ICIC Express Letters
Part B: Applications
Volume **9**, Number **6**, June **2018**
ICIC International ©2018 ISSN 2185-2766
pp. 485–492

TWO-DIMENSIONAL OBSTACLE AVOIDANCE BEHAVIOR BASED ON THREE-DIMENSIONAL ENVIRONMENT MAP FOR A GROUND VEHICLE

Hiroki Bingo and Hiroshi Ohtake

Department of Mechanical Information Science and Technology
Kyushu Institute of Technology
680-4 Kawazu, Iizuka-shi, Fukuoka 820-8502, Japan
m237206h@mail.kyutech.jp; hohtake@mse.kyutech.ac.jp

Received December 2017; accepted March 2018

Abstract. *In order to drive robots automatically under various environments, the robots themselves have to recognize the surrounding environment, determine appropriate motions, and perform the determined motions. The robot has to have some functional capabilities such as creating the environment map and avoiding obstacles. In this paper, as the basic research for realizing our goal, we propose the obstacle avoidance method for a ground vehicle using three-dimensional Laplacian potential method based on the information of self-localization and three-dimensional environment map which are obtained by RGB-D camera and simultaneous localization and mapping (SLAM) algorithm. However, the method needs high computational cost. GPGPU method is employed for solving this problem. The experimental results demonstrate the utility of this approach.*
Keywords: Potential method, Laplace's equation, Path-planning, 3D environment map

1. **Introduction.** In recent years, robots are utilized in various scenes. In order to drive robots automatically under various environments, the robots themselves have to recognize the surrounding environment, determine appropriate motions, and perform the determined motions. A lot of researches on environmental recognition, path-planning for mobile robot and motion-planning for multi-link robot have been reported [1,2].

On the other hand, recently, there are many researches on flying robots as typified by quadrotor helicopter or drones, for example, not only theoretical researches on flight control, but also application researches on ground survey, bridge inspection and so on. The goal of our research is to realize the survey of forest by using drone. For surveying forest, the drone has to have some functional capabilities such as creating the environment map of the forest and avoiding obstacles not for colliding with trees or branches.

In this paper, as the basic research for realizing our goal, we discuss the generation of three-dimensional environment map using RGB-D camera and the obstacle avoidance using a ground vehicle based on three-dimensional environment map.

For path-planning of mobile robot in unknown environment, the self-localization and the creation of environment map are important. There are many researches for achieving these, for example, self-localization method using markers which are pre-placed in the environment [3], the creation method of three-dimensional map in stereo vision using two RGB cameras [4], the fast detection method of wide range of surrounding obstacles using two-dimensional laser range finder (LRF) sensor [5], and the creation method of wide range of three-dimensional map using three-dimensional LRF sensor [6,7]. Moreover, for self-localization and mapping, SLAM algorithm is utilized in many researches [8,9].

On the other hand, in the research field of path-planning for mobile robot, the obstacle avoidance is important. Various methods have been proposed, for example, Khatib's artificial potential field method [10], method using velocity potential [11] or hydrodynamic potential [12]. Moreover, obstacle avoidance using deep learning [13], which is the hot topic recently, has also been reported. However, it is known that Khatib's mothod has the problem that the potential function may have local minima. And enormous amount of learning data are required for deep learning algorithm.

In this research, three-dimensional Laplacian potential [14] is employed for path-planning and obstacle avoidance. The paper of [14] is path-planning in two-dimensional potential field. In this paper, the path-planning is in three-dimensional potential field. The method using the Laplacian potential has the advantage that the potential function does not have local minima. However, the method needs high computational cost. In this research, GPGPU method is employed for solving this problem. The process of solving the Laplace equation can be parallel computation. Therefore, GPGPU with fast parallel computation is the best. GPGPU has low power consumption, so long-term path-planning becomes possible.

Moreover, many of conventional researches on path-planning for ground vehicles utilize two-dimensional environment map and two-dimensional Laplacian potential method.

In this research, we propose the obstacle avoidance method for a ground vehicle using three-dimensional Laplacian potential method based on the information of self-localization and three-dimensional environment map which are obtained by RGB-D camera and SLAM algorithm. The experimental results demonstrate the utility of this approach.

2. **Robot and System.** In this research, we develop a ground vehicle, which is shown in Figure 1. The vehicle has RGB-D camera (Microsoft Kinect V2), high speed computer for GPGPU calculation (NVIDIA Jetson TX1), vehicle controller (Pixhawk), batteries, and wireless HDMI device which is for checking activity of Jetson TX1 using external monitor. By using RGB-D camera, we can get color image and depth image, and can generate self-position and environment map based on SLAM algorithm from those image data. Figure 2 shows vehicle system and environment recognition system. In the environment recognition system, environment map is generated by the mounted computer based on RGB-D camera data and SLAM algorithm. In this research, we employ real-time appearance-based mapping (RTAB-MAP) algorithm developed by Labbe and Michaud [15], which is one of the SLAM algorithms. In the RTAB-MAP algorithm, feature points in RGB image are extracted based on the speeded up robust features (SURF) method, and self-localization is achieved from moving distance of feature points. At the same time,

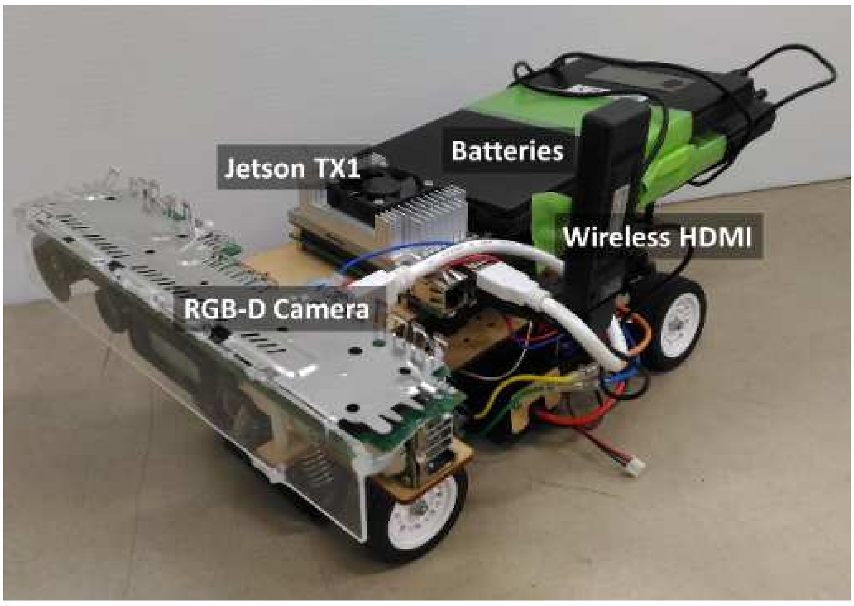


Figure 1. A ground vehicle

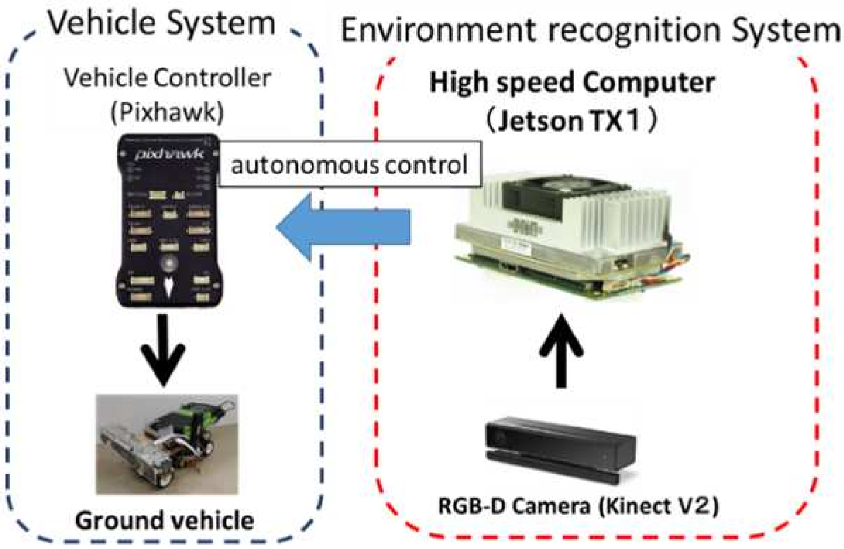


Figure 2. Vehicle system and environment recognition system

environment map is generated based on depth image data. The environment map has a large amount of point data. In this research, we reduce the point data by down-sampling using Point Cloud Library.

Then, path-planning is calculated based on the calculated self-position and environment map by using Laplacian potential method which is explained later, and vehicle control signals, which consist of direction including right, left and straight, and motion including move and stop, are generated based on the calculated path. By sending the signals to the vehicle controller, the vehicle moves to the desired direction. In the experiment performed later, steering angle is changed based on direction signal and wheels are driven based on motion signal.

3. **Path-Planning.** In this research, the method based on the Laplacian potential function, which is one of the artificial potential field methods, is employed for path-planning for the ground vehicle.

In the artificial potential field method, an attractive force is set to the goal point, a repelling force is set to an obstacle, and the potential field in the search area is formed. The mobile robot can reach the goal by moving based on the attractive force and repelling forces in the potential field. However, it is known that the potential field method has the problem that the potential function may fall into local minima where the attractive force and repelling forces are in equilibrium, and the mobile robot may not be able to move any more.

In this research, we employ the Laplacian potential method which is a type of the artificial potential field methods. In the Laplacian potential method, by considering a potential field φ that satisfies the Laplace's equation shown in Equation (1), it is possible to form the potential field which has no local minima.

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} + \frac{\partial^2\varphi}{\partial z^2} = 0 \tag{1}$$

where x, y, and z are axes according to three-dimensional Cartesian coordinates, which are shown in Figure 3. By discretizing Equation (1), the difference equation shown in Equation (2) is obtained. Moreover, Equation (2) can be converted into Equation (3) by partitioning the search area into grid patterns and by defining the grid width of each axis as $\Delta x = \Delta y = \Delta z$.

$$\begin{aligned} &\frac{1}{\Delta x}\left(\frac{\varphi_{i+1,j,k}-\varphi_{i,j,k}}{\Delta x}-\frac{\varphi_{i,j,k}-\varphi_{i-1,j,k}}{\Delta x}\right) \\ &+\frac{1}{\Delta y}\left(\frac{\varphi_{i,j+1,k}-\varphi_{i,j,k}}{\Delta y}-\frac{\varphi_{i,j,k}-\varphi_{i,j-1,k}}{\Delta y}\right) \\ &+\frac{1}{\Delta z}\left(\frac{\varphi_{i,j,k+1}-\varphi_{i,j,k}}{\Delta z}-\frac{\varphi_{i,j,k}-\varphi_{i,j,k-1}}{\Delta z}\right)=0 \end{aligned} \tag{2}$$

$$\varphi_{i,j,k}=\frac{1}{6}\left(\varphi_{i+1,j,k}+\varphi_{i-1,j,k}+\varphi_{i,j+1,k}+\varphi_{i,j-1,k}+\varphi_{i,j,k+1}+\varphi_{i,j,k-1}\right) \tag{3}$$

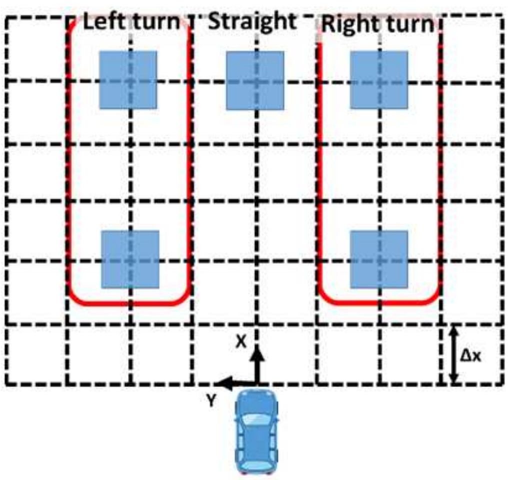
In this research, the potential value at the goal point is set as -1 and the position of the goal is known. And the potential values at the positions where obstacles have been found from environmental map are set as 0.

The potential value $\varphi_{i,j,k}$ at the grid point i, j, k with respect to x, y, z, respectively except the goal point and the positions where the obstacles exist is iteratively calculated from Equation (3) by using the Gauss-Seidel method. $\varphi_{i,j,k}$ is a potential value on each lattice point. The initial potential value of the unknown area is set as 0, and the value is changed by iterative calculation by the Gauss-Seidel method. In this research, the size of the search area is assumed to be known, and the iterative calculation by the Gauss-Seidel method is performed in the entire search area. The disadvantage of the Gauss-Seidel method is that the computational cost increases explosively according to the increase of the number of grid points.

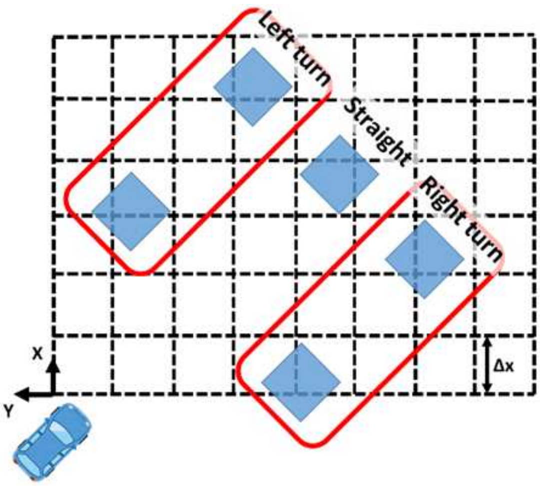
Most of conventional researches on path-planning for mobile robots use two-dimensional Laplace's equation. In this research, we utilize three-dimensional Laplace's equations. Hence, more computational cost is required. To solve this problem, we employ high speed calculation based on GPGPU. The search area in this paper is assumed as $0 \leqq x \leqq 5$m, -5m $\leqq y \leqq 5$m, $0 \leqq z \leqq 5$m, and the width of grid is defined as $\Delta x = \Delta y = \Delta z = 0.1$m. The total number of grid points is 237699 except the points on the boundary.

In the high-speed computer shown in Figure 2, it takes more than 2 seconds for the calculation of one step using CPU and memory. In contrast, it takes less than one second for that using parallel computation with GPU and video memory. In this research, the environment map and path-planning are updated every second, and the ground vehicle moves according to the optimal route at that point.

Next, we explain how to move the vehicle based on the potential field. We focus on the five points in front of the vehicle such as shown in Figure 3(a) and find the one which



(a) Ground vehicle is straight



(b) Ground vehicle is diagonal

FIGURE 3. Moving direction determination method

has the lowest potential value. When the attitude of the vehicle is diagonal, the focused points are also taken diagonally according to the attitude of the vehicle such as shown in Figure 3(b). If the point with the lowest potential value is in left side, right side or front with respect to the vehicle, steering signal is set as left, right or straight, respectively. And, motion signal is set as move. Then, the vehicle moves based on the signals. In the experiment performed in the next section, steering angle is constant as 20 degree, and wheels stop after moving 0.5m in the direction of x-axis, which is measured based on self-localization. Vehicle stops 0.5m at a time so as not to collide before the calculation is over.

Figure 4 shows the flowchart of path-planning in this research. Firstly, environment map is generated based on RGB-D camera data at the point where the vehicle is, and self-position of the vehicle is calculated at the same time. Secondly, path-planning is achieved based on the calculated self-position and environment map by using Laplacian potential method. Next, the vehicle moves to determined direction based on the created path. By repeating this flow, the vehicle can reach the goal finally.

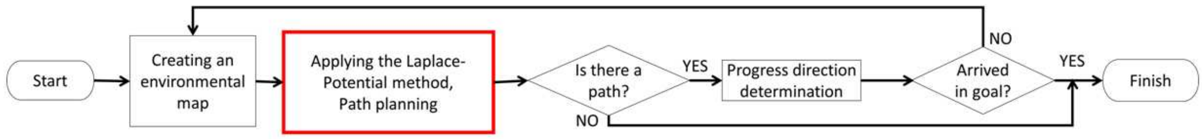


Figure 4. Flowchart of path-planning

4. **Experiment.** In this section, three types of experiments are performed. First experiment is simple obstacle avoidance, which uses only one obstacle that is put on the ground. Second one is avoidance of an obstacle which is hung up in the air. Third one is avoidance of multiple obstacles. We assume that the ground vehicle moves slowly. The goal point is set as $(x, y, z) = (4\text{m}, 0, 0)$ for each experiment.

4.1. **Simple obstacle avoidance.** In this experiment, only one obstacle is used and put on the ground. The obstacle is a cylindrical object whose diameter is about 20cm. The obstacle is put at $(x, y, z) = (2\text{m}, 0, 0)$. The experimental result is shown in Figure 5. The vehicle has been able to avoid the obstacle and reach the goal. However, the vehicle has moved zigzag after avoiding the obstacle since we used only proportional controller for vehicle control. By using PD controller, we expect that the vehicle could move smoothly.

Figure 5. Experiment of simple obstacle avoidance

4.2. **Avoidance of an obstacle hung up in the air.** In this section, we realize to avoid an obstacle which is hung up in the air. The bottom of the obstacle is placed at $(x, y, z) = (2\text{m}, 0, 0.2\text{m})$. The height of the bottom is lower than the highest part of the ground vehicle. Therefore, the vehicle would come into collision with the obstacle if the vehicle went straight to the obstacle. If we use two-dimensional LRF sensor which is mounted parallel with respect to the ground for detecting obstacles, the obstacle which is hung up in the air may not be detected. In this research, even if the obstacle is hung up in the air, we can detect the obstacle since we generate three-dimensional map based on RGB-D camera data.

The experimental result is shown in Figure 6. The vehicle has been able to avoid the obstacle and reach the goal even if the obstacle is hung up in the air. Figure 7 shows the obstacle detected by RGB image and depth image. Also in this experiment, the vehicle has moved zigzag for the same reason as the previous experiment. We have shown that the vehicle can avoid also the obstacle which is hung up in the air by using three-dimensional map and three-dimensional Laplace's equation.

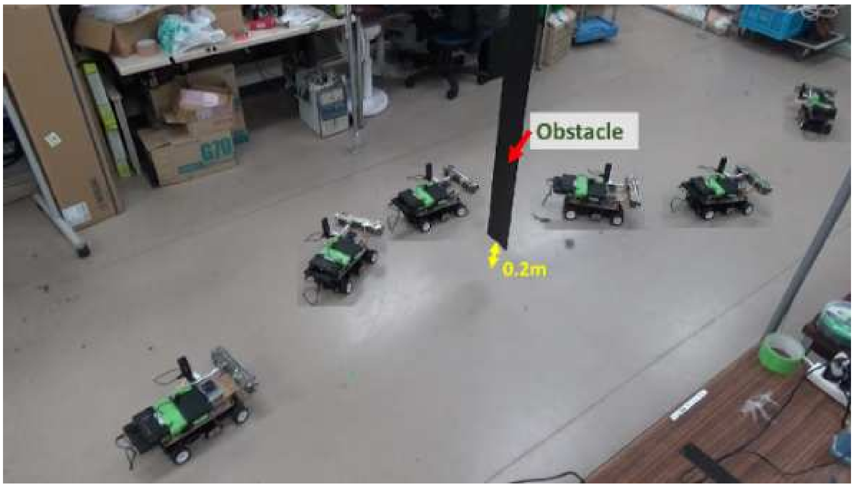


FIGURE 6. Experiment to avoid obstacle hung up in the air

FIGURE 7. RGB and depth images of an obstacle hung up in the air

4.3. **Avoidance of multiple obstacles.** In this experiment, we achieve avoidance of multiple obstacles which are put on the ground. The obstacles are cylindrical objects and rectangular objects. Diameters of cylindrical ones are about 10cm and 20cm. Sizes of rectangular ones are about 38cm × 8cm × 38cm, 25cm × 12cm × 33cm. The layout of obstacles is shown in Figure 8.

The experimental result is shown in Figure 9. And, Figure 10 shows a potential field at the time when the vehicle has reached the goal. Obtained potential field is three-dimensional. Therefore, potential graph is different depending on the height, that is,

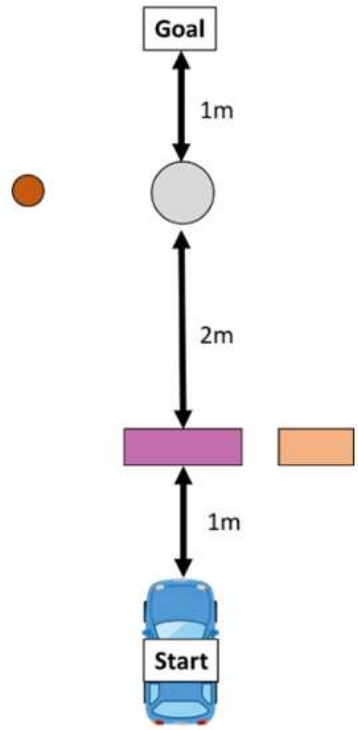


Figure 8. Layout of obstacles

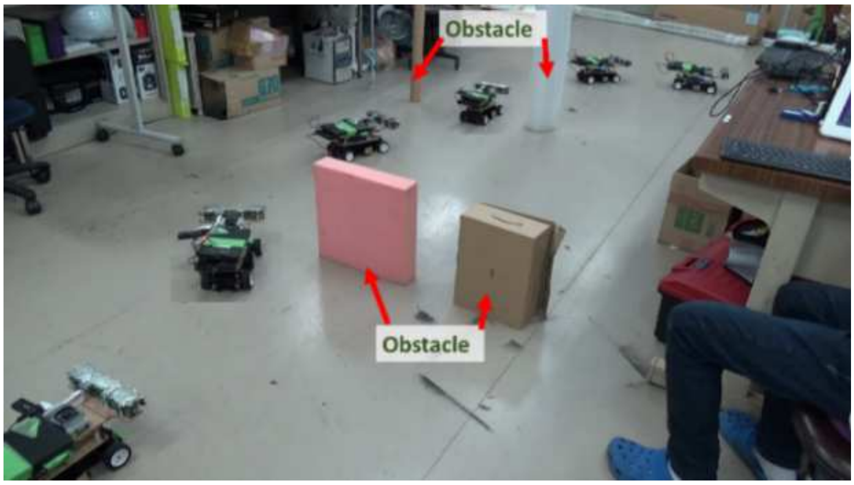


Figure 9. Experiment of multiple obstacles avoidance

z-axis. The potential graph shown in Figure 10 is the one at the same height as the RGB-D camera mounted on the vehicle. From the difference between potential values, good and obstacles can be recognized. The vehicle has been able to avoid the all of obstacles and reach the goal. Especially, the vehicle has passed between cylindrical objects without collision.

5. **Conclusions.** In this research, we have proposed the obstacle avoidance method for a ground vehicle using three-dimensional Laplacian potential method based on the information of self-localization and three-dimensional environment map which are obtained by RGB-D camera and SLAM algorithm. The experimental results have demonstrated the utility of this approach. The obstacle avoidance method can contribute as a safer vehicle.

Our future works are to apply this approach to flying robot such as a drone and to realize the three-dimensional obstacle avoidance in the forest.

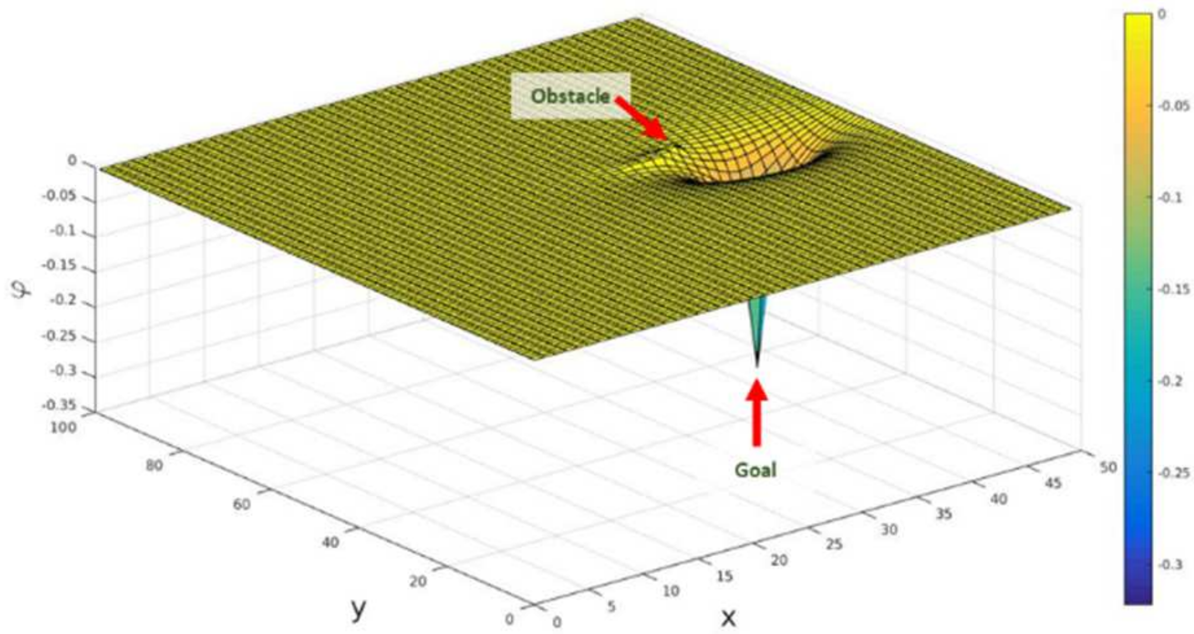


FIGURE 10. Potential field during avoidance of multiple obstacles

REFERENCES

[1] T. Matsumoto et al., Autonomous navigation system for mobile robots using the route map, *The Robotics Society of Japan*, vol.5, no.5, pp.351-360, 1987.
[2] T. Hasegawa, Collision avoidance using characterized description of free space, *Transactions of the Society of Instrument and Control Engineers*, vol.22, no.6, pp.616-622, 1986.
[3] T. Miki et al., Self localization with active attachment of AR markers by autonomous UAV, *Proc. of the Annual Conference of JSAI*, vol.29, pp.1-4, 2015.
[4] L. Heng et al., Real-time photo-realistic 3D mapping for micro aerial vehicles, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.4012-4019, 2011.
[5] T. Shimizu et al., Mobile robot system realizing human following and autonomous returning with obstacle avoidance, *JSME Annual Conference on Robotics and Mechatronics*, 2010.
[6] J. Jung et al., Development of kinematic 3D laser scanning system for indoor mapping and as-built BIM using constrained SLAM, *Sensors*, vol.15, no.10, pp.26430-26456, 2015.
[7] A. Hornung et al., Octomap: An efficient probabilistic 3D mapping framework based on octrees, *Autonomous Robots*, vol.34, no.3, pp.189-206, 2013.
[8] L. Meier et al., A system for autonomous flight using onboard computer vision, *Proc. of IEEE International Conference on Robotics and Automation*, pp.2992-2997, 2011.
[9] N. Stefas et al., Vision-based UAV navigation in orchards, *IFAC-PapersOnLine*, vol.49, no.16, pp.10-15, 2016.
[10] O. Khatib, Real-time obstacle avoidance for manipulators and mobile robots, *International Journal of Robotics Research*, vol.5, no.1, pp.90-98, 1986.
[11] S. Nawata et al., Collision avoidance for dynamic obstacles control via navigation function, *The Japan Joint Automatic Control Conference*, vol.53, p.142, 2010.
[12] H. Jacob, S. Feder et al., Real-time path planning using harmonic potentials in dynamic environments, *Proc. of IEEE International Conference on Robotics and Automation*, pp.874-881, 1997.
[13] A. Giusti et al., A machine learning approach to visual perception of forest trails for mobile robots, *IEEE Robotics and Automation Letters (RA-L)*, pp.661-667, 2016.
[14] K. Sato, Global motion planning using a Laplacian potential field, *Journal of the Robotics Society of Japan*, vol.11, no.5, pp.102-109, 1993.
[15] M. Labbe and F. Michaud, Online global loop closure detection for large scale multi session graph based SLAM, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.2661-2666, 2014.