Energy Efficient Path Planning of Hybrid Fly-Drive Robot (HyFDR) using A* Algorithm

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Keywords: HyFDR (Hybrid Fly-Drive Robot), A* Algorithm, Ground Nodes, Autonomous Navigation, Aerial Nodes.

Abstract: Hovering flight is agile and energy expansive, but driving on ground is slow and energy efficient method of locomotion. To get the benefits of these two methods of locomotion, we combined them in a single platform named as HyFDR. It is a Quadcopter with powered wheels, it can fly in air and drive on ground. Autonomous navigation of HyFDR creates new challenges in the field of path planning. The goal is to simulate the navigation of HyFDR with minimum energy consumption using A* algorithm. Depending upon the terrain, obstacles, energy constraints, and desired flight time, HyFDR can autonomously switch between flight mode, drive mode and hybrid mode. We showed that in some cases HyFDR is energy efficient than Quadcopter.

1 INTRODUCTION

Quadcopters have six degrees of freedom, which makes obstacle avoidance easy and their locomotion fast. Beside air drag, they require a continuous upward force against gravity to hover in air. This makes hovering flight energy expansive (Dietrich, 2017). Vehicles that drive on ground with wheels, require no hovering force against gravity, which makes them less energy expansive. During driving on ground, most of energy is consumed to overcome friction forces and air drag. Driving on ground with wheels has limited degrees of freedom, which makes the locomotion slow and difficult to avoid obstacles in the path.

To get the agility and energy efficiency in a single platform, four powered wheels were added to a simulation model of Quadcopter. This hybrid platform is named as HyFDR. It can fly in air like a normal Quadcopter and drive on ground. Addition of driving mechanism to a quadcopter increases its weight, but if the path has sufficient driving opportunities then this increase in weight can be compensated by using driving mode more frequently.

The autonomous navigation of HyFDR created new challenges in the field of locomotion mode selection, obstacle avoidance, energy efficient path planning, and travel time. Many algorithms are proposed by researchers for the path planning of mobile robots with single mode of locomotion, but not much research has been done for the path planning of mobile robots with dual mode of locomotion.

A virtual world in Gazebo simulator was created. Three different test cases were created by addition of obstacles at different positions in the virtual world. A 3D map of the environment was made. The nodes in the map were divided into four types, movement cost for each type of node was calculated. A modified A* algorithm was used to find the path with least energy consumption. During simulation, HyFDR followed the path created by A* algorithm, it autonomously navigated through the environment, avoiding obstacles, switching between flight mode and driving mode autonomously and reached the target. The energy efficiency of HyFDR depends upon the obstacles in the path and the duration of driving on ground.

1.1 Related Work

Hybrid mobile robots are made by addition of active or passive driving mechanism to a flying vehicle. These hybrid mobile robots can fly in air and drive on ground. They have better energy efficiency and agility. A Bio-inspired Morphing Micro Air and Land Vehicle is a micro aircraft with two wings, flaps, rudder and a front main rotor for propulsion. It is capable of locomotion in air and on ground as

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well (Jones, 2006). One of its unique features is its powered legs for crawling on the ground. A multi modal flying and walking robot (Daler, 2015) has a rotor on the front side and its wings are foldable. During aerial locomotion it acts like an air plane but during locomotion on ground its foldable wings act like legs. Flying Monkey robot (Mulgaonkar, 2016) is a world's smallest Quadrotor with the capability of flying, walking on the ground and grasping objects. It has a total weight of 30 grams, a tiny battery but the combination of flight and walking increases its mission life.

HyTAQ is a Quadcopter supported inside a cage-like structure which acts as a passive wheel for locomotion on ground (Kalantari, 2014). This combination increases its range as compared to the flying-only Quadcopters and it also solves the problems of obstacle avoidance related with wheeled robots. Quadroller (Page, 2014) is developed by addition of three pairs of passive skateboard wheels to a Quadcopter. As the energy efficiency is low for hovering vehicles, so the rolling motion on ground whenever possible will increase the range.

Flying cars are the future of transportation (Romli, 2014). They are in experimental phase and expected to be available as a personal air vehicle in near future. Humans can drive these flying cars on the road like a normal car and also fly them in air like an airplane (Rajashekara, 2016). A recent study (Araki, 2017) shows the path planning of a Swarm of hybrid mobile robots that can drive on ground and fly in air. They used a modified Safe Interval Path Planning algorithm and a multi-commodity network flow ILP algorithm for path planning and dynamic collision avoidance. A study on Starlings (Bautista, 2001) showed that how these birds decide between flight in air and walking on ground to reach a destination. Walking on ground consumes less energy as compared to flying but flying is faster method of locomotion as compared to walking.

To autonomously navigate the mobile robot from start point to destination, path planning is required. Path planning for mobile robots has been extensively studied. There are several algorithms for path finding in the map, but we used A* algorithm (Hart, 1968) for path finding. We used for path planning, because it works with nodes, it is easier to implement, it gives a unique and shortest path between start position and target. To implement A* algorithm for path finding, a map of environment in required in binary format. This map will be divided into nodes by a gird. The occupancy of node is obtained from the binary map. Start position and target position has to be provided by user. The movement cost is a value required to move from one node to its adjacent node. The G-cost of the adjacent node is the sum of the G-cost of current node and the movement cost to the adjacent node. The H-cost is the Manhattan distance from the current node to the target node. F-cost is the sum of G-cost and H-cost. For each adjacent node near the current node, G-cost, H-cost and F-cost values are calculated, and the adjacent node with minimum F-cost is selected. This process is repeated until the target node is achieved.

1.2 Problem Statement

The energy consumption during autonomous navigation of a Quadcopter is desired to be reduced.

1.3 Solution

To reduce the energy consumption by a Quadcopter during autonomous navigation, it is converted into a hybrid Quadcopter by addition of four powered wheels. Its simulation model is created and named as HyFDR. It has driving and flying capabilities. Driving on wheels consumes less energy as compared to flying. The HyFDR reduces the energy consumption by switching to driving mode whenever its possible. We modified A* algorithm to find the path with minimum energy consumption during autonomous navigation. Depending upon the location and size of obstacles in the path, HyFDR can switch to drive mode, flight mode or hybrid mode to reduce energy consumption.

2 METHODOLOGY

ROS (Robot Operating System) is an open source framework for robotics. It provides node based communication, low level code, high level software libraries and simulators. A simulation model of a

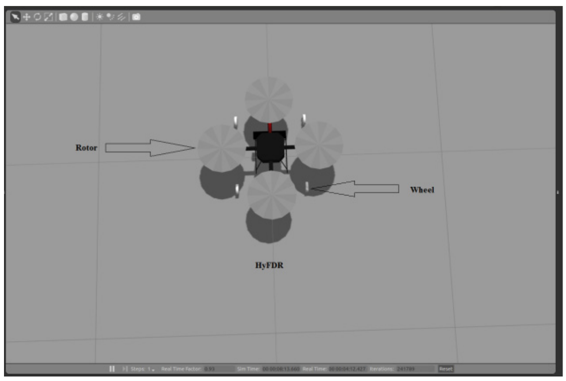

Figure 1: Visual model of HyFDR in Gazebo simulator.

Quadcopter named as Hector Quadrotor was used. This model is available as a ROS package. It runs with Gazebo simulator in ROS environment.

Hector Quadrotor has a depth camera and a Laser range finder attached to it. A hybrid vehicle named as HyFDR was developed by addition of four powered wheels to Hector Quadrotor model. The simulation model of HyFDR in Gazebo is shown in figure 1. The environmental constants and the physical parameters of HyFDR are given in table 1.

Table 1: Parameters and constants for HyFDR.

Parameters	**Symbol**	**Value**
Mass of HyFDR	m	1.477 Kg
Gravitational acceleration	g	$9.8ms^{-2}$
Top area of HyFDR	A_t	$0.5m^2$
Front area of HyFDR	A_f	$0.022m^2$
Coefficient of rolling friction	μ	0.06
Distance between nodes	d	1m
Density of air	ρ	$1.22\ kgm^{-3}$
Air drag coefficient	C_D	1.5
Tilt angle of HyFDR	α	20 degrees
Radius of propeller	r	0.127m
Velocity of HyFDR	v	$1ms^{-1}$

A virtual world in Gazebo simulator was created by using built-in models of houses, trees, and terrain. Later some obstacles were placed in this virtual world to create different scenarios for navigation. The size, amount and position of obstacles are important factors, which affect the locomotion mode of HyFDR. The virtual world is shown in figure 2.

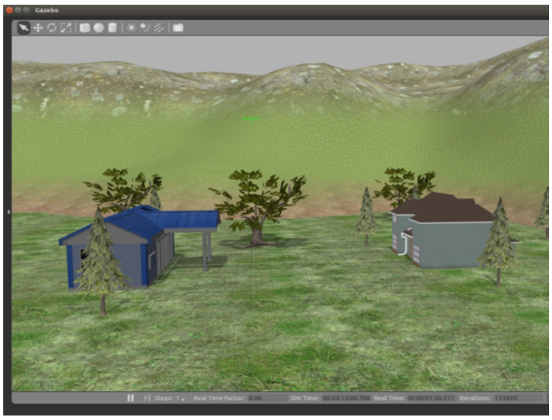

Figure 2: Custom world and obstacles in Gazebo.

Gmapping and Octomap are the ROS packages used to make 3D map of the virtual world. The map was saved as a binary format. The final 3D map of the virtual world is shown in figure 3. HyFDR is placed at the centre of the map. The start position and target position were marked. To find the path from start position to destination, we used node based path finding method, known as A* algorithm. It finds the shortest path from start position to the destination. The modified A* algorithm finds the path with least energy consumption. To implement the A* algorithm, the map has to be divided into a gird of three dimensional nodes.

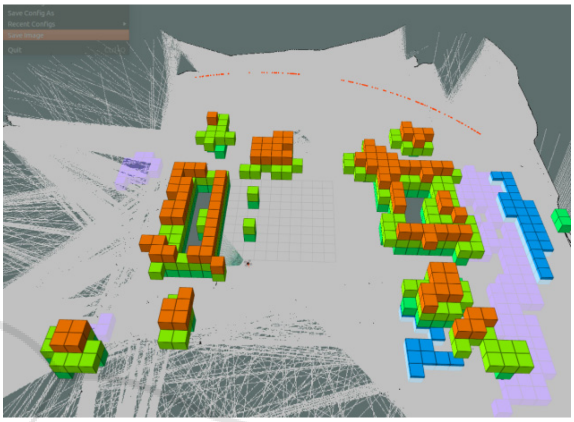

Figure 3: Map of the environment.

A* algorithm requires G-cost, H-cost and F-cost of the adjacent nodes, to find the shortest path. The G-cost of adjacent node is the sum of the G-cost for current node and the movement cost for adjacent node. The movement cost is the energy required to move from current node to its adjacent node (Yang, 2016). Considering Manhattan distance, the distance between current node and its adjacent node is one meter. A 3D node grid is created as shown in figure 4. The x-axis and y-axis contains positive and negative values. HyFDR is not allowed to go below the ground, so the z-axis contains only positive values. HyFDR has two modes of locomotion: flying in air and driving on ground. This 3D node grid contains two major types of nodes: Aerial nodes (green colored cubes) and Ground nodes (blue colored cubes).

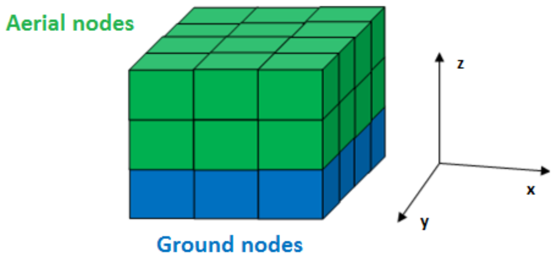

Figure 4: A 3D node grid.

Considering Manhattan distance, during driving mode, each current node (blue colored cube with red edges) will have five neighboring nodes as shown in figure 5. There are four nodes on the sides of the current node, they are named as Ground nodes (blue colored cubes). There is only one node on the top of current node and it is called Aerial node (green colored cube).

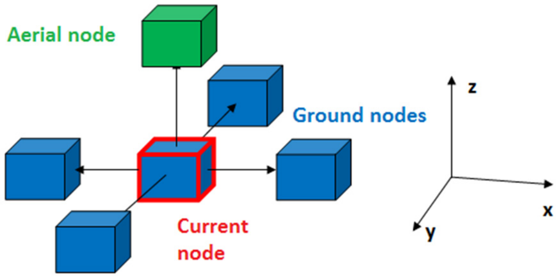

Figure 5: Neighboring nodes during ground locomotion.

During flight mode each current node will have six neighboring nodes, as shown in figure 6. Four nodes (green colored cubes) surrounding the current node in xy-plane and one node on the top of current node are Aerial nodes. The node below the current node is a Ground node.

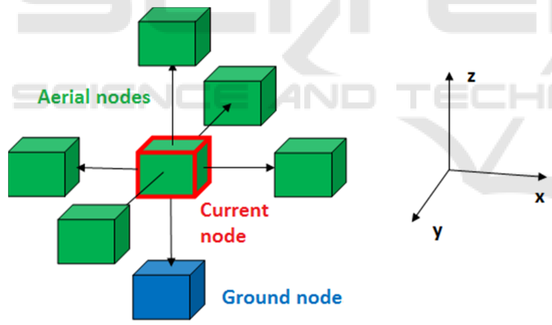

Figure 6: Neighboring nodes during aerial locomotion.

During the flight mode, HyFDR will be travelling through Aerial nodes. Depending upon the direction of motion, Aerial nodes are further divided into three categories: Fly-up nodes, Fly-down nodes, and Fly-around nodes as shown in figure 7. When the HyFDR is flying vertically upward then the Aerial nodes in the path will be named as Fly-up nodes. When the HyFDR is flying in horizontal direction along x-axis or y-axis, then the nodes in the path will be named as Fly-around nodes. When the HyFDR is flying down vertically, then the Aerial nodes in the path will be named as Fly-down nodes.

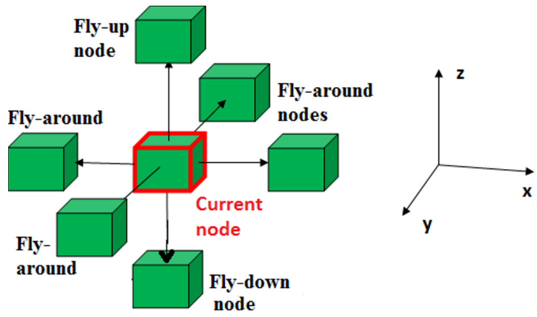

Figure 7: Three types of Aerial nodes.

2.1 Movement Cost for Ground Nodes

The movement cost of Ground nodes (M_g) is the amount of energy spend to travel a distance of one meter while driving on ground. This energy is consumed to overcome the rolling friction of wheels on the ground and against the air drag. It can be calculated by using following equation:

$$M_g = mg\mu d + \frac{\rho A_f C_D v^2 d}{2} \quad (1)$$

where m is the mass of HyFDR, g is gravitational acceleration, μ is the coefficient of rolling friction, d is the distance between two adjacent nodes, C_D is the air drag coefficient, A_f is the front area of HyFDR, ρ is the density of air and v is the velocity of HyFDR on ground. On the right side of equation 1, all the quantities are constants except velocity v. By substituting the values of constants from table 1, following equation is obtained:

$$M_g = 0.87 + 0.02\, v^2 \quad (2)$$

In real life scenario the velocity v of HyFDR will be a variable quantity, which may change from node to node, but we assumed that HyFDR will drive with constant velocity of $1ms^{-1}$ through all ground nodes. Substituting the velocity in equation 2, gives M_g = 0.89 joules.

2.2 Movement Cost for Aerial Nodes

The Movement cost for aerial nodes can be calculated by finding the energy consumption during flight. During Quadcopter's flight, most of energy is consumed in hovering and some of energy is consumed against air drag. The energy required against downward gravitational pull is called hovering energy E_h. This energy provides a constant upward pull and prevent the Quadcopter from falling down on ground. When the Quadcopter is in hovering state the thrust produced by its propellers is equal to the weight of Quadcopter (Leishman, 2006). Hovering energy per node can be calculated using the following equation:

$$E_h = \sqrt{\frac{1}{2\pi\rho}}\,\frac{4d}{rv}\left(\frac{mg}{4}\right)^{\frac{3}{2}} \quad (3)$$

where m is the mass of HyFDR, g is gravitational acceleration, ρ is the density of air, d is the distance between two nodes, v is the velocity of HyFDR during flight and r is the radius of propeller. The right side of the equation 2 has all constants quantities except velocity v. Substituting the values of these constants from table 1 in equation 2, we get hovering energy:

$$E_h = \frac{77}{v} \quad (4)$$

for v = 1ms^{-1}, we get the hovering energy per node equal to 77 joules.

2.2.1 Movement Cost for Fly-up Nodes

The energy required to fly vertically upward from current node to its above node is the movement cost for Fly-up nodes M_{fu}. It is the sum of potential energy, hovering energy and the energy required to overcome air drag. It can be calculated using following equation:

$$M_{fu} = E_h + (mgd) + \frac{\rho A_t C_D \mathrm{v}^2 \mathrm{d}}{2} \quad (5)$$

where E_h is the energy required to hover per node, m is the mass of HyFDR, g is gravitational acceleration, ρ is the density of air, d is the distance between two nodes, v is the velocity of HyFDR during flight, A_t is the top area of HyFDR and C_D is the air drag coefficient. By substituting the values of constants from table 1, we get:

$$M_{fu} = 14.5 + \frac{77}{v} + 0.46\,\mathrm{v}^2 \quad (6)$$

for v = 1ms^{-1}, we get the M_{fu} equal to 91.95 joules.

2.2.2 Movement Cost for Fly-down Nodes

The energy consumed by HyFDR to move vertically downward from current node to its adjacent below node is called movement cost for Fly-down node. This energy is equal to hovering energy minus the energy given by air drag. In this case the air drag force and the hovering force are acting in upward direction but the gravitational pull force and the motion of HyFDR are in downward direction. To calculate the movement cost for Fly-down nodes, we used following equation:

$$M_{fd} = E_h - \frac{\rho A_f C_D \mathrm{v}^2 \mathrm{d}}{2} \quad (7)$$

where E_h is the energy required to hover per node, m is the mass of HyFDR, g is gravitational acceleration, ρ is the density of air, d is the distance between two nodes, v is the velocity of HyFDR during vertical downward flight, A_t is the top area of HyFDR and C_D is the air drag coefficient. By substituting the values of constants from table 1, we get:

$$M_{fd} = \frac{77}{v} - 0.46\,\mathrm{v}^2 \quad (8)$$

for v = 1ms^{-1}, we get the M_{fd} almost equal to 76.54 joules.

2.2.3 Movement Cost for Fly-around Nodes

The energy consumed by HyFDR while flying horizontally is called the movement cost for Fly-around nodes and it is represented by the symbol M_{fa}. During horizontal flight HyFDR consumes most of energy for hovering in air and some energy against the air drag force. The movement cost for Fly-around nodes can be calculated using following equation:

$$M_{fa} = E_h + \frac{\rho\, A_t \sin\alpha\, C_D\, \mathrm{v}^2\, \mathrm{d}}{2} \quad (9)$$

where E_h is the energy required to hover per node, ρ is the density of air, d is the distance between two nodes, v is the velocity of HyFDR during horizontal flight, A_t is the effective area of HyFDR, α is the tilt angle of HyFDR and C_D is the air drag coefficient. The tilt angle α and the velocity v are the variable quantities but other terms are constants. After substituting the values of the constants from table 1, we get:

$$M_{fa} = \frac{77}{v} + 0.45 \sin\alpha\, \mathrm{v}^2 \quad (10)$$

for $\alpha = 20$ degrees, v = 1ms^{-1}, we get the M_{fa} equal to 77.15 joules.

In real world scenarios, the movement cost will not be a constant quantity. It will change with the speed of HyFDR, its tilt angle, the type of terrain, the slope of ground and the wind speed. In our case we assumed that the velocity of the HyFDR will be constant through the path, the ground surface is smooth, homogeneous and without any slope. The movement cost for all type of nodes are summarized in the following table:

Table 2: Movement cost for different type of nodes.

Node type	Symbol	value
Ground node	M_g	0.89 J
Fly-up node	M_{fu}	91.95 J
Fly-down node	M_{fd}	76.54 J
Fly-around node	M_{fa}	77.15 J

2.2.4 Arbitrary Movement Cost

The movement costs can be assigned arbitrarily to specific nodes to get the desired path. If the map contains smooth and rough terrain then we can assign a high movement cost to rough terrain so that HyFDR will avoid driving on rough terrain. If we want to completely avoid driving on ground, then we can assign movement cost to Ground nodes that is larger than the movement cost for aerial nodes. In this case the HyFDR will only fly to reach target position. In general if the less energy consumption during locomotion is desired then assign the Ground nodes a small movement cost and a high movement cost to Aerial nodes. If fast locomotion is desired then assign a high movement cost to Ground nodes and a low movement cost to Aerial nodes.

2.2.5 Movement Cost for Quadcopter

For comparison purpose, we have also calculated the movement cost for Quadcopter. The Quadcopter without wheels has a mass of 1.3 kg but the other parameters will remain similar to HyFDR. We have used similar method to calculate the movement cost for Aerial nodes as we did for HyFDR. In case of Quadcopter there will be no Ground nodes. The movement cost for Fly-around nodes is 65.15 joules, the movement cost for Fly-down node is 64.54 and the movement cost for Fly-up nodes is 77.95 joules.

2.3 Calculation of G-cost

In A* algorithm, the G-cost is the distance of the current node from the start node. It ensures the search of shortest path (Tan, 2016). The G-cost for the adjacent node is the sum of the G-cost of current node and the movement cost of the adjacent node.

2.4 Calculation of H-cost

In A* algorithm, H-cost (heuristic cost) is the distance between the current node and target node. H-cost makes the search faster. The H-cost is calculated by finding a Manhattan distance between current node and the target node. We assumed that the target is always located on the ground. The H-cost of adjacent node will depend upon the current node and the type of adjacent node. If the current node is Ground node then we shall use following equation to find the H-cost:

$$H = abs(x_f - x_i)M_g + abs(y_f - y_i)M_g \quad (11)$$

where M_g is the movement cost for Ground nodes, x_i, y_i are the coordinates of the current node and x_f, y_f are the coordinates for the target node.

If the current node is Aerial node and the adjacent node is Fly-down node then we shall use following equation to find the H-cost:

$$H = abs(x_f - x_i)M_g + abs(y_f - y_i)M_g + abs(z_f - z_i)M_{fd} \quad (12)$$

where M_g is the movement cost for Ground nodes, x_i, y_i, z_i are the coordinates of the current node and x_f, y_f, z_f are the coordinates for the target node. M_{fd} is the movement cost for Fly-down node.

If the current node is Aerial node and the adjacent node is Fly-around node, then to calculate the H-cost we shall use following equation:

$$H = abs(x_f - x_i)M_{fa} + abs(y_f - y_i)M_{fa} + abs(z_f - z_i)M_{fd} \quad (13)$$

where x_i, y_i, z_i are the coordinates of the current node and x_f, y_f, z_f are the coordinates for the target node. M_{fd} is the movement cost for Fly-down node and M_{fa} is the movement cost for Fly-around node.

2.5 Calculation of F-cost

After getting the G-cost and H-cost for each adjacent node around the current node, the algorithm will calculate F-cost by adding G-cost and H-costs. The node which has minimum value of F-cost will be selected. This process will be repeated until the target node is reached and the path with minimum energy consumption is discovered.

This energy efficient path will be translated into motion by motion algorithm. The motion list is generated from start node to the target node. The motions are driven by proportional (P) controllers, which gets the position feedback from the ground truth. If the desired position is achieved then the algorithm moves to the next motion in the motion list. This process will continue up to the last item in the motion list, resulting in the navigation of HyFDR to the target node on the map.

3 EXPERIMENT AND RESULTS

We created a virtual world in Gazebo as shown in figure 9. The task is to deliver a mail from the post office to the house with help of the HyFDR. The start position for HyFDR is in front of post office and the target position is in front of the house. The shortest distance between the start position and the target position is 9 meters. We created three test cases by changing the position and amount of obstacles in the path. The height, length and the width of each building block of obstacle is one meter.

3.1 Test Case 1

In the first test case, a boundary wall (obstacle) was created by joining the blocks around the post office as shown in figure 9. The red line shows the path followed by HyFDR from start point to target during autonomous navigation. It started by driving on the ground, after travelling a distance of 4 meters, it reached near boundary wall. It switched to flight mode and flew vertically upward for one meter, then flew horizontally for two meters. After passing the boundary wall, it flew down on the ground and switched to driving mode again. Finally it reached target position after driving three meters. During the navigation, HyFDR covered a distance of 11 meters. It navigated through seven Ground nodes, one Fly-up node, two Fly-around nodes and one Fly-down node. The movement cost for all these nodes has been already calculated. The total energy consumed during navigation can be calculated by addition of movement costs of the respective nodes present in the path. HyFDR consumed 329.02 joules of energy during the navigation in this map.

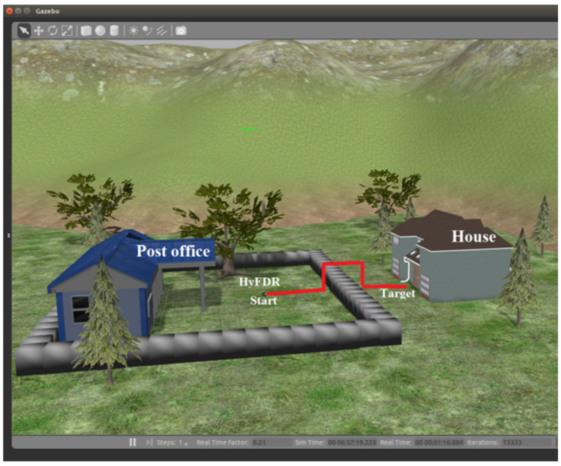

Figure 8: Simulation in Gazebo for test case 1.

The movement costs for Aerial nodes of Quadcopter are given in section 2.2.5. For the same virtual world as shown in figure 9, we did path planning for a theoretical Quadcopter. The virtual world has same start position, obstacles, and target position. The Quadcopter can only use Aerial nodes during navigation. In this scenario, for takeoff it used one Fly-up node, then it flew horizontally through nine Fly-around nodes and finally it passes through one Fly-down node for landing. It traveled a total distance of 11 meters. The total energy consumed by Quadcopter is the sum of the movement costs of nodes used in the path. The theoretical Quadcopter consumed 728.84 joules of energy. A comparison of energy consumed by a Quadcopter and HyFDR is shown in figure 9. Despite of a small increase in weight due to wheels, HyFDR consumed 399.82 joules less energy as compared to Quadcopter.

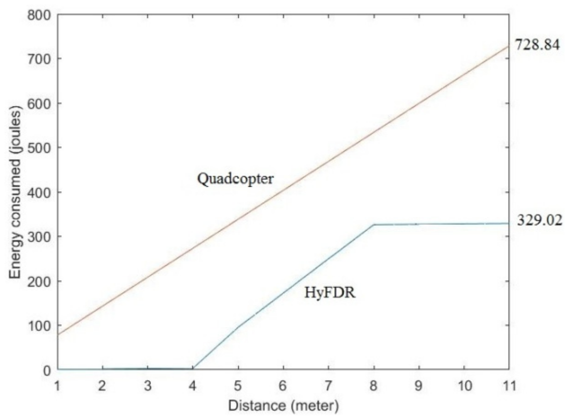

Figure 9: Comparison of energy consumption.

In figure 9, it can be seen that during flight mode the slope of the graph for HyFDR is slightly steeper than the graph of Quadcopter. This shows that, HyFDR consumed more energy during flight as compared to quadcopter. The increased energy consumption during flight is caused by additional weight of wheels. This test case shows that the energy consumption during flight can be reduced by switching to driving mode on ground, whenever there is a opportunity for driving is available. Flying consumes 87 times more energy as compared to driving on ground. During autonomous navigation if the movement cost of Ground nodes is less, then the A* algorithm makes the HyFDR to drive on ground more frequently. This reduces the total energy consumption during autonomous navigation.

3.2 Test Case 2

In the second test case a wall (obstacle) was placed between the start point and the target as shown in the figure 10. In this test environment, HyFDR has multiple options (paths) to reach the target. It can navigate by flight, driving or combination of both. The modified A* algorithm always find the path with lowest energy consumption, and in this case, the path for driving on ground is available and it requires least energy consumption. During simulation HyFDR used only single mode of locomotion (driving) and followed the driving path (red line) as shown in figure 10. It travelled a total distance 25 meters. It consumed 22.25 joules of energy during navigation on ground. The energy consumption during navigation can be calculated by multiplying the total distance covered with the movement cost of Ground node.

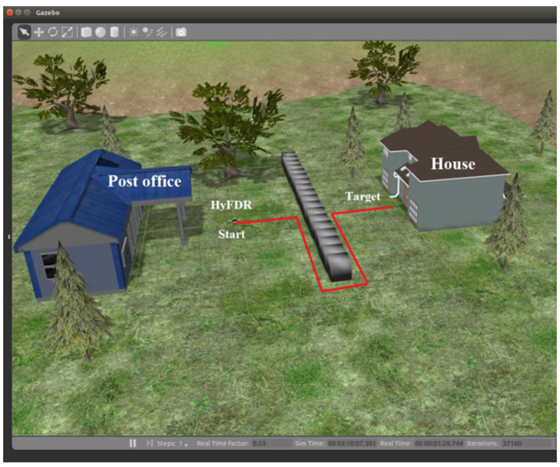

Figure 10: Gazebo world simulation for test case 2.

The results of this simulation showed that if there is a driving path on ground available, then HyFDR will only drive on ground. The reason for this behavior is the low movement cost of Ground nodes and high movement cost of Aerial nodes. The path followed by HyFDR in test case 2 requires minimum energy consumption but it is not the shortest path. The shortest path was in test case 1, where HyFDR used dual mode of locomotion. Figure 11 shows the comparison of path followed by HyFDR in test case 1 and the path followed by HyFDR in test case 2.

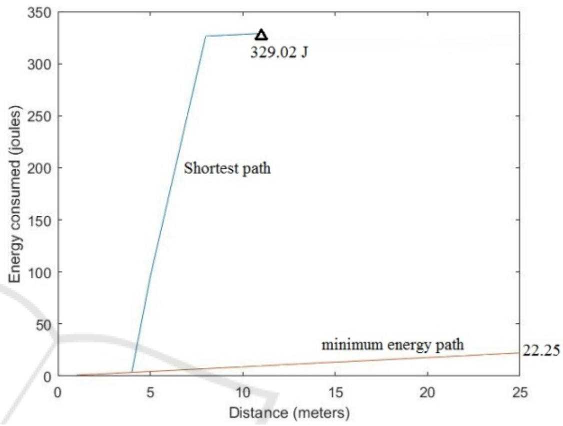

Figure 11: Comparison of energy consumption.

Figure 11 shows that with dual mode locomotion, HyFDR navigated through the shortest path, travelled a distance of 11 meters and consumed 329.02 joules of energy. But with driving mode it travelled a distance of 25 meters and consumed 22.25 joules of energy. It implies that in case of dual mode of locomotion the shortest path is not always energy efficient path. The drive only path saves energy but it is longer path and requires more time to reach the target point. The flight only path provides fast locomotion but it is energy expansive. A combination of flight and driving gives optimum results with respect to energy saving and time saving.

3.3 Test Case 3

This test case is not related to energy efficiency, instead it is designed to show the use of arbitrary movement cost for Ground and Aerial nodes. It has been mentioned in section 2.2.4, that the movement cost can be arbitrarily assigned to nodes based on their type and location. The virtual world shown in figure 12, has a rough terrain between post office and house. To avoid the driving on rough terrain, it is desired that HyFDR should only fly during autonomous navigation. To achieve this purpose, the movement cost of Ground nodes were made much higher than the movement cost of Aerial nodes. The path followed by HyFDR is shown as red line in figure 12. It only used flight mode during navigation from start point to target.

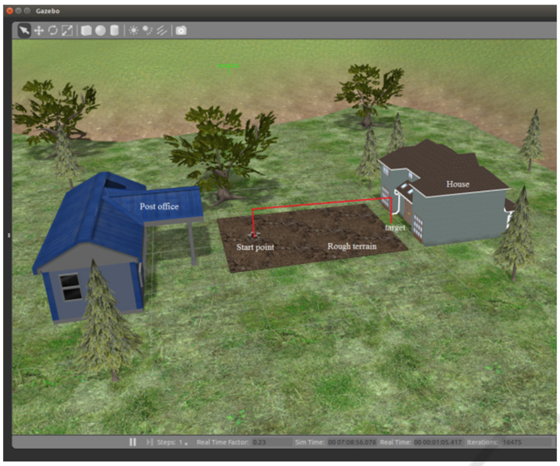

Figure 12: Gazebo world simulation for test case 3.

It is obvious from these experiments that movement cost of nodes decides whether the HyFDR will fly air or drive on ground during autonomous navigation. If the movement cost of Ground nodes is smaller than movement cost of Aerial nodes then the HyFDR will be energy efficient but will take more time to reach target. If the movement cost of Aerial nodes is less than Ground nodes then HyFDR will be less energy efficient but requires less time to reach the target. To get the optimum results with respect to energy efficiency and travelling time, the movement cost of Ground nodes and Aerial nodes can be arbitrarily assigned depending upon the position, size and number of obstacles in the path.

4 CONCLUSION

The energy consumption by a Quadcopter during locomotion can be reduced by giving it the ability to drive on ground. Addition of wheels to a Quadcopter increases its weight, and causes a slight increases in energy consumption during flight, but due to its ability to drive on ground, its overall energy efficiency increases. Our modified A* algorithm finds energy efficient path and influences the locomotion mode of HyFDR, forcing it to frequently drive on ground during autonomous navigation. Depending upon the obstacles and terrain, the movement costs of nodes can be arbitrarily assigned to achieve optimum results with respect to travel time and energy consumption.

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