Braitenberg Vehicle Simulator: Visualizing the Classic Thought Experiment

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***Abstract*—Braitenberg vehicles are a thought experiment created by Valentino Braitenberg that demonstrate how simple machines can display human-like behavior. These vehicles have impacted education, appearing as a topic in various undergraduate courses, however, there have not been many tools to visualize these vehicles beyond the source text. We develop a Braitenberg vehicle simulator and assess its educational effectiveness in a real classroom. We find that our simulator increased both learning and enjoyment of the topic.**

***Index Terms*—Braitenberg vehicles, robotics education, simulation**

I. Introduction

Braitenberg vehicles are a concept developed by Valentino Braitenberg in his book *Vehicles: Experiments in Synthetic Psychology*, in which he demonstrates how vehicles made of simple components can demonstrate complex or even human-like behavior [1]. A Braitenberg vehicle is an abstract vehicle with a propulsion system and a set of sensors that respond to stimuli in the vehicles' environment. The book describes a progression of vehicle complexity, from Vehicle 1, which is considered to be *alive*, to Vehicle 14, which is said to have *egotism*. These vehicles have made a large impact in robotics education, appearing as a topic in college robotics [2], artificial intelligence [3], and cognitive science courses [4]. Although reading the original text can provide insight into the behavior of the vehicles, research has shown the use of simulation in an academic setting can improve both student learning outcomes and attitudes towards the course content [5], [6], therefore a Braitenberg vehicle simulator may improve learning outcomes compared to just using the source text. While there are some existing Braitenberg vehicle simulators, they are missing components that would make them suitable for classroom use. Furthermore, to our knowledge, there are no studies assessing the educational effectiveness of these simulators. In this paper, we describe a new Braitenberg vehicle simulator we have created explicitly for classroom use. Then, we assess its educational effectiveness by analyzing its impact on learning outcomes and attitudes of students in the Claremont Colleges *Minds, Brains, and Programs* course.

II. Related Work

Although there are no studies on the educational impacts of Braitenberg vehicle simulators, there are many studies demonstrating the educational effectiveness of other simulators. One example that has been studied extensively is PhET, a simulation tool for learning a variety of STEM topics [7]. In one Electricity and Magnetism class at a Turkish university, students who interacted with PhET experienced a significant increase in score compared to the students who experienced traditional lecture teaching. The students who experienced PhET also felt that using the simulation improved both their conceptual understanding and factual knowledge of physics, and that simulations improved their problem-solving skills and their ability to think more logically, independently, and abstractly [8]. In one South African university, chemistry students felt that PhET simulations were fun and improved their confidence and understanding of chemistry concepts [9]. Chemistry students at City College of New York similarly felt that PhET simulations increased their understanding of chemistry [10]. Previous work on PhET shows that simulation can be an effective teaching tool, motivating further development of educational simulations.

Existing Braitenberg vehicle simulators either present technological barriers or have limited features. For instance, Kohler's xbraitenberg [11], Smart's "Planet Braitenberg" [12], Mathon et al.'s simulator [13] and Gupta's simulator [14] all require installation, which may pose a technical challenge to students and instructors. There are a few web-based simulators that are more accessible, however, they have limitations that make them not ideal for a classroom setting. De Weerd's simulator possesses many good educational qualities—clear instructions, vehicle explanations, and customizability of vehicles. However, the user is limited to only ten vehicles and ten sources, and the sources must be of the same intensity [15]. These restrictions hinder the expressivity of the simulator. Furthermore, while these simulators only model up to Vehicle 3, our simulation includes up to Vehicle 4.

III. Braitenberg Vehicles

In this section, we give brief descriptions of Braitenberg vehicles 1-4 [1]. Braitenberg vehicles exist in a frictionless environment with sources, where motor output is related to the source intensity detected by the vehicle's sensors. *Vehicle 1: alive* has one motor connected to one sensor, where the motor output is directly proportional to the sensor input. *Vehicle 2*

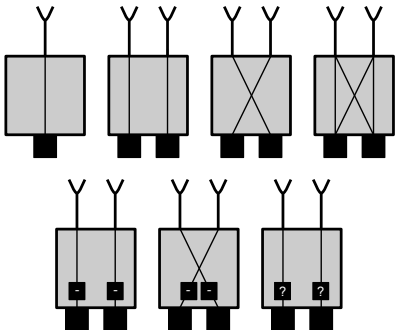

Fig. 1. First row *(from left to right)*: Vehicle 1, Vehicle 2a, Vehicle 2b, Vehicle 2c. Second row *(from left to right)*: Vehicle 3a, Vehicle 3b, Vehicle 4.

has two sensors and two motors. *Vehicle 2a: coward* has each sensor connected to the motor on the same side, causing the vehicle to avoid the source if not directly in front of it. *Vehicle 2b: aggressive* has each sensor connected to the motor on the opposite side, causing the vehicle to "attack" the source. *Vehicle 2c* has two sensors and two motors with each sensor connected to both of the motors, causing behavior similar to Vehicle 1. *Vehicle 3* also has two sensors and two motors, and additionally introduces the concept of an inhibitor which inverts the relationship between sensor input and motor output. In *Vehicle 3a: love*, each sensor is connected with an inhibitor to the motor on the same side, causing the vehicle to be attracted to the source. In *Vehicle 3b: explorer*, each sensor is connected with an inhibitor to the motor on the opposite side, causing the vehicle to approach the source before speeding away. *Vehicle 4* explores non-linear relationships between sensor input and motor output. The book does not specify the motor and sensor configuration, but we have implemented both types of Vehicle 4 as having two sensors and two motors where each sensor is connected to the motor on the same side via a mathematical function. In *Vehicle 4a: instincts* this function is differentiable, and in *Vehicle 4b: will* this function is non-differentiable.

IV. Braitenberg Vehicle Simulator

Our Braitenberg vehicle simulator[1] is a web-based sandbox world where users may interact with vehicles and sources. Source intensities range from 1-1000, and may be placed by clicking. After placement, users may drag and drop to move sources. As for vehicles, users may select from any of the vehicles described in section III. For vehicles 4a and 4b, users may additionally select functions to relate sensor input to motor output, such as *sinusoidal* or *quadratic* for Vehicle 4a and *hyperbola* or *step* for Vehicle 4b. While placing the vehicle, the user may use arrow keys to adjust the angle of the vehicle. Like sources, users may drag and drop to move vehicles after placement. The simulator displays additional information for the most recently placed vehicle, with position, velocity, and angle statistics in the top left and a trail drawing the vehicle's path. Users may further control the simulation

[1]https://hmc-alpaqa.github.io/braitenberg-vehicles/

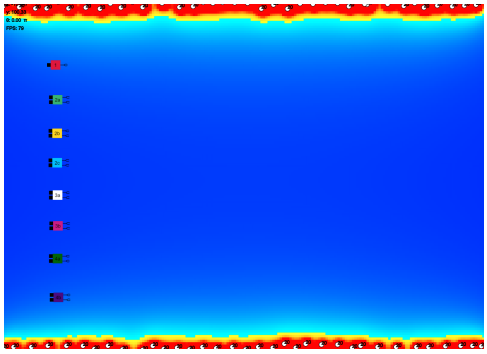

Fig. 2. Screenshot of the simulator demonstrating a racetrack configuration.

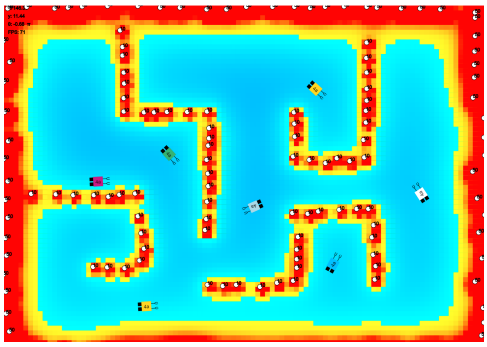

Fig. 3. Screenshot of the simulator demonstrating a maze configuration.

environment by playing or pausing the simulator, adjusting the default vehicle speed, and zooming in and out. We also include instructions for how to use the simulator and an "About Vehicles" page for describing the vehicles. Our simulator was coded using HTML, CSS, and p5.js and is open-source.[2]

The flexibility of our simulator allows for creative vehicle configurations and in-depth explorations of Braitenberg vehicles that were not possible with previous simulators, and also offers a visualization and interactivity component that is not present in the book. Furthermore, the web accessibility, friendly user interface, high degree of controllability, and explanations of vehicles mean that this simulator is suitable for educational purposes, for example in a classroom lab activity.

V. Evaluating Educational Effectiveness

We evaluated the educational effectiveness of our simulator when used in a lab in the Claremont Colleges *Minds, Brains and Programs* class. *Minds, Brains, and Programs* is an interdisciplinary cognitive science, neuroscience, and computer science course with the goal of understanding artificial intelligence from a variety of perspectives. Prior to the lab, students were asked to read Vehicles 1-7 of *Vehicles: Experiments in Synthetic Psychology* by Valentino Braitenberg. The lab was broken down into the following structure:

1) Instructor demonstration of important simulator features such as adding vehicles and sources and starting the simulator (5 minutes).

[2]https://github.com/hmc-alpaqa/braitenberg-vehicles

2) Student freeplay with the simulator (5 minutes).
3) Q&A about simulator features (5 minutes).
4) Experimentation with simulator. Students were given some optional prompts, such as "Set up a situation where you can keep a number of the variables constant, but then carefully change one variable to see whether the behavior changes in interesting ways." and "Can you figure out how to get a vehicle to orbit a source? Or to trace a figure-8 path?" (30 minutes)
5) Report back to the class about experiences with the simulator (10 minutes).
6) Evaluation of Braitenberg's claims through experimentation with the simulator. Students were asked to consider to what extent behavior of the simulated vehicles reflected their expectations from the book (30 minutes).
7) Report back to the class about experiences with the simulator in relation to Braitenberg's textual description of vehicles (15 minutes).
8) Survey of simulator experiences (15 minutes).

The survey was designed to assess the educational effectiveness and enjoyment of the Braitenberg vehicle simulator, and to pinpoint specific features of the simulator that were the most useful or required the most improvement. We modeled our questions on a study of the PhET simulation [10]. The survey consisted of five Likert-style questions and four qualitative short response questions. For the first four Likert-style questions, students were given a statement and asked to respond with 1 (strongly disagree), 2 (disagree), 3 (neutral), 4 (agree), or 5 (strongly agree). The last Likert-style question asked the students to rate their overall experience with the simulator from 1 to 5.

VI. Results

In this section, we discuss the 27 participant survey responses to both the Likert-type and the short answer questions.

A. Likert-type Questions

As indicated in Table I, each response to a Likert-type question was above "neutral", with most being above "agree". For each response to the Likert-style questions, we perform a one-tailed one-sample t-test (n=27) with a null hypothesis of a mean response of 3 in order to determine if it was statistically significant that the average response was greater than neutral. With $p = 0.01$, we reject the null hypothesis for all of the Likert-type question responses, indicating that students found our simulator to be both educational and enjoyable.

TABLE I
LIKERT-STYLE QUESTIONS AND AVERAGE RESPONSE

Likert-type Question	Average Response
The Braitenberg vehicles simulator helped me understand Braitenberg vehicles 1-4.	4.30
The Braitenberg vehicle Simulator was clear and easy to follow.	4.17
The Braitenberg vehicle simulator increased my interest in Braitenberg vehicles.	3.62
The Braitenberg vehicle simulator was fun.	4.22
Please rate your overall experience with the Braitenberg vehicle simulator from 1 to 5.	4.16

B. Short Answer Questions

1) Useful Features of Braitenberg Vehicle Simulator: To assess the effctiveness of different features of the simulator, we asked survey respondents "What features of the Braitenberg vehicle simulator were the most useful?" The most mentioned features with 5 responses (19% of respondents) each were the About Vehicles informational section, sources, speed control, and vehicles.

TABLE II
WHAT FEATURES OF THE BRAITENBERG VEHICLE SIMULATOR WERE THE MOST USEFUL?

Feature	Count
About Vehicles	5
Sources	5
Speed Control	5
Vehicles	5

TABLE III
HOW DID YOUR LEARNING EXPERIENCE WITH THE BRAITENBERG VEHICLE SIMULATOR COMPARE TO YOUR LEARNING EXPERIENCE WITH *Vehicles: Experiments in Psychology* BY VALENTINO BRAITENBERG?

Feature	Count
Visualization	13
More Understanding	9
Interactive	5

2) Comparison to Book: One aspect of the simulator we were interested in is how learning with the simulator compared to learning with just the book. 13 (48%) responses commented on the visualization capabilities of the simulator, 9 students (33%) stated that the simulator resulted in more understanding, and 5 (19%) students commented on the interactivity of the simulator.

3) Impact of Simulator on Understanding: One question we asked was "Did the Braitenberg vehicle simulator contribute

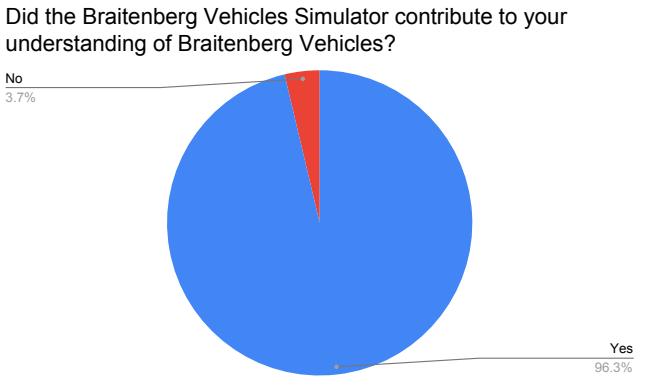

Fig. 4. The vast majority of students felt that the simulator contributed to their understanding of Braitenberg vehicles.

TABLE IV
WHAT IMPROVEMENTS WOULD YOU LIKE TO SEE MADE TO THE BRAITENBERG VEHICLE SIMULATOR?

Feature	Count
World Border	4
Vehicle 4 Differentiation	3
Improved Instructions	3

to your understanding of Braitenberg vehicles? If yes, why? If no, why not?". Out of the 27 respondents, 26 (96%) said yes. 13 (48%) responses mentioned the ability to visualize vehicles as a feature that contributed understanding of the vehicles. 13 (48%) responses cited the usefulness of the simulator as a visualization tool, 9 (33%) responses stated that the Braitenberg vehicle simulator allowed for more understanding compared to just using the book, and 5 (19%) responses mentioned the interactivity of the simulator.

4) Future Improvements: As for the most commonly requested improvements to the simulator, there were 4 responses (15%) mentioning a modification to the world border, such as the option for a toroidal world or a walled world border. Another 4 responses (15%) suggested improved UI for distinguishing the different Vehicle 4 types, and 3 responses (11%) requested improvements to the instructions.

VII. DISCUSSION

Our Braitenberg vehicle simulator allows for more in-depth exploration of Braitenberg vehicles that would be difficult to imagine given just the source text. For instance, the book focuses largely on the vehicles, but our simulator demonstrates that source placement also has a large impact on the behavior of the vehicles. With our simulator, users are able to visualize vehicle movement in a variety of creative source placements—like a maze—in a way that would be difficult to imagine with only the source text. The ability to see the vehicle's path additionally adds insight that is not present in the book nor the existing simulators. With the expressivity of our simulator, we are able to experience a much deeper understanding and appreciation of Braitenberg vehicles.

These benefits are not speculative—they are confirmed by our real-world classroom data. Both the quantitative and qualitative survey responses indicate that the visualization and interactivity of the simulator improved students understanding of Braitenberg vehicles beyond the book, and moreover, the simulator was enjoyable to use. These results corroborate existing research indicating that educational simulations have a positive impact on student learning outcomes [5]. With our findings, we suggest instructors teaching Braitenberg vehicles to use our simulator as part of their course materials. More broadly, we encourage the development of more educational simulations for robotics education.

VIII. CONCLUSION

We created a simulator of Braitenberg vehicles as described by Valentino Braitenberg in his book *Vehicles: Experiments in synthetic psychology*. Students in the Claremont Colleges *Minds, Brains, and Programs* course used our simulator in class and we surveyed their experience using our simulator. Our results indicated that our simulator improved their understanding of Braitenberg vehicles and was enjoyable to use.

While our simulator expands the imaginable possibilities for Braitenberg vehicles, there are still many more possibilities that have yet to be explored. For example, the book briefly mentions multiple types of sources and different sensors responding to different sources [1], however, our simulator only features one type of source and sensor. Additionally, vehicles can currently only be placed by clicking, but we are interested in implementing the ability to place vehicles and sources with more exact locations, such that an experiment done in the simulator can be reproduced, which may be desired for a classroom assignment. Future work includes incorporating more concepts from the book, improving mobile functionality, and making the simulator more suitable for classroom use.

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