JOURNAL OF AIRCRAFT
Vol. 47, No. 2, March–April 2010

Panel-Method-Based Path Planning and Collaborative Target Tracking for Swarming Micro Air Vehicles

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DOI: 10.2514/1.45469

This paper presents an application of the potential field panel method commonly used in aerodynamics analysis to obtain streamlinelike trajectories and use them for path planning and collaborative target tracking for swarming micro air vehicles in an urban environment filled with complex shaped buildings and other architectural structures. In addition, we introduce a performance matching technique that relates the fluid velocities, which are obtained as a part of the panel method solution, to vehicle velocities along each trajectory. The approach is further extended to track moving targets yet avoid obstacles and collision between the vehicles. Because of the inherent nature of streamlines, obstacle avoidance is automatically guaranteed. To make the micro air vehicles follow and track a moving target, dynamically changing streamline patterns are calculated for each and every one of the micro air vehicles within a swarm. To prevent vehicle-to-vehicle collisions, each micro air vehicle is represented using a point source singularity element within the potential field. The simulation results are quite encouraging, in the sense that micro air vehicle swarms quickly locate and track the assigned target in an environment filled with complex-shaped structures while avoiding obstacles and collisions among themselves. One benefit of the method is that the trajectory computations can be relatively fast and even have the potential to be applied in real time, depending on the number and complexity of the urban structures.

Nomenclature

a_∞	=	angle of attack
dq_{mn}	=	velocity induced at m by a small vortex element at n
K_{mn}	=	coefficient matrix of vortex strengths
r_{mn}	=	distance between the vortex element and the point at which the velocity is induced
s_n	=	length of the surface element
u_∞	=	x component of the freestream velocity
$\mathbf{V}_\infty$	=	freestream velocity vector
v_∞	=	y component of the freestream velocity
x	=	x coordinate
y	=	y coordinate
β	=	angle between the surface element and the horizontal
γ	=	vortex strength on a surface element

Introduction

THE problem of navigation and coordination of multiple unmanned vehicles is of recent interest when tasks like path planning, obstacle avoidance, collision avoidance, etc., are considered as part of their autonomy. The problem complexity increases even further when large numbers of vehicles are to navigate in swarms in complex environments [1,2]. Moreover, when micro aerial vehicles (MAVs) are considered, limited onboard sensor requirements make the problem more challenging. This problem can be solved either by designing systems made up of many autonomous decentralized unmanned vehicles all reacting independently (decentralized control) or by designing a total system that receives centralized information for swarmlike behavior (centralized control). In any case, the problem is usually mathematically large in size and computationally intensive, especially if some optimality is required. For example, calculating trajectories that both avoid obstacles and are also energy efficient or regenerating trajectories in case of moving obstacles or moving targets, or avoiding pop-up targets can quickly turn into a computationally heavy problem, often hard to solve even offline. Therefore, methods that provide fast solutions to dynamic trajectory generation for swarming MAVs while providing obstacle avoidance, collision avoidance, and target tracking are valuable.

Some researchers have proposed this problem as a large optimization problem, whereas others have attempted to propose this as a coordination problem of multi-agents. One way of attempting to solve this problem is the use of potential fields. The potential field approach for obstacle avoidance was first proposed by Khatib in 1986 [3]. In this work, goals were modeled as attractors and obstacles as repellers of an artificial potential field in which each vehicle moves. A more rigorous application of this idea to swarm robots and unmanned air vehicles (UAVs) was proposed a few years ago [4–7] and also more recently [8]. In these studies, the potential field of an irrotational flow of an ideal fluid around a geometry, which can be obtained as the gradient of a velocity potential [9,10], is calculated and used to obtain the stream functions and streamlines, which are then used as vehicle trajectories for solving the problem of navigation with obstacle avoidance. These streamlines can be obtained analytically by using and combining elementary complex potentials of flows like uniform flow, sink, and vortex. However analytical solutions can only be used to generate obstacle-avoiding trajectories around relatively simple geometries, such as cylinders, ellipses, etc. To obtain streamlines (trajectories) around complex geometries, a more specific numerical tool borrowed from the fluid dynamics/aerodynamics domain, known as panel methods, are more appropriate. These panel methods were previously used for robot motion planning [11] and real-time obstacle avoidance [12]; however, their application to swarming multiple unmanned vehicles in an environment filled with multiple obstacles of complex shapes and geometries is practically nonexistent.

In this paper, we apply the potential field panel method to obtain streamlinelike trajectories and use them for path planning and collaborative target tracking for swarming MAVs in an urban environment filled with complex-shaped buildings and other architectural structures. In addition, we introduce a performance matching

Received 15 May 2009; revision received 8 September 2009; accepted for publication 24 September 2009.

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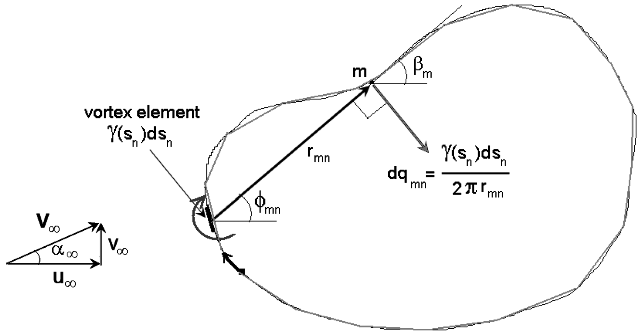


Fig. 1 Surface representation of an arbitrary geometry in a panel method using straight line segments and the velocity induced at *m* by a surface vortex element at *n*.

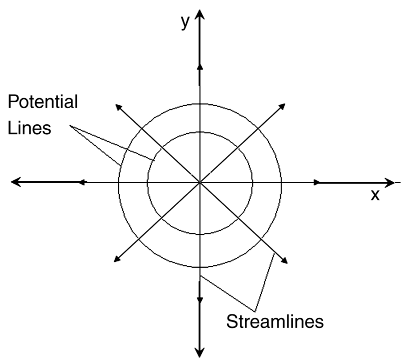


Fig. 2 Streamlines and potential lines due to a point source element. Each MAV is represented as a point source in the domain.

technique that relates the fluid velocities that are obtained as a part of the panel method solution to vehicle velocities along each trajectory and then restricts the maximum centripetal acceleration along the trajectory to the maximum permissible vehicle acceleration. As a result, the vehicle is allowed to fly as fast as it can along a selected trajectory, only restricted by its own permissible performance limits. The approach is further expanded to track moving targets yet avoid obstacles and collision between the vehicles. Here, every unmanned vehicle will have its own streamline solution, as opposed to a total solution of streamlines or potential lines. Because this might result in the possibility of vehicle collision, as each vehicle trajectory is calculated independently, each vehicle is represented as a repelling point source by itself. The method allows tracking of moving targets and can be tuned for vehicle performance. Results of tracking a moving target using multiple MAVs around an actual city is presented for the demonstration of effectiveness.

Methodology

Obstacle Avoidance in Complex Terrain: Two-Dimensional Panel Method

Panel methods are widely used in aerodynamics calculations to obtain the solution to the potential flow problem around arbitrarily shaped bodies. In these methods, the complex shape of a solid body is approximated by straight line segments (panels), and the potential field due to the presence of this solid body is represented by implementing a distribution of potential flow singularity elements on the body surface. For example, the flow of an ideal irrotational fluid around a two-dimensional body of arbitrary shape can be obtained by distributing a vorticity sheet, initially of unknown strength, covering the entire surface of the body (Fig. 1). The velocity dq induced at m by a small vortex element at n can be calculated using Biot–Savart law as [9,10]:

$$dq_{mn} = \frac{\gamma(s_n) ds_n}{2\pi r_{mn}} \tag{1}$$

where γ is the vortex strength on the surface element ds, and r_{mn} is the distance between the point m and the vortex element at n.

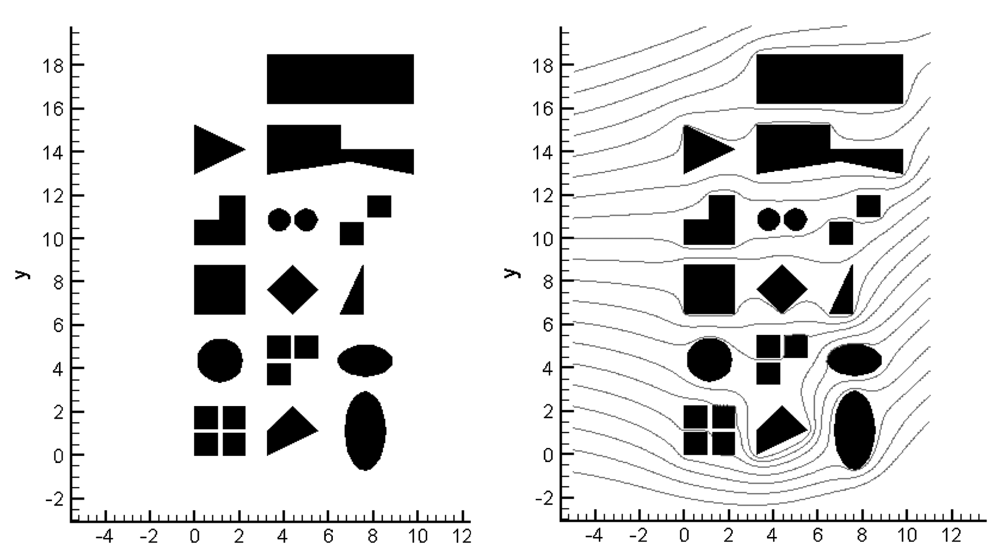
The total induced velocity at m is obtained by adding up all the induced velocities from all available surface vortex panels. This calculation is repeated for the finite number of line segments on the body surface. Then, the Dirichlet boundary condition is applied, which states that the velocity component normal to the body surface should be zero. Application of this condition results in a system of linear equations as

$$[K_{mn}][\gamma_n] = [\mathrm{RHS}_m] \tag{2}$$

where

$$K_{mn} = \frac{\Delta s_n}{2\pi} \left\{ \frac{(y_m - y_n)\cos\beta_m - (x_m - x_n)\sin\beta_m}{(x_m - x_n)^2 + (y_m - y_n)^2} \right\} \tag{3}$$

$$\mathrm{RHS}_m = -u_\infty \cos\beta_m - v_\infty \sin\beta_m \tag{4}$$



a) b)

Fig. 3 MAV swarm trajectories through arbitrarily shaped obstacles: a) sample synthetic urban environment and b) streamlines calculated by the potential flow panel method to be used as MAV trajectories.

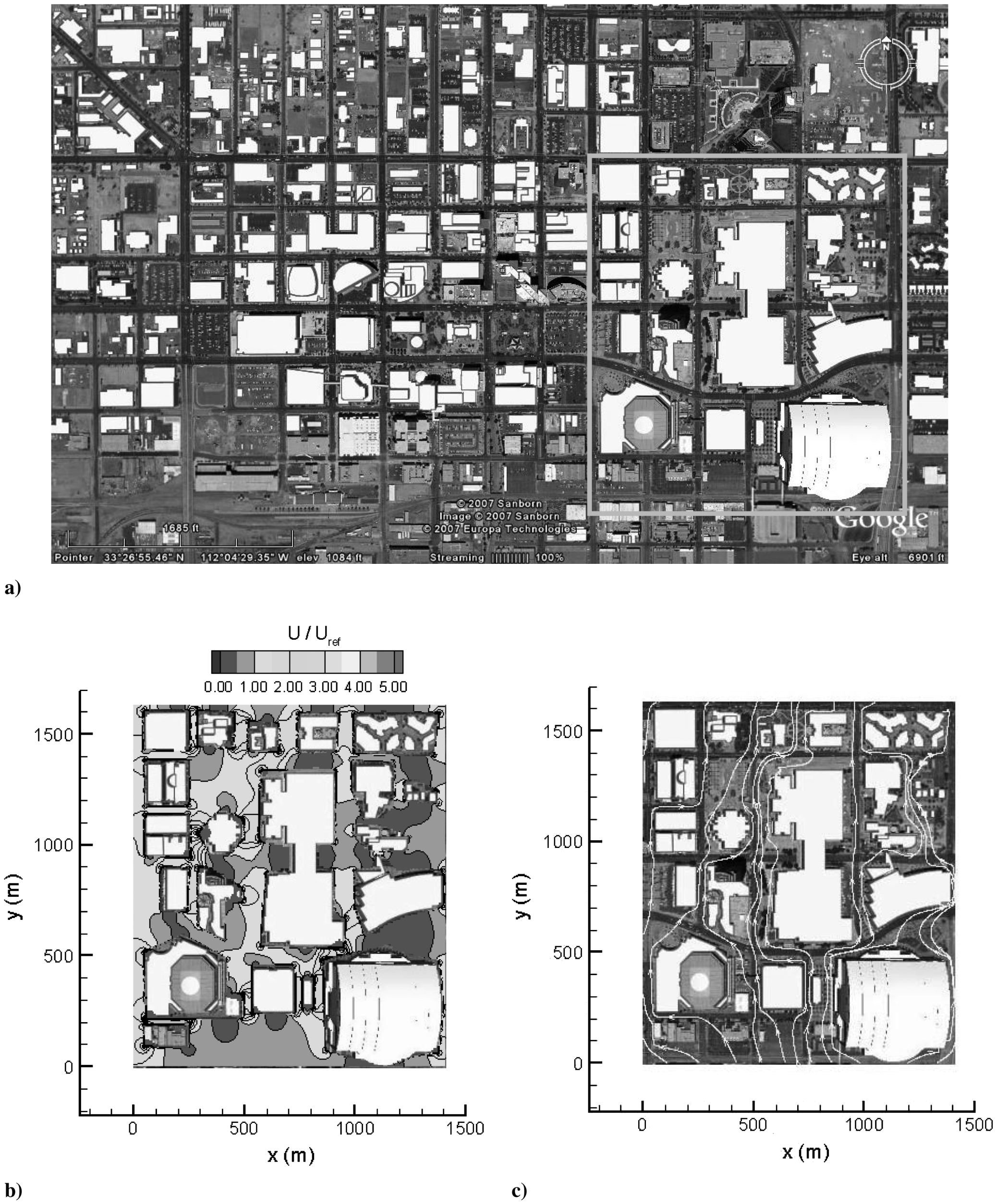


Fig. 4 MAV swarm trajectories through urban terrain: a) downtown Phoenix, AZ obtained from Google Earth. Marked region (rectangle) covering a four-block area; b) calculated representative steady-state fluid velocity field within the marked area in a); and c) corresponding steady-state trajectories (streamlines) between buildings in the lower downtown area.

and γ_n are the vortex strengths to be solved. Here, K_{mn} is the coefficient matrix and RHS_m is the right-hand-side matrix that is obtained using freestream velocity vector components.

After solving the system of equations given in Eq. (2), the vortex element strengths γ_n are determined, which allow the calculation of the steady-state shapes of streamlines as well as the velocity field within the domain of interest. The streamlines inherently avoid obstacles that are present in the domain. In addition, we extend this obstacle avoidance method, such that each MAV in a swarm of MAVs follows its own potential flow streamlines, which are no longer steady in time but change their shapes dynamically in order to follow and track a certain target within the domain of interest. The target tracking method will be explained in detail in the following sections.

The number of panels that is used for representing a geometry depends on the complexity of the geometry itself. For highly complex shapes, one needs many panels, and this increases the computational time, especially during the matrix inversion process. In this study, we use either a direct (Gauss–Jordan) or an iterative solver (Gauss–Seidel with relaxation), depending on the number of panels needed to represent a complex urban environment. For large scale or three-dimensional problems, for which the matrix inversion process in the direct solver would take too much computational time at each time step, the iterative solver should generally be preferred.

Dynamic Target Tracking: Unsteady Flow Calculation

One of the objectives of this study is to make each and every MAV in a swarm of MAVs track a target that has a known starting position and is changing its position in time. The MAVs could be released from any random location within an urban environment, and they are required to follow the target while avoiding collision with building structures and among themselves. To achieve this purpose using the obstacle avoidance method described in the previous section, each MAV follows its own dynamically changing potential flow streamline. At each time step of the simulation, the relative position of each MAV with respect to the target is first calculated. Then, this direction vector is used to obtain the U_∞ and V_∞ values used in Eq. (4) of the panel method, and the matrix solution is performed. The results of this solution are used to calculate the induced velocity components on the MAV, which are used to propagate the desired trajectory of the MAV

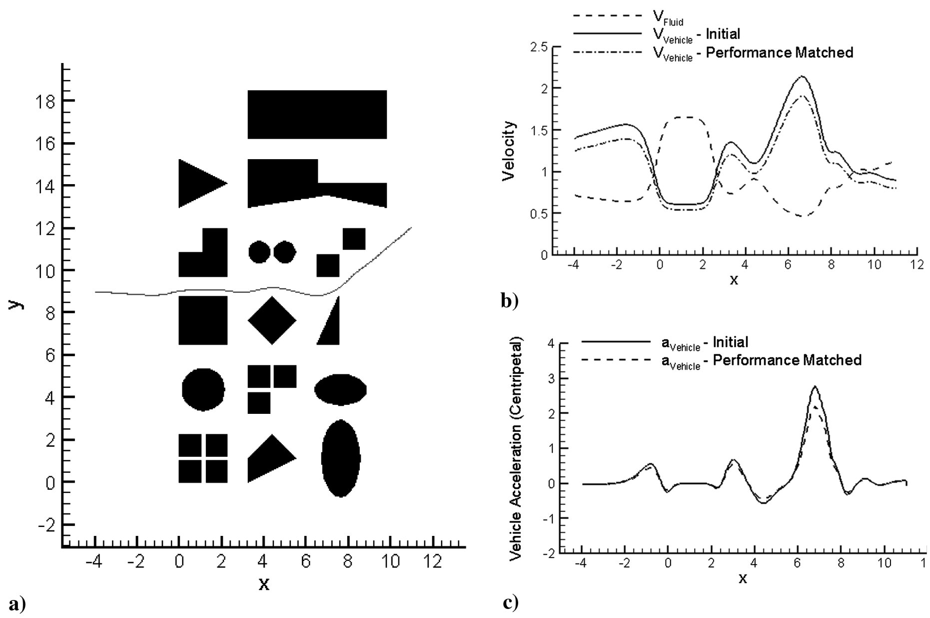


Fig. 5 Demonstration of the performance matching technique: a) a single MAV trajectory, b) fluid and initial and performance matched vehicle velocities, and c) initial and performance matched vehicle accelerations along the trajectory on the left.

in time. A second-order scheme is used for time integration. For a dynamically changing target position, the relative position vector direction changes with time, which in turn changes the right-hand side of the linear system given in Eq. (2), and hence produces a dynamically changing streamline pattern for each MAV. Note that all tracking MAVs know the target location at all times.

Automatic Collision Avoidance: Point Source Representation

The application of the previously mentioned methodology for dynamic target tracking and obstacle avoidance has an inherent problem, because each MAV is moving within its own dynamically changing streamline pattern, the patterns for different MAVs in a swarm inevitably cross each other at each time step, therefore bringing the possibility of potential collisions of MAVs with each other. This problem is overcome by defining each MAV as a point source, which is a potential flow point singularity element frequently used in potential flow analysis. The streamline pattern, due to a point source singularity element, is illustrated in Fig. 2, and the corresponding potential function for a source located at (x_0, y_0) is given as [10]:

$$\Phi(x, y) = \frac{\sigma}{2\pi} \ell n \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{5}$$

where σ is the strength of the source element.

Defining each MAV in the swarm as a point source singularity requires the modification of the right-hand-side term in Eq. (4). The new term becomes

$$\mathrm{RHS}_m = -u_\infty \cos\beta_m - v_\infty \sin\beta_m - \left(\sum_{i=1}^{N_{\mathrm{MAV}}} u^i\right)\cos\beta_m - \left(\sum_{i=1}^{N_{MAV}} v^i\right)\sin\beta_m \tag{6}$$

Therefore, the potential field at each time step gets slightly modified due to the presence of MAVs. In addition, when calculating the motion of an MAV, the influence of each and every MAV is included in the calculation, which results in an automatic collision avoidance of MAVs with each other. Note that all MAVs are modeled as point masses in this study, and more elaborate vehicle models will be applied in our future publications.

Results

Obstacle Avoidance

To demonstrate the technique, a two-dimensional geometrical layout of a synthetic urban environment is generated, as presented in Fig. 3a. The layout is composed of cross sections of various geometrical structures that could be found in a modern city. These structures could essentially be of any arbitrary and complex shape, because they are basically represented by a collection of straight panels, as described previously. The total number of panels can be selected as needed.

Figure 3b shows the calculated streamlines, using the panel method described previously. These streamlines are to be used as the trajectories of a swarm of MAVs that are released at varying y coordinates at a specified x location. Figure 3b shows 20 sample trajectories with release locations uniformly distributed along y. As is evident, due to the inherent nature of the fluid flow characteristics, the trajectories do not cross each other and automatically avoid any types of obstacles. Once the geometrical layout of an urban area is known, these trajectories can be precalculated, and the MAVs just have to

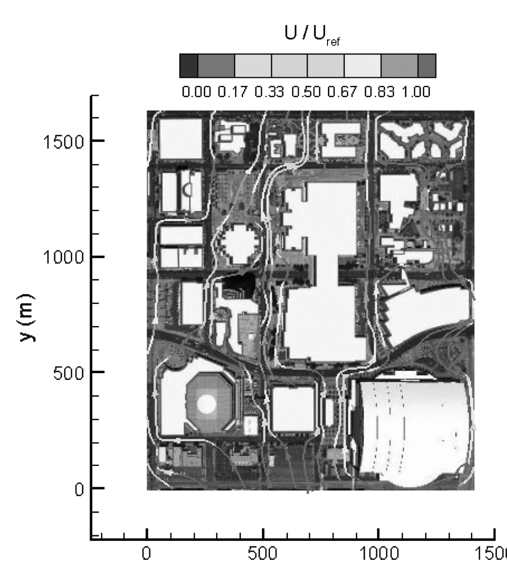


Fig. 6 Performance matched vehicle velocity variations along calculated trajectories through the lower downtown area of Phoenix, AZ.

choose and follow a streamline without having to locate and avoid obstacles with complex sensor devices and other hardware. Furthermore, for small aircraft like MAVs, which generally have their biggest dimension less than 15 cm, carrying onboard collision avoidance sensors is not usually possible or practical. Therefore, this type of trajectory calculation could be useful for swarming MAV systems. In the examples given next, it is assumed that the trajectory information is provided to the MAVs through a central command station, and the MAVs' closed loop performances are capable of following the commanded trajectories. Moreover, the closed loop performances of the MAVs are robust enough to reject disturbances like wind, gust, etc.

The method described previously is applied to the layout of an actual city. For this purpose, downtown Phoenix, AZ is chosen as an example, because it has nicely structured avenues and a well-organized city plan. Figure 4a shows a satellite image of the downtown area obtained from Google Earth (http://earth.google.com/). Main building structures are marked as white areas on this image, and the actual scale of the image is given in the lower left-hand corner. The calculation procedure starts with marking the boundaries of the building structures directly on the image obtained from the Google Earth software. A utility code converts these marked points to surfaces and prepares an input file for the panel solver. These surfaces are divided into a predetermined number of panels in the potential flow panel solver, and the panel vortex strengths are calculated. Once the vortex strengths are known, the velocities and streamlines are calculated on a background grid covering the entire calculation region.

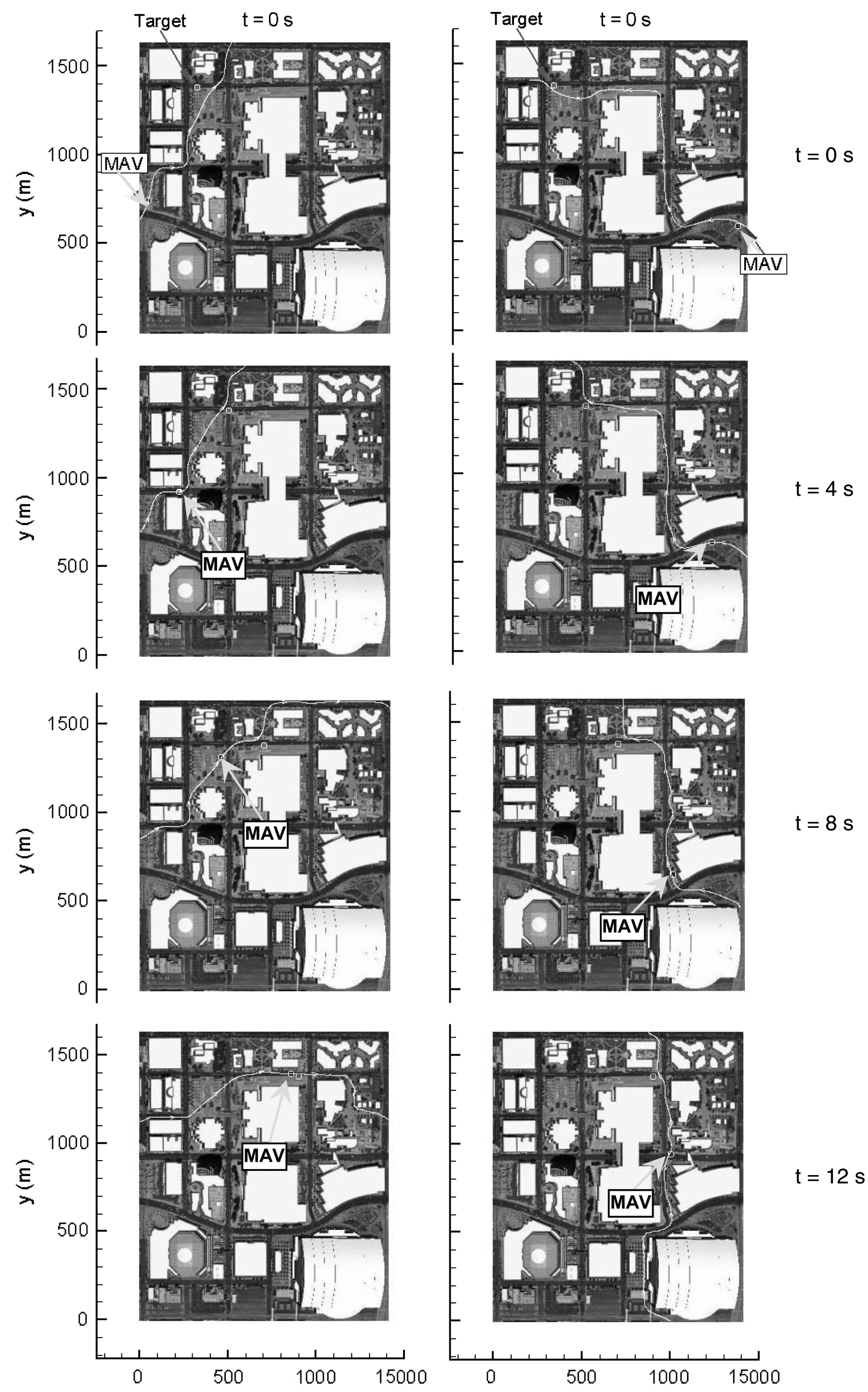


Fig. 7 Dynamically changing streamline patterns for orienting the MAVs toward the target. The left column is for an MAV that starts at $x = 40$, $y = 720$, and the right column is for an MAV that starts at $x = 1370$, $y = 580$.

The four-block area marked by the rectangle in Fig. 4a is arbitrarily chosen for this study. Figures 4b and 4c show a representative steady-state fluid velocity field and the corresponding steady-state streamline pattern, respectively, obtained as a result of the numerical solution of the potential field. The results are superimposed on the selected region of the city. The streamlines inherently avoid the building structures, which are defined as obstacles and could be used as MAV trajectories.

MAV Performance Matching

The panel method potential flow calculation not only gives the trajectories, but the results could also be extended to obtain the vehicle velocities along the trajectories. This is achieved by first relating the calculated fluid velocities to allowable vehicle velocities and then restricting the maximum centripetal acceleration along the trajectory to the maximum permissible vehicle acceleration. As a result, the vehicle is allowed to move using a certain speed performance criteria, such as fastest time, slowest time, etc., but it is restricted within its permissible flight envelope. Furthermore, because each vehicle will be flying at a scaled value of the fluid velocity, there will be no collisions among the vehicles that choose the same trajectory (at different times). Each vehicle will be commanded to fly with the same velocity vector at a corresponding position, hence making it impossible for them to catch one another.

The performance matching used in this work is demonstrated in Fig. 5. A corresponding sample single MAV trajectory is shown in Fig. 5a. Here, Fig. 5b shows the calculated fluid velocity V_{Fluid} along this trajectory. Notice the change in velocity as the fluid moves between the obstacles. In narrow regions (for example, between $x = 0$ and $x = 2$), the fluid accelerates and then subsequently decelerates in the wider parts. Instead of using this fluid velocity variation directly as the vehicle velocity, we choose to use $1/V_{\text{Fluid}}$ to ensure that the vehicle actually slows down in narrow passages and speeds up in wider passages, considering that this would be beneficial in terms of vehicle safety. This (i.e., $V_{\text{vehicle}} = 1/V_{\text{Fluid}}$) is what we refer to as the initial vehicle velocity in Fig. 5b.

Next, we check whether the vehicle could actually travel along this trajectory with the proposed V_{vehicle}. Here, the maximum permissible centripetal acceleration that the vehicle can handle during the maneuver along the trajectory is used as the criteria. Then, the centripetal acceleration is calculated using the trajectory and the calculated vehicle velocity (Fig. 5c). We see that the maximum centripetal acceleration occurs at about $x = 7$, with a value of about

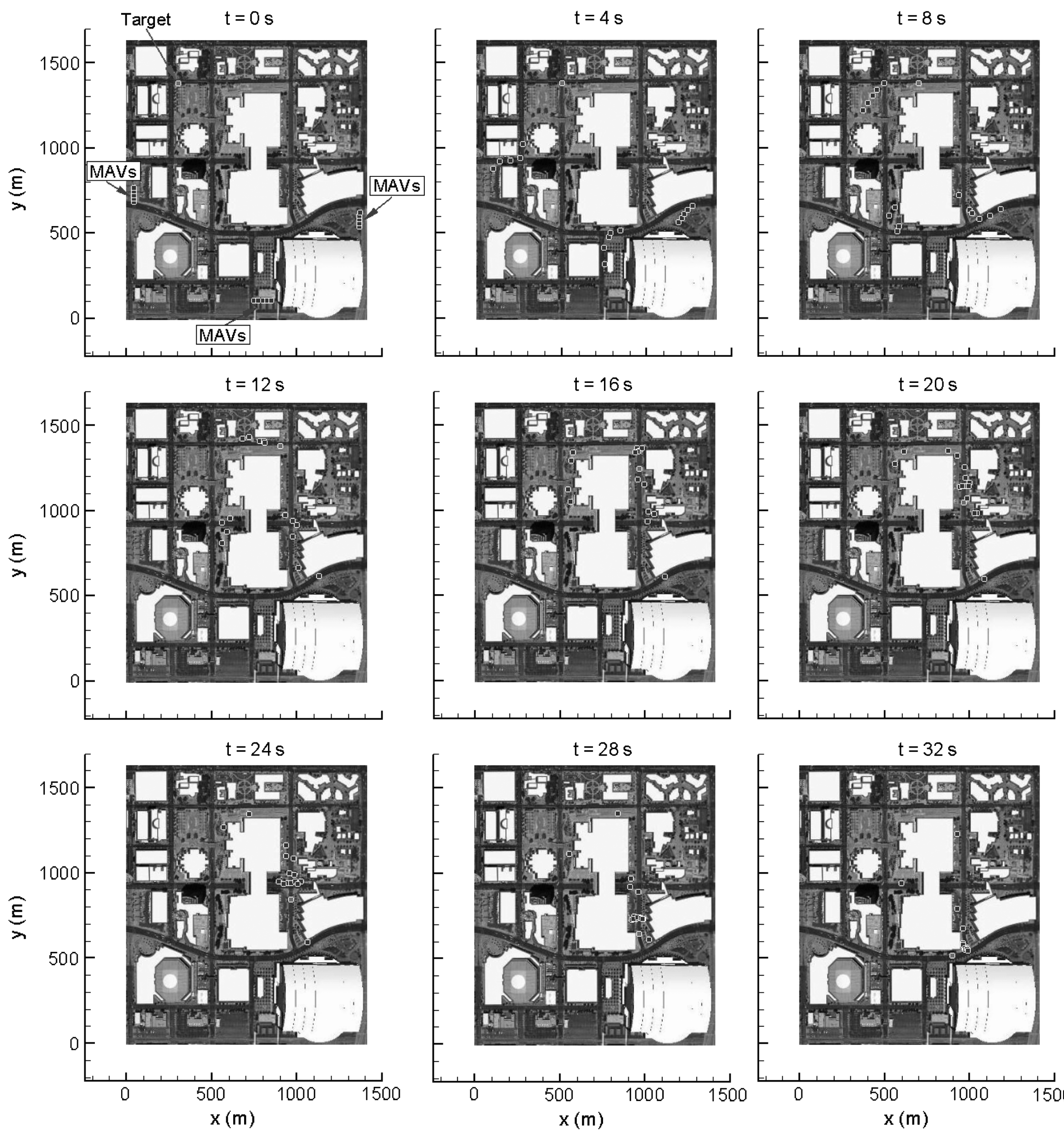


Fig. 8 The results of a 32 s simulation of 15 MAVs released at varying locations within the downtown area. MAVs automatically avoid obstacles (i.e., building structures), avoid collision among themselves while they track the target, move toward the target, and try to follow it with a 100 m preset separation. The target (dot) first moves two blocks east, then two blocks south, and then turns west.

$a = 2.8$ g. If this value is higher than the maximum permissible vehicle acceleration, the acceleration variation is scaled down, such that the maximum acceleration along the trajectory is the maximum permissible vehicle value. As an example, this value is chosen to be $a_{\text{vehicle}} = 2.2$ g, and the acceleration variation is scaled down accordingly and called the performance matched value (Fig. 5c). The corresponding performance matched vehicle velocity variation along the trajectory is presented in Fig. 5b. As a result, the vehicle will be able to fly with the performance matched velocity along the trajectory. The highest centripetal acceleration it will experience during maneuvering will be within its design limits. It will fly safe and slow in narrow passages and faster in wider areas. Should two different vehicles choose the same trajectory at different times, they will not be able to catch each other, as both will follow the same trajectory and velocity profile; hence, a possible collision will be avoided.

It is assumed that all the vehicles within the swarm are identical in performance. Note that a matched acceleration profile might not be aerodynamically achievable, for instance, if the trajectory would require a lower speed than allowable. In that case, the trajectory would simply not be included in the usable set of trajectories. Although not done here, it might also be possible to raise the velocity profile to match the maximum performance of the vehicle instead of reducing it for safety.

The performance matching technique is also applied to the urban environment presented in Fig. 4, and the results are presented in Fig. 6. Here, the streamlines (trajectories) are colored with the performance matched vehicle velocity magnitude values. As is evident, the vehicles adjust their velocities by speeding up in wider areas and slowing down in relatively narrower zones, ensuring vehicle safety while traveling at the maximum permissible performance to fly through the lower downtown area.

Collaborative Dynamic Target Tracking and Collision Avoidance

Figure 7 demonstrates the application of dynamic target tracking for two different vehicles that are released from different positions in the city. The simulation covers a 12 s period, in which a target (marked by the dot) starts moving from the upper left-hand corner and follows the street toward the east. The dynamically changing streamline patterns for the two vehicles initially located at $(x, y) = (40, 720)$ and at $(x, y) = (1370, 580)$ are shown in the left and right columns of Fig. 7, respectively. For a single vehicle, at each time instant, the vehicle is located on a different streamline (for example, if one follows the variations from $t = 0$ s to $t = 12$ s on the left column). The streamlines are dynamically changing in order to orient the vehicle toward the moving target at each time step. At a certain time instant, if one compares the streamline patterns for two different vehicles (e.g., at $t = 12$ s), the instantaneous streamlines for the vehicle on the left and for the one on the right are actually intersecting. Nevertheless, a collision is not possible, because when they get close to each other, streamline patterns will be modified because of the fact that they are represented as point sources. This is readily demonstrated in Fig. 8, which shows the results of a 32 s simulation for 15 MAVs that are released from varying locations within the city. As is evident, the MAVs automatically avoid obstacles (i.e., building structures) and avoid collision among themselves, while they keep tracking the moving target, flying toward it, and following it within a 100 m distance that is preset before the simulation. This last requirement was just for testing the tracking abilities of the MAVs using the methodology described previously, and it is observed that the results are quite satisfactory.

Conclusions

The application of the potential flow panel method for trajectory generation, obstacle avoidance, and collaborative target tracking of swarming MAVs operating within an urban environment filled with complex building structures is presented. Because of the inherent nature of streamlines, obstacle avoidance is automatically guaranteed. To make the MAVs follow and track a moving target, dynamically changing streamline patterns are calculated for each and every one of the MAVs within a swarm. To prevent vehicle-to-vehicle collisions, each MAV is represented using a point source singularity element within the potential field. The simulation results are quite encouraging, in the sense that MAV swarms quickly locate and track the assigned target in an environment filled with complex-shaped structures, while avoiding obstacles and collisions among themselves. One benefit of the method is that the trajectory computations can be relatively fast and even have the potential to be applied in real time, depending on the number and complexity of the urban structures. Using simple mapping tools, it is possible to generate obstacles of major city downtowns and allow the MAV swarms to move through streets and open areas. This idea of using streamlines and performance-based velocity profiles allows an easy, fast (and in many ways), and optimized solution to the multi-agent swarming problems. The downside one might claim is that we still need the full information of a city that is going to be swarmed, and the information has to be uploaded to each MAV. However, for MAVs with little computation power and limited onboard sensing, information sharing will be an essential part. Also, the method in its current form is two-dimensional and does not present a way to overcome disturbances that might be present in real environments (e.g., wind turbulence). These will be investigated in our future studies.

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