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A LEGO Mindstorms NXT Based Multirobot System

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Abstract— **Lego Mindstorms robots kits are popular hands-on robotics tools for math, science and engineering education. The recently developed NXT system is much more powerful than the previous RCX system, and has great potential for scholarly research. In this paper, we investigated and tested the capabilities and limitations of NXT system for its application to multirobot systems. To demonstrate our work, a functional prototype has been constructed and used to verify a swarm intelligence based algorithm.**

I. INTRODUCTION

MULTIROBOT systems offer considerable advantages over an individual robot [1]. They provide redundancy, spatially diverse functionality and flexible reconfigurability that allow a team of robots to collectively accomplish tasks beyond the capabilities of a single robot [2]. For that reason, it is an important research area within both robotics and artificial intelligence. These systems have great potential in military, industry, medicine, and overall efforts to improve quality of life.

Various multirobot systems have been developed in the last decades. Y. Meng and J. Gan developed a study that dealt with algorithms for multi-robot systems, focusing on the construction of a multi-robot system that could search an environment for randomly placed objects, and push said items to a predetermined space [3]. The study involved the development of an algorithm that exercised a combination of explorative searching and dynamic task allocation. In order to communicate amongst themselves, virtual pheromone trails were used, and Particle Swarm Optimization served to maintain task allocation. M. Dorigo conducted a study on Swarm-Bots, which among other things, served to analyze communication techniques that could be applied to any multi-robotic system [4]. The experimental scenario called for a swarm of s-bots to transport a heavy object from an initial position to a target location. The system consisted of several unitary autonomous robots called s-bots, which attach to other identical robots to create a Swarm-Bot. Each s-bot had left and right side motors allowing for efficient rotation on spot due to the large diameter of wheels. One s-bot was equipped with sensors necessary for navigation, such as infrared proximity sensors, light sensors, accelerometers and incremental encoders, while also having sensors and communication devices to detect and communicate with other s-bots, such as omnidirectional camera, colored LEDs, sound emitters and receivers. Finally, s-bots had additional sensors for perceiving the environment. In terms of local interaction, light signals have been used in several studies to provide a beacon of sorts to fellow robots. One study involved fetching and retrieval capabilities of a Swarm-Bot [5] in a specific dynamic environment. The robots were reactive in operation, holding no memory of previous history. Coordination was achieved through light signals, while actual transportation required the use of a force sensor. These interactions are further explored in terms of flocking and formation control. Hanada et al. [6] explored robotic swarm interactions through simulation of schools of tuna. Robots were programmed to sense range of neighboring robots to maintain equal distance. This allowed for robots to split into multiple groups and then reunite into one large swarm as needed. This study defines algorithms that can be used for spatial sensing, which is important in collaborative robotics. The information provided in this study can aid in understanding spatial pathways of the robots when they do not have direct communication with each other. We chose to construct the robotic team by using Lego Mindstorms NXT kits, which provided a foundation for our own unique system. Lego modular sets were employed by Labella e al. [7] to evaluate task allocation, controls, efficiency, communication, and task coordination, as these apply to foraging. Otherwise, little research has been conducted to employ Lego sets for multirobot systems. This paper serves to investigate the use of Lego Mindstorms NXT kits for mulitrobot systems. The algorithms developed in this study involve the expansion of the NXT sets' functionality to allow for successful navigation of the robots with only limited interaction.

The remaining sections of the paper are as follows: Section 2 presents the problem and system descriptions. The four fundamental requirements of multirobot systems are explored, as well as their respective components. Section 3 discusses an investigation of Lego Mindstorms NXT, and the capabilities and limitations of the system. Section 4 describes the robot prototyping, while the developed algorithms are discussed in Section 5. Section 6 is an explanation of the Experiments and Results.

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II. Fundamental Requirements of Multirobot Systems

In order to maintain desired functionality and remain successful in a given environment, multirobot systems require particular components within their design. These crucial attributes allow for the robots to interact autonomously, without any outside control. Communication and localization between each robot are two key technical challenges for the cooperation of multirobot systems [1]. Communication plays an integral role in the overall performance of the group, as each robot must maintain interaction with its neighbors to ensure swarm stability. Methods of robotic communication have diversified to include pheromone signals (similar to the hormone release signals produced by ants), coordinate systems, Bluetooth technology, visual-programming, signal or camera output, and many more creative techniques [2].

Localization is essential to the determination of robot location in the environment. Within flocking techniques, localization ensures relative positioning to maintain formation and also collision avoidance [3]. Studies have indicated successful localization through the use of transmitted light signals and sensors [3], [4].

Coordination is crucial in task allocation for maximized system efficiency. Coordination methods serve to control task performance so that each robot can adapt in a given environment to fulfill the system's shifting needs. Sensory outputs allow each robot to respond to changing stimuli, and react accordingly.

Finally, cooperation draws from the other three elements in order to combine the efforts of each individual agent. By expanding upon the capabilities of communication, localization, and coordination, each robot can contribute to the final outcome achieved by the entire system.

III. LEGO Mindstorms NXT Investigation

This section will investigate the capabilities of Lego Mindstorms NXT kits to meet the communication, localization, coordination and cooperation requirements for multirobot systems.

A. Hardware capability and limitation

The Lego Mindstorms NXT kit is a modular set that holds great potential in terms of hardware functionality. The Intelligent Brick aids in simplifying electrical components, while still providing a powerful basis for control. The Brick has a microprocessor and Flash Memory to render the NXT a very programmable device. Each Brick is Bluetooth capable, thus enabling inter-robot communication. Also, the brick has four inputs and three outputs to allow for connections to the sensors and motors, respectively. Although the NXT Intelligent Brick is robustly designed to control the robot, it does in fact have some flaws. As one encapsulated piece, the electronics cannot be easily altered to accept additional attachments to the seven ports. Also the connecting cables used for the NXT system differ from normal telephone RSJ cables, thus reducing part availability and interchangeability.

For communication, each robot was wirelessly connected by means of Bluetooth technology. Bluetooth allowed for each robot to send and receive information to execute commands almost instantaneously for accurate group navigation. However Bluetooth communication is limited as a robot can only be connected to a maximum of three robots at a time in a master/slave or queen/drone configuration. As per this configuration, a robot cannot be a master and slave simultaneously. Also connection between robots must be made before programs are executed. This means for teams larger than four robots, Bluetooth communication cannot be utilized.

Localization was achieved through the use of a variety of sensors and altered mechanisms. In order to determine distance, an ultrasonic sensor can be used. The ultrasonic sensor is effective in obstacle detection, but has a number of limitations. The ultrasonic waves can only be sent in one frequency thus producing interference between two or more sensors. The device operates through the use of sound waves that deflect off of objects. Due to the mechanical nature of the sound waves, performance varies with the temperature, humidity, and pressure of the air. As with any deflective measurement, the sensors work best with smooth flat objects perpendicular to the sensor. These conditions are difficult to replicate in practical applications such as moving targets or in dynamic environments.

Light energy can be also employed for localization, in both the visible and infrared light spectrums. The Electro Optical Proximity Detector (EOPD) measured the distance of objects by means of reflected light, through light intensity readings. Similar to the Ultrasonic sensor, the EOPD is best at close ranges with flat objects perpendicular to the sensor. When an object is at an angle to the sensor, its reflected readings can be fairly inaccurate. Also the EOPD reads light intensity values, yet the relationship between light and distance is not linear. An infrared sensor played an important part in detecting neighboring robots. The IR Seeker has the capability of detecting modular infrared signals with a 240° view angle. The Seeker can determine the distance and direction by measuring the intensity of an incoming infrared signal. Each robot can be slightly modified to have a small infrared light-emitting diode (LED) that could be recognized by the IR Seeker. This is crucial in differentiating between obstacles and other robots. Although effective, the IR Seeker does lack a high level of accuracy due to interference from sunlight. Readings are outputted in terms of directional heading and infrared intensity which can be difficult to quantify as a distance.

Coordination is achieved through the use of the compass sensors and the Servo Motors, which drive the robot. These Servo Motors contain rotation sensors for more accurate movements. They can also be run synchronously for a zero turning radius. The only drawback to the Servo Motors is that they can overshoot the programmed rotation, thus making 90 degree turning difficult. The implementation of the compass sensor helps to compensate for that problem. The compass sensor allows each robot to determine travel direction in the environment, and with respect to the other robots. This helps to ensure that each robot, when in formation, is moving in the proper direction. The compass sensor also has some restrictions that can lead to false readings. The compass must be completely level at a 90 degree angle and be isolated from the other sensors, motors and intelligent brick to avoid any magnetic interference. These issues can cause significant errors in the performance of the compass.

Cooperation utilizes the Bluetooth communication, the sensors, and the infrared mechanisms in order to maintain collaboration between all of the agents. Capabilities overlap among the systems, thus compensating for inefficiencies or drawbacks that may exist. Since the Bluetooth technology functions in queen/drone configuration, the sensors fill in the communication gaps to maintain complete control. The infrared attributes also compensate for differentiation through infrared signals. These mechanisms act to detect the robots when all other communication falls short. Consequently, the incorporation of all components permits each robot to recognize its neighbors and maintain formation simultaneously.

B. Hardware improvements

With the Lego Mindstorms NXT operating as a modular set, few modifications were required to fulfill design constraints and demands. In order to successfully implant the infrared mechanisms, the connector cables had to be spliced and soldered to accept an Infrared LED circuit. These LED components were then attached to LEGO building bricks in order to secure the lights in place, and to attach to the main frame. Otherwise, the hardware of the system remained the same, as some alterations are beyond the capabilities of this work. Possible improvements for future work should focus on the Bluetooth communication, in order to widen the scope of command to eliminate hierarchy. Also, adjustments should be made to the sensors to increase accuracy and to optimize readouts.

C. Programming capability and limitation

Numerous programming languages can be used to program the NXTs including NXT-G, LabVIEW, Next Byte Codes and Not eXactly C. For our investigation we used the graphical programming languages NXT-G and LabVIEW. LabVIEW enables the NXT and its sensors to be utilized to the full extent and allows for data logging. However, third party sensors from Hi-Technic Products did not have the Virtual Instruments required to operate in LabVIEW, therefore posing software problems. Conversely, NXT-G is compatible with all third party sensors from Hi-Technic. However NXT-G is limited in its computational ability as it is designed to handle small simple programs. Still NXT-G is capable of handling the swarm intelligence-based cooperation algorithm. Text based languages, NBC and NXC, have the capabilities of the NXT-G software but are not as user friendly. Overall, a combination of LabVIEW and NXT-G were found to be the best method for programming.

IV. MULTIROBOT SYSTEM PROTOTYPING

A multirobot system of four robots was constructed using Lego Mindstorms NXT kits to test their capability. The prototype of one robot member is shown in Figure 1. Using Legos for construction means all robots can be modified for any application. Each robot has one NXT intelligent brick and is equipped with other sensors for communication and localization. The NXT intelligent brick is the controller that regulates the robot and all of its sensors and motors. The intelligent brick uses Bluetooth to communicate with other NXT bricks.

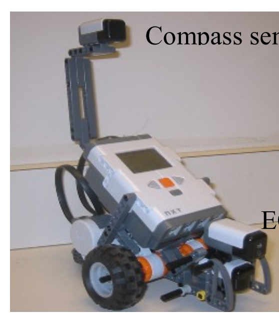

Figure 1: The prototype of one robot member

The steering system uses three wheels: left- and right-oriented wheels in the front, and a third independent wheel in the rear. The two front wheels are each connected to its own servo motor, while the rear wheel functioned to provide point turning and stabilization. The servo motors can be run synchronously for a zero turning radius.

Communication occurs through the use of light signals and Bluetooth. An infrared LED is attached to the back of each robot and can be continuously run or pulsed at different frequencies. The light can be discovered using an infrared detector. The signal is interpreted as a command to follow the infrared light. An external infrared light could also be used as a beacon to attract the robots to a particular spot. The Bluetooth allows for an intelligent brick to send and receive messages with three other robots. Robots are able to send information and commands in milliseconds to aid in their flocking and pattern formation.

Localization is achieved through the use of four different sensors. The compass sensor enables a robot to determine its heading as well as the relative direction compared to other robots. Each robot is equipped with either an ultrasonic sensor or electro optical proximity detector which allows a robot to determine how far it is from an object. Ultrasonic sensors are included in the Mindstorms NXT sets; however two or more ultrasonic sensors can interfere with each other. To minimize the interference EOPDs were implemented for the other robots. Once a robot was close enough to an object the IR Seeker, an infrared light detector, could help the robot distinguish between objects and the other robots.

V. A Swarm Intelligence Based Cooperation Algorithm

The application of swarm intelligence to the cooperation of multirobot system is a recently proposed novel approach. The application of swarm intelligence to multirobot systems is inspired from the observation of social animal behaviors such as foraging, fish schooling, bird flocking, and animal herding [8]. These animal interactions stand as fascinating examples of how a large number of simple individuals can interact to create collectively intelligent systems.

Triangular navigation is a swarm intelligence-based cooperation algorithm that was implemented for testing the developed Lego Mindstorms NXT based multirobot systems. The algorithm is inspired by the swimming behavior of a school of tuna, in which the schooling is based on the local interaction between its members in close proximity. Our algorithm is built upon an existing decentralized flocking algorithm which is achieved through individual decision-making [6], [9].

We employed a modification of triangular navigation to have each robot dynamically select two neighboring robots as shown in Figure 2.

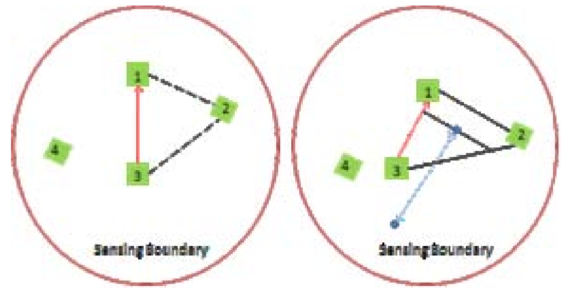

Figure 2: Neighbor selection

In doing so, one robot selects its nearest neighbor and then selects a second, which is closest to the first, to minimize the distance between the three robots. This results in the formation of a triangle. The robots then attempt to keep the same distance between each other to form an equilateral triangle. Our investigation supports that triangular navigation is a useful method for robot interaction and navigation.

VI. Experiments

Experiments were conducted to measure the effectiveness of the sensors used in the proposed prototype. The ultrasonic sensor was subjected to two tests: determining the distance from a flat object and then distance from another robot. The sensor was able to detect a flat object within two centimeters of accuracy, however once the object reached beyond 170 centimeters it was unable to detect any object. For detecting another robot the sensor was less accurate. It could only detect the robot to a maximum distance of 110 centimeters and the readings were within nine centimeters of accuracy. The Electro Optical Proximity Detector was subject to the same testing at much shorter distances, since it is a short range sensor. In this case we hoped to find a relationship between the intensity of light and distance. We found that for another robot it was only accurate up to 14 centimeters. From our analysis, it appears the intensity of light decays exponentially as an object moves further away, as seen in Figure 3.

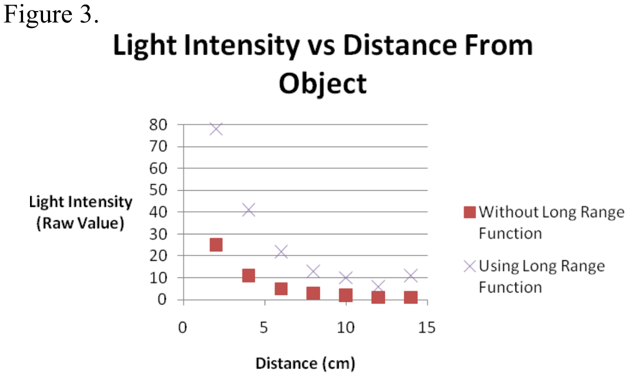

Figure 3: Light intensity values received from the EOPD at different distances

Knowing the capabilities of each sensor, we made the robots flock together and form a diamond shape by creating two equilateral triangles that share a common side, as shown in Figure 4. The robots were completely successful three out of ten total trials. The low success rate can be attributed to the limitations of the sensors. The inaccuracies of the distance sensors made it difficult to keep proper distance during formation travel. The compass sensors sometimes reported false values due to vibrations from robot movement, yielding slightly unlevel sensors. We also found scalability to be an issue when implementing the algorithm as we relied on Bluetooth communication between robots. However using NXT robots can be scalable as long as Bluetooth communication is not necessary.

Figure 4: Robot flocking pattern

The functionality of the NXT's Bluetooth was also examined through various tests. Each robot was able to connect to three other robots in master/slave configuration. In one experiment, a leader robot was able to send commands to each robot for synchronized spinning. In another experiment, a leader robot sent commands to others robots already in formation to move forward and turn synchronously. In both investigations, the robots' movements were in time, therefore demonstrating the effectiveness of using Bluetooth for communication.

In order to display the ability of the NXT's sensors, motors and Bluetooth communication we had each robot dynamically select two other robots to form a triangle and subsequently create a diamond shape. The robots were initially positioned in a straight line and the robots were able to develop the desired formation. After assembling into formation through the use of Bluetooth communication, they were able to synchronously travel towards a target. While traveling, each robot employed its sensors to control its distance and direction in relation to other robots to ensure intact formation. The robots performed these actions successfully, validating that LEGO Mindstorms NXTs can be used for multi-robot systems.

VII. CONCLUSION

Our investigation of Lego Mindstorms NXT indicates that the NXTs can be used for multirobot robotics applications. Lego Mindstorms can be effective in implementing swarming algorithms developed by computer scientists and mathematicians that may lack the necessary resources to design and construct their own robots. For applications in multirobot systems, it is important to know the capabilities and limitations of the NXTs and its sensors. While the inaccuracies of some sensors limited the success rate, we were able to apply a swarm intelligence- based algorithm to allow for the flocking of four NXT robots. This supports that triangular navigation can be an effective method for interaction between robots. Future improvements could also be made to improve the success and effectiveness of cooperation methods. The reconstruction of the robots to resemble a flat object and subsequently hold the sensors at right angles would improve accuracy. Implementing the use of touch sensors may also help correct the inaccuracies of the distance sensors. Finally, the elimination of Bluetooth communication would be helpful for scalability purposes.

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