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Adaptive Fuzzy Control for Autonomous Robot under Complex Environment

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***Abstract*—This paper studies an adaptive control method for an autonomous robot under a complex environment as static and dynamic obstacles with too many paths to target... A new obstacle avoidance approach for autonomous robots has been designed and implemented. This approach permits the detection of static or dynamic unknown obstacles simultaneously with the steering of the robot to avoid collisions and advancing toward the target. The robot is able to move in different areas. Through perception of surrounding environment the robot can interact and move following free-collision path in dynamic space. The controller for this study includes two inputs and two outputs to avoid the static obstacles as well as moving ones. Besides, a nonlinear controller based on the robot kinematics model of mobile robot is analyzed to apply to the adaptive fuzzy controller. The modeling and design of nonlinear fuzzy controller for a mobile robot are also described in this study. The performance results show that the algorithm of adaptive fuzzy controller can be used efficiently for controlling mobile robot work in complex environment.**

***Index Terms*—fuzzy controller, FLC, service robot, mobile platform, dynamic environment**

I. Introduction

Robot is often regarded as the biggest achievement of modern engineering. The modern robotics began as early as in the 1920s. Nearly a decade has gone, the robotics field has accomplished tremendous improvement. Nowadays, industrial robots take part in the manufacturing; replace manual labors in fields that require extreme precision. Robots are even used in space exploring by scientists. Besides, the service robots with mobile platform (mobile robot) recent attract a lot of attention from the public. Integrating with artificial intelligence of computer science, modern service robots has great potential as they are capable of perform many sophisticate work of the human. There is no doubt that, service robots are the prominent field in the near future.

The mobile robot will move to as well as interactive users. The service robot is designed to assist humans with public tasks. The robot will interact closely with a group of humans in their everyday environment.

In many references, there are three methods to navigate the mobile robot in complex environment. In the first one, robot can uses the occupancy map to approach the target. The second approach is to generate the map based on the information of sensors, and the robot uses this perception to navigate. The third one focus on the navigation without map, the robot recognized obstacles or track any object to navigate. A mobile robot should perform goal-directed tasks in not only many influence agents but also unknown environments. Both local reactive obstacle avoidance algorithms and path planning at global coordinate must be integrated and implemented in a single motion control module in order to provide the robot with this capability. Adaptive navigation supporting the mobile moves along the pre-determined path to reach the desired target and avoid the obstacles in dynamic environment. A service robot is a mobile robot that performs tasks without human's interaction. With data collection devices they are able to identify their surroundings from which to make their own responses accordingly. Robots must be able to perform from simple tasks such as care, house cleaning to more complex activities that require more intelligence and accuracy such as: transporting patients in hospitals, transportation, medicine transfer, information support for customers in airports and schools... The intelligence and accuracy of robots are two issues that require researchers to constantly apply modern scientific achievements to robots. Autonomous robots are the complex control object that includes data collection processes from the surrounding environment. For each change of the environment, the robot has corresponding response to that change. Furthermore, the classical controller has problem of high complexity, large computational range, multi-variables, frequently change. Therefore, the fuzzy controller contributes to solving optimal moving path [1]. In many previous studies, they showed the Fuzzy logic control can be applied to system of nonlinearity, uncertainty and complexity. Therefore, the Fuzzy control algorithm is suitable to embed on controller of mobile robot. To control adaptive the mobile robot has two tasks like as: move along pre-determined path and avoid the obstacles in dynamic environment. The controller would be plan the suitable path to reach the target by control two wheels of platform without collision [2], [3].

II. Autonomous Mobile Robot

The mobile robot is the wheel-driven platform being the most widely used in autonomous service robot. The

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problem of balance is often not a problem of much interest in mobile platform.

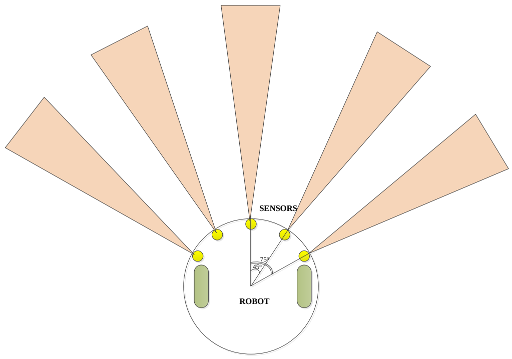


Figure 1. Arrange of sensor system and their working range.

The tricycle configuration is the most balanced structure, however, the 2-wheel configuration can also be balanced. When a robot has more than 3 wheels, it is usually necessary to design a suspension to maintain the contact of all wheels with the moving plane. In this paper, the robot model has the configuration including: Two driven wheels to create two degrees of freedom (one translation and one rotation) and one passive wheel (caster wheel). The navigation technique using artificial intelligence in autonomous robots can be divided into two main categories, which are computational navigation and adaptive navigation. In particular, computational navigation is a planned navigation method like as: the working environment of the mobile robot is completely defined, and the paths and obstacles are fully known. The adaptive navigation is instantaneous navigation according to the surrounding environment, which means that the robot operates in an unknown environment, or only partially known. At this time, the sensing and positioning system for the robot allows identifying the changing environment around the robot. There is also a hybrid navigation method that combines both adaptive and computational methods to build a smarter controller.

In this paper, the computational method is used, which means that the robot will plan its way to the destination based on static obstacles, divide the planning line into sections and control the moving robot along the planned trajectory. To ensure that robot can move smoothly along pre-determined as well as avoid the static and dynamic obstacles, the robot's navigation is considered to being high efficient results.

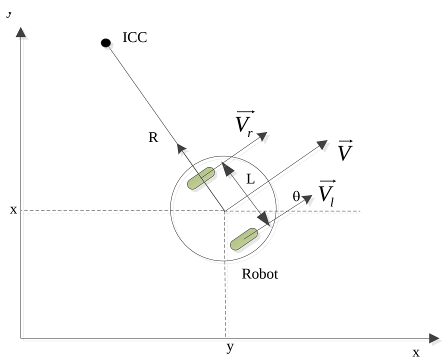


Figure 2. Autonomous robot kinematics.

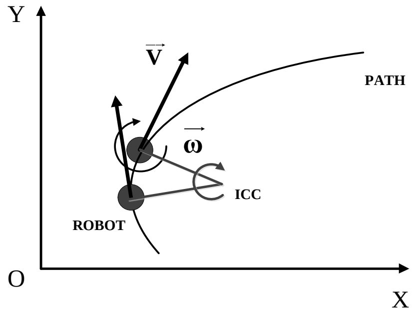


Figure 3. The movement components of robot on floor.

Detecting and avoiding obstacles is one of the basic problems to design and control the autonomous robots. The identifying obstacles are very important and require high accuracy. There are two main types of obstacles for robot: static restraints and dynamic obstacles based on acting accordingly to each special case. The robot for experiments is attached 5 ultrasonic sensors to detect obstacles like as Fig. 1. The range of sensor detects the obstacles of the sensor with an angle of α and the distance from the obstacle to robot the robot is d.

Kinematics shown as Fig. 2 is a problem of movement without considering the force on the robot to determine the position of the robot. It covers the relationship between control parameters and system state parameters in space. How to determine the position as well as orientation of mobile robot in working space, a relationship between a global coordinate and a local one attaching on robot. The location of point in the global coordinate system determines in respect to x and y axes is described in Fig. 3. The ICC point is called the Instantaneous Center of Curvature during movement.

ICC (Instantaneous Center of Curvature) has pose like as:

$$\begin{cases} x_{ICC} = x - R\sin\theta \\ y_{ICC} = y + \cos\theta \end{cases} \tag{1}$$

The angular velocity at robot center is given as follows.

$$\omega(t) = \frac{V_r(t) - V_l(t)}{L} \tag{2}$$

$$\omega(t) = \frac{V_r(t)}{R + L/2} \tag{3}$$

$$\omega(t) = \frac{V_l(t)}{R - L/2} \tag{4}$$

The instantaneous curvature radius of trajectory is shown like as.

$$R = \frac{L(V_l(t) + V_r(t))}{2(V_l(t) - V_r(t))} \tag{5}$$

From above equations, we can determine the linear velocity of mobile robot.

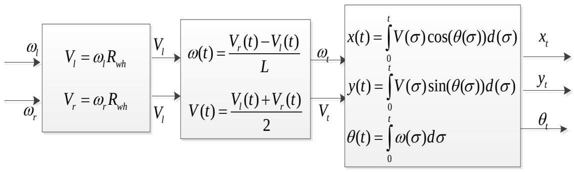


Figure 4. Calculate the coordinates of robot.

$$V(t) = \omega(t)R = \frac{(V_l(t) + V_r(t))}{2} \tag{6}$$

From these equations:

$$\dot{x}(t) = V(t)\cos\theta(t) \tag{7}$$

$$\dot{y}(t) = V(t)\sin\theta(t) \tag{8}$$

$$\dot{\theta}(t) = \omega(t) \tag{9}$$

The kinematic variables in respect to world coordinate can be shown as follows.

$$x(t) = \int_0^t V(\sigma)\cos(\theta(\sigma))d(\sigma) \tag{10}$$

$$y(t) = \int_0^t V(\sigma)\sin(\theta(\sigma))d(\sigma) \tag{11}$$

$$\theta(t) = \int_0^t \omega(\sigma)d\sigma \tag{12}$$

The robot has 3 wheels including two active drives and a caster wheel. Two incremental encoders are integrated the motors to count the wheel revolutions. The position of mobile robot as well as its orientation can be determined by the kinematic solution and track the trajectory by comparing geometric algorithm. Method of analysis of the coordinates of moving robots in the plane: The coordinates of the robot include 3 parameters (x_{robot}, y_{robot}, θ_{robot}) as shown in Fig. 4. Two encoders are integrated on motors to measure the rotation speed of the two driven wheels. The speed of the wheels is converted into the linear velocity of the left and right wheels. From the velocity of the left and right wheels, the velocity of mobile robot can be calculated. The robot's length and rotation speed are based on formula (4) and (6). Finally, the calculation of current pose and orientation in global coordinates follows the formula (10), (11) and 12).

III. Design of Fuzy Controller

Traditional logic is based on two values, one (true) and zero (false). This is inadequate for approximating the human decision-making process. Fuzzy logic uses the entire interval between zero and one, therefore, to be used to closely mimic human reasoning. The fuzzy decision making controller is made up of three steps [4]:

1) Fuzzification: Converts controller inputs into information that the inference mechanism can be easily used to activate and apply rules;

2) Rule base: A set of IF-Then rules which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control;

3) Defuzzification: This converts the conclusions of the interface mechanism into actual inputs for the process.

The components of fuzzy controller are an inference engine and a set of linguistic IF-THEN rules that encode the behavior of the mobile robot [5]. However, the main difficulty in designing a fuzzy logic controller is the efficient formulation of the fuzzy IF-Then rules. If it is easy to produce the antecedent parts of a fuzzy rule base, it is however very difficult to produce the consequent parts without expert knowledge. The distance from robot to surrounding obstacles is defined by ultrasonic sensors.

As previous defined section, the fuzzy controller is used to implement the robot navigation, which is divided into two main categories: computational and adaptive navigation. Computational navigation is a planned navigational method, the process of automatically responding to the surrounding environment.

As mentioned above, the fundamental problem in motion control for robots is the design of the controller with the appropriate input and output variables to control the robot to move from point to point on trajectory accurately. So the acquired data is the current position of the robot (x_{Start}, y_{Start}, α_{Start}) and the coordinates that the robot needs to target is (x_{Goal}, y_{Goal}, α_{Goal}) based on the trajectory like as Fig. 5. The movement of the robot reaches the desired position, in which the motion trajectory of the robot is determined by the straight velocity V(t) and the rotation velocity ω(t). In fact, the input variables are only position relative to the global coordinate system. During the movement, the global coordinate system does not change, thus only the relative position between the robot and the target point is changing over time. We choose only linguistic variables that represent the relationship between the beginning positions and the end ones. In order to find the appropriate input variables, it is necessary to simulate actual simulation cases in accordance with output response requirements.

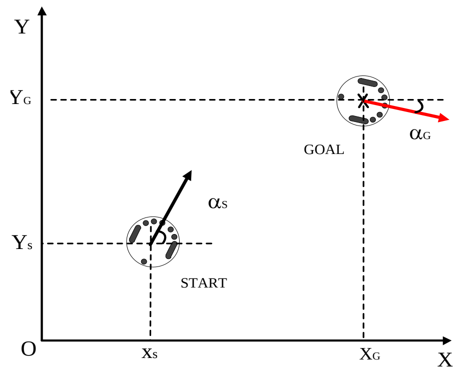


Figure 5. Algorithm of moving from point to point.

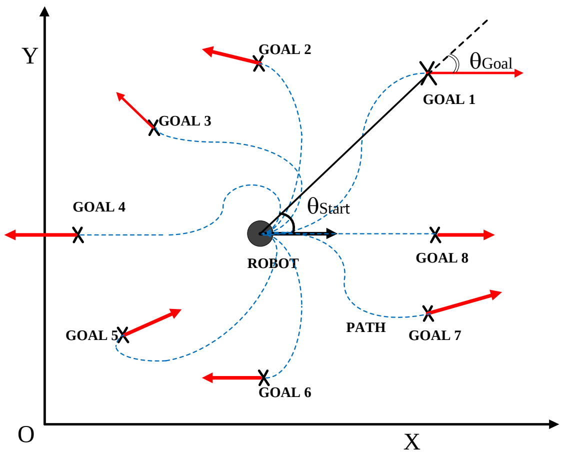


Figure 6. The typical solutions for moving from point to point.

In Fig. 6, there are 8 typical cases shown 8 targets with different coordinates and orientation angles. In which: θ_{Start}, θ_{Goal} are respectively rotation angles of the robot at the initial point, the endpoint. The goal is moving smoothly and continuously when the robot moves from one point to the next one. As the Fig. 6, the distance from the starting point to the destination, θ_{Start}, θ_{Goal} all change, if the robot moves. The θ_{Start}, θ_{Goal} angles decide to trajectory of the robot, assuming the straight line connecting the two starting points and the destination divided into planes into two regions, each vector shows the direction of the robot at the a location at the same time. The robot will move according to the "S" trajectory, 2 vectors indicate the direction of the robot at 2 different locations, the robot will move according to the curved trajectory "C". Finally, trajectories with large or small radius depend on the magnitude of θ_{Start}, θ_{Goal}. Thus, there are 3 input variables for the controller based on general cases: the first variable is distance D between the initial - target points, the second variable is the angle between θ_{Start} to initial orientation, the third variable is the angle θ_{Goal} at the target axis as shown in Fig. 7.

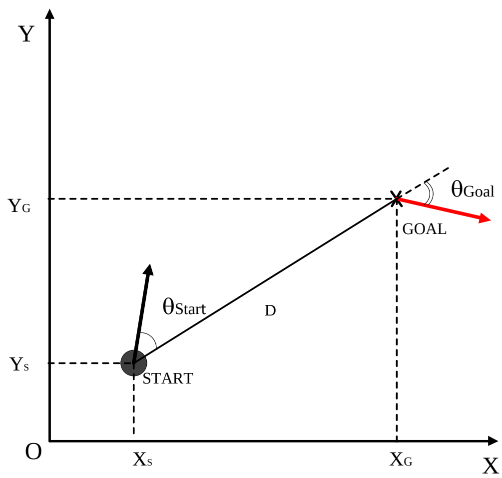


Figure 7. Output of Fuzzy Controller.

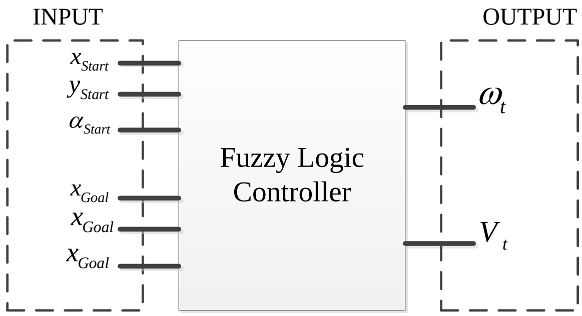
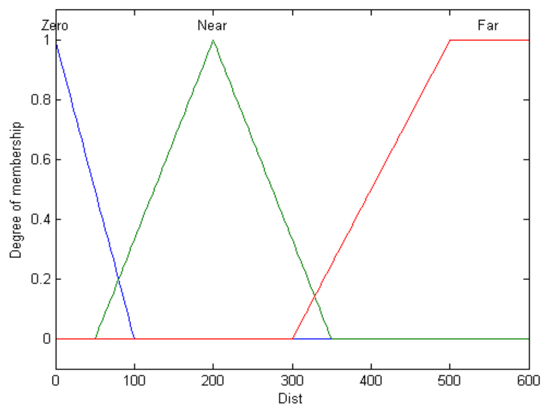


Figure 8. Structure input and output of Fuzzy Controller.

Fuzzy controllers have become the new controllers in industrial machines. These controllers can use in majority of machine to adopt the requirements of industry and human life. Mobile robot is the intelligent platform that makes decision the safe of whole upper robot's body and moving precisely in different environment and situation. In which, the key issue is navigation itself to avoid obstacles, follow defined trajectory and move to destination point.

They are able to perform highly adaptive control although human beings do not need precise, numerical information input to make a decision. Robot with explicit measurements or computations that has a remarkable capability to perform a wide variety of physical and mental tasks likes human being. To recognize the trajectories, obstacles and targets, robot must consider the provided details from surrounding also the working environment obtained from its sensor system like as Fig.8. Besides, it is extremely important to select the membership function, which represents the level of the impact of the input on the system and as well as the system's response. However, selecting a membership function does not have a consistent rule for the matter of choosing a function that is simply a way of selecting the function from known functions and modeling it. The Input and Output sets for Fuzzy controller are shown in Fig. 9-10. The relationship between input and output is described by the controlling surfaces in Fig. 11, which is nonlinear ones.



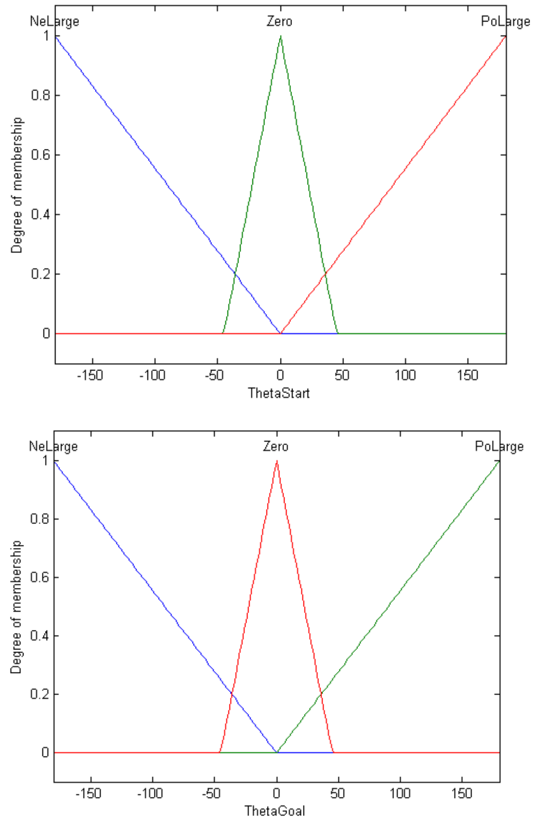


Figure 9. Membership functions of Input set.

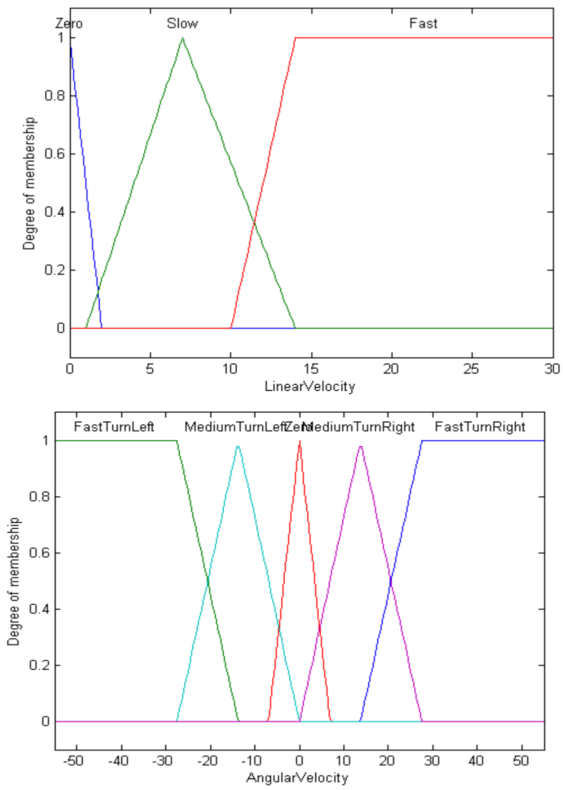


Figure 10. Membership functions of Output set.

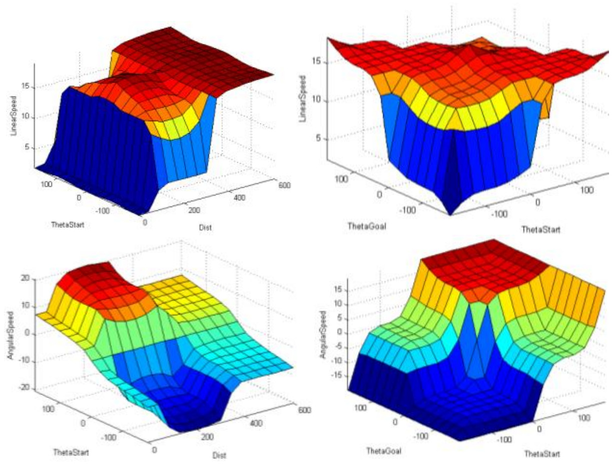


Figure 11. Controlling surfaces based on input and output.

IV. ALGORITHM FOR SEARCHING PATH UNDER COMPLEX ENVIRONMENT

Suppose that the workspace of mobile robot is indoor with static obstacles (tables, chairs, bookcases, ...) and dynamic ones as shown in Fig. 12. The robot is required to be able to move and follow the desired path without colliding with any obstacles. In the map, the fixed obstacles will be digitized into white and black areas (white - movable robot area, black - obstacle area). Currently, the research works have introduced many algorithms for path planning for robots, but the overview study shows the following cases of robot movement: The robot moves in a static environment according to predetermined schedule and move in dynamic environments when encountering mobile obstacles [6]. Within the scope of the research, the robot moves in a static environment according to a predetermined schedule. According to the Probabilistic Roadmap (PRM) method, this is the algorithm to create the shortest path according to the probability method. The nodes are randomly generated on areas where the robot can move (the White area) on the map shown in Fig. 12, then the nodes will be connected together by straight lines on the principle that these lines do not cross obstacle zone (Black zone), because this is the path that the robot must follow. Algorithm A* is used to find the straight lines connecting the current robot position to the target in the shortest path. The path is not really optimal because it still carries out randomness. The robot cannot reach the target in several cases due to uneven nodes. The straight lines create even if they do not cross the obstacle but very close to the obstacle, the robot will collide with obstacles.

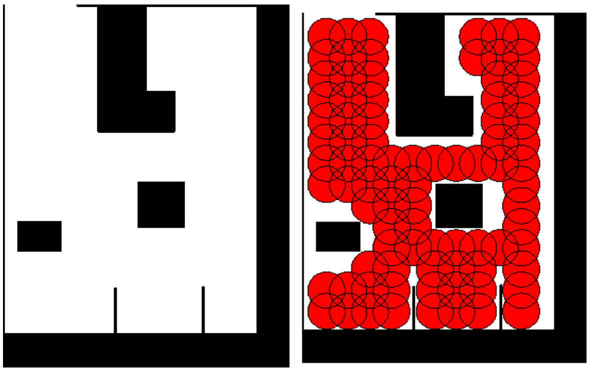


Figure 12. Workspace of autonomous robot (left) and generation of node map robot can reach (right).

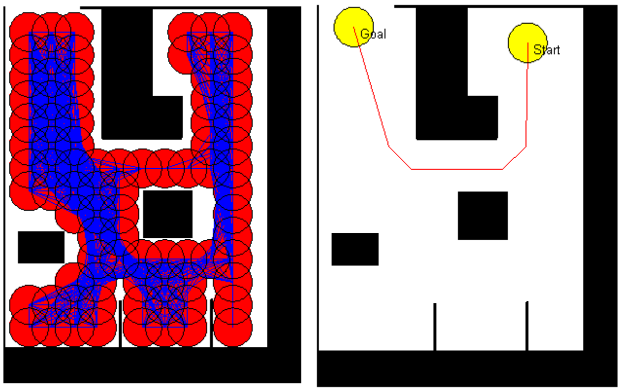


Figure 13. Algorithm of searching shortest path (left) and searching result (right).

After generating the nodes, straight paths connect between the nodes based on the principle like as each node would connect to all the remaining nodes, and the straight lines must not cross the obstacle area. Therefore, these will be the paths of the robot, the straight line must be far enough away from the obstacle area, the robot does not collide with the obstacle when moving shown in Fig. 13. An algorithm A* is used for shortest path to target. This path search algorithm is a result of point coordinate set, which divides the path planning into many straight lines. The robot can use the fuzzy controller to control the movement through these straight lines until it reaches the final point, then it stops.

V. Experiments and Discussions

The movement of the robot can be grouped into two main types: (1) normal movement, (2) avoid the statics and dynamics obstacles. The experiment is made on the mobile platform of service robot, which is an ideal testing paradigm in Fig. 14. The mobile robot is autonomously controlled by the on-board computer, which is responsible for the intelligent strategy. The data from distance sensors send to main controller for determining the current position of the obstacles [7]. Therefore, this test platform has the non-holonomic constraints, stores the requirement on start and end position and orientation, and monitors the full environment information.

Figure 14. Service Robot for experiment mobile platform.

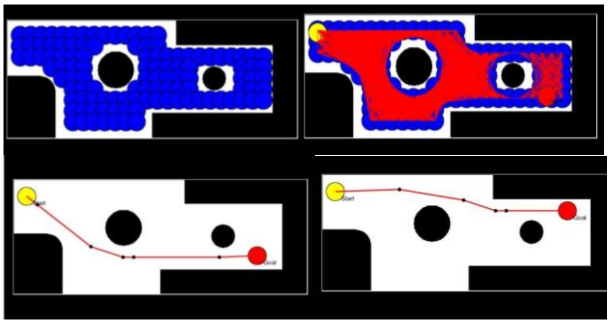


Figure 15. Fuzzy controller is combined with A* algorithm allows robot reach the location on the workspace and shortest path.

Those characteristics are the premise of our control strategy. The values of setup start and end of trajectory are given, then the controller generates the optimal pre-determined path from point of start to one of end. In moving process of mobile robot, it can meet the obstacles and controller keep giving the other adjust pre-determined path to produce new trajectory, which robot can track on and avoid the obstacles to reach the target.

In case, the mobile robot moves quickly in free workspace, then reduce speed when the end point nearby; and it will stop at target.

The data acquired from distance sensors attached on mobile robot, then robot determine the surrounding obstacles thus it reduces the moving velocity to avoid the objects. If the robot reach near the obstacle or its working space is very complex and narrow, then robot have to reduce the velocity to keep safety. We know that the robot has active behavior to decelerate to not impact the obstacles. Experiments of the controllers are done in a physical indoor environment with a variety of static collisions as well moving ones.

The robot's fuzzy controller defines the optimal path with A* algorithm in indoor uncertain and unknown environment with obstacles having different shapes and sizes shown like as Fig. 15, an experiment is carried on testing the controller's ability to respond which allows robot reach the location on the workspace and shortest path.

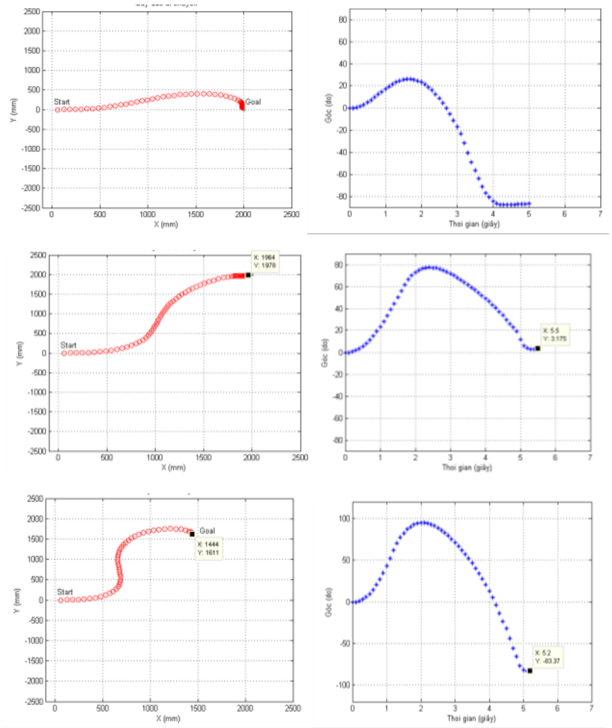


Figure 16. The position and angle variables in experiments

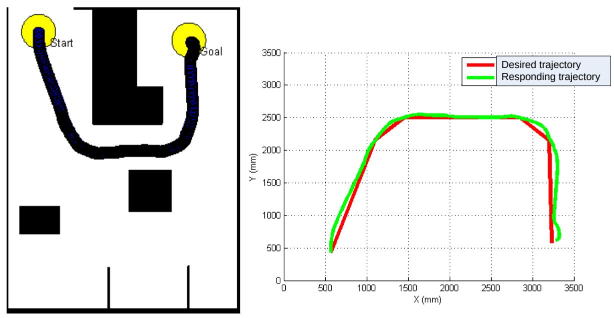


Figure 17. Simulation (a) and experiment (b) results for the obstacle avoidance.

The robot's path planning in the moving space is divided into smaller moving areas. This moving algorithm from point to point is used the defined space. The fuzzy controller allows the robot moving from point to point until the path finishes. The robot chooses the suitable planning path based on accuracy of the fuzzy controller. Besides, the accuracy of the controller is simulated and experimented with initial conditions in this section.

The accuracy of the controller is determined by simulating the movement trajectory of the robot with the different input and assuming conditions. Suppose that with the initial position of the robot is same starting point (0, 0, 0) and let the robot move to different targets. For motion trajectories, each different target will have many responding moving trajectories, therefore the fuzzy controller controls the robot to move in the same trajectory as the case assumed in Fig. 16. With curved trajectory, the robot will move flexibly and continuously in smooth. However, the radius of curvature of the robot's movement is too large to easily collide with obstacles in a narrow space. The errors of the robot occur in the x-axis and y-axis as well as rotation angle of z-axis, they would be compared to the local coordinate system. However, these errors are still small (<1%) and completely acceptable, as in 6 cases like as Fig. 16, the x-axis errors are 15mm, 36mm, 0mm, 56mm, 58mm, 55mm respectively, the error of the y-axis is 52mm, 12mm, 12mm, 111mm, 97mm, 34mm, 35mm respectively and the error of robot rotation angle is 3.70, 3.20, 00, 6.70, 3.30, 3.20, 2.90, respectively. The radius of curvature of the orbit is depended on the angle of incidence by the robot direction vector and the line connecting two original points and destination point. For experiment in dynamics environment, it is purpose to reduce this radius of curvature, we only need to reduce the speed of the robot (V(t)) and increase the speed of turning the robot (ω(t)), in terms of the parameters of the fuzzy controller we only need to change the fuzzy rule in the case of the angle of the variable into θ_{Start}. The experiment's trajectory tracking of mobile robot generates the control commands for the robot to follow the previously defined path by taking into account the actual position and orientation, linear and angular velocities, non-holonomic constraint and dynamic constraints imposed by robot. The changes in the terrain topography and texture as in Fig. 17(a) play major roles in the robot movements. The robot uses ultrasonic sensors detect and locate the obstacles to choose the best solution avoid them like as Fig. 17(b).

VI. Conclusions

The paper has generalized fuzzy controller for mobile robot of 2 driven wheels and a caster wheel within the defined space. Besides, it has shown the outline of the robot moving algorithm using the A* algorithm to calculate the shortest trajectories, ensuring that the robot can move to the target without collision of obstacles. The velocities and accelerates of the two driven wheels were independently controlled. The results for experiments of the adaptive fuzzy control system were shown the high efficient performance of the velocities on the left and right wheels, while the positions of obstacles and the angle between the robot and the target position were first-come variables exactly. Being equipped with ultrasonic sensors, tested on real platform, an mobile robot is now giving spectacular results that the developed robot could adaptive with the complex environment in different speeds and stops when robot approaches to obstacle. Moreover, robot can easily find the shortest way to the target by applied A* algorithm shown as the simulation results which are provided to emphasize the effectiveness and feasibility of this research.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tuong Phuoc Tho, Nguyen Dao Xuan Hai contributed to the analysis and implementation of the research, to the analysis of the results and to the writing of the manuscript.

All authors discussed the results and contributed to the final manuscript. Besides, Nguyen Truong Thinh conceived the study and were in charge of overall direction and planning. Nguyen Truong Thinh is a corresponding author.

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