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AUTONOMOUS NAVIGATION OF A LUNAR EXCAVATION ROBOT USING ARTIFICIAL POTENTIAL FIELD METHOD

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ABSTRACT

NASA Lunabotics Mining Competition is an annual robotics competition organized by NASA Kennedy Space Center at their Visitors Complex in Florida every year. In May 2013, a team from Manipal University participated in the 4^{th} Annual Lunabotics Mining Competition. The participating teams need to develop a tele-operated or automatic lunar excavation robot to mine lunar soil (regolith) on a simulated lunar surface. This article presents the methods used by the team in order to achieve full autonomy of the robot for the traversal of the pre-described arena. This paper describes the project from the formulation of the navigation algorithm to the simulation in detail keeping focus on the basic and specific functionality of the robot.

KEYWORDS: Mobile Robot, Autonomous Navigation, NASA Lunabotics Mining Competition, Artificial Potential Field Method, Encoder Based Tracking

I. INTRODUCTION

Robo Manipal, the official robotics team of MIT, Manipal was formed in the August of 2010 and participates in national and international level robotics competitions. In 2013, the team participated in the 4^{th} NASA Lunabotics Mining Competition [1] and developed a lunar excavation robot with a teleoperation system. The team stood #19 in the Joe Kosmo Award for Excellence from 50 teams. In order to achieve more points in further versions of the competition, the team developed a plan for autonomous control of the lunar robot (called Lunabot). The plan involved modification of only the systems that failed or did not perform to the team's satisfaction – improvements to the telemetry system and an autonomous navigation system. The team decided on the implementation of the Artificial Potential Field Method for the autonomous navigation. This article describes the research of this method and the development of the system for simulation.

II. NASA LUNABOTICS MINING COMPETITION

NASA conducts its annual Lunabotics Mining Competition every year since 2010 to encourage and enhance practical education and promote interest in space and science, technology, engineering and mathematics (STEM). NASA also encourages participating teams in the field of technical management or more specifically, systems engineering. This event is attended by teams from all over the world and in May 2013, the competition saw 50 student teams from across 6 continents.

Each participating team must build a teleoperated or autonomous lunar excavator which can mine and deposit a minimum of 10 kilograms of lunar regolith. This robot has to traverse a 7.38m by 3.88m simulated lunar surface.

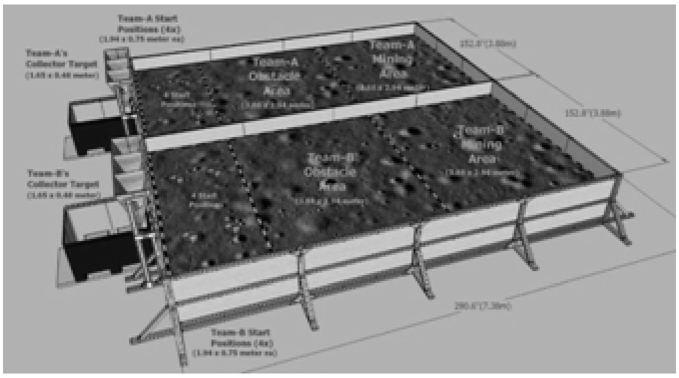

Figure 1: Lunar Arena (Lun Arena) [1]

The robot, starting from one of the four randomly chosen starting points has to avoid obstacles (rocks and craters) to reach the mining zone where the excavation operation has to be carried out. The robot has to move back across the same path and dump the mined soil in the collection box (or LunaBin). The judging will be done according to a scoring system where points will be added for weight of the lunar soil mined, dust tolerant design, ability to demonstrate measurement of power usage and autonomy.

III. THE ROBO MANIPAL LUNABOT

The robot design was a one year process and was accepted as a Junior Year Industrial Training Project by the department of Electronics and Communication Engineering.

Figure 2: Isometric View of the Lunabot

Mechanically, the robot was chosen to be a four wheeled differential drive. Additionally, the robot was equipped with a vertically sliding bucket excavator and a swiveling hopper for the dumping of the excavated regolith in the collection box.

The mechanical system was developed by in-house designed and produced mechanisms and commercial off-the-shelf (COTS) products. The electrical and software system was designed initially to do the following tasks:

- Connect to NASA's network
- Process input keyboard strokes to send control signals via Wi-Fi

- Receive control signals onboard the robot
- Process control signals and send values to the electronic control unit (ECU) to drive the robot.
- Provide telemetry to the system. Access state details of motors, shaft encoders and the current and voltage states of the robot overall.

However, as a need for the development of an autonomous system rose, the electrical and software system was modified but the telemetry was maintained.

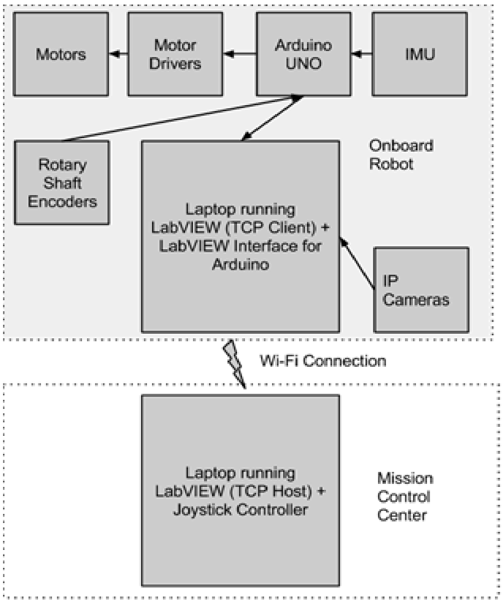

Figure 3: Electrical and Software System

The only thing that changed in the final electrical system are the four sensors for initial orientation measurement as described in Figure 10 and the 9 Infrared Range Finding sensors (Figure 5) according to the sensor placement on the Khepera III (Figure 4) robot. The sensors on the Khepera III platform are placed at the distances shown in the figure below. All measurements are in meters. This platform was used for the simulation of the Lunabot's autonomy system.

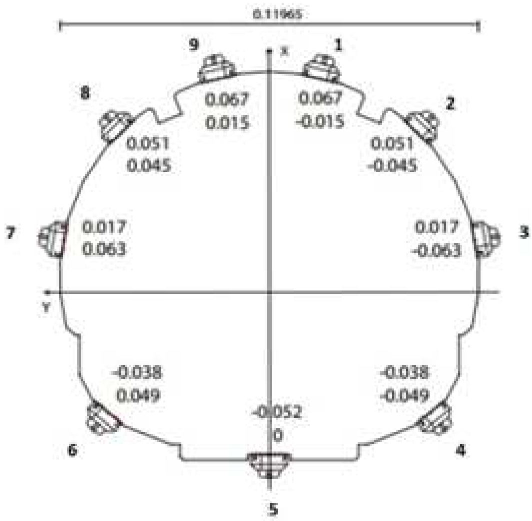

Figure 4: Sensor Placement on the Khepera III [2]

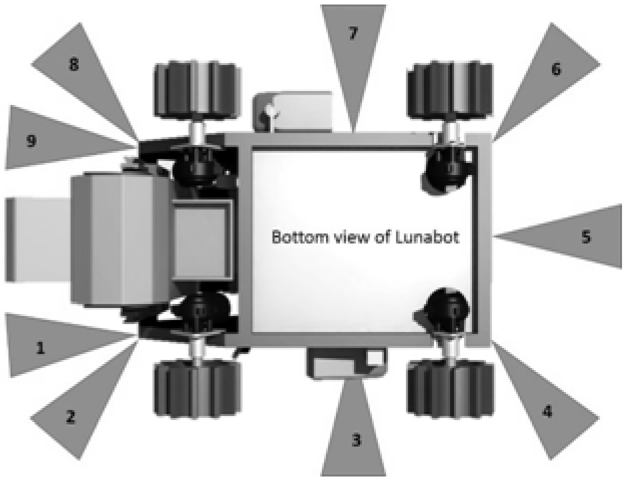

Figure 5: Sensor Placement on the Lunabot According to the Placement (Angular) on the Khepera III

IV. TRAJECTORY DESCRIPTION

This section describes the basic idea behind the motion of the robot – i.e. how the trajectory is to be decided. According to the problem statement of the competition, there are three zones in the LunArena – the start zone, the obstacle zone and the mining zone. As only the obstacle zone contains the obstacles (rocks and craters), the Artificial Potential Field Method will be applied in that zone only. In the competition attempts at NASA Kennedy Space Center in May, 2013, it was observed that the mechanical structure of the robot was capable of traversing over craters without any hindrance. Hence, in this implementation, only the rocks are considered as obstacles.

The following figures describe the motion of the robot from the start position of the robot till the beginning of the mining zone.

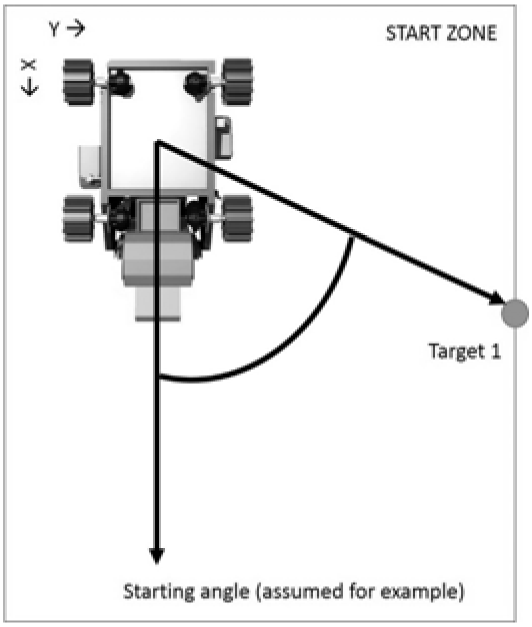

Figure 6: Detection of Angle towards Target 1. This Starting Position is Assumed (Can be One of 4 Start Positions and Directions According to the Problem Statement)

Figure 6 describes the detection of the position of the robot and the calculation of the angle the robot has to turn to face Target 1 (middle of the line between the start and the obstacle zones) using the *GTA* (Go to Angle) vector. The following method was used for the same:

- Initialize [x_inity_init] (calculated), initial coordinates of the robot, the top left of the image being the origin.
- Initialize [x_target1 y_target1], final coordinates of the robot, i.e, the coordinates of Target 1
- Find angle to Target 1 using atan2(y_target1 – y_init, x_target1 – x_init)

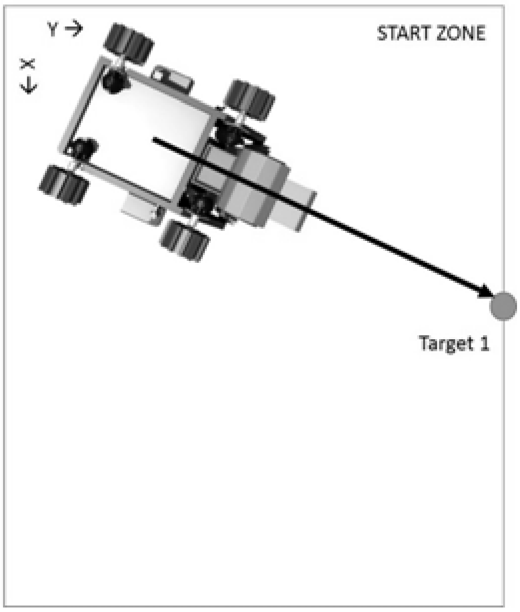

Figure 7: The Vector Directing the Robot towards Target 1

Figure 7 shows vector *GTT* (Go to Target) which drives the robot till Target 1.

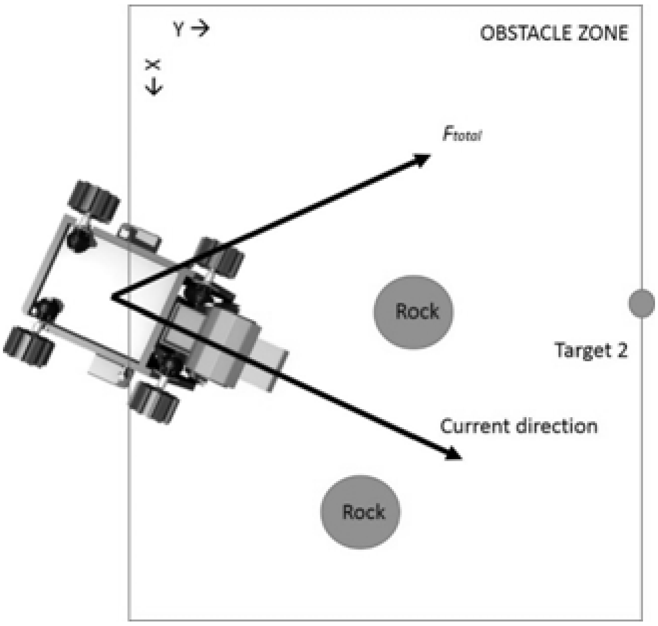

Figure 8: Vector Obtained after APF Calculations. Vector Moves towards Target While Avoiding Obstacles

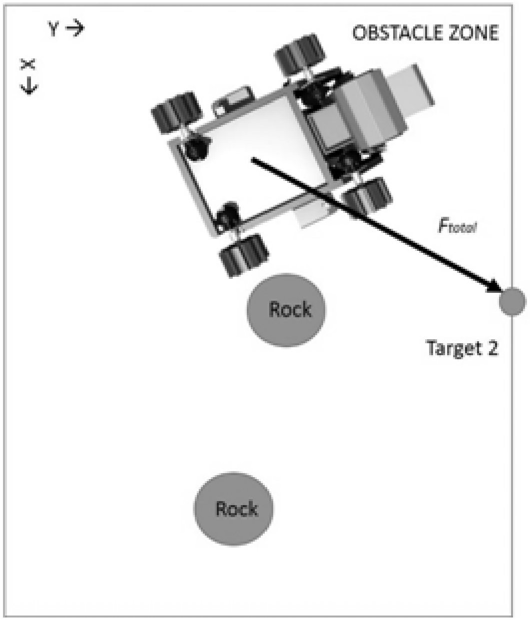

Figure 9: The Robot at its Intermediate Position in the Middle of the Mining Zone

The above figures describe the motion in the obstacle zone. The F_{total} vector shown is described in Section VII. This vector is calculated using the Artificial Potential Field Method and drives the robot towards Target 2 (middle of the line between the obstacle and the mining zone).

V. INITIAL POSITION AND ORIENTATION DETERMINATION

According to the problem statement provided by NASA Kennedy Space Center, the participating teams are not allowed to provide initial position and orientation details to the robot during the setup time. Moreover, if the robot is to operate in the autonomous mode, no positional data is to be provided to the robot from the mission control station (i.e. no human contact except the signal to start). In accordance to the problem statement, the robot is placed in one of the four start locations in the start zone in one of the four directions – North, East, West, and South. As the options for initial position and heading were limited, a simple algorithm was developed. Four IR based range-finding sensors were placed, one on each side of the robot – Front, Left, Right, Back, as described in Figure 10.

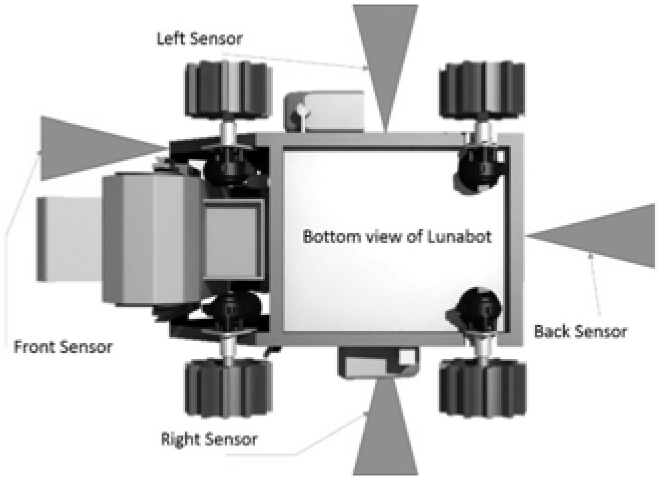

Figure 10: Locations of the Sensors for Initial Position Calculation

Once the sensors were fixed, the following algorithm was followed.

- Initiate Front, Back, Left and Right sensors
- Measure values of the sensors
- Check with ranges calculated for each of the four initial positions and directions and decide initial position and heading. Since the robot will start from one of the four pre-defined positions and one of the four cardinal directions, the sensor value ranges for each position was calculated and stored.
- Using exact sensor values, initiate values for the rotary shaft encoders.

Note that these sensors were used only for the calculation of the initial position of the robot and not for the obstacle avoidance.

VI. POSITIONAL TRACKING

To follow the Artificial Potential Field Method, it was imperative to track the robot. GPS tracking couldn't be used as it was found to be inaccurate over a small area. Moreover, GPS cannot be used in lunar applications. The usage of optical shaft encoders were involved. As a four wheeled differential drive was incorporated, shaft encoders were attached to each of the four motor shafts. The average of the movements of each wheel encoder was calculated to determine the path of the center of mass of the robot. The following steps were used:

- Store initial coordinates.
- Using telemetry system, monitor movements of each wheel encoder.
- Convert each rotation of each wheel encoder into linear distance travelled. Accordingly, track the exact location of the robot in the workspace.

VII. ARTIFICIAL POTENTIAL FIELD METHOD

The potential field method is widely used for path planning in mobile robotics owing to its mathematical simplicity. With leading publications from multiple authors in the past decade, the potential field method is used commonly as a method of navigation for autonomous robots. Latombe, in 1991 [3] described the basic concept of the potential field method – fill the robot's workspace with an artificial or virtual potential field. The robot is attracted to the target and repelled by the obstacles. Although, in most examples of implementation, the environment is dynamic – the robot and the target are continuously moving – in this case, a stationary target is considered.

In a paper authored by Ge and Cui [4], a representation of the attractive and repulsive potential field functions are mentioned which will be used in this paper. In convention, the attractive potential field is described as a function of the distance between the robot and the target when the target is fixed in the robot workspace. However, as described in the research by Ge and Cui, a new function was developed which also considered the velocity of the robot and the target, considering the target is moving. Using the same equation but considering a stationary target, we get the following function (Equation 1):

$$U_{att}(p,v) = \alpha_p \parallel p_{tar}(t) - p(t) \parallel^m - \alpha_v \parallel 0 - v(t) \parallel^n \quad (1)$$

The target velocity is considered zero. The positions of the robot and the target are described as p(t) and $p_{tar}(t)$ respectively, where each of the position vectors are given in the form of $p=[x\ y]^t$ where x and y are the coordinates of the robot on the defined axes on the lunar arena. The velocity of the robot is defined as v(t) at a given time t. α_p and α_v are positive scalar parameters while m and n are positive constants.

The virtual attractive force is defined in Equation 2:

$$F_{att}(p) = -\nabla U_{att}(p) = -\frac{\partial U_{att}(p)}{\partial p} \tag{2}$$

In terms of both position and velocity, this can be described as

$$F_{att}(p, v) = F_{attp}(p) + F_{attv}(v) \tag{3}$$

Where, each of the forces can be described as

$$F_{attp}(p) = m\alpha_p \parallel p_{tar}(t) - p(t) \parallel^{m-1} n_{RT} \tag{4}$$

$$F_{attv}(p) = n\alpha_v \parallel 0 - v(t) \parallel^{n-1} n_{VRT} \tag{5}$$

Where n_{RT} and n_{VRT} are unit vector pointing from the robot to the target and the unit vector denoting the relative velocity direction with respect to the robot, (i.e the robot velocity vector) respectively

To consider the obstacles along the way, Ge and Cui involved the relative positions and velocities between the robot and each of the obstacles, while considering moving obstacles. In the similar manner as before, we can describe the equations of the repulsive potential while considering the relative velocity between the robot and the obstacle as the robot velocity itself. Hence modifying the equations, we get the following function:

$$U_{rep}(p, v) = \begin{cases} 0 \ if \ \rho_s(p, p_{obs}) - \rho_m(v) \geq \rho_0 \ or \ v \leq 0 \\ \eta\left(\frac{1}{\rho_s(p, p_{obs}) - \rho_m(v)} - \frac{1}{\rho_0}\right), \\ if \ 0 < \rho_s(p, p_{obs}) - \rho_m(v) < \rho_0 \ and \ v > 0 \\ not \ defined \ if \ v > 0 \ and \ \rho_s(p, p_{obs}) - \rho_m(v) < 0 \end{cases} \tag{6}$$

Where $\rho_s(p, p_{obs})$ is the minimum distance between the robot and the obstacle and $\rho_m(v)$ is the distance traveled by the robot if the robot velocity equals zero when an acceleration of a_{max} is applied.

Similar to the attractive force, the repulsive force can be defined by Equation 7

$$F_{rep}(p, v) = -\nabla U_{rep}(p, v) = -(\nabla_p U_{rep}(p, v) + \nabla_v U_{rep}(p, v)) \tag{7}$$

Considering multiple obstacles, we can describe the total repulsive force as a summation of all repulsive forces from all obstacles.

$$F_{rep} = \sum_{i=1}^{n_{obs}} F_{repi} \tag{8}$$

And hence, the total force acting on the robot can be defined as the summation of the total attractive forces and the total repulsive forces.

$$F_{total} = F_{att} + F_{rep} \tag{9}$$

SIMULATION

The total force obtained determines the motion of the robot at that particular instant. Since the functions applied provide with the x and y values of the force, the magnitude and angle of the total force applied is obtained. Using the angle of the force vector, the angular velocity is determined and the magnitude of the force corresponds to the linear velocity. The left and right motor speeds can then be calculated using the following unicycle to differential drive model using the following code.

```
r = v/R + (w*L) / (2*R);

l = v/R - (w*L) / (2*R);
```

In the above expressions, r and l describe the right and left motor speeds respectively, v describes the linear velocity, w is the angular velocity and L and R stand for the distance between the left and right wheels and the wheel radius respectively. The angular and linear velocities are varied using a PID regulator.

The simulation was performed using the Sim. I Am [5] robotics simulator developed by the Georgia Robotics and Intelligent Systems Laboratory (GRITS Lab) [6] at Georgia Tech [7]. In this simulation, the artificial potential field concepts were applied on a Khepera III robot, since the sensor placement was incorporated from the same. Below are some images from the simulation.

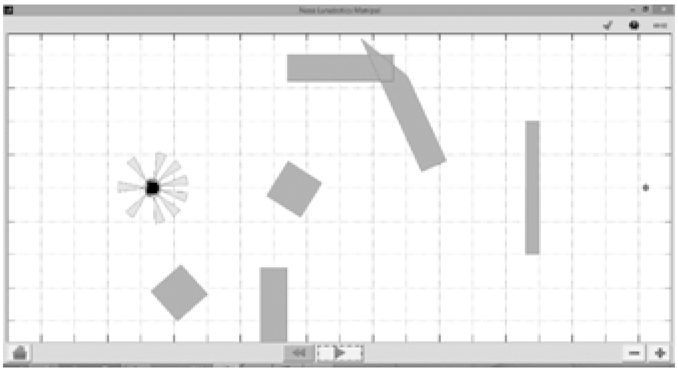

Figure 11: The Robot at its Starting Position

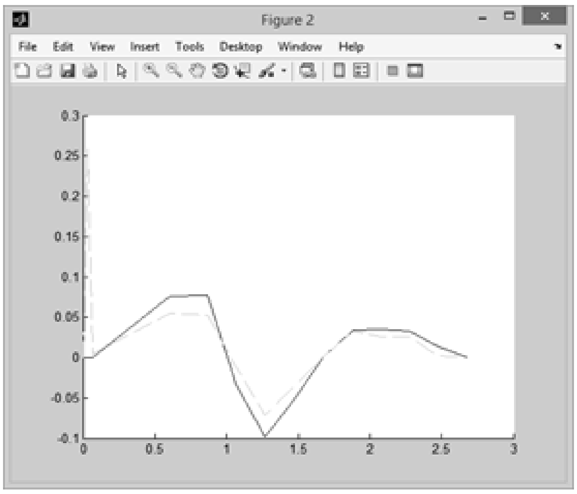

Figure 12: The Graph of the Angle of the Robot. The Dotted Lines Describe the Reference Angle While the Solid Line Describes the Actual Angle

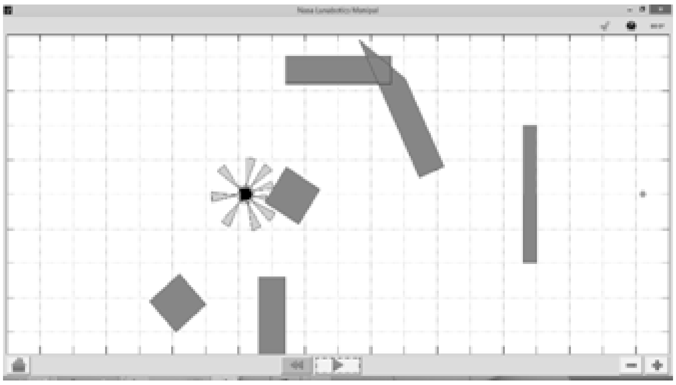

Figure 13: The Robot at an Intermediate Stage

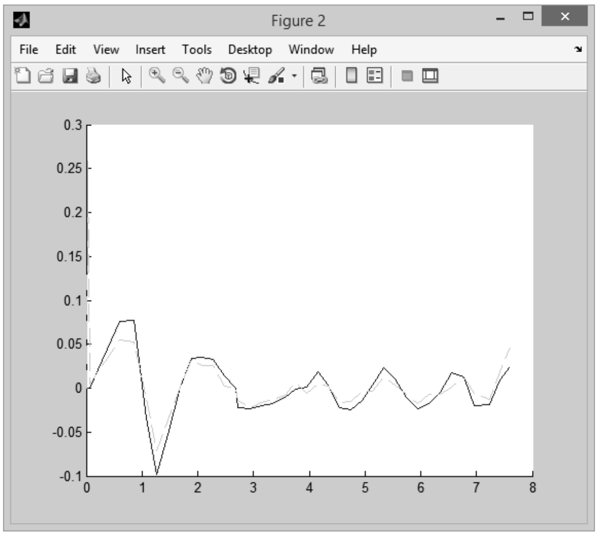

Figure 14: Steering Angle Graph at the Intermediate Stage Described in Figure 13

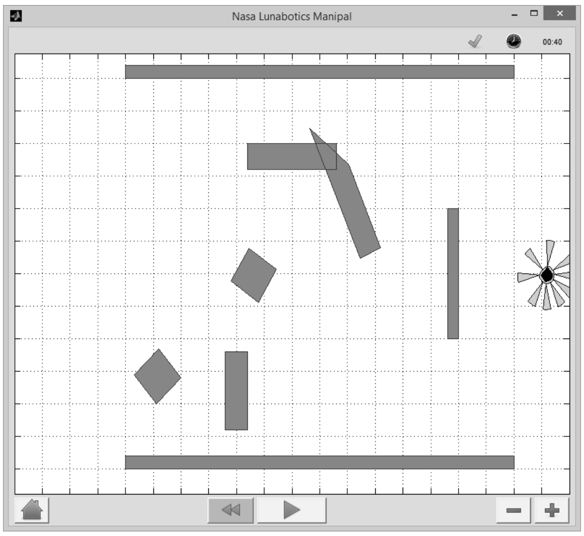

Figure 15: Robot at Goal

The simulation was successful considering the robot managed to reach the target destination without collisions on any of the obstacles.

FUTURE WORK

The application of the Artificial Potential Field Method described above contains specific shortcomings which need to be rectified. Firstly, depth sensors will be incorporated to accurately identify craters as well. These craters will also be identified as obstacles and will be avoided using the methods described above.

This application also describes the trajectory of the robot from the start position till Target 2 [Section IV]. A pre-programmed sequence will be added to this application so as to allow the robot to dig for regolith from Target 2 and return to the start zone to dump the regolith in the LunaBin.

CONCLUSIONS

This article describes an application of the Artificial Field Method for an international student competition. This paper incorporates the description of all aspects of the autonomy system of the robot – from the sensor placement to the algorithm. Additionally, this research and development serves as a reference for robots participating in student competitions where a robot has to traverse on an unknown workspace.

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REFERENCES

1. NASA's 4th Annual Lunabotics Mining Competition, 2014: http://www.nasa.gov/offices/education/centers/kennedy/technology/lunabotics.html
2. Khepera III Specifications, K-Team Mobile Robotics, http://www.k-team.com/mobile-robotics-products/khepera-iii/specifications
3. Latombe, J. 1991. Robot Motion Planning, Kluwer Academic Publishers: Boston.
4. Ge, S.S. and Cui, Y.J., 2002, "Dynamic Motion Planning for Mobile Robots using Potential Field Method", Autonomous Robots 13, 207-222.
5. Sim.I.Am, The Math Works, Inc, File Exchange http://www.mathworks.com/matlabcentral/fileexchange/40860-sim-i-am
6. GRITS Lab, Georgia Robotics and Intelligent Systems Lab, Georgia Institute of Technology, http://gritslab.gatech.edu/home/
7. Control of Mobile Robots, Georgia Institute of Technology, https://www.coursera.org/course/conrob