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PATH PLANNING USING PANEL METHOD FOR URBAN AIR MOBILITY IN BIG CITIES WITH TALL BUILDINGS

Zeynep Bilgin* and İlkay Yavrucuk†
Middle East Technical University
Ankara, Turkey

ABSTRACT

In this study, a numerical method, namely panel method, is used to model a potential flow around obstacles and resultant stream lines are used as vehicle trajectories for air taxi applications in Dubai Marina region for urban air mobility. This solution approach offers collision free path around complex obstacles for a number of vehicles at the same time.

INTRODUCTION

Utilizing electric Vertical Take Off and Landing (eVTOL) vehicles as means of Urban Air Mobility (UAM) can reduce ground traffic congestion and carbon emissions in cities. Several companies have stepped up to manufacture vehicles to be used as such [Ohear [2017]; Hawkins [2020]; Sampson [2020]; Volocopter [2021]].

Figure 1: eVTOL for Urban Air Mobility [Volocopter [2021]]

*GRA in Aerospace Engineering Department, Email: zeunal@metu.edu.tr
†Assoc. Prof. in Aerospace Engineering Department, Email: yavrucuk@metu.edu.tr

One of the important issues to address in UAM operations is path planning. The goal of path planning is to determine a collision-free path for a vehicle from an initial point to a target location. Path planning in big cities involves complex shaped architectural structures and a number of eVTOL vehicles operating simultaneously. As a result, the path planning problem is mathematically large in size and computationally intensive. Therefore, methods that provide fast solutions to dynamic trajectory generation for eVTOL vehicles, while providing obstacle avoidance and collision avoidance are valuable [Uzol et al. [2010]].

Various path planning techniques for Unmanned Aerial Vehicles (UAV) are studied over the past years. One common approach in the path planning problem is formulating it as an optimization problem with constraints. The cost function can be selected to optimize time, distance, energy consumption, number of maneuvers, etc. Dynamics of the vehicle and urban air traffic regulations can be included as constraints [Teshnizi et al. [2020]; Teshnizi and Kosari [2019]; Chen et al. [2014]; Ge and Topcu [2019]; Pradeep and Wei [2018, 2019]].

Another approach is employing potential functions for path planning. In using artificial potential functions, repulsive functions prevent collisions and attractive functions guide the vehicle to its destination without getting trapped in local minima [Lifen et al. [2016]; Yingkun [2018]; Chen et al. [2014]; Liu and Zhao [2016]; Rizqi et al. [2014]; Wang et al. [2015]]. An extension of potential field approach is using principles of fluid mechanics for path planning [Liang et al. [2014]; Wang et al. [2015]]. Potential field of an irrotational flow around a geometry can be obtained as the gradient of a velocity potential. The stream functions and streamlines can be obtained by using the potential field and then used as vehicle trajectories. Analytical solutions can be obtained by combining elementary potentials. However, elementary flow elements can only be used to express collision free paths around simple geometries, such as ellipses [Lewis [1991]; Katz and Plotkin [2001]]. To generate collision free paths around complex shaped obstacles panel methods can be employed. Previously, panel methods were used for robot motion planning [Zhang and Valavanis [1997]] and path planning and target tracking for swarming MAVs [Uzol et al. [2010]]. Panel method is a strong numerical tool that solves the whole path planning problem in a single step. Hence, the path of each eVTOL vehicle in an air taxi fleet can be determined simultaneously. A path planning method using panel method was suggested in [Unal [2021]] where, the potential field panel method is used to obtain streamline like trajectories for eVTOL operating in urban environment.

In this study, the method is applied to path planning problem for eVTOL in Marina region of Dubai city.

METHOD

Panel method is a numerical tool that is used to solve potential flow problems around arbitrarily shaped bodies. Here, the bodies are obstacles in a city, such as buildings, etc. In this method, the boundary of the obstacle is approximated by straight line segments, called panels. Each line segment is modelled as a vortex element with unknown strength (Fig. 2). Vortex strengths can be found by solving a system of linear equations. [Uzol et al. [2010]; Katz and Plotkin [2001]]

Using vortex strengths, fluid trajectory around obstacles and fluid velocity field can be found. Then, streamlines are found and are thought as vehicle trajectories to be followed. Moreover, sources and sinks can be added to panel method equation to avoid moving obstacles or to attract the vehicles to destination points. Hence, in this study each vehicle is modelled as a source element to avoid collisions between vehicles and goal points are modelled as sink elements. Therefore, concepts of fluid dynamics are used for the purpose of vehicle trajectory generation.

In order to find unknown vortex strengths, velocity induced by a panel on other panels is calculated. Integrating velocity induced by each panel, total velocity induced on a point on obstacle surface can be found in terms of vorticity strength γ. System of linear equations are obtained by setting velocity component normal to the obstacle surface to zero. Linear equation system to be solved is given in Eq. (1). Details of derivation of this method can be found in [Uzol et al. [2010]; Katz and Plotkin [2001]]. Following [Unal [2021]];

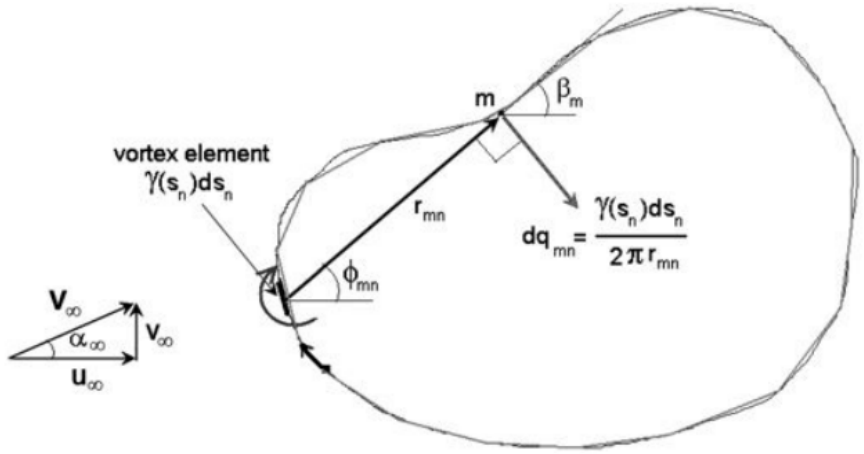


Figure 2: Surface representation of an arbitrary geometry in a panel method using straight line segments and the velocity induced at m by a surface vortex element at n. [Uzol et al. [2010]]

$$K_{mn}\gamma_n = RHS_m \tag{1}$$

$$K_{mn} = \frac{\Delta s_n}{2\pi}\frac{(y_m - y_n)\cos\beta_m - (x_m - x_n)\sin\beta_m}{(x_m - x_n)^2 + (y_m - y_n)^2} \tag{2}$$

$$RHS_m = -u_\infty \cos\beta_m - v_\infty \sin\beta_m \tag{3}$$

Here, K_{mn} is a coefficient matrix and γ_n are the unknown vortex strengths. The matrix RHS_m is obtained using freestream velocity components.
In order the avoid collisions between vehicles, each eVTOL can be modelled as a point source element. Since there is no unknown in source element, it is added to RHS_m.

$$RHS_m = -u_\infty \cos\beta_m - v_\infty \sin\beta_m - \sum_{i=1}^{N_{eVTOL}} u^i_{source}\cos\beta_m - \sum_{i=1}^{N_{eVTOL}} v^i_{source}\sin\beta_m \tag{4}$$

Here, u_{source} and v_{source} are velocities induced by point source element and σ is the source strength. Similarly, in air taxi concept, each vehicle can have a different destination. This destination can be modelled as a point sink. Then, RHS_m becomes:

$$RHS_m = -u_\infty \cos\beta_m - v_\infty \sin\beta_m - \sum_{i=1}^{N_{eVTOL}} u^i_{source}\cos\beta_m - \sum_{i=1}^{N_{eVTOL}} v^i_{source}\sin\beta_m - u_{sink}\cos\beta_m - v_{sink}\sin\beta_m \tag{5}$$

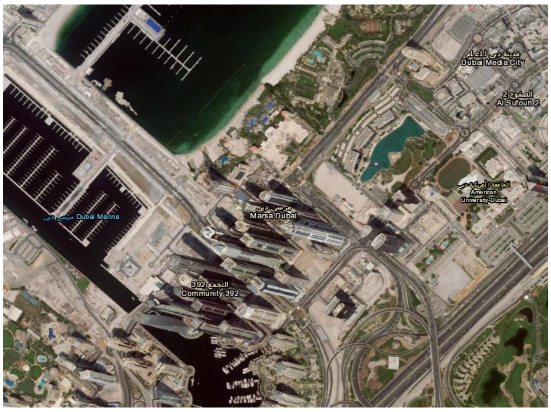
The panel method can further be extended to obtain vehicle velocities along the trajectories. Fluid velocities that are obtained as a part of the panel method solution can be related to vehicle velocities along each trajectory. Fluid velocity is slower in open areas and faster in tighter areas. Such velocity profiles are not desirable for eVTOLs in big cities for safety reasons. Instead, vehicle velocity is calculated using the inverse of calculated flow velocity. This way, the vehicle moves faster in open areas and slower in narrow passages.

SIMULATION RESULTS

Simulation Setup

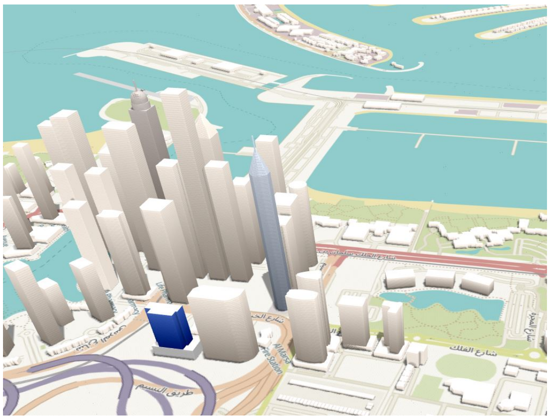
For simulations Marina district of Dubai city is considered. This region in Dubai is considered because it is densely populated with skyscrapers. Outline of buildings are generated using satellite images (Fig. 3) and 3-D model of buildings are generated in MATLAB. Buildings considered in simulation are tabulated in Table 1.

For panel method calculations cross-section of buildings in operation altitude is considered. Vortex strengths and vehicle trajectories are calculated using 2-D panel method described in Methodology.

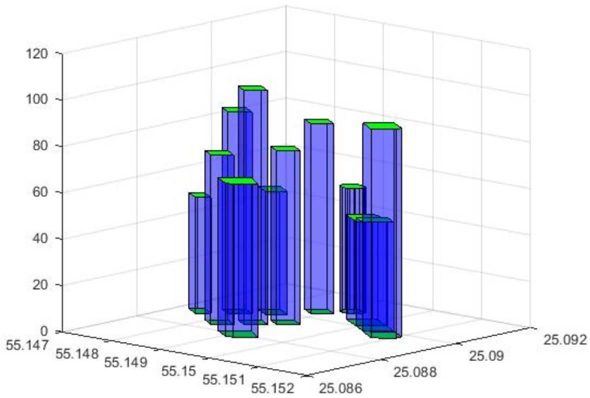


(a) Satellite image of Dubai Marina District [Earth-Explorer [n.d.].]

(b) Outlines of buildings in Dubai Marina [Krogh [2017]].



(c) 3-D Satellite Model of Dubai Marina [Open Street Map [n.d.]].



(d) 3-D Model of Dubai Marina in MATLAB.

Figure 3: Dubai Marina

Building	Height [m]	Levels
Le Reve Tower	214	50
Elite Residance	360	87
Marina Crown	207	53
Ocean Heights	310	82
Tamani Hotel	207	54
Marina Pinnacle	280	73
Marina 101	432	101
Sulafa Tower	285	75
Al Seef Tower	215	45
MAG 218	232	66
Marina Arcade Tower	192.7	47
23 Marina	370	90

Table 1: Buildings in Dubai Marina [Open Street Map [n.d.]].

Simulations with a Single Vehicle

First, panel method equations are solved for 2-D map. Then using vortex strengths, flow velocity at every point in grid is calculated to generate streamlines. Streamlines are plotted in Fig. 4. Here, vertical axis is the latitude and horizontal axis is the longitude. Free stream velocity is from left to right with zero angle of attack.

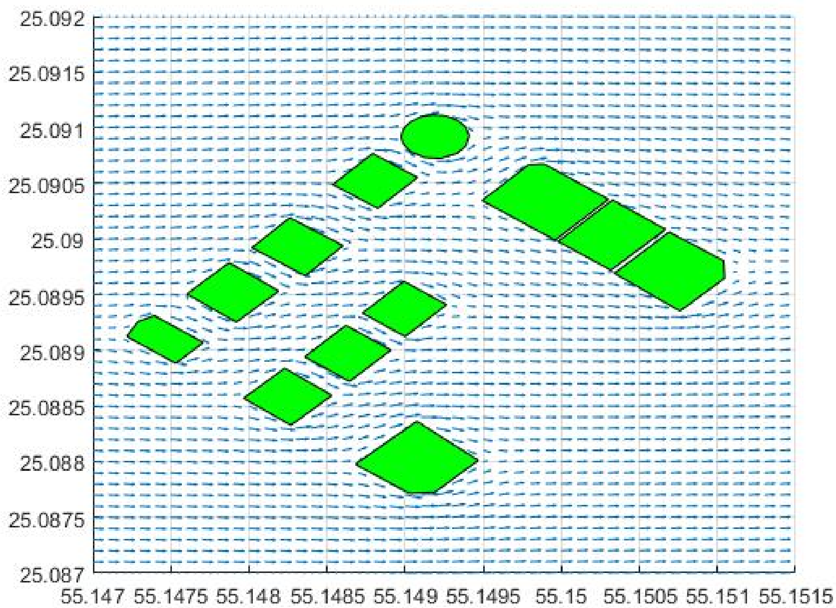
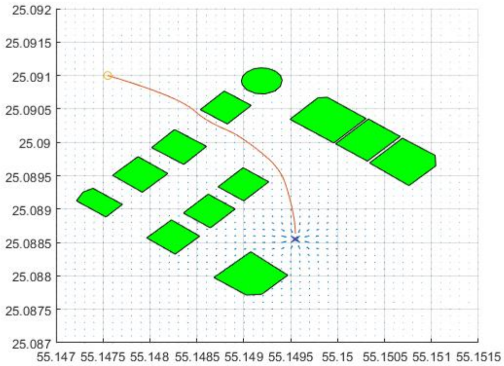


Figure 4: Streamlines in 2-D Map.

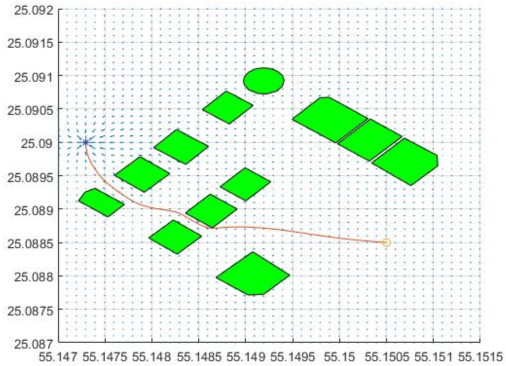
In air taxi application, each vehicle has a starting point and a destination. Hence, a sink element is introduced to lure the vehicle into its destination. In Fig. 5 trajectories of different vehicles are plotted together with governing streamlines. Starting position of vehicles are marked with 'o' and destinations are marked with 'x'. To assist vehicles to reach their destinations angle of attack of the free stream velocity is altered in each simulation. For Vehicle 1, angle of attack is 0; for Vehicle 2 angle of attack is $180\,\mathrm{deg}$ (flow is from right to left). For Vehicles 3 and 4 angle of attack is $65\,\mathrm{deg}$. To generate vehicle trajectories, first panel method equations that include sink element are solved and unknown vortex strengths are found. Then, velocity induced by flow elements is calculated for starting position. Fluid velocity is slower in open areas and faster in tighter areas. Such velocity profiles are not desirable for eVTOLs in big cities for safety reasons. Instead, vehicle velocity is calculated using the inverse of calculated flow velocity. Then, the vehicle moves with this velocity for one time step, 0.1 sec. and reaches its new position. Velocity is calculated again for this new position and procedure is repeated until the vehicle reaches its destination.

In Fig. 6 trajectories of vehicles in 3-D environment are plotted. Here, horizontal axes are latitude and longitude, vertical axis is building levels. Starting position of vehicles are marked with 'o' and destinations are marked with 'x'. For these simulations, vehicles are assumed to take off and land vertically and maintain constant altitude during cruise. Vehicle 1, 2, and 3 take off from land, cruise at 35th level of buildings and land to ground again. Vehicle 4 takes off from land, travels at 60th level of buildings and lands on roof of Tamani Hotel, circular building at top right. Trajectories are calculated by solving 2-D panel method equations on cross-section at cruise altitude.

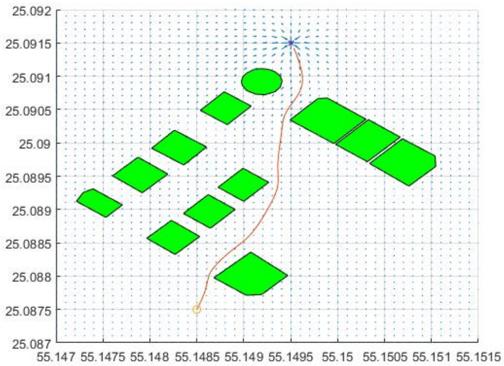
Another approach for 3-D simulations is modelling destination point as a 3-D point sink element. Then, instead of flying at a constant altitude, the vehicle will start to descent slowly towards



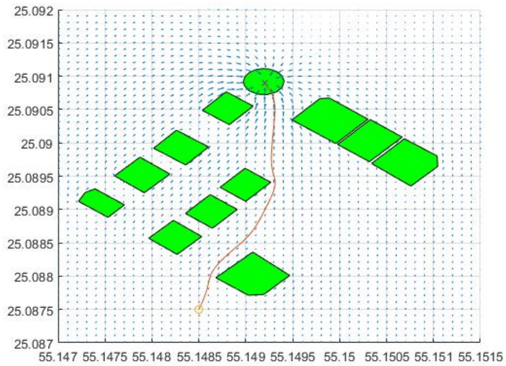
(a) Streamlines and Trajectory of Vehicle 1.



(b) Streamlines and Trajectory of Vehicle 2.



(c) Streamlines and Trajectory of Vehicle 3.



(d) Streamlines and Trajectory of Vehicle 4.

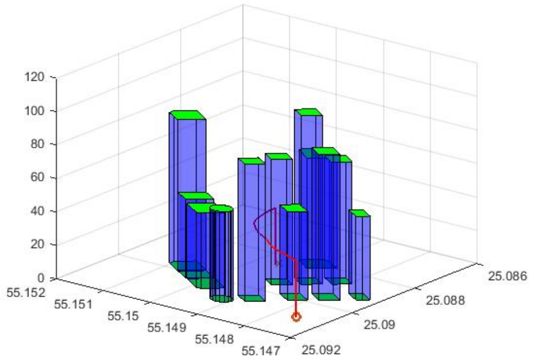
Figure 5: Trajectories and Streamlines in 2-D Map

destination. In Fig. 7 trajectories of vehicles whose destination is a 3-D sink are plotted. Notice that, only 3-D element in these simulations are destination points and vortices around building edges are still 2-D. Therefore, whenever elevation changes, a new 2-D map is generated from city cross-section and used in panel method calculations. In order to reduce computational work load and generate shorter paths, buildings whose max level is lower than current altitude are excluded from map. For example, in Fig. 7a the vehicle does not collide with mid building, it is simply flying over that building. In these simulations the vehicle takes-off vertically and moves vertically upward until it reaches to a certain ceiling pre-determined by the designer. Then, it stats to travel to its destination. Movement in horizontal plane is governed by 2-D panel method equations and movement in vertical direction is controlled by 3-D sink element placed at destination. When the vehicle reaches to a point directly above the destination, it starts to vertically descent.

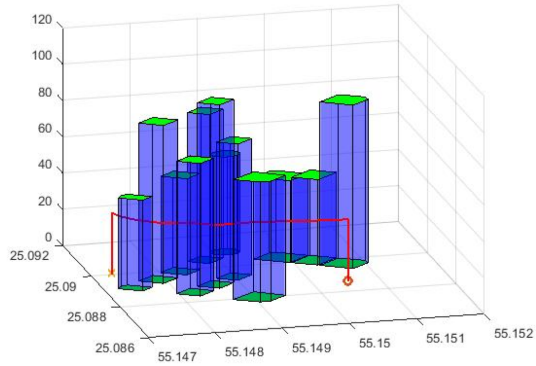
Simulations with Multiple Vehicles

In a more realistic scenario, there will be multiple vehicles operating at the same time. Panel method solution can be extended to multiple vehicle case as well. In Fig. 8 trajectories of 3 vehicles are plotted. Starting position of vehicles are marked with 'o' and destinations are marked with 'x'. Similar to single vehicle simulations, vehicles are assumed to take off and land vertically and maintain constant altitude during cruise. All vehicles fly at same altitude. As it can be seen from Fig. 8a trajectories of vehicles cross each other and at these intersections, vehicles collide with each other. In order to prevent these collisions, each vehicle is modelled as a point source element and included in panel method equations.

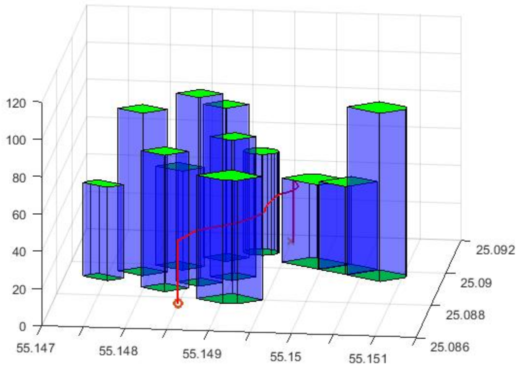
In Fig 9 trajectories of 3 vehicles that are modelled as source elements are plotted. In this case, in



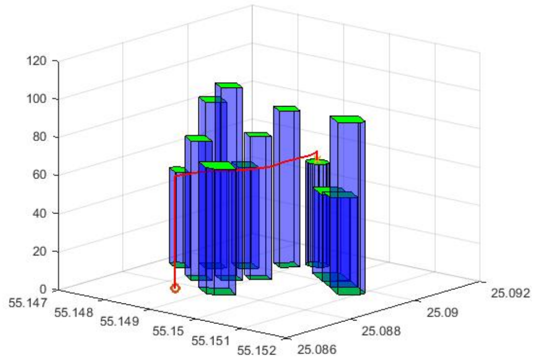
(a) Trajectory of Vehicle 1.



(b) Trajectory of Vehicle 2.



(c) Trajectory of Vehicle 3.



(d) Trajectory of Vehicle 4.

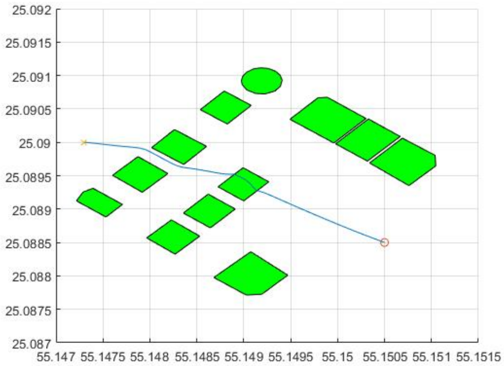
Figure 6: Trajectories in 3-D Map

order to avoid collisions, vehicles repulse each other and alter their path. Source strength is a design parameter. If sources are not strong enough, vehicles come too close to each other, or may push each other into buildings at last second. If sources are too strong, vehicles prevent each other from reaching their destinations.

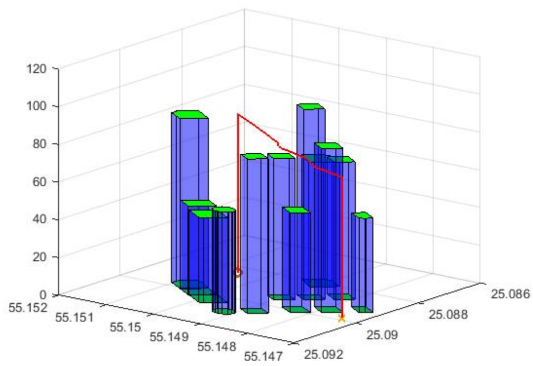
For these simulations, position of source elements (vehicles) are not fixed. Hence, panel method equations have to be updated and solved again each time a vehicle moves. Therefore, this solution is demands more computation power as number of vehicles increases. Furthermore, each vehicle has a different destination (point sink element); that is, each vehicle needs to have its own set of panel method equations. To reduce the computation time, panel method equations for each vehicle can be solved simultaneously.

When vehicles are modelled as point source, they end up taking a detour to avoid collision. Separating vehicles with altitude bears more efficient results in terms of path length. In Fig 10 trajectories of multiple vehicles separated by altitude is plotted. In this scenario, each vehicle follows a path in its own altitude corridor and vehicles on different altitudes do not repulse each other. Since there are no moving source elements, panel method equations are only solved once for each altitude. Notice that, for panel method equations, 2-D cross-section of the buildings at cruise altitude is used. Hence, if vehicles are flying above maximum level of a building, that building is not included in panel method equations. The vehicle simply flies over the building. This way, landing on building roofs is also possible.

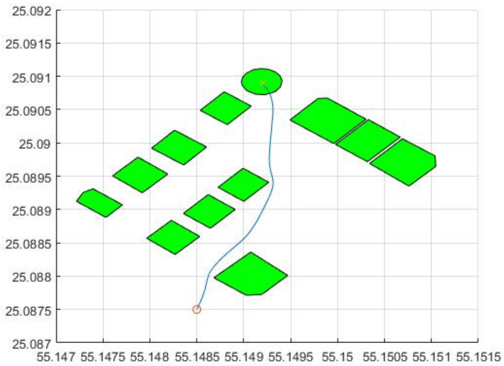
Another approach to avoid collision without taking a large detour is modeling vehicles as 3-D source elements. This way, vehicle can dodge each other by changing their altitude instead of their direction. An example case is plotted in Fig. 11. Here, assume 'o' in the middle of the map is an other vehicle



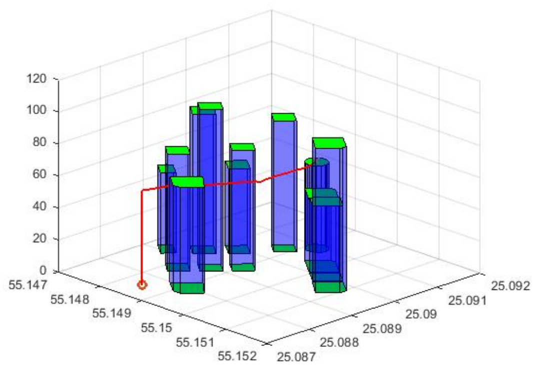
(a) Trajectory of Vehicle 1 in 2-D Map.



(b) Trajectory of Vehicle 1 in 3-D Map.

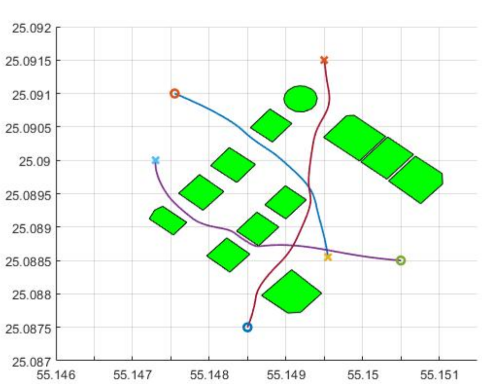


(c) Trajectory of Vehicle 2 in 2-D Map.

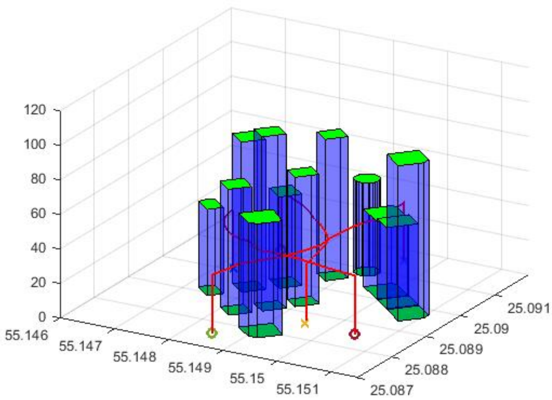


(d) Trajectory of Vehicle 2 in 3-D Map.

Figure 7: Trajectories with Destination as 3-D Sink Element



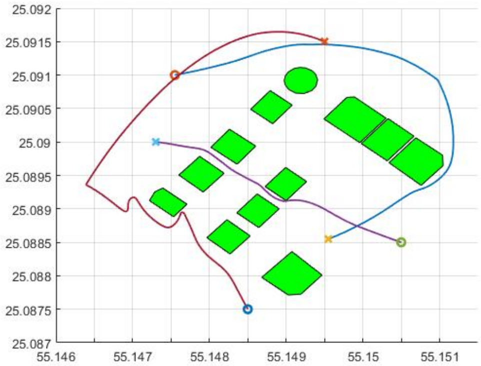
(a) Trajectories of Multiple Vehicles in 2-D.



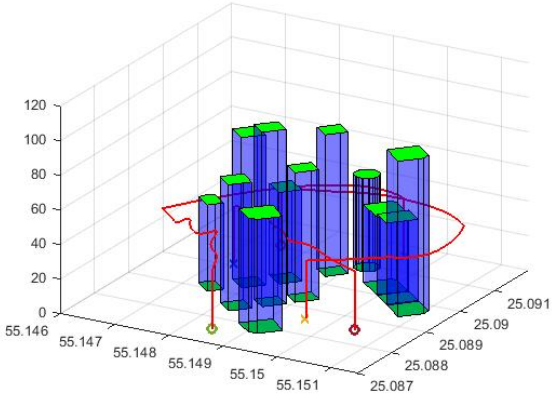
(b) Trajectories of Multiple Vehicles in 3-D..

Figure 8: Trajectories of Multiple Vehicles without Source Element.

blocking the path. This vehicle (the obstacle) is modelled as a 3-D point source element. Moreover, destination point is modelled as a 3-D point sink element similar to the case presented in Fig. 7. Motion in horizontal plane is governed by 2-D panel method equations derived from 2-D cross-section at current altitude. Elevation of the vehicle changes due to attractive/repulsive effect of 3-D sink and source elements. In Figures 11a and 11b, obstacle appears on position marked with 'o' at the start of the simulation. The trajectory is generated with the knowledge of this obstacle's position

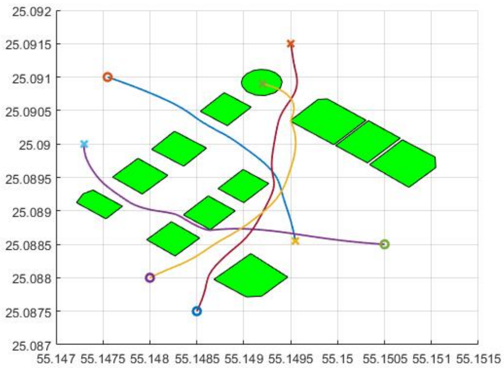


(a) Trajectories of Multiple Vehicles in 2-D.

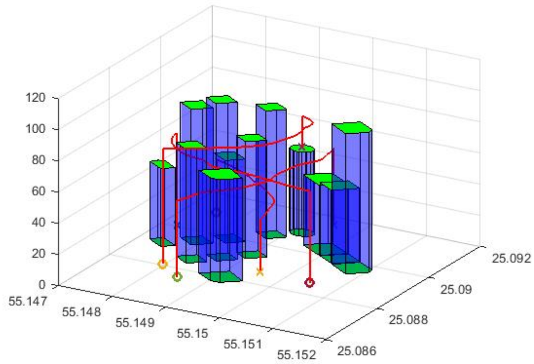


(b) Trajectories of Multiple Vehicles in 3-D.

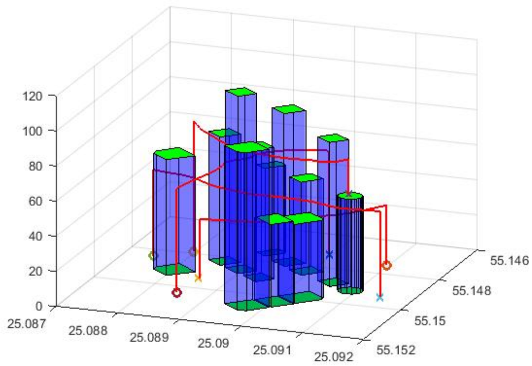
Figure 9: Trajectories of Multiple Vehicles with Source Element.



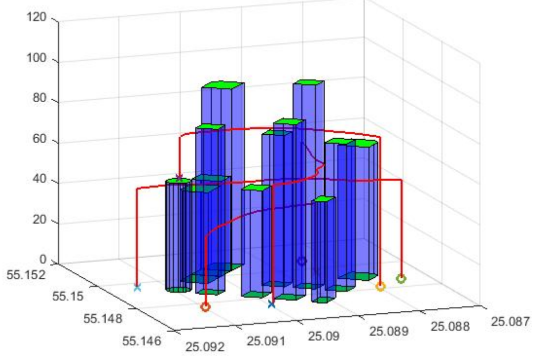
(a) Trajectories of Multiple Vehicles in 2-D .



(b) Trajectories of Multiple Vehicles in 3-D.



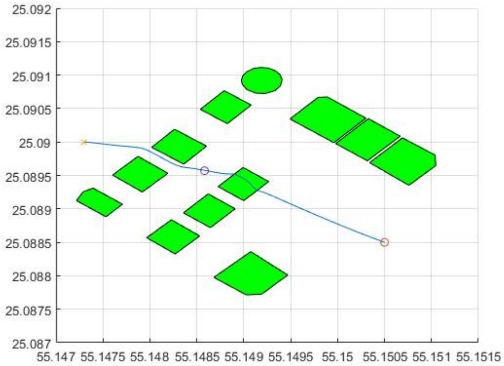
(c) Trajectories of Multiple Vehicles in 3-D.



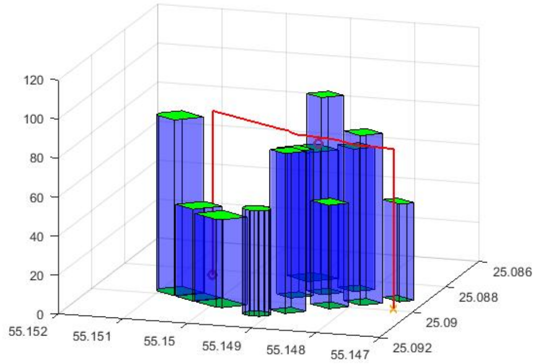
(d) Trajectories of Multiple Vehicles in 3-D.

Figure 10: Trajectory of Multiple Vehicles with Altitude Separation.

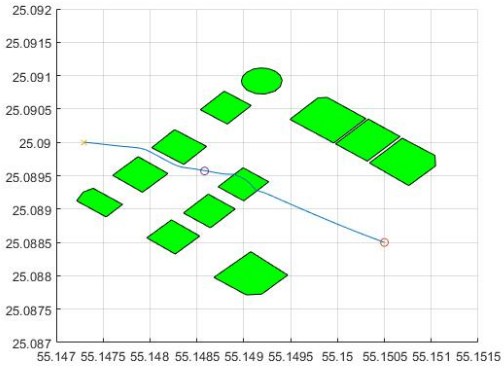
at the start of the simulation. For the second case, the obstacle suddenly appears at $t = 9s$. of the simulation. When the obstacle appears, trajectory is altered to avoid collision. In Fig. 12 elevation change for 3 cases are plotted. For the first case, there is no obstacle, the vehicle descends steadily towards the destination. Corresponding motion is given in Fig 7a and Fig. 7b. For the second case, a static obstacle blocks the way. For this case, the vehicle employs a less steep descent to avoid collision. Corresponding motion is plotted in Fig. 11a and Fig. 11b. For the final case, there is no obstacle at the beginning of the simulation. The obstacle suddenly blocks the path at $t = 9s$. of the simulation. In this case, the vehicle follows a steady descent pattern when there is no obstacle. When the obstacle appears, the vehicle starts ascending to prevent collision. Corresponding motion is plotted in Fig. 11c and Fig. 11d.



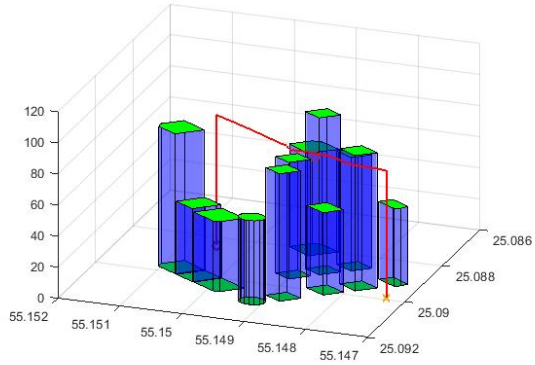
(a) Trajectory in 2-D with Static Obstacle.



(b) Trajectory in 3-D with Static Obstacle.



(c) Trajectory in 2-D with Dynamic Obstacle.



(d) Trajectory in 3-D with Dynamic Obstacle.

Figure 11: Trajectories with Static and Dynamic Obstacles.

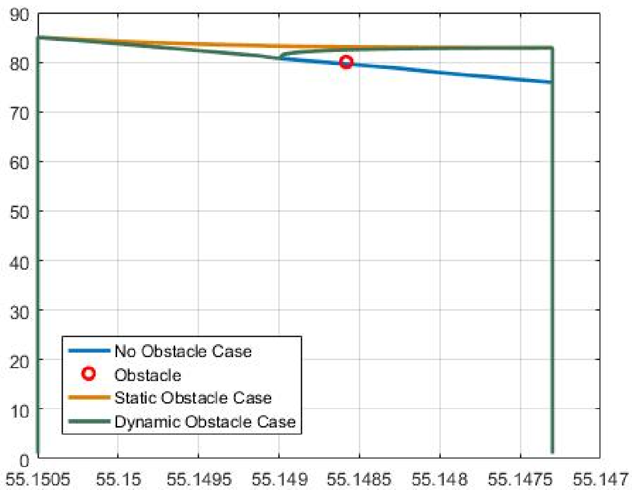


Figure 12: Elevation vs Longitude.

CONCLUSIONS

In this study, a method given in [Uzol et al. [2010]] and [Unal [2021]) is applied to solve path planning problem for urban air mobility in Dubai Marina region. In this work, panel method is used to model potential field around arbitrarily shaped objects and vehicle paths are modelled using resultant velocity field.

In the air taxi concept, each vehicle has a different destination point; hence, destinations are modelled using point sink element. In addition to sink element, uniform flow from staring position to destination is added. For 3-D simulations, a 3-D sink element can be used as destination point. This way, instead of flying at a constant altitude, the vehicle steadily descents towards its destination.

Collisions between vehicles are prevented by modelling each vehicle as a point source element. In order to prevent collisions vehicles may take large detours around the map. Two solutions are proposed to have shorter paths without collision. One solution method is placing vehicles to different altitude corridors. Second solution is modelling each vehicle as a 3-D source element. This way, even if vehicles are traveling in the same altitude corridor, they would go over/under each other to prevent collision. This maneuver results in shorter paths compared to 2-D source case.

Panel method requires a matrix inversion at each step. Size of the matrix to be inverted grows with each additional panel in map. Furthermore, vortex strengths have to be re-calculated if flow elements are not stationary, such as moving source elements attached to vehicles. Hence, computational work load grows with increasing number of vehicles and buildings. In order to reduce computational load, obstacles are considered individually and velocity vector is calculated locally. For 3-D scenarios, instead of taking all buildings into account, only the buildings that are higher than cruise altitude are considered. To conclude, multiple vehicles can travel from arbitrary starting positions to different destinations without colliding with each other or obstacles. Panel method solves path planning problem for multiple eVTOL in urban environment simultaneously.

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