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Quadrotor Path Planning Based On Modified Fuzzy Cell Decomposition Algorithm

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Abstract

The purpose of this paper is to present an algorithm to determine the shortest path for quadrotor to be able to navigate in an unknown area. The problem in robot navigation is that a robot has incapability of finding the shortest path while moving to the goal position and avoiding obstacles. Hence, a modification of several algorithms is proposed to enable the robot to reach the goal position through the shortest path. The algorithms used are fuzzy logic and cell decomposition algorithms, in which the fuzzy algorithm which is an artificial intelligence algorithm is used for robot path planning and cell decomposition algorithm is used to create a map for the robot path, but the merger of these two algorithms is still incapable of finding the shortest path. Therefore, this paper describes a modification of the both algorithms by adding potential field algorithm that is used to provide weight values on the map in order for the quadrotor to move to its goal position and find the shortest path. The modification of the algorithms has shown that quadrotor is able to avoid various obstacles and find the shortest path so that the time required to get to the goal position is shorter.

Keywords: *Cell Decomposition, Quadrotor, Fuzzy, Shortest Path, Modified Potential Field*

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1. Introduction

Quadrotor is an autonomous robot that moves by using four rotors [1] without requiring an operator but a navigation system that is capable to direct it to the goal position in an unknown area. Quadrotor is one type of UAV used by SAR team and the military to perform missions such as surveillance, search and rescue victims of disasters in the areas. Given the mission, quadrotor must fly low in which it has a challenge to avoid several obstacles. To overcome the problem, several researchers have conducted research on path planning algorithm that enables UAVs to be able to avoid obstacles and move to the goal position.

Graph-search theory has been used by Filippis et al., [2] for UAV path planning in a 3D environment. This theory is used to create a 3D map in an unknown environment by dividing the environment into small grids. The 3D map with grids is a contour map with colors that represent different heights above the ground. The algorithm used for path planning are A* and theta* applied to UAV in a 3D environment. In various tests, the theta* algorithm has smoother movement than the A* algorithm. The drawback of the theta* algorithm is that it is not able to detect dynamic obstacles.

In addition to the researcher mentioned previously, the theory of graph-search has also been developed by Garcia et al [3] for UAV path planning in dangerous environments. The environment is divided into small grids on a 2D map in which several lines are drawn to connect them. Besides using 2D environment maps, the researcher also used a 3D environment map because the UAV works in that environment. The algorithm used in this study is lazy theta which is then compared with A* and A*PS (Post-Smoothing) algorithms. The simulation result shows that lazy theta algorithm requires faster time than the other two algorithms. However, this algorithm has merely been applied in static but not dynamic environments.

Graph theory of B-Spline curve method used by Elbanhawi et al., [4] is a modification of B'ezier curves used for Car-Like Robots path planning. By using Curves B'ezier algorithm, the robot is able to move to the goal position and avoid obstacles. The algorithm is modified into a

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B-Spline curve due to the robot motion that is not smooth. The weakness of this algorithm is that the robot cannot avoid moving obstacles.

Heuristic algorithm has been used by Yao et al., [5] for robot path planning in an unknown environment. The algorithm used is the combination of neural network and genetic algorithms applied for robot in a plannar environment using global path planning method. Neural network algorithm is used to model a static environment obtained by using a global view, so that the starting, goal, and obstacle positions of the robot can be viewed, while the genetic algorithm is used for robot path planning. With these algorithms, the robot is able to move to goal position and avoid obstacles, but the weakness of this algorithm is that it is applied only for static environment and because of this the robot cannot avoid dynamic obstacles.

There are heuristic algorithms which have properties resembling creatures such as bacteria and bees. Foragin bacteria algorithm used by Liang et al., [6] is one of the heuristic algorithms having characteristics like bacteria in which this algorithm can create a contour map of the environment that is used to avoid obstacles and move to goal position in a static environment. Honey Bee Mating Optimization algorithm used by Rashmi et al., [7] for multi-robot path planning has a characteristic like insect colony in which this algorithm can make maps of the safest path and avoid obstacles to move to goal position. The track paths created using colony bees. By using this algorithm multi-robot can identified a short path in a dynamic environment.

Genetic algorithms have been studied by Yang et al., [8] used for robot path planning algorithm combined with visibility graph. Visibility graph algorithm is used to create a map of an environment model by using global view, so that the obstacles position can be determined, while genetic algorithm is used to make robot path planning. By using both of the algorithms, robot can avoid obstacles and move to the goal position.

Genetic algorithms has been used by Pehlivanoglu [9] for path planning by combining Voronoi diagram method. This algorithm is applied to a UAV for path planning in an urban-like environment. In the neighborhood there are obstacles in the form of skyscraper models or tall buildings. Voronoi diagram method is used to create a map of an unknown environment. A UAV is set at a certain height, so that with this algorithm the UAV will avoid skyscrapers and pass over the buildings.

The other heuristic algorithm such as Bacterial Potential Field is a merger of two algorithms that is potential field and bacterial potential field algorithms conducted by a researcher named Montiel et al., [10]. Bacterial algorithm is used to create an environment map and a path planning. The weakness of the algorithm is that it stops at certain obstacles, so that it is modified with the potential field algorithm. With the modification of the two algorithms, a robot is able to find the shortest path and avoid obstacles in a static environment.

Heuristic algorithm was developed by Ghosh et al., [11] who applied Fuzzy algorithm for Micro air vehicle path planning. The algorithm used was the development of fuzzy algorithm with quadtree framework. Quadtree fuzzy algorithm framework is the combination of fuzzy algorithm and graph theory. Graph theory is used to create 2-dimensional environment, while the fuzzy algorithm is used for path planning. The quadtree algorithm is used for path planning in a static environment for fixed wing aircraft models. However, this algorithm has not been able to determine the shortest path.

The other researcher combined virtual force fuzzy algorithm with graph theory as conducted by Zhuoning et al., [12]. Graph theory is used to create a 2-dimensional environment map by dividing the map into small grids and then the fuzzy algorithm used to get to the goal position and avoid obstacles is identified. In order to reach the goal position quickly, fuzzy algorithm is combined with virtual force algorithm. The problem of the algorithms is that the force obtained from virtual force algorithm is considerably great that results in frequent fails in avoiding obstacles.

Fuzzy algorithm has been used by Wang et al., [13] for path planning in an unknown environment. The algorithm is combined with exact cell decomposition graph method used to create a map by dividing the tracks into equal size to avoid obstacles and reach the goal and the fuzzy algorithm is used for path planning. To reach the goal position, the algorithm does not seacrh for the shortest path.

Several algorithms previously mentioned have not been able to identify the shortest path and cannot be applied in a dynamic environment. Hence, this paper presents fuzzy algorithms combined with cell decomposition method and modified by adding potential field algorithm in order to reach the goal position more rapidly and avoid dynamic obstacles.

2. Non Linear Quadrotor Modeling

Quadrotor is an unmanned aircraft with rotary wing type using 4 rotors at each end of the frame that moves with thrust as shown in Figure 1 which is a model of Mahony et al [14] presented in this paper. In the figure it is seen that the quadrotor moves by using the four rotors which rotate in opposite direction i.e. two rotors rotate in a clockwise direction and the two other rotors rotates counterclockwise.

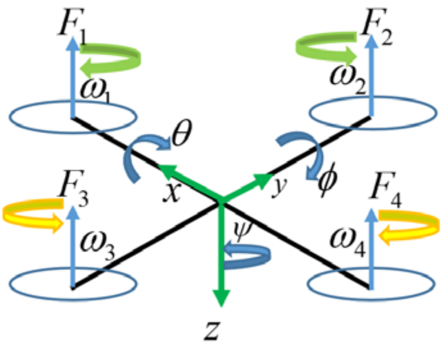

Figure 1. Quadrotor modelling

Quadrotor system is a non-linear system that can be controlled by six out of the twelve states that regulate the attitude of quadrotor system that is. The first six states involves Euler angles consisting of roll, pitch, yaw angles denoted as $\beta_2 = [\phi \quad \theta \quad \psi]^T$ and angular speed on three orthogonal axes of the body of quadrotor denoted as $\beta_4 = [p \quad q \quad r]^T$. While six other states are three axis positions denoted as $\beta_1 = [k \quad l \quad m]^T$ and three linear velocity of the center of mass of the quadrotor associated with fixed reference frame denoted as $\beta_3 = [\dot{k} \quad \dot{l} \quad \dot{m}]^T$. So that the equations of non-linear model of the quadrotor are as follows:

$$\begin{aligned} \dot{x} &= k \\ \dot{y} &= l \\ \dot{z} &= m \end{aligned} \quad (1)$$

$$\begin{aligned} \dot{\phi} &= p + s_\phi t_\theta q + c_\phi t_\theta r \\ \dot{\theta} &= c_\phi q - s_\phi r \\ \dot{\psi} &= \frac{s_\phi}{c_\theta} q + \frac{c_\phi}{c_\theta} r \\ \dot{k} &= -\frac{1}{m} T\left(c_\phi s_\theta c_\psi + s_\phi s_\psi\right) \\ \dot{l} &= -\frac{1}{m} T\left(c_\phi s_\theta s_\psi - s_\phi c_\psi\right) \end{aligned} \quad (2)$$

$$\dot{m} = g - \frac{1}{m} T\left(c_\phi c_\psi\right) \quad (3)$$

$$\dot{p} = \frac{db}{I_x}\left(\omega_2^2 + \omega_3^2 - \omega_1^2 - \omega_4^2\right) - \frac{I_z - I_y}{I_x} qr$$
$$\dot{q} = \frac{db}{Iy}\left(\omega_3^2 + \omega_4^2 - \omega_1^2 - \omega_2^2\right) - \frac{I_x - I_z}{I_y} pr$$
$$\dot{r} = \frac{k}{I_z}\left(\omega_2^2 + \omega_4^2 - \omega_1^2 - \omega_3^2\right) - \frac{I_y - I_x}{I_z} pq \quad (4)$$

3. Research Method

Path planning is an algorithm that is needed by a quadrotor in order to reach its goal position and avoid obstacles. There are two methods of path planning that is global and local path plannings. Local path planning is planning that uses sensors attached to the body of the robot so that the robot identifies merely the obstacles placed in front of it, while the global path planning uses sensors to see globally. This paper presents a research method for the study of global path planning. The research methods used in this paper are map creation, path planning, quadrotor application and potential value provision to the map.

3.1. Map Creation

Cell decomposition is one of the methods in graph theory used to create two-dimensional maps for robot path planning. This method divides the map into a several grids that serves to make the robot path. There are two methods that is approximate cell decomposition and exact cell decomposition. Approximate cell decomposition is used by Valente et al., [15] for a quadrotor path planning coverage. An environment is divided into several equal grids by using these methods. Then a path is created on the grids located in the map. Path planning coverage algorithm is used in this study, so that the quadrotor moves to the goal position and avoid obstacles without seeking the shortest path.

Path planning coverage algorithm has been used by Galceran & Carreras [16] for different path planning coverage to create a map in an unknown environment by using exact cell decomposition. Several grids made in the map by using this algorithm have equal size. Path planning coverage algorithm is used for the grid division. It is applied for floor cleaning robot in which the robot achieves the goal and avoid obstacles without seeking the shortest path.

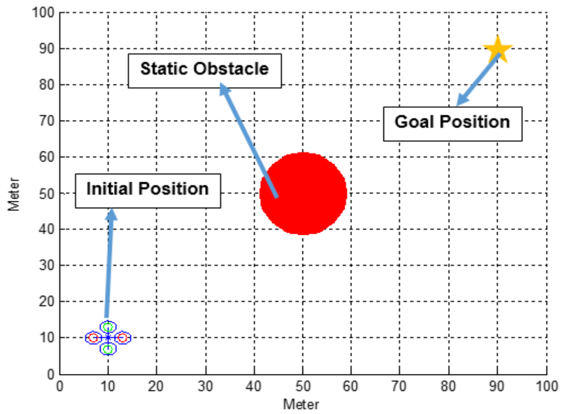

Figure 2. Environment model

Approximate cell decomposition algorithm is presented in this paper as shown in figure 2. It shows that there are initial potition of (Xr, Yr), static obstacles position of (Xo, Yo), and the goal position of (Xg, Yg) in an unknown environment by viewing globally. Using the position data, an environment map is obtained. The source code shown in Figure 3 is used to create a map and split it into several grids.

Figure 3 shows that (X_R, Y_R) is the position of the robot, (X_O, Y_O) is the position of obstacle 1, and (X_G, Y_G) is the position of goal. R_G is the formula of the distance between the position of the robot and the goal and R_O is the formula of the distance between the position of the robot and the obstacle. Then R_G and R_O are summed to an environment matrix value.

for $I = 1 : K : 100$

for $J = 1 : K : 100$

$X_R = I$;

$Y_R = J$;

$$R_O = \sqrt{\left(\frac{Y_R}{10} - y_O\right)^2 - \left(\frac{X_R}{10} - x_O\right)^2} ;$$

$$R_G = \sqrt{\left(\frac{Y_R}{10} - y_G\right)^2 - \left(\frac{X_R}{10} - x_G\right)^2} ;$$

$$A(I,J) = \left(\frac{1}{R_O}\right) + (R_G);$$

if $(A(I,J) > 300)$, $(A(I,J) = 300)$; end

end

end

Figure 3. Matrix environment of cell decomposition

3.2. Fuzzy Path Planning

Basic behavior of robot path planning in decomposition cell algorithm is go-to-goal. In this behavior, the robot searches for the smallest grid to move by grid following to get to the goal position. Cell decomposition algorithm is a path planning algorithm in $\Re^2$ environment while position of quadrotor is in $\Re^2$ environment. Hence this paper proposed quadrotor path planning with fuzzy algorithm for $\Re^2$ environmental position by providing a constant value at a certain height. In this study, the quadrotor is controlled with reference values of grid spacing obtained from fuzzy algorithm.

This algorithm which is an artificial intelligence algorithm used for robot navigation in unknown environment is discovered by zadeh [15] and used by Lee [16]. Fuzzy input is an ultrasonic sensor attached to the front body of the robot with angle between sensors is 30° and there are 12 sensors. Fuzzy algorithm used has a rule base by comparing detection distance of objects to detection angle of object. The fuzzy algorithm has successfully passed the obstacle toward goal position.

The other researchers such as Kala et al., [17] combining fuzzy algorithm with A* used for robot path planning. A* algorithm is used for path planning on colored maps created by using graph algorithm, while fuzzy algorithm is used for navigating robot. With the merger of the two algorithms, the robot can avoid obstacles and reach its goal position.

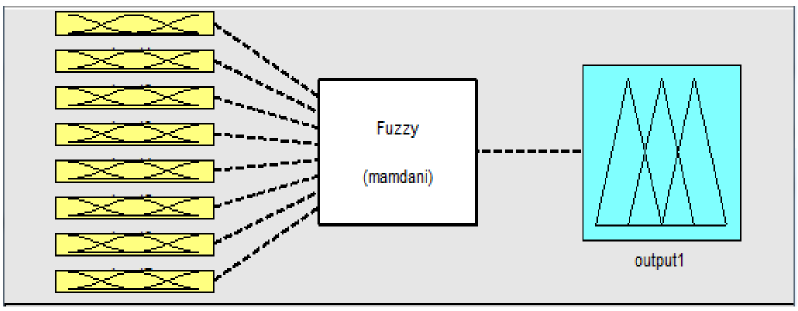

Figure 4. Fuzzy path planning design

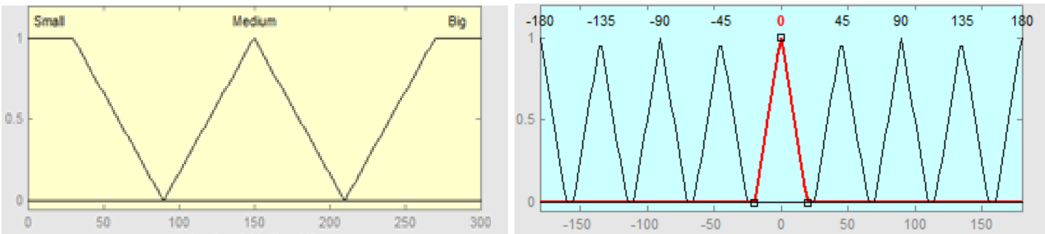

Figure 5. Set of fuzzy input and output

if $u_1 < u_2 \& u_1 < u_3 \& u_1 < u_4 \& u_1 < u_5 \& u_1 < u_6 \& u_1 < u_7 \& u_1 < u_8$
  $\theta = 0^0$;
else if $\& u_2 < u_3 \& u_2 < u_4 \& u_2 < u_5 \& u_2 < u_6 \& u_2 < u_7 \& u_2 < u_8$
  $\theta = 45^0$;
else if $u_3 < u_4 \& u_3 < u_5 \& u_3 < u_6 \& u_3 < u_7 \& u_3 < u_8$
  $\theta = 90^0$;
else if $u_4 < u_5 \& u_4 < u_6 \& u_4 < u_7 \& u_4 < u_8$
  $\theta = 135^0$;
else if $u_5 < u_6 \& u_5 < u_7 \& u_5 < u_8$
  $\theta = 180^0$;
else if $u_6 < u_7 \& u_6 < u_8$
  $\theta = 225^0$;
else if $u_7 < u_8$
  $\theta = 270^0$;
else
  $\theta = 315^0$;
end

Figure 6. Fuzzy path planning rule base

The fuzzy input of grid values is obtained from cell decomposition on global path planning while the member set fuzzy output is motion direction of quadrotor as shown in figure 4. The path planning proposed in this study is for the robot in R^2 position while quadrotor is a robot that is in R^3 position. Therefore, the quadrotor will work in R^2 position in which the altitude is set up.

The fuzzy method used in this pape has eight inputs consisting of three members ie small, medium, and large ranging from 0 to 300 as shown in Figure 5. There is one output of fuzzy and it has eight members derived from their places namely oblique front right, front, oblique front left, left, oblique rear left, rear, oblique rear right, right and. The fuzzy path planning rule base is shown in Figure 6.

3.3. Potential Field

The merging of both algorithms enables quadrotor to avoid obstacles and go to the goal position, but the quadrotor has unidentified the shortest path. The algorithm of this paper is modified by adding potential field algorithm used to give a weight value for each grid cell formed from decomposition. Potential field algorithm is an algorithm for robot navigation that is used by Park et al., [20] using magnetic theory that is attraction and repulsion. In robot navigation, attractive potential is the force generated by the goal potition of robot in which the equation is as follows:

$$U_A(x) = \frac{1}{2} k_a |x - x_d|^2$$

$$U_A(y) = \frac{1}{2} k_a |y - y_d|^2 , \quad (5)$$

Where k_a is the potential field constant. The value of (x_d, y_d) shows the goal position of the robot and (x, y) shows the coordinate position of the robot. While potential repulsion is a force generated by obstacles in robot environment isshown in the following equation:

$$U_R(x) = \frac{1}{2} k_r \left(\frac{1}{x} - \frac{1}{x_O} \right)^2$$
$$U_R(y) = \frac{1}{2} k_r \left(\frac{1}{y} - \frac{1}{y_O} \right)^2 , \quad (6)$$

Where k_r is the repulsive constant. The value of (x_o, y_o) shows the obstacle position. In this paper the potential field in attractive and repulsive equations is modified to be used to provide the value of the grid on the cell decomposition. The modification of the equation is:

$$U_A = k_a \sqrt{\left(\frac{Y_G}{10} - Y_G \right)^2 + \left(\frac{X_R}{10} - X_G \right)^2} ; \quad (7)$$

$$U_{R_S} = \frac{k_r}{\sqrt{\left(\frac{Y_R}{10} - Y_S \right)^2 + \left(\frac{X_R}{10} - X_S \right)^2}} ; \quad (8)$$

$$U_{R_D} = \frac{k_r}{\sqrt{\left(\frac{Y_R}{10} - Y_D \right)^2 + \left(\frac{X_R}{10} - X_D \right)^2}} ; \quad (9)$$

Which U_{R_D} is the potential field force for dynamic obstacles, U_{R_S} is the potential field force for static obstacles, and U_A is the potential field atraction. While (X_G, Y_G) is the goal position, (X_S, Y_S) is the static obstacle position, and (X_D, Y_D) is the dynamic obstacle position.

3.4. Modifed Map Creation

This paper uses a dynamic environment where the environment has a moving obstacle as shown in Figure 6. In the figure R_G is the distance betwen the robot and the goal position, R_{O_D} is the distance betwen the robot and the dynamic obstacle, and R_{O_S} is a distance betwen the robot and the static obstacle. By using a cell decomposition, the environment is divided into grids with source code as in Figure 7.

Figure 8 shows that cell decomposition algorithm is modified to update the information data of the environment that is used to detect moving obstacles so that the algorithm is placed in the main source code. In this figure K is the value for the size of the grid, (X_R, Y_R) is the position of the robot, (X_G, Y_G) is the robot goal position, (X_{O_S}, Y_{O_S}) is the position of static obstacles, and (X_{O_D}, Y_{O_D}) is the position of dynamic obstacles. Having created an environment map using cell decomposition, fuzzy path planning algorithm is performed.

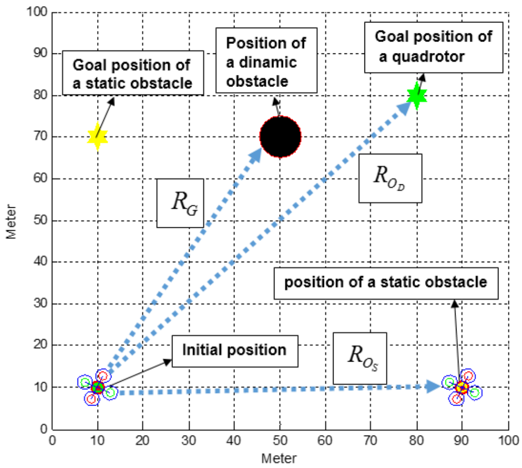

Figure 7. Dynamic environment model

while(1)
for $I = 1 : K : 100$
for $J = 1 : K : 100$
$X_R = I;$
$Y_R = J;$

$$R_G = \sqrt{\left(\frac{Y_R}{10} - Y_G\right)^2 + \left(\frac{X_R}{10} - X_G\right)^2};$$

$$R_{O_s} = \frac{1}{\sqrt{\left(\frac{Y_R}{10} - Y_S\right)^2 + \left(\frac{X_R}{10} - X_S\right)^2}^2};$$

$$R_{O_D} = \frac{1}{\sqrt{\left(\frac{Y_R}{10} - Y_D\right)^2 + \left(\frac{X_R}{10} - X_D\right)^2}^2};$$

$A(I,J) = R_G + R_{O_s} + R_{O_D};$
if $A(I,J) > 300$, $A(I,J) = 300$; end
end
end
call Fuzzy
end

Figure 8. Modified cell decomposition

The novelty of the algorithm in this study other than updated information is to modify cell decomposition algorithm to provide weight values to each grid with modified potential field algorithm. From Equation (7), (8), and (9) the value for each grid obtained is:

$$F = U_A + U_{R_S} + U_{R_D} \qquad (10)$$

Equation (10) is used to provide values to grids by modifying the source code as shown in Figure 9.

for $I = k : l : n$
for $J = k : l : n$
$X_R = I;$
$Y_G = J;$

$$U_A = k_a \sqrt{\left(\frac{Y_G}{10} - Y_G\right)^2 + \left(\frac{X_R}{10} - X_G\right)^2};$$

$$U_{R_s} = \frac{k_r}{\sqrt{\left(\frac{Y_R}{10} - Y_S\right)^2 + \left(\frac{X_R}{10} - X_S\right)^2}^2};$$

$$U_{R_D} = \frac{k_r}{\sqrt{\left(\frac{Y_R}{10} - Y_D\right)^2 + \left(\frac{X_R}{10} - X_D\right)^2}^2};$$

$A(I,J) = U_A + U_{R_s} + U_{R_D};$
if $A(I,J) > 300$, $A(I,J) = 300$; end
end
end

Figure 9. Matrix environment of modified cell decomposition

Matrix environment of modified cell decomposition is shown in Figure 9 in which the total force of potential field is used for weight values of columns and rows in it. If the sum of attraction and repulsion is considerably large, a limit value is given.

3. Results and Analysis

The experiments in this paper is conducted by using Matlab software to model environment and quadrotor and also simulate the performance of quadrotor in reaching the goal position and avoiding static obstacles in an unknown environment. There are two experiments in this paper to test the modified algorithms. The first experiment uses static and dynamic obstacles and the second experiment uses static obstacles. The experiments compare modified Fuzzy Cell Decomposition Artificial Potential Field (FCDAPF) to Fuzzy Cell Decomposition (FCD) algorithm.

The first experiment tests the FCDAPF algorithm in an unknown environment contained static and dynamic obstacles as shown in Figure 8. The figure shows that the static obstacle is located at the position of (5,7) and the dynamic obstacle is located at the position of (9,1) and it moves to position (1,7). The environment tested with FCD algorithm is shown in Figure 10(a) and FCDAPF in Figure 10(b). In Figure 10(a), it can be seen that the green quadrotor will collide with the yellow one at the position of (5, 5), while Figure 10(b) shows that the green quadrotor will avoid the moving obstacle of yellow quadrotor at the position of (4.5, 4.5).

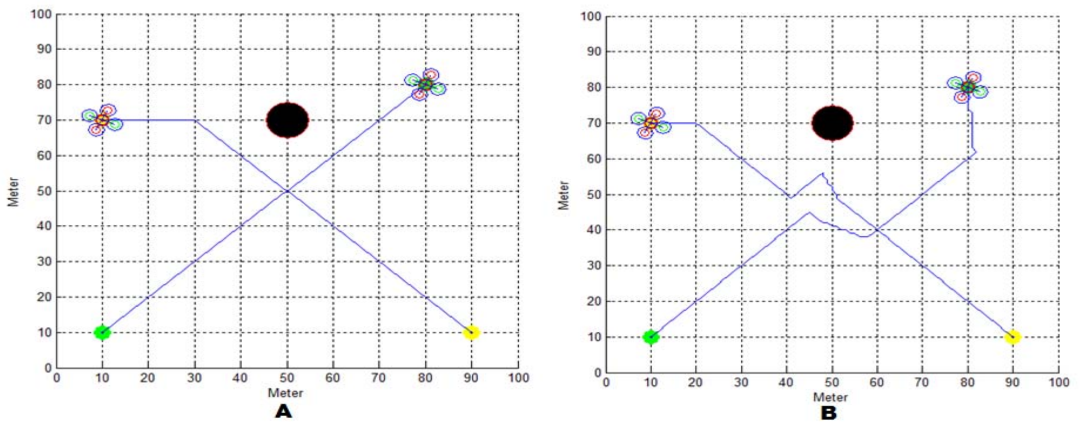

Figure 10. Experiment with FCD and FCDAPF algorithms

In this experiment the robot is placed at the initial position of (10,10) moving to the goal position of (90, 100) in the environment having four circular obstacles located at the position of (3, 3), (3,6), (6, 2.5), and (6, 7) as shown in Figure 11. The figure is simulated by two methods namely fuzzy cell decomposition method indicated by the green line and fuzzy cell decomposition that has been modified with the potential field indicated by the blue line. It shows that by using modified fuzzy cell decomposition algorithm, the quadrotor rapidly moves to the goal position and stably flies because it moves in each grid.

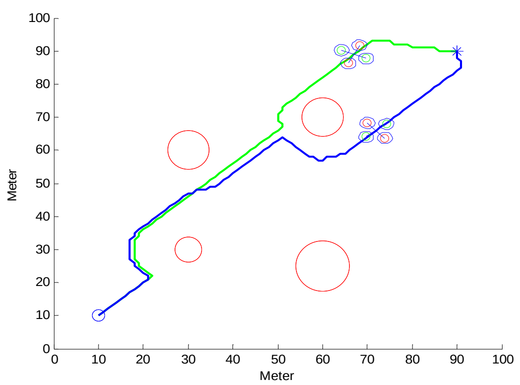

Figure 11. Experiment with FCD and FCDAPF algorithms

4. Conclusion

The paper presents a new algorithm using the merger of cell decomposition and fuzzy algorithms. Fuzzy algorithms is typically used for path planning which serves to detect an obstacles located in front of the robot by using sensors. In this study the algorithm is used to detect obstacles that are read from the cell decomposition algorithm. By using the algorithm, the quadrotor is able to move to the goal position and avoid obstacles but it requires a long process to reach the goal. So that an additional algorithm to resolve the issue is needed. With the merger of the three algorithms, the quadrotor is able to avoid obstacles in a dynamic environment and moves to the goal position more quickly.

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