that varies with the total time of travel. Because a high-ratio gearbox results in a longer travel time, the difference between simulated travel time and real travel time is greater for a high-ratio gearbox than for a low-ratio gearbox.

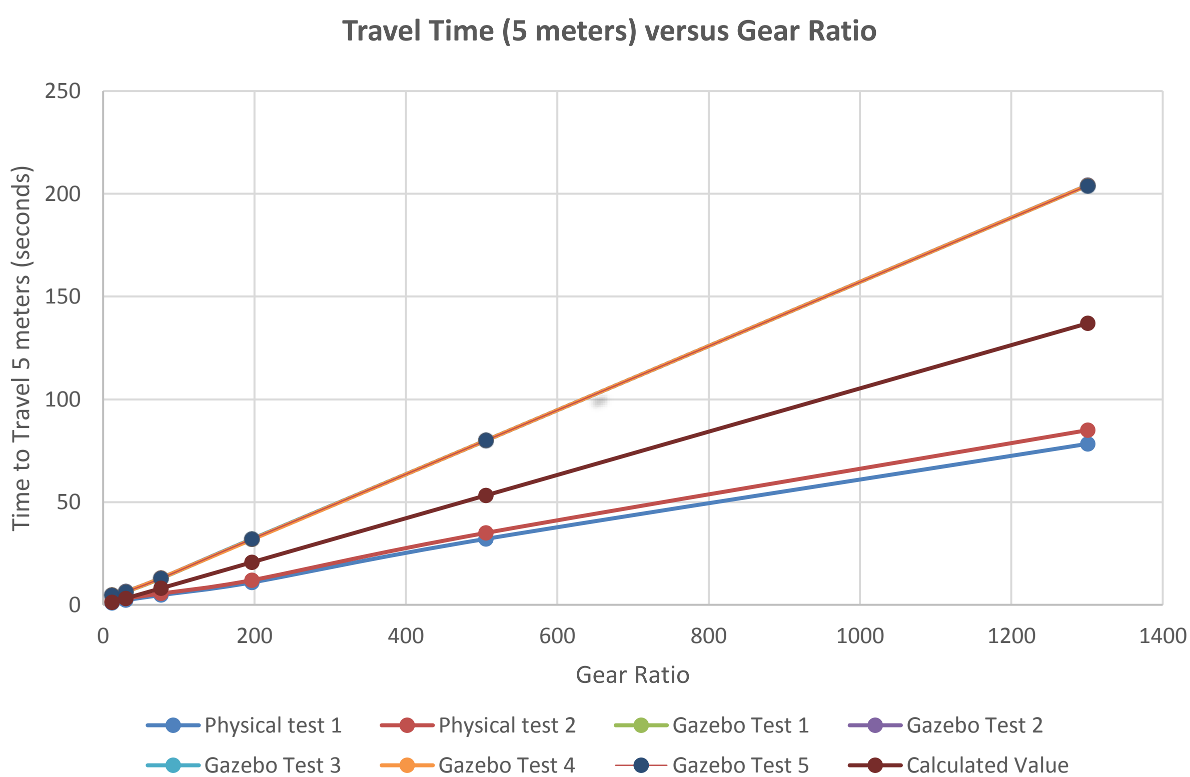

Figure A-1. Initial vehicle simulation validation test results, comparing several Gazebo trials (overlapping lines), hand calculated times, and physical car tests (two trials shown).

The Gazebo properties used for the validation study for the motor, battery, wheels, and gearbox are described below.

The motor used in the vehicle is a Mabuchi RE-260RA-2295, and the properties in Table A-1 were found in its datasheet. However, the parameters given in the datasheet are those when the motor is operating at 3 V, and we are powering the motor in our vehicle with a 9 V battery. The only parameter that this directly affects is the motor's no-load speed, which had to be measured with a shaft encoder. The changes in the rest of the values had little-to-no effect on how we characterized the motor for simulation, as the only motor parameters that can be input into Gazebo are torque constant, back emf, and motor resistance.

Table A-1: Motor properties

Model	Voltage		No Load		Max Efficiency				Stall	
	Operating Range	Nominal	Speed @ 9V(rpm)	Current (A)	Speed (r/min)	Current (A)	Torque (mN*m)	Power output (W)	Torque (mN*m)	Current (A)
RE-260RA-2295	1.5-4.5	3V	16800	0.15	7610	0.64	1.31	1.04	6.86	2.7

	From max efficiency	From stall	
k_t (torque constant)	0.002046875	0.002540740741	k_t = torque/current
Resistance (ohms)	4.2		
V_emf	8.37		
Back EMF (for Gazebo)	0.63	Back EMF assuming no load conditions	0.004757736295

Battery properties (Table A-2) were taken from the Energizer 522 9V Battery datasheet.

Table A-2: Battery properties

Voltage (V)	9.00E+00
Max current (amp)	5.65E-01

The coefficient of static friction between the wheels and Masonite is a constant that describes the friction between the wheels and the racing field when there is no slipping. The coefficient of kinetic friction between the wheels and Masonite is a constant that describes the friction between the wheels and the racing field when there is slipping. Friction between the wheels and the ground depends on the coefficients of friction and the normal force between the wheels and the ground (i.e., the mass of the car and the force of gravity). The values listed in Table A-3 for the coefficients of static and kinetic friction were measured using a force gauge and a physical model of the car.

Table A-3: Wheel properties

Diameter	0.054
Rolling friction	0.001
Coefficient of friction on Masonite	mu_static = 0.74
	mu_kinetic = 1

Gearbox efficiency (Table A-4) is a measure of how much energy is lost to friction, heat, etc. in the gearbox. The gearbox efficiency values were calculated based on known typical efficiency values for spur gears and the number of stages of each gearbox.

Table A-4: Gearbox efficiency

Gear Ratio	Efficiency
11.6	0.9216
29.8	0.8154
76.5	0.8493
196.7	0.8154
505.9	0.7827
1300.9	0.7514

Moment of inertia is a property of rigid bodies that relates torque with angular acceleration in the form $\tau = I\alpha$ in which τ is torque, I is moment of inertia, and α is angular acceleration. An object's moment of inertia describes how the vehicle behaves when torque is applied. The moments of inertia listed in the table are values that were calculated by Solidworks, a 3D modeling and analysis program, from the 3D models of the vehicle components.

Table A-5: Moments of inertia

	Moments of Inertia (kg*m^2)						
Part	**ixx**	**ixy**	**iyy**	**iyz**	**izz**	**ixz**	**Mass (kg)**
Chassis	0.00026481	0	0.00023092	-0.00008387	0.00013298	0	0.09250981
Gearbox	0.00003724	0	0.00003192	-0.00000318	0.00002236	0	0.0659059
Battery	3.69E-06	0.00E+00	3.40E-05	0.00E+00	3.69E-06	1.87E-08	0.0461811
Wheels+axle	2.05E-05	0	9.61E-05	0	9.61E-05	0	0.0517414
Motor body	0	0	3.82E-07	0	3.82E-07	0	0.0294
Caster wheel	9.20E-07	0	4.32E-07	0	9.17E-07	0	9.4
Switch	-1.96E-07	0	3.84E-07	0	4.53E-07		0.0046742
Assembly	0.000792	-3.32E-06	0.000809	-0.000206	0.000323	2.25E-06	0.276

The test results clearly indicate that simulation is a useful tool for gaining mechanical intuition. It is much faster to run a series of tests in simulation to discover the effects varying a particular property has on the behavior of the system than it is to run these tests in the real world.

Increasing the gear ratio can result in requiring a longer time for the car to travel five meters. To discover the effect of varying the motor's back EMF, you can change the property in Gazebo, keeping all other parameters constant, and run the simulation again to find out more about the relationship between the car motor's back EMF and speed of travel.

The validation study also shows that Gazebo is less effective for exactly determining a system's resulting behavior; however, it is useful for approximating a system's behavior and for observing behavioral trends as different parameters and properties of the system are varied.

APPENDIX B: MARMC 1 PRE-POST MULTIPLE CHOICE SURVEY RESULTS

Table B2: SRI Pre and Post multiple-choice answers (correct answers highlighted in green)

Q1. If two similar vehicles that differ only in their gear ratios are stopped on a ramp, which one has a better chance of making it up the ramp?	**SRIPost**	**SRIPre**	
The vehicle with a higher gear ratio (more speed reduction between the motor and wheels)	82%	45%	↑
The vehicle with a lower gear ratio (less speed reduction between the motor and the wheels)	18%	58%	
Q2. If two similar vehicles that differ only in their gear ratios are started from a stop, which one will accelerate faster?	**SRIPost**	**SRIPre**	
The vehicle with a higher gear ratio (more speed reduction between the motor and wheels)	36%	42%	↓
The vehicle with the lower gear ratio (less speed reduction between the motor and wheels)	64%	33%	
There will be no difference in acceleration.		17%	
Guess		8%	
Q3. If two similar vehicles that differ only in their gear ratios are started from a stop, which one will have a higher top speed?	**SRIPost**	**SRIPre**	
The vehicle with the higher gear ratio (more speed reduction between the motor and wheels)	9%	50%	
The vehicle with the lower gear ratio (less speed reduction between the motor and wheels)	73%	33%	↑
They will have the same top speed	18%	17%	
Q4. What is a reasonable gear ratio for a small electric toy car?	**SRIPost**	**SRIPre**	
3:1	18%		
30:1	18%	17%	↑
300:1	27%	17%	↑
3000:1	27%		
Guess	9%	67%	
Q5. In a full-size car with a manual transmission, how does first gear compare to third gear?	**SRIPost**	**SRIPre**	
First gear has a higher gear ratio between the engine and the wheels	73%	58%	↑
First gear has a lower gear ratio between the engine and the wheels	27%	42%	

Table B3: SRI Pre and Post multiple-choice answers (continued..)

Q6. When loading weight on a car that will be driven up a steep ramp, where should you put the weight?	**SRIPost**	**SRIPre**	
As far forward in the car as possible	9%	17%	
At the far back of the car	9%	17%	
Directly over the drive wheels	9%	17%	
Slightly in front of the drive wheels	73%	42%	↑
Guess		8%	

APPENDIX C: MARMC 1 OPEN ENDED SURVEY RESULTS

Table C1: SRI Pre and Post open-ended survey

No.	Pre	No.	Post
7	**What basic subsystems or components would you expect to find in an electric car?**	**7**	**Would you use a simulator when building a mechanism? Why or why not?**
	electric motor, battery, controlling unit, braking system		I would. It eliminates the consumption going back and forth. Assembling and disassembling equipment.
	battery, alternator		To test theory. also to see what can be done to maximize potential
	motor, power source, drive train, wheels, mini transition, some sort of aesthetic body parts		yes, to get a visual of the system and identify potential failures
	battery, alternator, ac, radio, cooling system, brake lines, power steering		yes, so I can see what works before wasting materials
	motor, drive train, battery, wheels		Yes. Especially really a larger, more expensive machine. If the simulator wasn't exactly accurate it still helps give an idea of what to do next.
	Drive motor, gears, chassis, wheels/tires		yes, if I was proficient in the simulator
	not sure		Depending on the cost/time constraints I would not use a simulator. For something small, like the project, making changes and testing is done rapidly w/o the use of a simulator. more complex projects with funding would require simulators
	Transmitter battery wires tires axels other stuff		yes because it saves time building it on the computer then less time building car by hand
	Power (battery) Power distribution Motor Transmission/gearing Wheels/Tires Frame/Body Steering RF/Control Receiving		yes as it is more safe to test virtually
	Frame, Wheels, motor, gears		yes, less man hours at motors and explained in the virtual environment
	electric motor, gear system, drive train		To test before physical build i.e. to fail faster

Table C1: SRI Pre and Post open-ended survey (continued..)

8	**Have you ever used a simulator before? If so, what simulator and what did you use it for?**	**8**	**What does the Pause/Play button do in a simulator?**
	no		Pause gives a brief pause to the test. Play simulates actual test.
	no		apply real life movements to items in the simulator
	Flight combat simulators, video games		Stop/start the sim. at the same position
	Yes, flight simulator, ship driving simulator		it plays/pauses selected module
	Yes. helicopter flight, human-machine interfaces, robotics, etc.		allows you to view the results of your alterations, then allows you to stop and try again
	yes, plane simulator		applies real time laws of physics to the model created in gazebo
	Yes, landing signal elistedman simulator		Started and stopped the simulation? It allowed the user to be able to access model editor and stop the simulation if it wasn't working properly.
	Flight (job) MATLAB - modeling (research)		runs your project
	No, I have never		play what would happen, pause what would happen
	yes, flight simulator		stop/start simulator
			run background physics engine

Table C1: SRI Pre and Post open-ended survey (continued..)

9	What do you expect a simulator to be able to do?	15	Did the simulated vehicle always perform as expected? [yes/no] If not, please describe the situation.
			Open-Ended Response
	Simulate real time actions		There were some gray areas on the simulation and the actual situation but the results are very close.
	Simulate real world scenarios and improve life skills		no it failed me several times
	Simulate what I want to perform/do in real life to save time/money on projects		Unable to implement friction coefficients in GUI. Changing physical size changed parameters in background that sometimes were undesired. Consider the option to scale "on/off" background data (of inertia, etc.)
	Demonstrate necessary steps to perform a task in an engaging way.		Yes it will simulate well until you reset world then it just goes crazy after so many resets.
	Test design parameters in support of less modifications during actual build		no, strange bugs involving inertia values
	Simulate a conceptual design		No but I feel it was more of not knowing how to fully use the model editor to adjust and control vehicle.
	simulate a real life procedure		Yes & no. when resetting the world, sometimes. The model would maintain its inertia and shoot off.
	Simulate stuff or an experience or task		exactly the same
	Calculate outputs based on user defined inputs and algorithms/rules		yes
	To run up different scenarios in which we have to figure out how and what to fix		yes
	simulate actual effect of the object of the real thing		No, physics was off with inertia + mass

Table C1: SRI Pre and Post open-ended survey (continued..)

10	Have you used Ubuntu before? If so, how many years of experience do you have?	16	What part (if any) of using the simulator was most useful to you in accomplishing the challenge activity? Why?
	Open-Ended Response		Open-Ended Response
	Yes, less than 6 months		Everything. It helped me build ideas to tackle an actual task.
	I do not even know how to pronounce Ubuntu. 0 years' experience.		It was just kind of cool to mess around with. I didn't get much real help out of it
	No		gear ration changes
	Yes. FAB modules. little experience		Simulating gear ratio. showed me which to use when applying it to live model
	no		figuring out configurations that would not work is faster to do in gazebo than it is in real life
	once or twice		using the simulator to test the gear ratio
	No		running the model prior to physical tests helped determine approximately what gear ratio to use
	1 (14.04 LTS)		playing the action
	No I have never		gear ratios
	no		build portion to assist in understanding build and concept designs
			visualization of model
		17	**What part, if any, of using the simulator was least useful to you in accomplishing the challenge activity? Why?**
			Open-Ended Response
			Everything on the activity was very useful.
			It crashed and it was difficult to manage and use to apply to real world situations
			inability to make 2 moving models interact as desired
			it was useful to me
			I very rarely solved the problem in the simulator. I more so narrowed down the least likely solutions

Table C1: SRI Pre and Post open-ended survey (continued..)

		17	**What part, if any, of using the simulator was least useful to you in accomplishing the challenge activity? Why? (continued..)**
			changing the tires (scaling)
			there were a few glitches
			none
			physics simulator
		19	**Please provide feedback regarding your interactions with Gazebo. What did you find difficult to do in Gazebo? What did you find easy?**
			Open-Ended Response
			I found some difficulties with world edit and linking 2 vehicle together
			change some properties, align objects as desired
			It wasn't too difficult, it was just too sporadic sometimes as far as how reset world works, but once I was used to program it because a lot more user friendly
			Moving and changing camera angle orientation where your cursor is (on an object, including the ground). Usually it seems most programs orient zooming and rotation at the center of the screen. Items have individual orientation, no global orientation. no undo button
			I think the most difficult part rotating/transitioning back to absolute zero. I found the program as a whole fairly user friendly and didn't have too many issues learning the simulator
			Gazebo is a very good physics engine. There are bugs that were noted, but the biggest problem was no undo button. it was easy to simulate the model and see the interactions
			The wire needs to be able to be deleted

Table C1: SRI Pre and Post open-ended survey (continued..)

		19	**Please provide feedback regarding your interactions with Gazebo. What did you find difficult to do in Gazebo? What did you find easy? (Continued..)**
			I found navigation while rotating difficult
			Difficult - getting used to virtual environment. some was difficult to understand and visualize easy - navigating
			select, undo, redo, extra windows
		20	**Please provide feedback regarding the physical assembly of the kit. What did you find easy? What parts did you find difficult to do?**
			Open-Ended Response
			the assembly kit is amazing, made me understand more about gear ratio
			no issues
			tools that were included and the assembly of each didn't really find anything difficult
			the spring pins behind the wheels are difficult
			assembly was easy with little issue
			The kit was very straight forward except for the spring pins, but I think the new material will solve the problem.
			it was easy and fun
			screwing in the wheels was pretty annoying but assembling was easy
			intricate parts difficult to get to and assemble
			Worked fine but wiring from motors, switch boxes, and battery. we needed better connection

APPENDIX D: STATUS OF FINAL DELIVERABLES

The status of each task described in the approved Statement of Work is provided below.

Task 1. Develop analysis and simulation tools

Completion Criteria: Tested software ready for integration with other components of the MENTOR2 program.

Deliverables: SiMPLE software and documentation, quarterly progress updates and financial status reports, participation in semi-annual demonstrations, and final program report.

Status: Completed. Deliverables delivered.

Task 1.1. Develop a new graphical representation for specifying electromechanical components

Completion Criteria: Components and interactions adequately represented for demonstration projects.

Status: Completed.

Task 1.2. Augment the Gazebo simulation server

Completion Criteria: Augmented and tested Gazebo simulation server and GDK GUI, ready for demonstrations.

Status: Completed.

Task 1.4. Design and implement interfaces to MOOC and physical prototyping tools

Completion Criteria: Tested interfaces to the MOOC software and prototyping tools.

Status: Completed.

Task 1.5. Support Demonstrations and Project Documentation

Completion Criteria: Completed demonstrations and analysis/simulation project reports incorporated into overall project reports.

Status: Completed.

Task 3. Develop project kits and MOOC materials

Completion Criteria: Integrated and tested SiMPLE system demonstrations ready for students to use.

Deliverables: Project kit specifications, MOOC curricula, quarterly progress updates and financial status reports, participation in semi-annual demonstrations, and final program report.

Status: Completed. Deliverables delivered.

Task 3.1. Develop Project-Based Courses

Completion Criteria: Stand-alone courses for each of the project kits are completed.

Status: Completed.

Task 3.2. Develop project kits

Completion Criteria: The project kit materials are judged by students/users as sufficient for executing the course during the demonstration.
Status: Completed.

Task 3.3. Adapt MOOC framework

Completion Criteria: Selection, installation, and operation of an open source MOOC platform.
Status: Completed.

Task 3.4. Implement MOOC content

Completion Criteria: Exemplary project courses hosted on the MOOC available for student use in time to support the phased demonstration cycles.
Status: Completed.

Task 3.5. Develop Interfaces and Learning Companion

Completion Criteria: Integration and testing of the component interfaces; development, testing, and integration of the Learning Companion.
Status: Completed.

Task 3.6. Support Demonstrations and Project Documentation

Completion Criteria: Completed demonstrations and courseware/project kit updates incorporated into overall project reports.
Status: Completed.