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Simulation of Rover Mission in Martian Environments using Swarm Technology

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Abstract

The National Aeronautics and Space Administration (NASA) and the University of New Mexico's Swarmathon competition challenges students to develop search algorithms for robotic swarm technology and encourages them to design and simulate a Mission to Mars. The goal is to create algorithms that make swarm rovers (Swarmies) find and collect as many resources as possible within a fixed period. The grander purpose of this project is to contribute to the advancement of technology that will help homo sapiens become a multi-planetary species. The mission was focused on exploring Martian lava tubes because they may offer explorers protection from radiation and on exploring the Valles Marineris based on evidence suggesting the existence of water on Mars from previous expeditions. Where water lied, life may have had a chance to thrive. This technical report focuses on the value of exploring these environments and how different computer software and hardware was used to optimize resource collection by Swarmies when they arrive in the proposed locations. The Robotic Operation System (ROS) and NetLogo are used to run, develop, and test the algorithms. Blender and Photoshop are used to create models that are imported into Gazebo to simulate Martian environments and the code was tested on physical computer hardware from Swarmies. The work was done through the collaborative efforts between students from San Jacinto College (SJC), the University of Houston Clear Lake (UHCL), and regional high schools who were included in the project as a form of community outreach to promote interest in programming.

Keywords: Mars, NASA Swarmathon, Simulate

1. Introduction

The project's objective is to promote the goal of becoming a multi-planetary species by furthering rover research, finding habitable environments and understanding the history of Mars. The main concern is to create effective search algorithms to assess landing environments, study how water played a role on the Martian planet and find out if the planet ever supported life. Before developing the project's mission simulation, the most appropriate way to address these issues is by studying previous rover missions and incorporating applicable mission elements. The information gathered from the results of the Sojourner, Spirit, Opportunity, and Curiosity rover missions help establish the approach for the project when evaluating their locations and optimal technology.

1.1 Background

The evaluation began with the four successful NASA rovers in chronological order. In July 1997, Sojourner landed in Ares Vallis to study the geology of Mars.[8] In January 2004, Spirit landed in the Gusev crater and Opportunity in

Meridiani Planum to search for evidence of past water activity.[1] In August 2012, Curiosity landed in the Gale Crater to investigate its climate and topology to prepare for human exploration and to search for evidence that Mars supported microbial life.[21] Curiosity was the first non-solar paneled rover and was powered by a plutonium generator instead.[20] On board is an environmental monitoring station, cameras, and tools to study the chemistry and mineralogy found.[9] All three of the rovers had different versions of Alpha Particle X-ray Spectrometers (APXS) to analyze their surroundings.[25, 3, 5]

The conducted rover expeditions were fruitful, and valuable lessons were learned from them to ensure optimal success. The Pathfinder Mission ended when Sojourner lost communication with NASA.[12] Spirit and Opportunity were identical rovers that were projected to operate for ninety days but lasted for almost six years and more than ten years respectively.[18] They had different lifespans despite being identical rovers due to their discrete landing locations.[15] Spirit lost most of its functionality when it got stuck in soft sand, yet the Opportunity rover is still operational, proving that sending more than one rover makes a mission more robust. The Mars Pathfinder Mission may have lasted longer if Sojourner was accompanied by other rovers, and the current Mars Science Laboratory mission is susceptible to the same limitation by only working with the Curiosity. Lone rovers also have the limitation of only completing one task at a time.[22] Additionally, individuals who maneuver rovers are not capable of receiving feedback quickly enough to avoid damage from Martian terrain. Furthermore, Mars rovers have been expensive, with costs ranging from $25 million to $2.5 billion as seen in Figure 1, and a reduction of cost may increase the amount of rover missions attempted.[28, 11, 29] The authors of this report offer solutions to issues NASA has faced with Martian rovers and propose new landing sites for future missions.

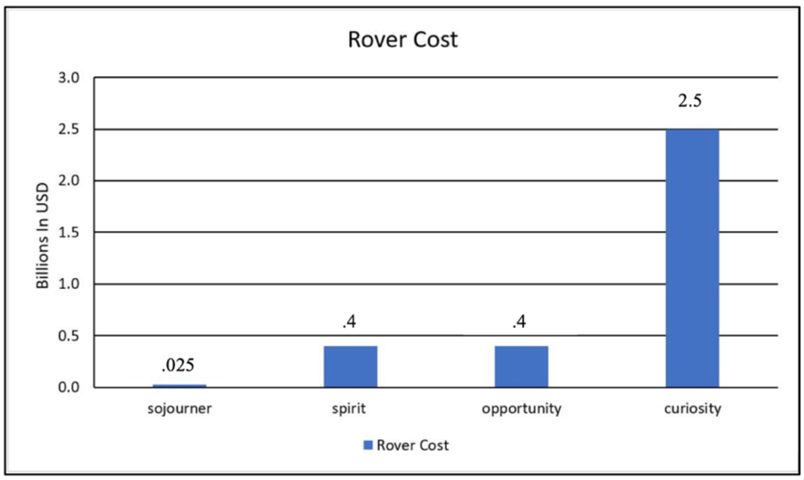

Figure 1. Cost of previous rover expeditions to Mars

1.2 Location Assessment

The objective for these missions was to analyze the geology of Mars to assess how the planet developed over time and if it ever held life. To further that objective, the project focuses on the unexplored Valles Marineris and subsurface Martian lava tubes that shall advance research in Martian geochronology and human exploration. The Valles Marineris is a canyon that some researchers believe has been formed by water erosion, but they cannot assert whether the valley was formed by fluvial activity, subsurface seepage, atmospheric precipitation, or if it was formed by water at all.[19, 17, 23] Lava tubes on Mars were likely formed when lava flowed through the subsurface until flow diminished to create empty tunnels.[4] On average, these tunnels are much larger than terrestrial lava tubes at an average of 250 meters wide and between 20 to 50 meters deep.[26] Additionally, lava tubes make good candidates for human habitats because they can potentially offer inhabitants protection from hazards on the Martian surface like radiation, dust storms, and temperature changes.[4] The current understanding of the characteristics of Valles Marineris and Martian lava tubes is limited to what researchers can gather from satellite images, and Swarm rover exploration in these areas shall make progress in gathering information relevant to human exploration.

1.3 Relevance Of Swarm Robotics

The use of swarm technology is a suitable approach to the project based on lessons learned from past rover expeditions and the newly proposed locations of focus. The Valles Marineris and the Martian lava tubes shall be effectively explored by swarm rovers because of their specifications. Swarmies are customizable, and specifications, like power source, can be adjusted to fit the mission.[6] They can use technology used in previous missions like a webcam, a GPS system, an IMU among other sensors, an ultrasonic obstacle detector, a Wi-Fi antenna for wireless communication, and an on-board computer.[16] The use of multiple Swarmies has the following advantageous specifications:

- Cost efficiency
- Time efficiency
- Increased success rate
- Automaticity

It costs about $5,000 to build a Swarmie,[6] and the average cost of a Mars rover mission is over $800 million without adjusting for inflation.[24] The average rover mission can buy 160,000 Swarmies, making Swarmies a cost-effective solution. Swarmies operate in groups, so they can gather information from landing locations much faster than one rover can, and they can cover a large range of land easily. Their multiplicity can give them a higher success rate, for the mission shall continue if one Swarmie becomes unusable, since other Swarmies can supersede the duties of the malfunctioning Swarmie. Swarmies can do this because they can function autonomously, and they have no need to be operated by someone on Earth.[2] Algorithms determine how the Swarmies operate on their own with artificial intelligence, and the Swarmathon team considered the benefits and drawbacks of taking either a deterministic or random approach for the development of these algorithms.[22] When collecting samples, deterministic algorithms make Swarmies take linear paths, and random algorithms make rovers take arbitrary paths.[22] Testing is required to ascertain what type of algorithm is best.

1.4 Testing By Simulation

Swarm technology specifications must be tested before Swarmies are sent to Mars so that the best approach will be taken for the mission design. A simulation of a Mars mission is the most efficient method to test these specifications because it can replicate the physics and characteristics of the mission elements with cost effective technology.[13] Open source simulation technologies make state-of-the-art programming tools accessible to beginners and are sophisticated enough to be used regularly in the robotics industry.[7] Simulation technology is available at different levels of sophistication, ranging from computer programs that simulate in 2D to those that simulate in 3D or facilitate physical simulations, and the tests presented in this report use these three methods to assess the viability of Swarmies for Mars exploration.[13] Virtual simulation programs are advantageous when testing for the validity of a robotic system because they can repeat an identical or controlled experiments.[13] The simplicity of a program like NetLogo facilitates the creation of controlled experiments because each variable can be manipulated independently. NetLogo is a reputable program that has been used to test behavioral patterns of artificial life, which is relevant to testing the automaticity of the Swarmies.[27] ROS can be used in conjunction with Gazebo to develop and customize the mechanics of a robot in a virtual simulated environment.[7] Gazebo has the capacity to test both the behavior and the mechanical components of the Swarmies alongside models of different Martian environments.[7] ROS can incorporate algorithms on hardware that will be used to create physical simulations of the mission.[7] Testing the functionality of Swarmies in a physical setting incorporates external variables not accounted for in the virtual simulation. Conducting experiments on Swarmies by using multiple simulation technologies helps determine if the results are accurate, for each method of testing may expose weaknesses not visible among respective simulations. The simulations will test algorithms modified by the participating students for the NASA Swarmathon. The tests will measure the algorithms' efficiency by using autonomous rovers that will execute the mission by collecting resources in an organized manner within a fixed period. The process of creating swarming intelligence can be done using the methods described in this document and provide a justified method of exploration of the Mars surface with Swarm technology.

2. Methodology

The work involved with the testing and simulation process is divided into three teams that will simulate the mission and test algorithms in a 2D environment, a 3D environment, and on physical Swarmie hardware. Windows 10 and Ubuntu 16.04 are the operating systems utilized for this project. Ubuntu 16.04 is used to simulate the Swarmie mission in Gazebo and communicate with physical Swarmie rovers. Windows 10 is used to access Photoshop, Blender, and NetLogo. ROS is used to implement code into the Gazebo simulations and physical Swarmies. The Swarmie hardware and software used was provided by the NASA Swarmathon competition. NASA has also provided every team with markers named April Cubes to symbolize the resources Swarmies will collect on Mars.

2.1 2D Simulation Team

The 2D simulation team's goal is to use NetLogo to simulate rovers collecting rocks, represented by yellow pixels on the interface, in the allotted time of 1800 and 3600 ticks, representing seconds, then drop the rocks at the base located at coordinates (0,0). The black symbols, as seen in Figure 2, represent Swarmies that have been programmed to cover as much of the surface as possible. The ability to cover the surface depends on the code developed and on the type of robots chosen for the simulation. The 2D team established an understanding of the fundamental skills for the program after going through the modules provided by NetLogo. The team tweaked robot settings to fit the needs of the project so that each robot used operated by using either a deterministic or random method to collect rocks. The DFS, Iii, Spiral, Respiral, and Random are the types of robots chosen for the simulation. The team evaluates qualitative behaviors, such as looking at deterministic vs. random walk programming, as seen in Figures 2A and 2B respectively, and the use of communication or breadcrumb trails. The 2D team tested different codes that became precursors of what can be simulated using 3D and physical Swarm rover technology.

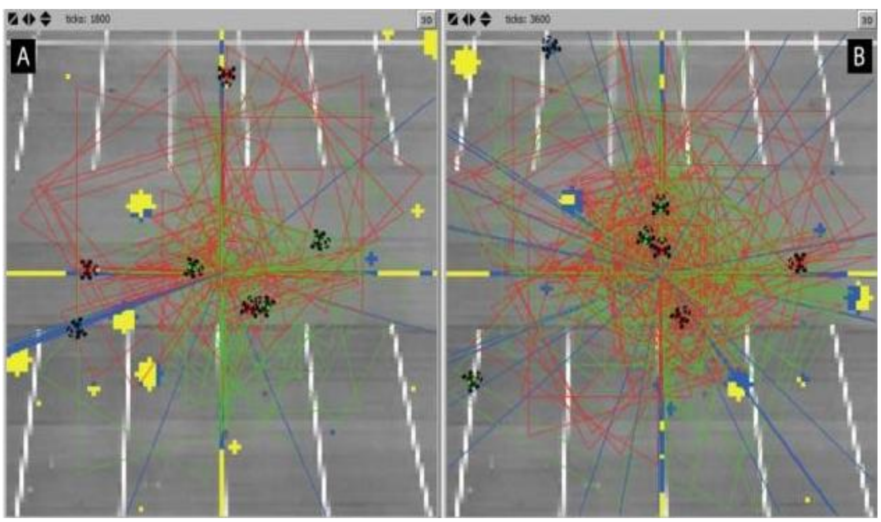

Figure 2. Deterministic vs. random robotic paths generated in NetLogo

2.2 3-D Modeling

Photoshop is used to create the ground texture for the Gazebo simulation. Applying texture allows for the illusion of 3D detail without slowing down the simulation. The textures are created by taking open source images of material, such as gravel and sand, then modifying them to make a seamless pattern that tiles when overlaid on the surface below the Swarmies. An offset filter is applied so that the four corners of the base image are repositioned within the frame of the image. The sharp lines that originally form the boundaries of the base image are blended together using the clone stamp tool. This Photoshop tool takes a reference point within the image and paints over another part of the image by using pixels found at the reference point. This allows for the clone stamp tool to blend away the seams created by the offset filter, and the new edges of the image will tessellate without distinguishable borders between tiles. The final step in creating a texture is applying a hue/saturation filter set to colorize and adjusting the levels to create a color that resembles the color of soil on Mars. Six textures are created using this method.

Blender is an open source 3D content creation program that is used to develop the models that are imported in Gazebo. The models are created to resemble the Valles Marineris and Martian lava tubes, the mission locations of focus for the Swarmies. The Valles Marineris is created using an open source STL (*.stl) file of the Valles Marineris from the NASA 3D Resources website, as seen in Figure 3A. The model is cropped down by using the box select tool in edit mode and deleting the vertices until only the desired portion of the Melas Chasma, a canyon within the Valles Marineris, remains. The resulting 3D model contains a high polygon count that is reduced with the decimate modifier in object mode, as seen in Figure 3B. The lower polygon count reduced the amount of faces needed to form the object, thus reducing the file size of the model for faster rendering in Gazebo. This model is then cut into many pieces by importing the reduced Melas Chasma model to the Blender file several times and reducing each new import to different portions of the model. A new rectangular prism is added, and the pieces of the Melas Chasma are arranged and merged on top of the prism, as seen in Figure 3C.

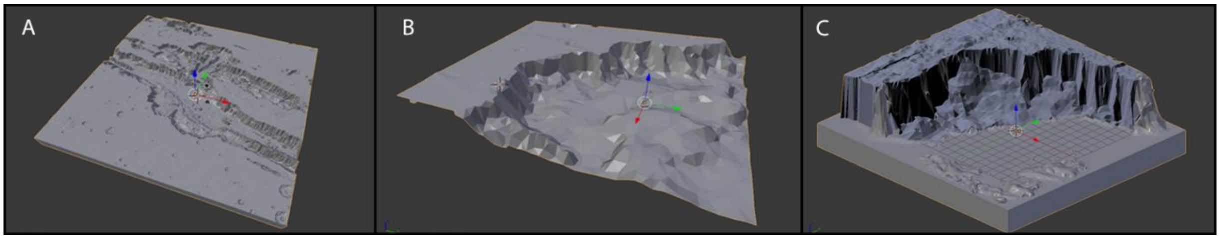

Figure 3. Modeling of Melas Chasma in Blender

The lava tube model is created by combining four different meshes together. The first mesh is a sphere that has its lower half cropped out by deleting the vertices selected with the box select tool in edit mode. The semi-sphere is then scaled to form an oblong dome and subdivided to gain more faces to mold. The dome is then reshaped with the f grab brush to give the dome the natural shape of a cave. In edit mode, portions of the narrow sides of the dome are selected with the circle select tool and deleted to make way for new meshes to bond there. A cylinder mesh is added to the Blender environment, and both circular faces are selected and deleted. The bottom half of the cylinder is cropped in out by deleting the vertices selected by the box select tool. The resulting mesh is subdivided then duplicated so that there were two half cylinders that can be bonded to both sides of the dome, as seen in Figure 4A. The cylinders are scaled to fit the approximate shape of the holes created in each side of the dome, and then the edges of the dome and the cylinder are selected and bonded by using the bridge edge loops too, as seen in Figure 4B. Next, the faces at the top of the dome are selected with the circle select tool then deleted to create an opening. A circle mesh is added in the center of the opening, and the outer edges of the circle are bonded with the edges of the opening by using the bridge edge loops tool. The new circle opening is created on top to resemble the opening of lava tubes in satellite images.[4] A plane mesh is added then merged with the bridge edge loops tool to the bottom vertices of the first three meshes to create a flat surface. The resulting combination of meshes is then cut open, as seen in Figure 4C, so that the Swarmies are within view when operating within the Gazebo simulation.

All sculpting brushes were used on both Blender models to give the smooth faces of the models a rocky surface. Both Blender models also have their origin set at their center of mass to provide the necessary data for Gazebo to maneuver the object within the simulation program. The models are then exported as both COLLADA files (*.dae) and STL (*.stl) files to provide more than one file option for Gazebo import.

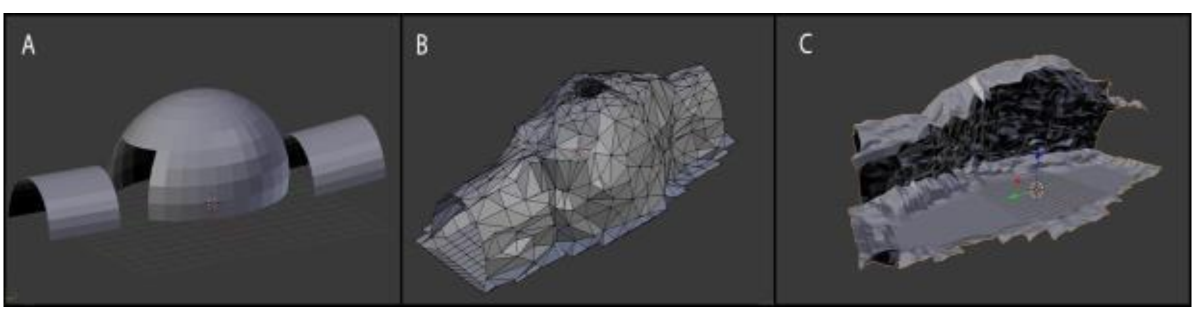

Figure 4. Modeling of Martian lava tube in Blender

2.3 3D Simulation

ROS is the software used to simulate the mission in 3D. ROS is a meta-operating system that provides robots the services usually found on most operating systems. These services include hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. ROS has a distributed framework of processes, comparable to a robotic framework, that lets executables be designed and loosely coupled at runtime one by one. These processes can be compacted into stacks and packages to allow for easy stability and distribution. ROS's modular design allows users to easily customize how much of the available stacks and packages they want to use, what they want to use them for, and what they want to create on their own.

Furthermore, the built in managing system saves time when implementing robot applications created by the user to the framework. The anonymous publish/subscribe mechanism allows users to efficiently communicate between distributed nodes while managing the application's details. The core middleware component, the common robot-specific libraries, and the extensive set of tools available in ROS also speed up the process of simulating robots. In addition, the transform library can easily keep track of each of robot's moving parts. ROS also has a large online community is available to aid users whenever they encounter an issue.

Gazebo is a robotics simulation program that allows for the integration and manipulation of models and code. Gazebo serves as the tool that allows for the quick testing of algorithms, designs, and AI systems by replicating real life scenarios within the program. Most of the Blender models can only be integrated into the Gazebo simulation through unconventional methods. Gazebo's pre-existing models and files act as placeholders for the Blender model files. The directory can be accessed to find the pre-existing models to delete the original (*.stl) or (*.dae) file and rename the Blender model file the same name as the original file. For example, Gazebo's original lunar_lander.dae file is deleted, and the Melas_Chasma.dae file now takes its place after being renamed lunar_lander.dae. The Gazebo rendering of the lava tube and Melas Chasma models are represented in Figure 5A and 5B respectively.

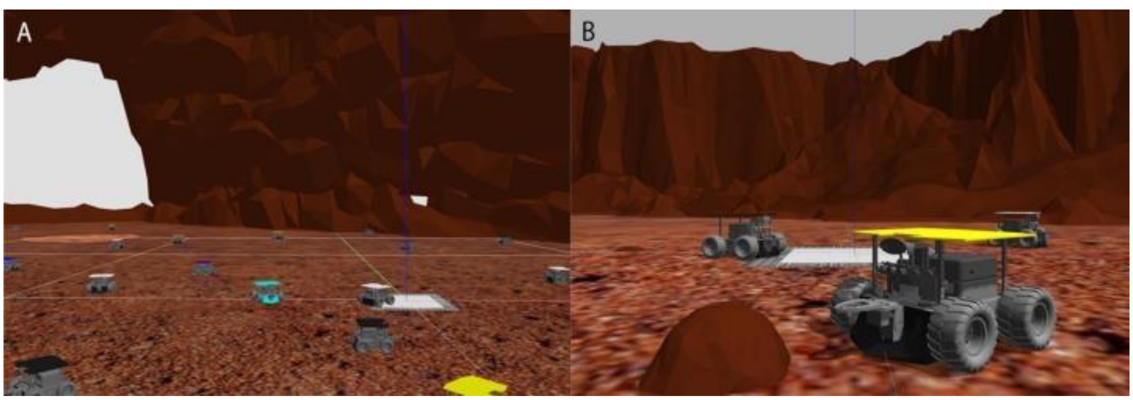

Figure 5. Gazebo Simulation of Swarmies operating on Mars

The process uses the push and pull method to pull a pre-existing package from the repository available on the Swarmathon GitHub. This package includes a source code compatible with ROS libraries that the simulation uses to control different parts of the Swarmie. These parts include the Swarmie's obstacle avoidance, user interface elements, search strategies, and diagnostics. The package also includes STL models for the physical Swarmie build and bash shell scripts that can initialize simulated and physical Swarmies. For other STL models, files, and textures the researchers use the command git push origin master to push local changes to the online repository.

After the models, files, and textures were imported into Gazebo, the simulation capabilities of Gazebo were used to conduct experiments on simulated Martian environments that imitate obstacles found on the Martian surface. This type of simulated experiment is more accessible than conducting an experiment on Mars itself. The Swarmie models used in the simulated experiments were programmed to avoid obstacles and take as many of the 256 April Cubes as possible back to the home base within a 40 minute time window inside a 22x22 meter walled arena. The experiments tested the efficiency of deterministic vs. random walk algorithms by comparing the collection rate of April Cubes by simulated Swarmies that used both types of algorithms.

2.4 Physical Testing

For the real-life experiments, the team customized physical Swarmies to collect April Cubes by splitting up the team into two task groups. The first task group focused on the Swarmie's hardware by assembling the rovers using the Swarmthon's Assembly Manual provided by the Swarmathon competition's official Github, and maintaining the rovers by repairing them when needed. The second task group focused on implementing the code that was debugged and modified for the 3D simulation onto the physical Swarmies. If the code successfully allows the simulated Swarmies to avoid obstacles and pick up April Cubes without it or the program crashing, it is then implemented into the physical Swarmies and tested on a basketball court, as seen in Figure 6. Just like in the Gazebo simulated experiment, the physical Swarmies were programmed to avoid obstacles and take as many of the 256 April Cubes as possible back to the home base within a 40 minute time window inside a 22x22 meter walled arena. The experiments tested the efficiency of deterministic vs. random walk algorithms by comparing the collection rate of April Cubes by physical Swarmies that used both types of algorithms.

3. Results

Figure 6. Students testing code on physical Swarmies

The results of the 2D simulation, Modeling, 3D Simulation, and physical Swarmies portions of the project are discussed in that order. After the first NetLogo module, problems arose with bracket placement and this issue continued until the development of the final code. Another issue was getting all the robots to work as a single cohesive group when using pheromones, a trail to signal other robots about a rock cluster in an area. The first test run resulted with 217 rocks retrieved from the random walk Swarmies and only 19 rocks were retrieved by the deterministic Swarmies. The adjustments needed for the final code were the robot types, number of each robot type, adding pheromones, and fine tuning the code to run more efficiently. After the issue was mitigated by having the Swarmies work in a localized area, the rate of resource collection increased to 271 and 27 rocks by the random walk and deterministic Swarmies respectively.

The final models presented in section B are not the first models made in Blender. Unlike the current models of the Melas Chasma and the Martian lava tube that made the tests visible, as presented in section B, the structure of the first models obstructed the view of Swarmies in Gazebo. The walls of the original Melas Chasma model were parallel to each other, so when attempting to use one wall as a backdrop for the Swarmies, the other wall would block the camera view. This was resolved in Blender by creating the current models with perpendicular walls that made it possible to collect data from the 3D simulation. The original lava tube, as seen in Figure 4B, had a similar issue, so it was cut in half so that the inside of the tube was visible, and data could be collected from the simulation test runs. The renderability of the first models that were made for the project was also improved by changing the dimensions of the models. Originally, the first models were not visible in Gazebo when the camera angle was rotated around the z-axis. The models did not render automatically because they were too thin in width and did not have a large enough volume. This limitation was mitigated by applying a solidify filter to the models in Blender. The filter gave the models a thickness that allowed Gazebo to render the models fully.

During the processes of using command git push origin master to push local changes, the team realized that there is an alternate way to upload files to Gazebo. It is easier to access the Swarmathon repository by renaming and replacing the models and textures needed, with existing textures and models in the Swarmathon repository packages. When opening Gazebo, it would call the models and textures made in Photoshop and Blender as if they were the original ones from the Swarmathon repository. The best results from the experiments conducted on Gazebo demonstrated that deterministic Swarmies retrieved 26 April Cubes and random walk Swarmies collected 46 April Cubes.

The obstacle avoidance of the physical Swarmies was not working correctly and temporarily interrupted tests. The Swarmies did not know when to pick up, reach, or avoid an object. This issue was resolved by setting priority handling to optimize obstacle avoidance against picking up April Cubes. The physical simulations were not conducted in an environment that closely resembled the environmental conditions the Swarmies would face on Mars, such as tire friction, weather conditions, and other external forces. These variables were not considered in the analysis of the data or in the development of the code. Physical Swarmies occasionally malfunctioned due to faulty assembly parts and were not included in the data collection process to prevent the data being skewed by issues not related to the use of either deterministic or random walk algorithms. The data from physical experiments is useful because they create a guideline that can be used to improve code. The best results from the physical experiments demonstrated that deterministic Swarmies retrieved 11 April Cubes and random walk Swarmies collected 18 April Cubes.

4. Conclusion

Simulating a rover mission using swarm technology in Martian environments is a suitable approach based on the results from each simulation. Although there were minor challenges involved with deciding which variables to test, NetLogo was used to improve the algorithms sent by NASA. The improvement of the code signifies that autonomous rovers are a viable method to collect resources on unknown terrain. Furthermore, the NetLogo simulation demonstrated that random algorithms worked more effectively than deterministic ones because linear paths cover more ground in a predictable manner. The project then transitioned to a 3-D simulation in Gazebo that tested the mechanics of the Swarmies in a virtual environment. The simulation revealed that the proposed Swarmie specifications need to be improved to properly address obstacles that will be present on different locations on Mars. The physical environment introduced variables that revealed weaknesses that the code did not take account of. The physical simulation created a guideline for future improvements of software that shall align it closer to physical world conditions. Physical simulations serve as a demonstration of how multiple autonomous rovers can collect resources more efficiently than the single manual rovers used in previous missions. The array of mission simulations developed for this project by means of swarm technology, demonstrate the approaching reality of homo sapiens colonizing and studying Mars in areas such as the Valles Marineris and Martian lava tubes. One example is the proposed expansion of this project into drone design research. Emerging research in drone design is being focused on creating a structure capable of flying on Mars. If successfully constructed, algorithms comparable to those used on Swarmies could be implemented into drones to guide them into locations inaccessible to Swarmies. In addition, similar methods to those of the Swarmathon project will be utilized to test new drone designs. Additionally, a more sophisticated method will be introduced by testing models in a vacuum that replicates Mars' air pressure. When refined, algorithms developed for the Swarmathon may potentially be incorporated into other technologies used for space colonization.

5. Acknowledgements

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