

Mobile Robot Navigation in Unknown Environment Using Improved APF Method

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Abstract: This project deals with the navigation of a mobile robot in an unknown environment. The aim is to develop a complete method that allows controlling a robot to reach its goal while avoiding unknown obstacles on its way. The approach developed is based on the Artificial Potential Field (APF) method in which the target creates a virtual force that attracts the robot while obstacles create a virtual force that repels the robot. APF-based methods are very interesting because they are simple to implement; however, they have some inherent limitations, that the trajectory can have undesirable oscillations. A new form of repelling potential is proposed in order to improve quality of the trajectory and to reduce the oscillations when the goal is close to obstacles.

The simulation results of a differential mobile robot are given to show the effectiveness of the proposed method.

Keywords: Mobile robot, autonomous Navigation, obstacle avoidance, unknown environment.

1. Introduction

The autonomous navigation of mobile robot in unknown environment is a difficult problem which is still far from being solved. To be really autonomous, a robot must be able to interpret what it perceives from its environment, to model this environment if that is useful, to choose an adapted trajectory and to have the most effective possible locomotion, whatever the present situation [4][7].

The development of mobile robotics is synonymous of development of the control techniques; we search to integrate more powerful techniques on more compact structures. Numerous methods on mobile robot navigation using various approaches were studied. Among these navigation techniques, we choose that of the artificial potential field, it allow in a very simple manner the navigation of a mobile robot under various conditions, particularly in unknown environments [6][3][10]. In this work we study the development and the improvement of the artificial potential field method. Thereafter, we apply the developed method on a mobile robot in order to illustrate the limitations and possible improvements of this method.

2. Mobile robot model

Dependently of the considered application, there is a large variety of mobile robot models. It is clear that the framework of mobile robotics exceeds largely that of the wheeled vehicles and includes the vehicles with legs, the nautical vehicles and autonomous planes [11]. A major characteristic for the wheeled mobile robots is the non-holonomy; the displacement of the robot in the plan cannot be done in all the directions since a wheel can move without slipping only into its own plan of rotation. Non-holonomy of a robot is expressed by an equation binding its speed to its orientation [9][1].

In this project a four-wheeled robot with differential steering is used: the two wheels on the same side are mechanically coupled in order to have the same speed. Each side is actuated by an independent motor. We develop in this section the kinematic model allowing finding the relationship between the position and the speed of the mobile robot [12].

2.1. Kinematic model

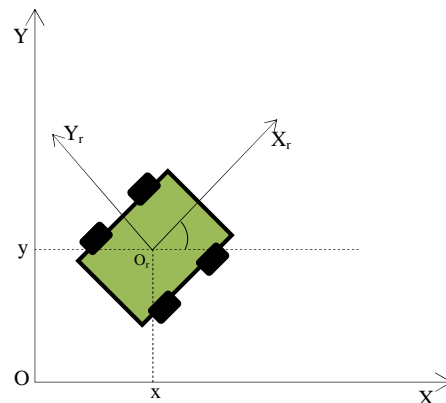


Fig. 1. Robot positioning.

The positioning of the robot is illustrated in figure 1, we start by defining a fixed reference (X O Y), in which the center of the robot has as coordinates x and y.

We define also the reference (Xr Or Yr) related to the robot, its center is fixed at the center of the robot. The Xr axis is defined by the robot (Forward/backward) and the Yr axis is directly perpendicular to the Xr axis.

The position of the robot is defined by the vector $[x \ y]^T$, with x and y are the Cartesian coordinates of the robot center and is the orientation angle of the robot with respect to the fixed reference.

According to [12], the kinematic model of the robot is given in matrix form by:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} v \\ w \end{bmatrix} \quad (1)$$

Where V is the linear velocity of the robot center and W is the robot rotational speed around its center.

This model can be written in system of equations form as follows:

$$\begin{cases} \dot{x} = v \cdot \cos \theta \\ \dot{y} = v \cdot \sin \theta \\ \dot{\theta} = w \end{cases} \quad (2)$$

2.2. Environment sensors

In order to perceive the state of its environment, the robot is equipped with 8 ultrasonic sensors (Figure 2). These sensors send a high frequency signal in a given direction and receive the wave reflected after a certain time which depends on the distance to an obstacle.

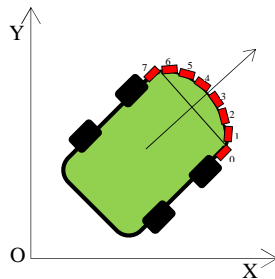


Fig. 2. Ultrasonic sensors positioning

3. Mobile robot Navigation

The navigation of a mobile robot consists in determining a succession of coordinates that the robot must follow to reach a given destination. We distinguish in theory two types of complementary tasks: the trajectory generation and the trajectory following [2]. When the robot environment is entirely known, that means the knowledge of the obstacles positions, the problem of trajectory generation returns to an optimization problem which consists in dividing the chart of the environment into grid and to fix points in the accessible zones. A graph of nodes is made and bonds are built [8]. The

passage between two nodes implies a certain cost (generally the distance), the algorithm carries out an exhaustive research in order to minimize the total cost and the final trajectory that the robot must follow is a whole of segments of which the overall length is minimal. In several applications, the planner of trajectory does not have necessarily the information which it needs to generate the trajectory in advance [15][5]. Under these conditions, it is not possible to generate a complete trajectory before the robot start to move; it is necessary to generate the trajectory as the robot moves while collecting local information on the close obstacles, we speak here about unknown environment [13]. In this situation, we try to illustrate the performances and the limitations of the use of the artificial potential field method and the improvements suggested.

3.1. Classical artificial potential field method

It consists in allotting to the space of the robot a scalar field called artificial potential field, this field is the resultant of two components:

1. A computed field according to the position of the goal relative to the instantaneous position of the robot; this field is concave and minimal in the goal.
2. A computed field according to the form and the relative position of the obstacles with respect to the robot position; this field increases when the robot approaches an obstacle.

According to [6]:

$$\Phi = \Phi_b + \Phi_o \quad (3)$$

Where Φ_b represents the goal potential field, Φ_o represents the obstacles potential field, and Φ represents the total potential field.

Once the total potential field is calculated, a field of forces is then calculated by the gradient of the potential according to the equation (4).

$$\vec{F} = -\overrightarrow{\text{grad}} \Phi \quad (4)$$

That is equivalent to two algebraic equations:

$$\begin{cases} F_x = -\frac{\partial \Phi}{\partial x} \\ F_y = -\frac{\partial \Phi}{\partial y} \end{cases} \quad (5)$$

The expression of the force in the equation (4) is not other than the line of greater slope, In other words the robot moves towards the goal according to the decreasing potentials in the direction where the potential is minimal.

In the classical method, the goal potential is given in parabolic form by the following equation:

$$\phi_b = \frac{1}{2} \cdot \zeta \cdot [(x - x_b)^2 + (y - y_b)^2] \quad (6)$$

Where ζ represents the goal attraction coefficient and x_b, y_b represent the goal coordinates.

The usual form of the obstacles repulsive potential is given by the function [6]:

$$\begin{cases} \phi_o = \frac{1}{2} \cdot \eta \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_0} \right)^2; \rho \leq \rho_0 \\ \phi_o = 0; \rho > \rho_0 \end{cases} \quad (7)$$

Where ρ represents the minimal distance between the robot and the obstacle surface, ρ_0 is a constant characterizing the sight distance of the ultrasonic sensors and η is a multiplicative factor.

For the force we obtain:

$$\begin{cases} F_{xb} = -\zeta(x - x_b) \\ F_{yb} = -\zeta(y - y_b) \end{cases} \quad (8)$$

$$\begin{cases} F_{xo} = \eta \cdot \frac{1}{\rho^2} \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_0} \right) \cdot \frac{\partial \rho}{\partial x}; \rho \leq \rho_0 \\ F_{yo} = \eta \cdot \frac{1}{\rho^2} \cdot \left(\frac{1}{\rho} - \frac{1}{\rho_0} \right) \cdot \frac{\partial \rho}{\partial y}; \rho \leq \rho_0 \\ F_{xo} = 0; \rho > \rho_0 \\ F_{yo} = 0; \rho > \rho_0 \end{cases} \quad (9)$$

Once the force is calculated, we can now deduce the robot speed reference from the following equation:

$$\vec{F} - \lambda \cdot \vec{v} = m \cdot \frac{d\vec{v}}{dt} \quad (10)$$

Where, \vec{F} represents the virtual force applied to the robot, \vec{v} is the speed reference given to the robot and m is the robot mass. The coefficient λ is a friction factor.

Indeed, the classical potential field method gives to the system an oscillatory behavior; the trajectory generated by such a method tends easily to oscillate in particular when the robot is in narrow passages (obstacles very close) or if the direction of the robot is perpendicular to the surface of an obstacle [11]. It is also to note that this method is extremely vulnerable to the local minima, where the robot is immobilized and cannot achieve the goal any more. This problem often occurs when an obstacle is very near to the goal (**GNRON** Goal Not Reachable when Obstacles are Nearby).

3.2. Improved potential field Method

Initially, let us start by defining the framework of the method: we search to navigate the robot from an initial position towards the goal with obstacles avoiding. The conditions which we set are as follows:

- The robot does not have total information on the environment; no environment chart is put in memory and no preliminary information is known concerning the obstacles.

- The robot has like entries only those of its sensors.

- No preset trajectory, the method consists in generating a trajectory in real time.

3.2.1. Solution to GNRON problem

Returning to the expression of the potential field (Equations 6 and 7), a limitation can be highlighted. Indeed, the expression of the goal potential is minimal when the robot is in goal. However, the expression of the obstacles repulsive potential is not minimal when an obstacle is sufficiently near to the goal, its potential is not null there and the total potential, being the sum of these two components, is not minimal in the goal. Under these conditions, the robot will not achieve the goal exactly but will be placed at different coordinates. To guarantee that the total potential is minimal in the goal, it is enough to make that the obstacles repulsive potential is minimal. For that, we propose a modified form of the repulsive potential:

$$\begin{cases} \phi_o = \phi_m \cdot \left(\frac{\rho_0 - \rho}{\rho_0} \right)^\eta \cdot (1 - e^{-k \left(\frac{\rho}{R} \right)^2}); \rho \leq \rho_0 \\ \phi_o = 0; \rho > \rho_0 \end{cases} \quad (11)$$

Where:

$$D = (x - x_b)^2 + (y - y_b)^2 \quad (12)$$

With D represents the distance between the center of the robot and the target, k is a multiplying factor, R represents the robot diameter, ϕ_m is the maximum repulsive potential and η is a parameter that makes the repulsive potential polynomial increasing when the robot approaches the obstacle.

In this equation, the repulsive potential is relatively null in the goal. The multiplicative quantity is well equal to zero in the goal and it is strictly positive everywhere, but it is negligible when the robot is relatively far from the goal. In this way the distortion is local and does not affect the behavior of the robot when it is far from the goal. Thus the *GNRON* problem is well solved.

Applying the equation (5) to the components of the potential, we finally obtain for the repulsive force:

$$\begin{cases} F_{ox} = -\frac{2k\phi_m}{R^2}(x-x_b) \cdot e^{-k\left(\frac{D}{R}\right)^2} \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^\eta \\ -\frac{\eta\phi_m}{\rho_0} \left(1 - e^{-k\left(\frac{D}{R}\right)^2}\right) \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^{\eta-1} \cdot \cos(\theta+\alpha_i) \\ F_{oy} = -\frac{2k\phi_m}{R^2}(y-y_b) \cdot e^{-k\left(\frac{D}{R}\right)^2} \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^\eta \\ -\frac{\eta\phi_m}{\rho_0} \left(1 - e^{-k\left(\frac{D}{R}\right)^2}\right) \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^{\eta-1} \cdot \sin(\theta+\alpha_i) \end{cases} \quad (13)$$

3.2.1. Minimization of oscillations

We have noted previously that when the robot has a perpendicular direction to the surface of the obstacle, it tends to enter in an oscillatory movement to avoid the obstacle. This problem is due to the fact that the force which pushes aside the robot from its unstable position is very small compared to the forces of attraction and repulsion. In order to resolve this problem, we propose to add a tangential force to the surface of the obstacle. This force should make so that the robot tends to move parallel to the surface of the obstacle rather than to move away from the obstacle. Under these conditions, when the robot approaches perpendicular to the obstacle, it will not enter in an oscillatory movement of distance-advance, but will follow a smoother trajectory of tangential skirting. We introduce a similar force to that of radial repulsion, but whose direction is tangential on the surface of the obstacle:

$$\begin{cases} F_{ox} = \text{sgn}(\alpha_i) \cdot \frac{\eta\phi_m}{\rho_0} \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^{\eta-1} \cdot \cos\left(\theta + \alpha_i - \frac{\pi}{2}\right) \\ F_{oy} = \text{sgn}(\alpha_i) \cdot \frac{\eta\phi_m}{\rho_0} \cdot \left(\frac{\rho_0-\rho}{\rho_0}\right)^{\eta-1} \cdot \sin\left(\theta + \alpha_i - \frac{\pi}{2}\right) \end{cases} \quad (14)$$

This expression of the force ensures that when the direction of the robot is perpendicular to the surface of the obstacle, the tangential force is higher, this force is discontinuous around 0 for the angle between the direction of the robot and that of the force of radial repulsion, in order to well discriminate the direction that must take the trajectory of the robot.

4. Simulation results

In this section, we put under test the theory developed in the preceding sections. We start by comparing the performances of the improved form of the repulsive potential compared to the traditional form. Then, we evaluate the improvement due to the use of the skirting force.

4.1 Comparison criterions

In order to objectively measure the performance of the algorithm under various conditions, it is significant to specify objective criteria which allow to easily measuring the effectiveness of it. For this reason, we introduce the three following parameters:

1- Total course length:

$$L_t = \sum_{k=0}^N v_k \cdot \tau \quad (15)$$

Where N is the number of calculation steps between the starting moment of the robot and the moment of its arrival to the goal. v_k represents the speed module at the moment k , and τ represents the duration of the calculation step.

2- Total course duration:

$$D_c = N \cdot \tau \quad (16)$$

3- Coefficient of oscillations: The measurement of the instantaneous average quadratic rotation speeds (w_k) constitutes an interesting criterion for the measurement of the trajectory oscillations:

$$C_o = \frac{1}{N} \sqrt{\sum_{k=0}^N w_k^2} \quad (17)$$

4.2. Simulations

In order to apply the developed theory, it is important to specify an experimentation framework. Let us start by summarizing the theoretical algorithm of navigation.

With each step of calculation, the following stages would be carried out:

1. Calculation of the potentials ϕ_b , ϕ_o .
2. Calculation of the forces by space derivation of the respective potentials.
3. Application of the movement equation to calculate the reference speed.

4.2.1. Classical form of the repulsive potential

We start by simulating the algorithm by using the classical form of the obstacles repulsive potential.

The graph of figure 3 shows that the robot tends to have exaggerated oscillations as soon as it approaches the obstacles.

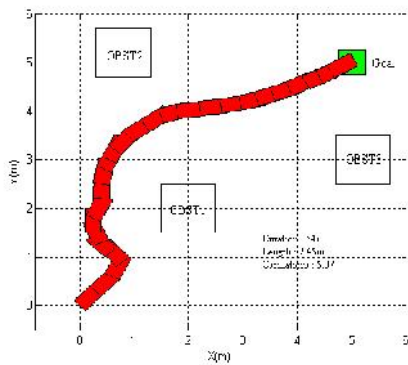


Fig. 3. Classical form of repulsive potential

4.2.2. Improved form of the repulsive potential

The use of the new form of the repulsive potential improves the behavior of the robot in the vicinity of an obstacle. Indeed, the limitation of the maximum potential with ϕ_m keeps the repulsion force in a more reasonable interval of variations. Figure 4 shows softer variations of the repulsive potential than those of figure 3.

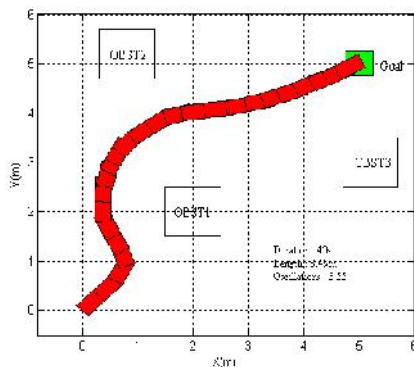


Fig. 4. Improved form of the repulsive potential

4.2.3. Improved form of the repulsive potential with skirting force.

By combining the new form of the repulsive potential and the use of the skirting force, we succeed in improving largely the form of the trajectory.

The following graph (figure 5) shows clearly the advantage brought by the addition of the skirting force. Indeed, when the robot moves towards an obstacle, a tangential force is applied to the robot, which softens the response of the robot, therefore there is less of oscillations.

Moreover, an interesting effect is highlighted, it is when the robot is taken between two obstacles, the tangential forces coming from each obstacle are added, which gives an additional push to the robot to surmount the virtual barrier. In this case the robot succeeds in finding the good way to achieve the goal, thing which was not observed in the preceding cases.

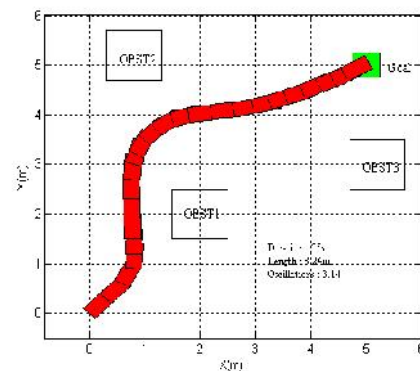


Fig. 5. Improved Form of the repulsive potential with skirting force.

Finally, by comparing the three cases between them, each one under its best conditions, we can conclude that the new form of the repulsive potential improves the performance of navigation on several levels: the oscillations and length are minimal. The duration of the course was observed proportional to the distance. Moreover, the use of the skirting force contributes to reduce even more the factor of oscillations.

5. Conclusion

In this paper we contributed to the improvement of mobile robot navigation using the artificial potential field on the following points:

The force of repulsion of the obstacles is, in the traditional case, too simplistic from the flexibility point of view. Indeed, the only possible action of the robot in the vicinity of an obstacle is to move away quickly as possible (centrifugal radial force). The addition of a skirting force adds an additional degree of freedom to the robot and allows smoothing the trajectory around the obstacles by considering a less simplistic avoidance which stabilizes the trajectory by modulating the action of the robot between avoidance and skirting.

We synthesized in this paper a complete method for mobile robot navigation. The developed method improves the performances of navigation in an unknown environment. Indeed, the limitations of the classical artificial potential field method, in fact the problem of oscillation and that of the *GNRON* were minimized, even eliminated.

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