Swarm Robotics: A Research Project with High School Students as Active Participants

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This paper was presented at the American Society of Engineering Education Annual Conference, Louisville, KY, June 2010, Paper No. AC 2010-1655.

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SWARM ROBOTICS: A RESEARCH PROJECT WITH HIGH SCHOOL STUDENTS AS ACTIVE PARTICIPANTS

Abstract

This paper is concerned with an educational project to provide a rich research experience on swarm robotics to high school students. A group of three mobile robots (the popular Lego NXT) was used to implement a 'search and rescue' operation. A bio-inspired global optimization technique called particle swarm optimization (PSO) was used as the principal algorithm. Each robot was placed in pre-defined positions with a target position corresponding to a single target. The robots were programmed to search in spirals until the target was found by any one of the robots. Once the target was detected the robots attempted to reach the target using the PSO algorithm. Results were encouraging. The high school students were wholly responsible for all programming and experimental tasks and got an immersive experience of a real-time cutting-edge engineering research application.

Introduction

Robotics is viewed as a relatively new and exciting field that has the potential to significantly impact the nature of engineering and science education at all levels, from K-12 to graduate school[1-7]. A recent development in robotics is swarm robotics[8], where the use of a large group (swarm) of small, simple and cheaper robots with limited local processing capability in place of a large, powerful and expensive robot is being envisioned in many hazardous, unknown and dynamic environments. The advantages of using swarms instead of a single centralized robot include enhanced capabilities in terms of wider dynamic coverage and fault tolerance. Some extraordinary consequences (not always evident) include self organization and emergence of new patterns and behavior as has been observed in nature in groups of ants, birds and fish, for example. Application areas of robot swarms include: autonomous search and rescue operation, decentralized autonomous systems for protection and damage control, among others. For successful implementation, both hardware and software issues of such co-operative robots need proper investigations[8-13]. Swarm robotics is hence a legitimate research problem at the cutting edge. This was an important consideration for us as we wanted to ensure that the students would have a rewarding experience of a non-trivial problem that would create an excitement that would sustain their interest and enthusiasm. In addition, the goal of the project was to truly explore the research problem as well in order to obtain new results that could be published in a research venue with the high school students as active and direct participants, and not be used in a secondary role.

Villanova University has a structure of outreach to involve K-12 students including communities which are under-represented in Science and Engineering. Two main projects are the V.E.S.T.E.D. Academy and BEST. The V.E.S.T.E.D. Academy in its fourth year at Villanova University aims to promote academic achievement in mathematics, science, technology, and engineering for at-risk middle and high school students. BEST is a non-profit, volunteer-based organization whose mission is to inspire students to pursue careers in engineering, science, and technology through participation in a sports-like, science and engineering-based robotics competition. Villanova University is also a participant for GEAR UP, a teacher training program to increase teacher and student understanding of math subjects and to help them use robotics to accomplish their mathematics goals.

To provide educational and research experiences to high school students, a project on swarm robotics was initiated in Summer 2008 in the Department of Mechanical Engineering at Villanova University with a team of two high school students (Chiraag was a Freshman, and Sanjeev was a senior); a senior Mechanical Engineering undergraduate (Mark) as a mentor; and, with the supervision of two faculty members. The aim was to test the feasibility with a small group with the intention to extend the program to a larger group in line with the outreach programs of the University and with potential funding support from external agencies. In this paper, the activities and results related to this pilot project are reported.

We selected a group of three simple mobile robots (Lego NXT) to study 'search and rescue' operation in the context of swarm robotics. A bio-inspired global optimization technique called particle swarm optimization (PSO) was used as the main algorithm. PSO was originally proposed by Kennedy and Eberhart[14] as a population based stochastic optimization technique inspired by the social behavior of bird flocking. PSO is a computationally simple algorithm based on group (swarm) behavior. The algorithm searches for an optimal value by sharing cognitive and social information among the individuals (particles). PSO has many advantages over evolutionary computation techniques like genetic algorithms in terms of simpler implementation, faster convergence rate and fewer parameters to adjust[14, 15]. The popularity of PSO is growing with applications in diverse fields of engineering, biomedical and social sciences, among others[16-18].

The basic aspects of the Lego NXT platform are discussed briefly in Section 2. In Section 3, the fundamental principles of PSO are presented. The implementation issues and results are presented in Section 4. Conclusions and future steps are summarized in Section 5.

LEGO NXT Robot platform

Hardware

Lego Mindstorms NXT robotics kit [19] was used as the robotic platform for the project. Four kits were procured; at any time three were used, and the fourth was kept as a stand-by. The main component of a NXT kit is the NXT intelligent brick. There are two microcontrollers embedded inside the brick. One brick can take inputs from four sensors and can control up to three motors at once. The NXT kit comes with four sensors, namely, light, sound, touch and ultrasonic sensors. In this project only two of these sensors, touch and ultrasonic sensors were used. Two of the motors were used for driving the robot. The third motor was used to rotate the ultrasonic sensor through a geared mechanism. Figure 1 shows the photograph of two assembled NXT mobile robots. For communication with a PC laptop, the wireless Bluetooth connection was used. The robot also has a speaker for sound and a LCD display to display the status.

NXT Brick

Figure 2 shows the photograph of the NXT intelligent brick. The NXT brick contains an Atmel 32-bit ARM7 processor running at 48 MHz with 64 KB of RAM and 256 KB bytes flash memory. There is a second processor which is an Atmel 8-bit AVR running at 8 MHz with 512 KB RAM and 4KB of flash memory. The AVR controls the peripherals while ARM7 has the main processing power. The 100 x 64 LCD display is used to navigate through the NXT menu and shows the status of the brick. The NXT is connected to its peripherals through a six-wire cable digital platform.

Servo Motors

Figure 3 shows the external and internal views of one of the servo motors. The gears help reduce the wheel speed and increase its torque. Each motor has a built-in tachometer to keep track of the motor rotation with an accuracy of $\pm 1°$. Each motor is also equipped with a servo loop for velocity and position control.

Touch Sensor

Figure 4 shows a photograph of the touch sensor used in the NXT kit. The touch sensor senses when it is pressed and when it is released. This signals to the robot that it has contacted another object. The sensor was activated using a mechanical link in front of it. When the robot hits an object with the link activating the touch sensor, the NXT was programmed to stop moving forward.

Ultrasonic Sensor

Figure 5 shows the photograph of the ultrasonic sensor mounted on a geared platform driven by one motor. The ultrasonic sensor was used for the robot to avoid obstacles and measure distance. The rotating platform was used programmed so that the ultrasonic sensor can cover the range of -90° to +90° in front of the robot. The sensor measures the distance by calculating the time it takes for a sound wave to hit an object and to return. It measures a distance of up to 255 cm with a precision of ± 3 cm.

Bluetooth

The communication between any NXT robot and the PC laptop (host) was implemented using a D-Link DBT-120, wireless Bluetooth 2.0 USB Adapter. It is compatible with Windows 2000/XP, follows the IEEE 802.15.1 standard, uses USB 2.0 interface, and sends signals at 2.1Mb/s. [20]. The Bluetooth USB Adapter supports the Microsoft Service Pack 2 Bluetooth stack.

Java Software Platform for NXT

The NXT needs to have a firmware installed in order to be usable. The default firmware and software, NXT-G, are adequate for normal users. However, for greater flexibility, an alternate firmware and software system for the NXT, called leJOS NXJ, was adopted for the project. It interfaces with the NXT hardware and allows users to program in Java. The PC laptop used leJOS JVM (Java Virtual Machine) under a Linux operating system. An open source integrated development environment (IDE) suitable for leJOS NXJ, called Eclipse, was used in this project. It is noteworthy to observe that all of these issues with leJOS and Linux were investigated, debugged and implemented exclusively by the high school students.

Particle Swarm Optimization (PSO)

Standard Particle Swarm Optimization (PSO)

In this section, a brief introduction to the PSO algorithm is presented; for details, a suitable text[15] can be referred to. Recent overviews of PSO and its variants can be found in the literature[16-18]. For a problem with *n*-variables, each possible solution can be thought of as a *particle* with a position vector of dimension *n*. The population of *m* such individuals (particles) can be grouped as the *swarm*. Let x_{ij} and v_{ij} represent respectively the current position and the velocity of *i*th particle ($i=1,m$) in the *j*th direction ($j=1, n$). The fitness of a particle is assessed by calculating the value of the target or objective function for the current position of the particle. If the value of the objective function for the current position of the particle is better than its previous best value, then the current position is designated as the new *best individual* (*personal*) location *pbest*, p_{bij}.

The best current positions of all particles are compared with the historical best position of the whole swarm (*global* or *neighborhood*) *gbest*, p_{bgj}, in terms of the fitness function. The global best position is then updated if any of the particle individual best (*pbest*, p_{bij}) is better than the previous global best (*gbest*, p_{bgj}). The current position and the velocity determine the trajectory of the particle. The velocity of the particle is influenced by three components, namely, inertial, cognitive and social. The inertial component controls the behavior of the particle in the current direction. The cognitive and the social components represent the particle's memory of its personal best position (*pbest*) and the global best position (*gbest*). The velocity (v_{ij}) and the position (x_{ij}) of the particle are updated for the next iteration step ($k+1$) from its values at current step k as follows:

$$v_{ij}(k+1) = v_{ij}(k) + c_1 U(0,1)(p_{bij}(k) - x_{ij}(k)) + c_2 U(0,1)(p_{bgj}(k) - x_{ij}(k)), \qquad (1)$$

$$x_{ij}(k+1) = x_{ij}(k) + v_{ij}(k+1), \qquad (2)$$

where, r_1 and r_2 represent uniformly distributed random numbers in the range of (0,1). These random numbers present the stochastic nature of the search algorithm. The constants c_1 and c_2 define the magnitudes of the influences on the particle velocity in the direction of the individual and the global optima. N represents the maximum number of iterations (epoch).

In many early applications, good results were obtained when the inertia term ω was decreased from 0.9 to 0.4 linearly enhancing the exploration at the beginning and exploitation towards the end of the solution process. In this work, c_1=2.0, c_2= 2.0 were used.

Distributed Particle Swarm Optimization (DPSO)

In the present work, each robot is assumed to be a particle in the swarm. Each robot is equipped with touch and ultrasonic sensors in addition to the two servo motors for keeping track of the robot's position. Each robot measures its position, updates its velocity and position, and updates its personal best value (*pbest*) and its personal best position. Each robot then sends to the PC the values of its current position, and its personal best value. The PC receives the *pbest* values of all robots and transmits to them the global best (*gbest*) to be used by each robot for updating its velocity and position for the next move. This arrangement allows each robot to make its calculations locally and in parallel, and shares the information of *pbest* and *gbest* with the host PC minimizing the communication overhead and the attendant delay.

DPSO Based Implementation

The aim of the present approach is to select the robot positions such that each robot heads towards the target. In order to implement that, an objective function representing the sum of squared error of the robot position relative to the target is minimized.

$$J = \sum_{l=1}^{N} [((x_d - x_l)^2 + (y_d - y_l)^2]) \qquad (3)$$

Where l is the robot index, N represents the total number of robots, (x_d, y_d) is the desired position and (x_l, y_l) represents the current position of the robot 'l'. In the present work, DPSO was used from a user-given range for each particle position [-400, 400] mm to cover the entire search space.

Implementation Results and Discussions

The project steps were (i) to get familiarized with the Lego Mind storms NXT hardware, (ii) to interface the sensors and actuators (motors), (iii) to program the NXT brick using leJOS NXJ, (iv) to establish communication between NXT robots and a PC laptop using Bluetooth, (iv) to program each NXT for uniform spiral coverage using Archimedes' curve, and (iv) to implement the distributed particle swarm optimization (DPSO) algorithm for 'search and rescue' operation using a swarm of NXT mobile robots.

Four NXT robot kits were procured for the project. Each robot was assembled using two servo motors for driving, the other servo motor for rotating the base of the ultrasonic sensor for the total front view of the robot and the touch sensor with a link in the front for avoiding obstacles. At any time three of these robots were used and the fourth one was kept as a stand-by.

LeJOS NXJ codes were written for acquiring data from the sensors and motors and for sending signals to the motors. The sensors were calibrated and the motors were tested. The program was written using classes for the corresponding functionalities of the sensors and the motors. The communication between the NXT robots and the PC laptop was implemented using leJOS JVM with the laptop running under a Linux operating system and with a D-Link DBT-120 Bluetooth wireless adapter. After substantial experimentation, the Linux became the preferred operating system for the current application since the Windows operating system was very buggy with the real-time wireless communication, and never worked satisfactorily. In the first phase, the two students essentially competed by dividing the work to experiment with the two operating systems, and the subsequent phases proceeded with the “winning option” of the friendly competition.

The coverage and target reaching was implemented in a decoupled manner. The uniform spiral coverage using Archimedes’ curve was implemented in leJOS NXJ. The pseudo code for DPSO, shown in Table 1, was implemented in leJOS NXJ. The codes were developed in Eclipse IDE and the firmware was uploaded to each NXT.

The NXT robots were placed in three known positions in the lab for this project. In the first phase, the robots would search for an object in covering the respective local area in spirals. Figure 7 shows a typical coverage plot for one NXT. In the next phase, the NXT would be required to go the target position using DPSO. Figure 8 shows the paths of the robots in a typical run. As is clear from the figure, all the robots reached quite close to the target. The separation between the robots is due to the errors in the built-in tachometers in the motors.

As there were only two high school students we did not carry out any surveys to determine the outcomes. An informal interview showed a very positive feedback with a heightened interest in both of them to pursue science/engineering careers. Sanjeev is currently a sophomore Mathematics major at Carnegie Mellon University, and Chiraag is a junior in high school.

Roles of Team Members

As stated earlier, the team consisted of a faculty project director (CN), a research faculty (BS) specializing in computational intelligence techniques, an undergraduate senior student (MW), a high school senior (SR), and a high school freshman (CMN). CN directed the project, BS developed the algorithm, and both of them provided supervision for the students. MW was a general resource person who, in particular, helped with MATLAB processing of collected data. SR and CMN were completely responsible for all hardware assembly and software coding and debugging. All experiments were conducted by them with some help from MW. Initially, we set up a competition between C and Java as possible contenders for executing the programs on the NXT platform. Neither one of these languages is supported by Lego and required substantial hacking. SR chose C (on Windows), and CMN chose Java (on a Linux platform); after a few weeks, it became clear that Java & Linux were the better solution with a higher degree of reliability. CMN then took over all programming aspects of the project with some assistance from SR. They did not need any assistance from the senior team members; in fact, it is fair to say that the senior team members themselves do not have any knowledge of the intricacies of the software and hardware/software interactions.

Extension of the project to larger teams have not been fleshed out yet. A competition set-up between different teams would perhaps make the most sense. Only one of possible swarm tasks was explored in this project; with multiple teams, more swarming tasks could be posed as challenges. PSO is a less complex algorithm compared to other optimization algorithms and lends itself nicely to implementation on simpler controller architectures; in addition, it is quite intuitive and its principles can be grasped by reasonably well-trained high school students. This would hence not represent a significant obstacle to them as would many other more sophisticated algorithms.

Conclusions

The paper presents an exploratory project on swarm robotics involving high school students. The project provided educational and research experiences to the students covering a wide range of areas like sensing and actuation, control, swarm intelligence, hardware and software implementation. The students got a first-hand immersive experience of testing hardware and implementing a novel algorithm in a cutting-edge engineering research application.

Some hardware and software issues would need closer and more thorough investigations for further enhancements. These are currently under consideration for the next phase. For example, for seamless implementation of coverage, search and rescue would be considered using a multimodal approach where the operation would switch from one mode (coverage) to the other (search and rescue). The involvement of larger groups of students with potential external funding is also envisioned in the future.

Acknowledgment

The work was carried out with partial support from Naval Sea Systems Command (NAVSEA) grant N00024-07-C-4212 (Monitors: Marc Steinberg, Richard Wagner and John Metzer). This support is gratefully acknowledged.

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Table 1: The pseudo code for distributed PSO (DPSO) algorithm

```
Initialize the swarm
While (mission on)
     get sensor readings
  If (no object is found) Then
       move in spiral
   Else
     evaluate the target position
     report the target position to the host
     set dPSO on
         While (dPSO on)
           get sensor readings
           update local best
           update global best;
           report to host the current position and
           get global best
           move to the next best position
           avoid obstacle(s), if present
                 If (target reached)  set dPSO off
         End /end while (dPSO off)
      Endif /endif/
   If (mission completed) set mission off
End /end while/completion of mission/
```

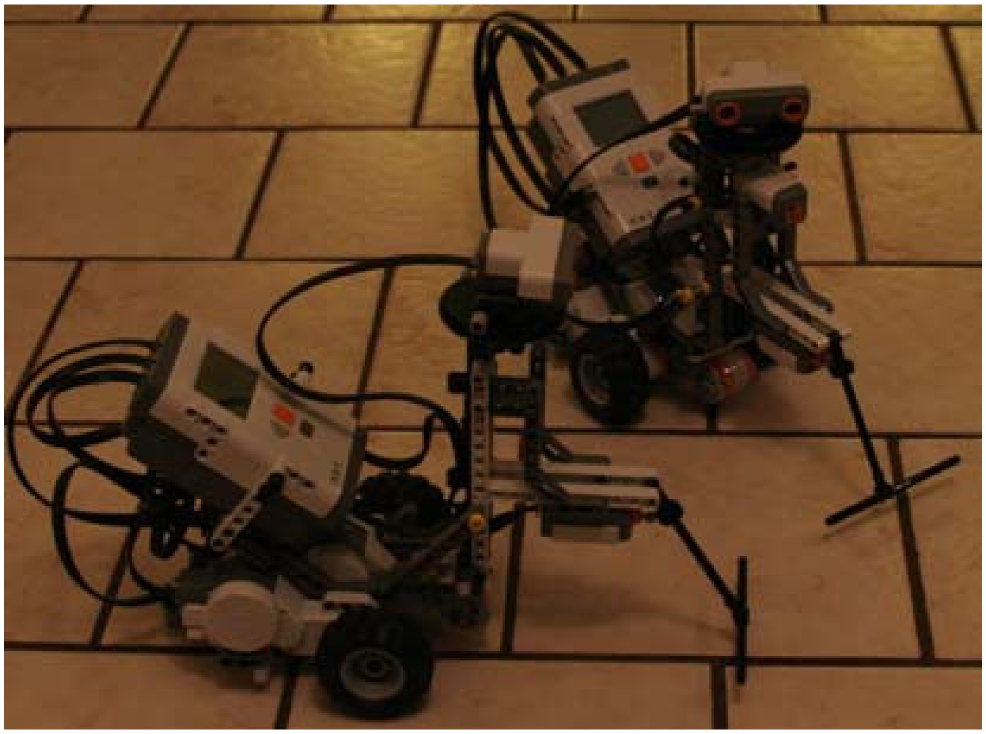
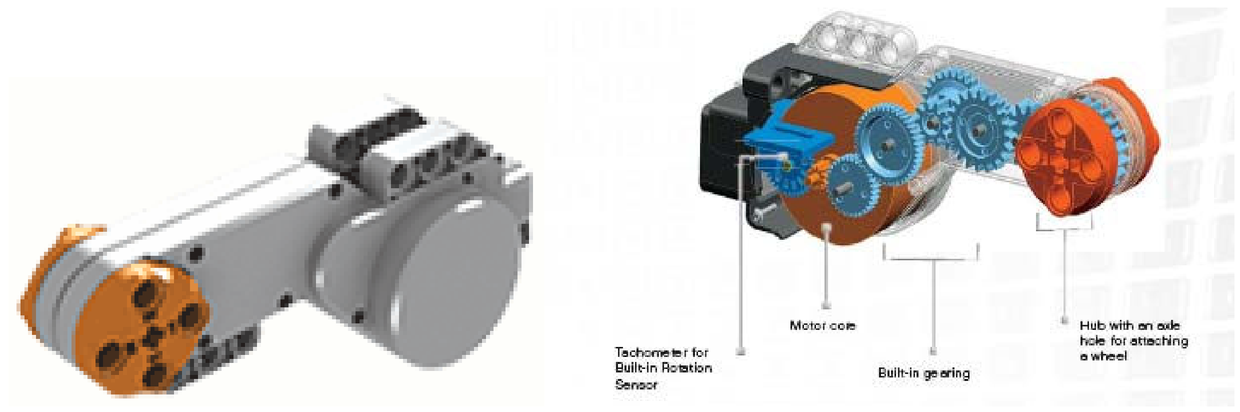


Fig. 1 Two assembled Lego NXT mobile robots

Fig. 2 NXT Intelligent brick


Motor core
Tachometer for Built-in Rotation Sensor
Built-in gearing
Hub with an axle hole for attaching a wheel

(a) (b)

Fig.3 Views of a servo motor (a) External view, (b) Internal view [19]

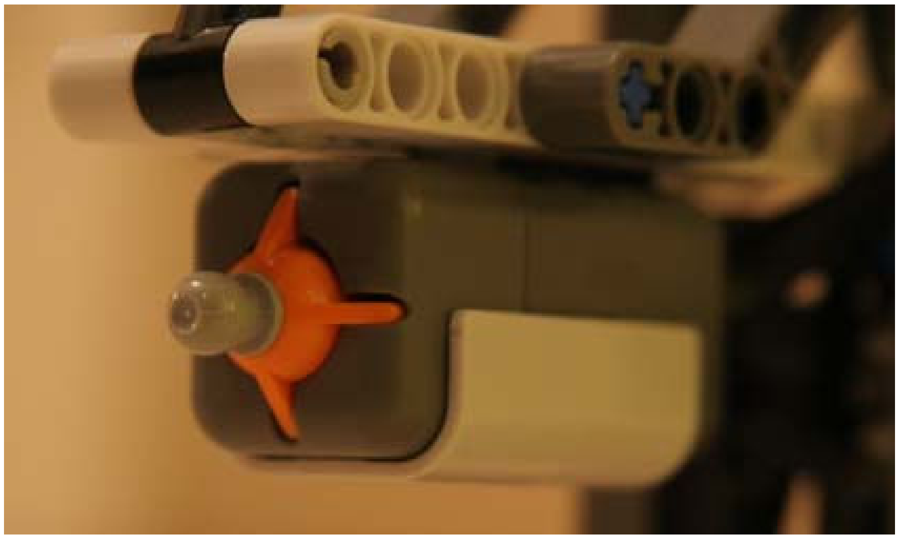


Fig. 4 Touch sensor of NXT

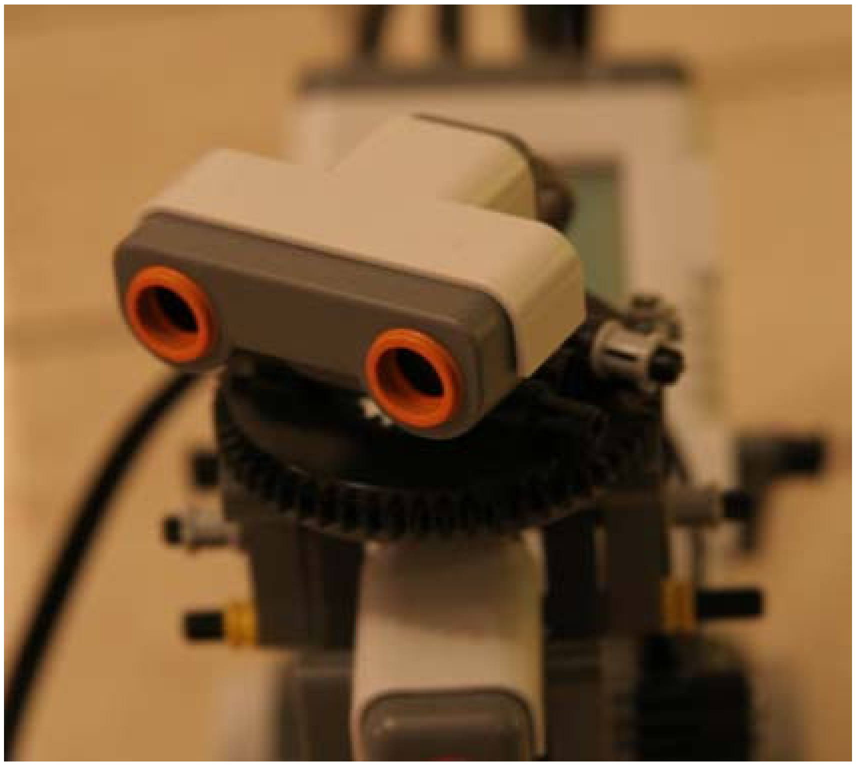


Fig. 5 Ultrasonic sensor of NXT

Fig. 6 D-Link DBT-120 Bluetooth adapter [20]

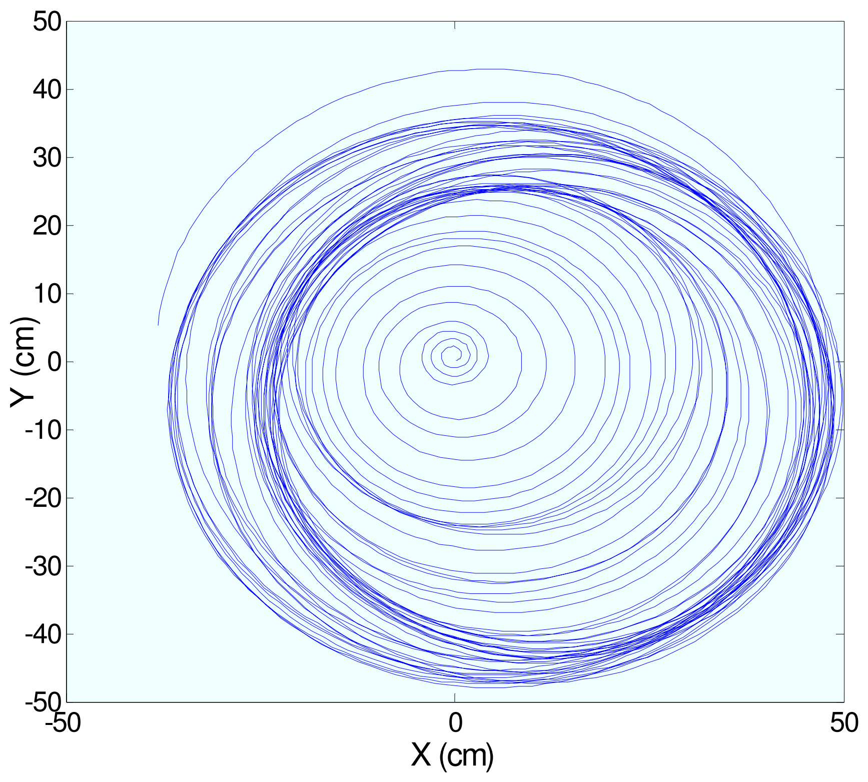


Fig. 7 Area coverage (spiral)

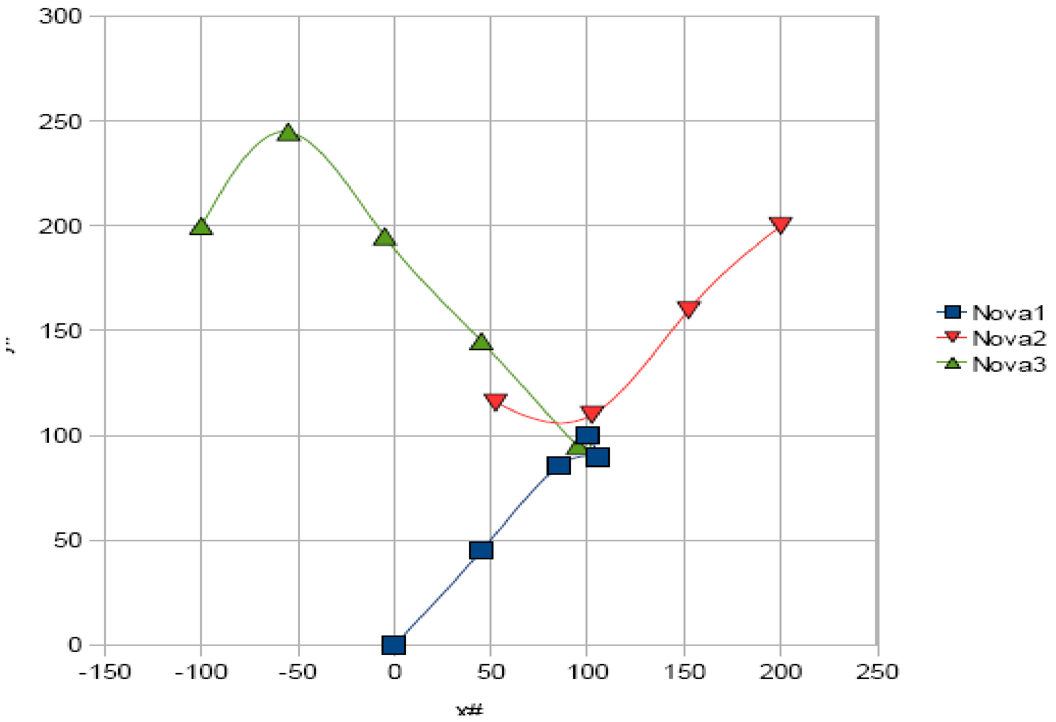


Fig. 8 Paths of robot swarm