Movement strategies selection of a mobile robot to avoid obstacles

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Abstract. The movement of a mobile robot in a non-deterministic environment is accompanied by maneuvering due to the need to avoid a collision with a fixed or moving obstacle. Under certain conditions, several obstacles, including moving ones, may appear in the near zone of the robot. In this case, trajectory-planning algorithms based on a “static” approach to the position of obstacles will not be effective; their application may lead to collisions. Finding the path of movement in conditions of dynamic obstacles is an urgent task that researchers are trying to solve using various methods. The article proposes a method for planning the actions and movements of a mobile robot in non-deterministic conditions, in the presence of fixed and moving obstacles. The processes of planning the trajectories of a mobile robot in the presence of obstacles in the near zone are considered. Methods and algorithms for making decisions on avoiding obstacles based on the estimated collision probabilities in the forecast interval are proposed. Key words: mobile robot, robot trajectory planning, robot control, avoidance a group of obstacles.

1 Introduction

Robotics systems are increasingly used in industry and service sector to solve different kind of problems in factory, hospital, space and in other areas. Guarantee of reliability controlling the robot requires reliable methods for making decisions to direct robot movement in environment that required obstacles bypass. Famous algorithms are carried out avoiding obstacles without considering the possibilities of random changing that happened with the obstacles that nearby zone of a mobile robot. Therefore, it is necessary to develop algorithms to making decisions of avoid obstacles, reliable robot control to planning trajectory free of collision so that ensure reach the goal safely and its adequate behavior in uncertainty environment with the presence of static and dynamic obstacles.

An analysis of publications shows different methods to solve the task of controlling mobile robot in dynamic environment depending on which conditions that the robot have to work in. The article [1, 10] proposes the using of fuzzy logic to solve the problems of trajectory planning and control the robot so it’s can bypass all obstacles. The rules of fuzzy method used to control the mobile robot wheels in order to avoid the obstacle using the linguistic variables “distance to the obstacle”, “the location of the obstacle regarding the robot course”. The main advantage is the ease of implementation and small computational costs.

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The main defect that its ineffectiveness method in the presence of group of obstacles, such as fixed and movable obstacles.

The article [2, 11] proposes and considers a navigation method of a mobile robot that prevents collision with obstacles. Decisions are based on video camera image processing and uses a neural network of deep learning to determine the right direction of mobile robot movement. The article discusses various methods to teaching a neural network, which determines the necessary direction so that the robot navigate safely. In order that the neural network effectively recognize the situation and the direction of movement, additionally a lot of time needed to become an expert neural network as long as data source of training is required. In addition, the resulting decision based on this method will be ineffective in the presence of movable obstacles which randomly changing direction.

The article [3] proposes the use of neural networks with deep reinforcement training (DRL), Q-net (Double DQN), dueling Q-networks so that mobile robots can avoid obstacles and reach the target point when moving in an indefinite environment. As initial information, data from the lidar and the odometry sensor are used. For the formation of data necessary for training, an artificial potential function is used. Depending on the distance to the nearest obstacle, reward and discount functions are calculated for various motion trajectories. At the same time, the obstacles are static. The implementation of the concept of the use of neural networks with deep training proposed by the authors to form a robot trajectory in an indetermination environment requires a significant time to create and training a neural network. When changing the apparent size of the obstacles, the accuracy of the decisions made will be decrease and collision may occur. As well as in the presence of movable obstacles.

2 Materials and Methods

Conditions for implementation the movements.

This article discusses the issues of decision-making which is necessary to bypass obstacles that have stochastic nature of their movement, taking into account the nearby obstacles and the direction of the robot to the target point. The position of the target point, as well as static obstacles, will be considered constant, and the parameters of dynamic obstacles are determined by their coordinates \( X_{\text{doi}}, Y_{\text{doi}} \) and motion parameters \( V_{\text{doi}}, M_{\text{doi}}, D_{\text{doi}}, \sigma_{\text{doi}} \). Where \( V_{\text{doi}} \) is the current estimate of the speed of movement of each obstacle, \( M_{\text{doi}}, D_{\text{doi}}, \sigma_{\text{doi}} \) are the mathematical expectation, variance and standard deviation of the direction of movement of each movable obstacle.

The behavior of the robot involves determining the direction to the target point and choosing of its direction for the next time interval, taking into account the location of the obstacles in the near zone. At the same time, widely algorithms [4, 7] used parameters such as “react”, “distance to the obstacle”, “location of the obstacle relative to the robot” and sometimes “obstacle size”. However, these algorithms do not take into account how, and to which trajectory the obstacle will moved within the time interval. The assessing of the direction and movement parameters to the mobile robot without taking into account the probable movement parameters to the dynamic obstacles [5, 9] cannot ensure the safety of movement (collision-free).

This article is considering the trajectory planning of mobile robot after estimating the possible location of obstacles on the interval \( t_0 \). We assume that for each obstacle, the coordinates of its location are known at the time \( t \), when the mobile robot is planned to move for the next time interval. We believe that data about the (position, size, speed) of obstacles and direction of their movement obey the normal distribution law due to the multiplicity of existing measurement errors and other factors. Then one of the tasks of assessing the safety of robot navigation along the chosen trajectory (for example, to an alternative point) is to
check the probability of a collision with a fixed or movable obstacle. Figure 1 shows the trajectory $y_1$, the mobile robot movement on time interval $t + t_0$.

Movement along this trajectory can lead to a collision with a fixed obstacle if it is "close" to the robot's trajectory $y_1$. The figure 1 shows the initial and final position of the robot in the interval $t_0$, as well as the closest to the obstacle B and alternative point C, which planned to bypass the obstacle. When the robot moves near static obstacles, several options can be considered:

1. A static obstacle is located in such a way that the area limited by its dimensions does not intersect with trajectory of the mobile robot to the target or alternative point; In this case, it is possible a) the distance from the center of the obstacle position to the robot's trajectory exceeds the sum of the robot radius safety zones and the obstacle, so the safety of the robot's movement is ensured; b) the distance from the center of the obstacle to the trajectory of the robot is less than required for the safe passing of the robot;

2. A static obstacle is located in such a way that the area limited by its dimensions intersects the trajectory of the mobile robot to the target or alternative point.

![Fig. 1. Mobile robot trajectory at interval $t_0$.](image)

With option 1b) - the robot's trajectory must be adjusted - "shifted" away of the obstacle to achieve movement free of collision, then the robot must move until reach the target point. With option 2) - it is necessary to solve the problem of choosing the direction ("left" or "right") to avoid the obstacle. In this case, the criteria to evaluate the solution is by depending on the length of the path or the time that required to detour. The robot chooses its detour angle, taking into account the location of the nearest obstacles and the forecast of changes of the situation in its nearby zone. Thus, it can be assumed that upon detection of the situation described by option 2, the robot control system should solve the full-scale problem of planning a new trajectory to the target point or planning a detour with access to a previously designed trajectory. In the first case, significant computational resources will be required, as well as time to detect and applied the solution. According to the random nature of dynamic obstacles movement, it can be assumed that after a time interval the “new trajectory” will also require correction. In the next stage, minimal time and computing resources are required, which is preferable.
Conditions and criteria for choosing solutions. With the variant of the obstacle option 2, the choice of the direction of the detour is not obvious, since should be considered the presence of other obstacles in the nearby. According to the location of obstacles corresponding to conditions 1a, the obstacle does not intersect with the path of the robot. And in case 1b it will be necessary to bypass the obstacle. The coordinates of an alternative point for a detour (angle) are easy to calculate from geometric considerations. Most obstacle avoidance algorithms do just that. The trajectory of the robot can be represented by the equation:

\[ y_1 = k_1 * x + b_1 \]

\[ k_1 = \frac{y_R(t + t_0) - y_R(t)}{x_R(t + t_0) - x_R(t)} \]

\[ b_1 = \left[ \frac{-x_R(t)}{x_R(t + t_0) - x_R(t)} \right] * (y_R(t + t_0) - y_R(t)) + y_R(t) \]

To calculate the coordinate of the "nearest" point to the obstacle, we find that the equation of the normal (reference) robot's trajectory passing through the center of the obstacle

\[ y_2 = k_2 * x + b_2 \]

\[ k_2 = \frac{1}{k_1} \]

\[ b_2 = y_{Sol}(t) - k_2 * x_{Sol}(t) \]

The coordinates of the point of intersection the lines \( y_1 \) and \( y_2 \) can be found as:

\[ x_B = \frac{b_1 - b_2}{k_2 - k_1} \]

\[ y_B = k_1 * x_B + b_1 \]

\[ AB = \sqrt{(x_{Sol}(t) - x_B)^2 + (y_{Sol}(t) - y_B)^2} \]

An alternative point for a detour (angle) must be located at a safe distance from the obstacle center such that:

\[ AC > AB + dz \]

Where \( dz \) is an additional distance that guarantees the safe movement of the robot around the obstacle. Then:

\[ y_C = y_B + dz * (y_B - y_A) / AB \]

\[ x_C = x_B + dz * (x_A - x_B) / AB \]

Directions to bypass a single fixed obstacle are usually selected based on the criteria of the path/time to reach the target point, by which they will increase due to the detour. However, there may be situations such as presence another obstacle in the alternative path that robot chooses to detour, which may be located so that the robot movement along the
detour trajectory will be impossible. For example, a previously performed search determined
the trajectory of the robot nearby to some obstacle. But at the time of the search for the
trajectory, the “correct” size of the obstacle was unknown, which led to enforce the robot to
detour. After interval, the robot has approached to the obstacle, and with the help of sensor
information the real dimensions of obstacle became known to the robot so it’s decided to
detour. On the other hand, when the robot planning a detour around a "near" obstacle, the
robot can have information about a "remote" obstacle. But if the information about the
location and size of the obstacle is not “actual”, then in the process of avoiding “near”
obstacle by choosing alternative path may be will led to possibility of collision with a
“remote” obstacle.

A solution may be to take into account the uncertainties in the location of obstacles, their
size and motion parameters at the stages of planning the detour trajectories. In many real
situations, avoiding fixed obstacle can be complicated with the presence of movable obstacle
approaching the area under consideration that make it difficult or impossible to the robot to
move along the chosen trajectory. Consider possible solutions in situations where a mobile
robot needs to go around several fixed obstacles and, in its vicinity, a movable obstacle. The
purpose of the consideration is to analyze the variability of possible solutions, taking into
account the forecast for the formation of a method on the basis of which decisions will be
made by the robot control system in similar situations. Figure 2 shows one of the options for
the location of obstacles at some point in time. Robot 4 at time $t_0$ moved to the next scheduled
point $x_R(t + t_0), y_R(t + t_0)$,

![Fig. 2. The scheme of fixed and movable obstacles, when selecting an alternative trajectory to detour at the time $t + t_0$. 1 - fixed obstacles, 2 - movable obstacle, 3 - target point (2 location for analysis a or b), 4 - mobile robot moving to the target point.](https://example.com/figure2)

At this stage as in figure 2, the robot movement is planned for the next time interval $t_0$,
which it becomes clear that a collision is possible through a straight-line movement to the
target point and it is necessary to go around a fixed obstacle. When the target point is located,
for example, in position a, the best trajectory will be $p_1$ and the movable obstacle 2 will not
interfere with the movement. However, if the target point is at position b, the best trajectory
is $p_2$. Note that at the time $t + t_0$, when the trajectory $p_2$ is planned, there is no probability
of the robot colliding with the movable obstacle 2 on the planned time interval $t_0$ and known
trajectory planning algorithms would choose the path $p_2$ as the best one for avoiding fixed
obstacles. However, after two planning time intervals, the movement of a movable obstacle
can lead to the possibility of its collision with a mobile robot. Thus, robot moving further
along the trajectory $p_2$ will be impossible, and the permissible safe trajectories will be
“worse” than trajectory $p_1$. Summarizing of procedures for “bypassing” obstacles, it can be argued that when a mobile robot works in non-deterministic conditions, in order to avoid collisions, it is required to predict changes in situations for two or more planning intervals, and the algorithms of (decision-making) that based on the results of forecasting are also needed. In this regard, a method is proposed for trajectories planning of the mobile robot to avoid fixed obstacles, which considering the time/path criteria, also takes into account the probability of spatial movement of movable obstacles in the nearby zone of the mobile robot, leading to a possible collision in an extended forecast interval. The algorithm of the method is shown in Figure 3.

**Fig. 3.** Algorithm of planning trajectories around fixed obstacles, taking into account dynamic obstacles.

The algorithm should be executed after detecting the probability of the robot colliding with a fixed obstacle at the next scheduled interval of the robot's movement. With known values of the coordinates of movable obstacles $x_{dol}(t), y_{dol}(t)$ and fixed obstacles $x_{sol}(t), y_{sol}(t)$, the movement parameters of the obstacles (in a stochastic setting) the algorithm determines two possible alternative points to one of them the robot must move at the next scheduled time interval $t_0$ to bypass a fixed obstacle. The trajectories of the robot's movement to these alternative points are planned. To estimate the probability of collision with movable obstacles, a prediction of their movement is performed on an extended time interval $2 * t_0$. 

Since the movement of dynamic obstacles is undeterministic, then the prediction of their movement is based on the distributions laws of random values of its speeds and the direction of their movement. Next, the possibility of collisions at the time interval $2 \times t_0$ between the robot and movable obstacles is checked, then the algorithm select the possible or best of alternative trajectories which is free of collisions. Using this method of trajectories planning to bypass fixed obstacles will prevent the robot to get into situations that lead to an unjustified increase in (path / time) of movement to reach target point or are fraught with collisions.

Let us consider a situation, typical for detecting a movable obstacle with which a robot may collide. Known algorithms consider the following options for the behavior of the robot:

- change the direction of the robot to avoid collision;
- change the speed of the robot to avoid a collision;

At the same time, an alternative point to a trajectory passing through is also planned, to ensure the safety of movement and performance criteria. However, in the presence of a plurality of static and dynamic obstacles, there may be cases makes the robot movement to an alternative point inefficient so led to collisions. Figure 4 shows the situation at the time $t + t_0$, when the probability of a collision of a robot along a trajectory $p$ with a dynamic obstacle is detected.

To avoid collision, two alternative points are defined, through which two possible trajectories $p_1, p_2$ are planned for implementation. The static obstacle does not interfere with the robot's movement when its detour at time interval nor along the trajectory $p_1$ neither along the trajectory $p_2$. However, after the time interval $t_0$ has elapsed, it will be found that the fixed obstacle must be bypassed in the next time interval, and this will lead to a deterioration efficiency in the time/path (more time /long path). It is clear that if, at the stage of choosing the best trajectory, the situation is predicted for a time interval that is a multiple of the planning interval $t_0$, then the decrease in efficiency can be avoided.

Based on the analysis of possible situations and the spatial arrangement of objects in robot environment when planning movements associated with the detour of movable or fixed obstacles, the authors propose a method and an appropriate algorithm (Fig. 5).
This algorithm is supposed to be executed at each step of movements planning of the robot, when the probability of a collision with a movable obstacle is revealed. To select the best trajectories for continuing the robot movement, a forecast is made at the interval $t_0$, as well as possible trajectories for this interval are determined, then a forecast is made at the interval $(2 \times t_0)$ and possible paths are determined for executing.

### 3 Results

As a result of the analysis of possible situations of the location of obstacles and the behavior of the robot, typical tasks for avoiding obstacles by a mobile robot were determined. Given the large number of possible options for the location of static and dynamic obstacles, methods are proposed that generalize solutions for avoiding obstacles. The first method is for avoiding static obstacles, taking into account a nearby movable obstacle. The second method is for avoiding dynamic obstacles, taking into account nearby fixed obstacles. Both methods are applicable for navigation and motion control of mobile robots in a non-deterministic environment.
Since the decision on the direction of avoiding an obstacle must be made on the basis of the available information about the parameters and location of obstacles, a predictive estimate of the change in the location of obstacles in the time interval when the robot makes a detour around the obstacle is necessary. Information about static obstacles, received by the robot with the help of its sensors during operation, can change in terms of the size of the obstacles. For dynamic obstacles, their movements are estimated based on a stochastic representation. Predicting the change in the position and motion parameters of dynamic obstacles is based on the theory of random processes, where the direction and speed of the obstacle in the forecast interval are taken as random variables with a normal distribution law.

4 Discussion

All detour methods and algorithms can be divided into two groups. In the first, methods that determine the direction of the detour and alternative points without taking into account the locations of nearby obstacles [6, 8, 12]. The main disadvantage of such methods is the possibility of a collision with another obstacle when performing a detour, and, accordingly, a decrease in the criteria of finding safety movement along the trajectory to the target point. Methods of the second group estimate the current locations of obstacles and plan the trajectory of movement, taking into account all known obstacles. Some methods plan a new full path [13, 14] to the target point, some methods [15] plan a detour through an alternative point(s). However, dynamic obstacles in these methods are either considered as fixed, or it is assumed that the motion parameters of these obstacles are known and do not change.

An analysis of the known solutions to find options for avoiding obstacles made it possible to draw the following conclusions: First, widely used robot motion planning algorithms searching for trajectories around detected obstacles without predicting changes in the current situation at the near future. Secondly, when avoiding both static and dynamic obstacles, geometric or temporal criteria are used to evaluate the solution, however, a probabilistic assessment to deterioration of the criteria on a certain event horizon is not performed. Thirdly, when a possible collision is detected, performing a full-search of new movement trajectory to the target point requires significant computational and time resources furthermore may not always be considered appropriate. It may be preferable to search and perform a detour around the obstacle then a return to the previous reference movement trajectory to the target point. Fourth, the search for robot movement paths when avoiding obstacles should provide a forecast, based on currently available information about the possibility of presence other static or dynamic obstacles in the planned robot movement zone.

This article proposes a method for planning and controlling the movement of a mobile robot with ensuring a path without collision is found when bypassing static and dynamic obstacles, taking into account other obstacles in the nearby zone of a robot which operating in non-deterministic conditions.

5 Conclusions

The method proposed in the article of planning the trajectories of a robot to bypass static or dynamic obstacles provides a search for options to avoid obstacles without significant time or computational resources of the onboard control system. The method takes into account possible collisions at a given time interval of the prediction area. The information necessary for the algorithms that implement the method can be obtained by the information-sensor system of the robot based on a stochastic representation of the motion parameters to dynamic obstacles [6]. The proposed method for planning and controlling the movement of a robot when avoiding obstacles takes into account a variance in the location of static obstacles and
the random movement of dynamic obstacles. When a possible collision is detected, a detour is implemented to avoid collision so ensures the safe movement of the mobile robot nearby the obstacle area. The generated solutions are effective for any initial conditions for the relative positions of obstacles and the location of the target point.

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