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Framework for Developing and Evaluating MAV Control Algorithms in a Realistic Urban Setting

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***Abstract*—An investigation has begun to evaluate the behavior of Small Unmanned Aerial Vehicles (SUAVs) and Micro Aerial Vehicles (MAVs) flying through an urban setting. This research is focused on a cooperative scenario between a SUAV and MAVs for the Air Force Research Laboratory (AFRL) Cooperative Operations in UrbaN TERrain (COUNTER) 6.2 research and flight demonstration program. There is great interest in MAV/SUAV use but limited simulation work has been dedicated specifically to issues associated with very small vehicles that cruise at slow speeds near the ground. Development of satisfactory six-degree-of-freedom models of an MAV and SUAV were the first tasks to be tackled, along with the integration of these models into the MultiUAV 2.0 simulation environment. The second task was to model and integrate wind data for complex urban flows into this simulation. This involved creating modules to interface the simulation with CFD results and data obtained through urban airflow experiments. An urban environment for the MAV to fly through was constructed using the geometry of a likely COUNTER flight test location. These basic elements coupled with future cooperative control task assignment and path planning algorithms will complete this engineering simulation.**

I. Nomenclature

Symbols

b	Wing Span
d	Distance
$\bar{c}$	Mean Aerodynamic Chord
C_l	Roll Moment Coefficient
S	Wing Area
t	time (seconds)
V	Velocity (m/s)

Subscripts

β	Sideslip Angle
w	Wind
∞	Free Stream

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II. Introduction

This work is designed to provide a framework for the test and evaluation of cooperative control algorithms for Micro Aerial Vehicles (MAVs) and Small Uninhabited Aerial Vehicles (SUAVs) operating in a cluttered urban environment. Others have developed algorithms to adapt paths for UAV constant line-of-sight problems which deal with placing sensors onto known locations but not for MAVs or SUAVs operating in or near the complex flow fields of urban environments.[1] The effectiveness of MAVs to accomplish a specific task is highly dependent on the wind environment in which they operate. With cruising speeds as low as 9-13 m/s, even a 4 m/s breeze can significantly affect the utility of these vehicles. When examining complex flow-fields found in cities, examining only the geometrically shortest feasible path between the vehicle and its objective is insufficient to accomplish the mission at hand. This is especially true when considering multiple vehicles operating at various points throughout the mission area. Known wind data must be used to calculate the shortest feasible path through the air mass, not relative to a map of the terrain. The goal of this research program is to quantify the utility of MAVs and SUAVs in a complex urban environment and provide a realistic simulation. The primary function of this simulation will be to test cooperative control algorithms.

III. COUNTER Program Description

The Cooperative Operations in UrbaN TERrain (COUNTER) program is designed to investigate and develop the cooperative control algorithms, software, and hardware needed to perform a flight demonstration of the concept of operations described below. This is an Air Force Research Laboratory (AFRL) 6.2 research program and will take place from Fiscal Year (FY) 2005 until the end of FY 2007. The Air Vehicles (VA), Human Effectiveness (HE), and Munitions (MN) directorates are AFRL participants in the program.

A layout of the general concept of operations is shown in Figure 1 below. The SUAV will be launched from a forward area and fly over a city, town, or other area of interest. The SUAV will act as the "mother ship" and carry the MAVs. The SUAV will observe the area of interest from a survivable altitude, and potential targets will be designated through the video imagery transmitted to the human operator on the ground as illustrated in Figure 1. When a positive identification cannot be made of a potential target due to target obscuration or low sensor resolution a MAV is launched to take a closer look at the target. The MAV provides the needed viewing angle and distance to target to provide the operator with positive target identification. The launched MAV is then available for re-tasking to examine other targets of interest within the area of operations. When multiple high-priority targets are sensed in a short period of time multiple MAVs are required to accomplish the verification mission. The MAVs will be recovered if convenient but are considered expendable. The purpose of this staged system is to get time-sensitive information unobtainable by other means.

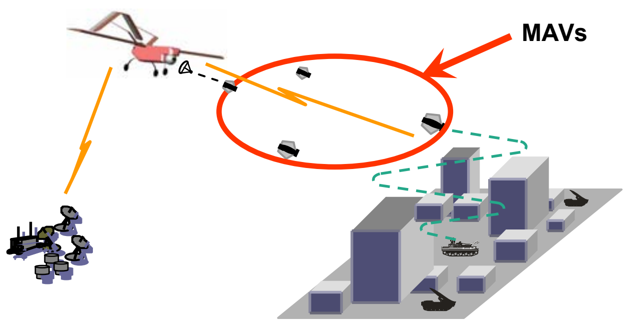

Figure 1: COUNTER Operational Concept

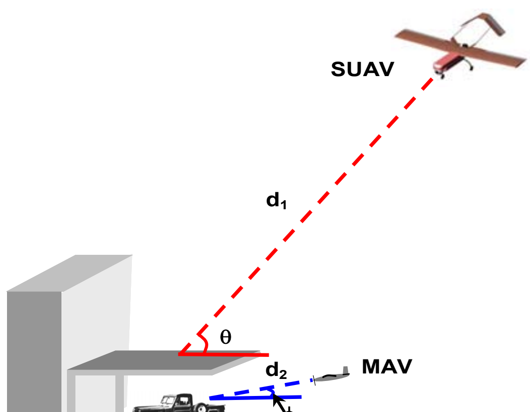

Figure 2: Geometry of Sensor Placement

Figure 2 shows the physical rational for this staged MAV/SUAV system. The figure shows a SUAV operating at an altitude needed for sensor coverage of a wide area while placing the SUAV vehicle a survivable distance from the possible target. The distance d_1 from the target to the small UAV is much greater than the distance d_2 from the target to the MAV. The MAV needs to get close to the target in order to obtain both the desired viewing angle and adequate pixel resolution to achieve a positive identification. Figure 2 illustrates that no matter how good the optical sensor on a high-flying UAV or SUAV is there are still categories of targets that cannot be seen. The obscuration can be caused by manmade means such as buildings, tents, covers, pollution degrading sensor resolution, or smoke. Natural causes could include clouds and dust that render images taken from standoff distances less useful than those from short distances.

This heterogeneous system of vehicles will provide a staged team capable of providing persistence, range and the ability to provide positive identification of an obscured target in an urban environment. The SUAV will serve as the communications relay for the MAV and may also provide processing of the MAV video signals. Some of the autonomous decision making/planning capability will be carried aboard the SUAV in the final version of this concept.

IV. MAV AND SUAV AERODYNAMIC MODELS

A six-degree-of-freedom aerodynamic model was created for representative MAV and SUAV airframes. There are a limited number of tools available for rapidly developing simulation models of varied aircraft configurations and a number of compromises must be lived with. The model used assumes that the vehicle behaves as a rigid body and that the aerodynamic characteristics of the MAV are steady. This assumption is only good as a first-order approximation for a flexible-winged MAV.

Missile Datcom was used to develop the aerodynamic model of the MAV and the SUAV.[2] Although originally developed for tactical missiles, the code has been applied successfully to approximate the characteristics of a wide variety of air and undersea vehicles. It uses the component buildup technique to predict vehicle aerodynamics. This method computes the characteristics of the fuselage, wing and tail in isolation, and then sums the components with the appropriate interference factors included (downwash, etc). Code inputs consist of body, wing and tail geometry, Mach number, altitude, angles of attack and sideslip, and control deflections. At each flight condition, the six body axis forces and moments are provided.

Mass	0.40 kg
$\bar{c}$	1.5×10^{-1} m
B	5.3×10^{-1} m
S	8.0×10^{-2} m^2
V_{cruise}	13 m/s

Table 1: MAV General Characteristics

A generic MAV style vehicle with a maximum mass of 400 grams propelled by an electric propulsion system was considered the reference vehicle for the purpose of this work. The vehicle characteristics are shown in Table 1. The resulting vehicle would cruise at a chord-based

Reynolds number of 127,000 at sea level. This puts the MAV it in the regime of very small model aircraft.

Creating the aerodynamic model required comparisons between the Datcom results, wind tunnel data, and some limited telemetry data from MAV flight tests.[3] Lift and moment characteristics were matched to similar flight test and wind tunnel data by manipulation of the Datcom input file. Stability derivatives were compared with wind tunnel data and a simple panel method was used to confirm these results.

The simplified MAV geometry used in the Datcom input file is shown in Figure 3. The wings are constant chord without twist or sweep. The body is made up of cylindrical sections. There are no control effectors on the wing of the vehicle. This MAV model relies solely on the V-tail's ruddervators for control. This means that the vehicle essentially controls two-axes of pitch and yaw instead of the normal pitch, roll, and yaw. The aircraft is yawed to produce roll through the C_{l_β} derivative term. This means that to enter a turn the vehicle yaws; this creates a sideslip which then induces a rolling moment and then the desired bank angle. Another feature of the V-tail for controlling an aircraft without ailerons is that in a steep turn the vehicle can run out of control power if yaw and pitch are simultaneously commanded. This can make a coordinated (zero sideslip) level turn quite challenging to accomplish. The practical upside of few effectors is lower weight and complexity due to fewer actuators and the associated increase in payload in performance. This is not an insignificant benefit on a 400 gram airframe.

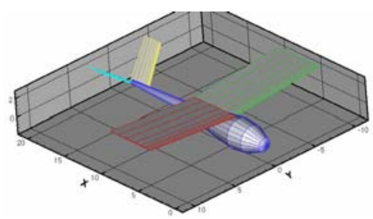

Figure 3: Geometry Used in Missile Datcom for 6-DOF MAV Model Generation

The Datcom input file used a NACA-65A001 airfoil as there was some difficulty in matching data with extremely thin, highly cambered MAV airfoil sections. A simple MATLAB function was written to modify the Datcom data sets in order to more closely match the observed behavior of the MAV model and similar vehicles. The model was first flown in the simulation and the performance recorded. It was then compared with the flight data and the wind tunnel data. The only term that was significantly different from the Missile Datcom file was the C_{l_β} term which caused the initial simulation model to fly poorly. The Datcom value for this derivative was half of the value obtained from the HASC model and six times less than that of the flexible winged wind tunnel results.[4] The dynamic behavior of the vehicle was examined with values of C_{l_β} from -0.001 to as high as -0.006. The vehicle behaved in the most controllable fashion with the HASC C_{l_β} value of -0.002.

Mass	9.5 kg
$\bar{c}$	3.3x10^{-1} m
B	1.8 m
S	5.9x10^{-1} m^2
V_{cruise}	13 m/s

Table 2: SUAVs General Characteristics

The MAV aerodynamic model is designed to provide a simulation model that will approximate the dynamics of an MAV. It is designed to be of sufficient fidelity to examine outer-loop guidance and navigation issues. As more experimental and flight-test data becomes available it will be updated to reflect this improved information.

A six-degree-of-freedom aerodynamic model has been created for a representative SUAV in the same manner as the MAV model. The configuration modeled is shown in Figure 4. This vehicle is powered by an internal combustion engine with a pusher propeller and has conventional ailerons and an inverted V-tail. The simulation model depends solely on the Missile Datcom results as wind tunnel tests were not performed on this configuration. This UAV flies at a chord-based Reynolds number of 280,000 at cruise. While low this puts the vehicle out of the very low Reynolds number regime encountered by an MAV. Mass properties of this vehicle were estimated from the geometry.

Figure 4: SUAV Configuration for Simulation

V. MOUT SITE MODEL

The Fort Benning Georgia McKenna Military Operations on Urban Terrain (MOUT) Site was chosen as a possible "urban" setting for flight testing for the COUNTER program. This site has been used for the Association for Unmanned Vehicle Systems International (AUVSI) International Aerial Robotics Competition.[5] This site offers the safety of flight through a small European style town while maintaining a controlled environment. The buildings are a maximum of three stories tall. There is a 3700' dirt runway adjacent to the McKenna site which may be useful for SUAV operations. The site is nearly encircled by trees and has limited open areas. These features may make the small scale wind effects challenging to calculate.

Geometry of the buildings and roads are obtained from three-dimensional data of the MOUT site. This geometry was duplicated in a 3-D drawing package and imported into a simulation visualization environment. Figure 5 shows the CAD model of the McKenna MOUT Site that will be used in the simulation of COUNTER.

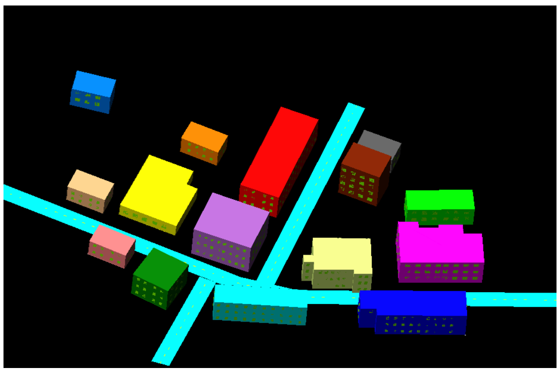

Figure 5: McKenna MOUT Site Simulation Model

The buildings in the MOUT simulation model are simplified to box structures and their main purpose is to designate areas that the MAVs cannot fly through. The lack of open areas and narrow streets will require the MAVs to have the ability to precisely hold altitude and turn within a tight radius. The loss of Global Positioning System (GPS) for navigation should only become a factor when the vehicles are flown below the tops of the buildings and line-of-sight to the satellites is obscured. At the McKenna MOUT site these effects are expected to be much less severe than in a highly developed urban area.

VI. Treatment of Wind Field

Manned aircraft and larger UAVs use wind-aloft data in the mission planning in order to derive the best possible flight path to accomplish the mission. As the operational altitudes are reduced and size of the vehicle becomes smaller, micrometeorology becomes progressively more important to the effective utilization of the vehicle. The winds become a greater percentage of the vehicle's cruise speed and the utility of the vehicle becomes heavily dependent on the environment.

Given an estimate of the wind field through a city a path plan should be formulated to most effectively find the optimal assignment and path for each target and corresponding vehicle. This is a situation where the effects of complex flow past the buildings can have a significant effect on the flight path of a slow vehicle.

The wind data for input to the MAV simulation is designed to read in a tabular data file. This table contains the X, Y, and Z position of the data point and the magnitude and direction of the wind at this point in space. The data follows a format which treats the wind field as a series of horizontal layers. This allows more layers of data closer to buildings or other features of interest. When there is more vertical variation in the wind field there can be more layers of data. The areas of high data density will correspond to areas of areas of the flow field that are the most complex and dangerous for an MAV to operate in. Once the vehicle leaves the flow field of the city a constant wind velocity is assumed to reduce the size of the input data file to a manageable size.

As the vehicle moves through the simulated world an interpolation is performed in order to get and estimate of the winds when the vehicle location does not fall exactly on a data point. This interpolation uses information from the eight closest points surrounding the vehicle at that time step. This forms an eight-point hexahedron. An interpolation is performed for the three dimensional wind data at each point. The hexahedron is collapsed to a quadrilateral figure by the first interpolation. This collapsed down to a line on the second interpolation and down to a point on the third and final interpolation. This yields an interpolated value for the three-dimensional wind at the vehicle's location.

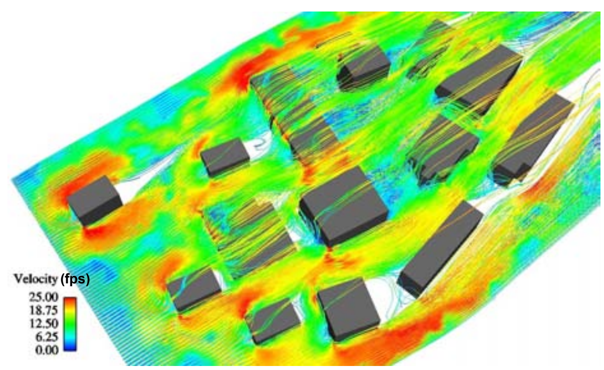

Figure 6: 3-D Flow through MOUT V_{∞} =4.6 m/s (15 fps)

To provide an initial set of data for simulation testing the Air Vehicles Unstructured Solver (AVUS) to compute the flow field through the McKenna MOUT site.[6] Some results from the initial run returned from the CFD solver can be viewed in Figure 6 and Figure 7. Figure 6 shows a picture of the entire MOUT site. Notable are lee side regions where particles are trapped by vortices and the vertical variations in the flow. The particles used for the visualization all start out at the same height in the boundary layer. As they flow past the buildings their paths are changed both horizontally and vertically. Also of interest are regions between buildings where the flow is accelerated by the contraction of the flow.

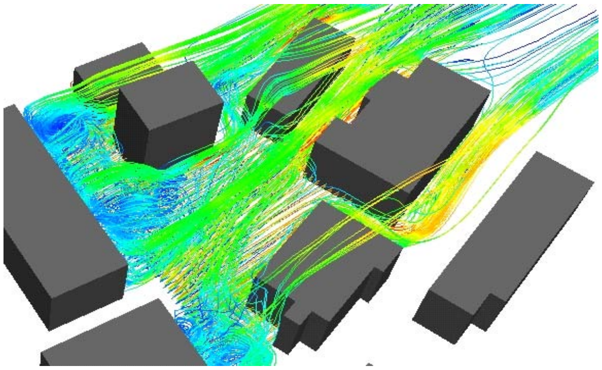

Figure 7: Flow through MOUT V_∞ =4.6 m/s (15 fps)

Figure 7 shows a close-up view of the region between several buildings. There is a clear recirculation region with standing vertical structures as well as vortices shedding down stream. The areas of vortical flow in the building wakes are potentially very challenging areas for an MAV to fly through. There are large variations in velocity direction in an extremely short distance which could present severe challenges to a light, small, and slow vehicle attempting to fly below the building tops. Reaching the area of interest to view a target may become secondary to simple survival of the vehicle. Planning 3-D paths to get around these physical constraints is essential to make urban MAV and SUAV flight practical over a wide range of weather conditions.

VII. INTEGRATION AND VEHICLE MODEL TESTING

The MAV and SUAV aerodynamic models and wind-field interpolation were brought together into the Multi-UAV 2.0 simulation environment. The MultiUAV simulation was created to allow multiple-UAVs to be simultaneously simulated for the purpose of developing control algorithms in an environment that can be easily adapted for different missions and scales of vehicles.[7] The integration of the MAV aerodynamic model and a simple flight control system was performed in C++, MATLAB, and SIMULINK. The two-axis control of the MAV is handled with a simple proportional/integral controller with adjustable gains and a V-tail mixer. The gains were adjusted to mirror the inner-loop performance measured on a similar MAV in-flight.

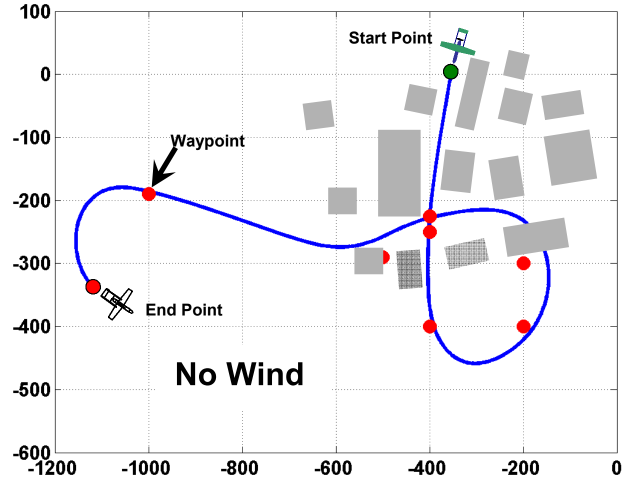

Figure 8: Flight Path through Ft. Benning MOUT Site with No Wind (t_{flight} = 45 Seconds)

Once the 6-DOF model of the MAV was flying in the simulation a simple waypoint following routine was implemented. This involved commanding a specific climb or decent rate to get to new altitude between waypoints and then commanding a true course to the next waypoint. A tolerance is specified that the MAV must get within one turn radius of a waypoint before sequencing to the next waypoint. Figure 8 shows the result of a course that goes through open areas in the McKenna MOUT site geometry. This flight takes 45 seconds with no wind and a minimal number of waypoints. The MAV cruises at 30 m/s, and has a turn radius of approximately 30m.

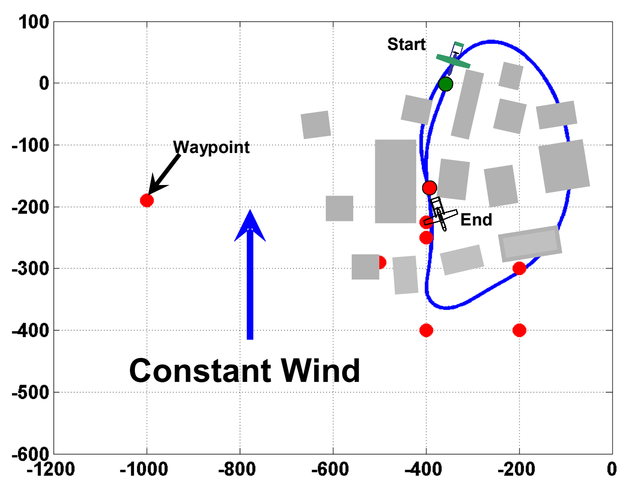

Figure 9: Flight Path with V_w = 4.6 m/s South to North Wind (t_{flight} = 45 Seconds)

Figure 9 shows the same waypoints with a 4.6 m/s constant wind that blows from bottom to top in the figure. With waypoints programmed as in Figure 8, the vehicle follows a much different path. In this case the MAV cannot hit its waypoints, and the end of the flight is in a different location. This rather obvious result aids in visualizing how large an effect even a light breeze can have on MAV operations. This will require much closer waypoint spacing and that some path re-planning be performed when adverse wind conditions are encountered.

The SUAV model has been integrated into the MultiUAV 2.0 simulation utilizing the standard dynamic inversion controller. The conventional vehicle layout and multiple control surfaces allowed this approach. The simulation was modified to accommodate multiple vehicle types to perform missions in concert. Further modifications are underway to model sensors and integrate the mission profile into the simulation.

VIII. Direction for Future Research

The first step in creating an environment to test and develop cooperative control algorithms for MAVs has been accomplished. The individual parts are now being integrated into the MultiUAV 2.0 simulation to allow multiple vehicles to simultaneously fly through and above the urban environment. The MultiUAV simulation must be further modified to include collision modeling, and add building constraints into path planning algorithms. Work will be performed to adapt the existing path planning algorithms to utilize known wind information to the greatest advantage. This will consist of estimating possible wind fields before paths are planned, then using this data for the simulation. How the algorithms deal with the difference between known and unknown information will be critical to their utility in actual flight operations.

IX. Conclusion

This work is setting the framework to test cooperative control algorithms for MAVs operating in and above complex urban environments. Approximate aerodynamic models for both MAVs and SUAVs have been created. These models allow the general performance of a MAV and a SUAV to be accurately modeled in simulation. The ability to import three-dimensional wind data has been created and an interpolation scheme developed for simulation purposes. A model of an urban MAV flight test environment has been created. Simple calculations have been performed examining the effect of steady wind on the austere waypoint following incorporated in the standard MAV autopilot.

X. Acknowledgements

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References

[1] Rysdyk, Rolf, “UAV Path Following for Constant Line-of-Sight,” AIAA 2003-6626, 2nd AIAA "Unmanned Unlimited" *Conf. and Workshop and Exhibit*, San Diego, California, Sep. 15-18, 2003

[2] Blake, W. B., “Missile DATCOM Users Manual,” AFRL Technical Report AFRL-VA-WP-TR-1998-3009, 1998

[3] DeLuca, A. M., Reeder, M. F., Ol, M. V., Freeman J., Bautista, I, and Simonich, M., “Experimental Investigation into the Aerodynamic Properties of a Flexible and Rigid Wing Micro Air Vehicle,” *24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference*, AIAA-2004-2396, 2004

[4] SimGen, Software Package, Ver. 1.0, Bihrle Applied Research Inc., Hampton, VA, 2004

[5] http://avdil.gtri.gatech.edu/AUVS/CurrentIARC/2003VenueInfo.html

[6] Hoke, C., Burnley, V., and Schwbacher, G., “Aerodynamic Analysis of Complex Missile Configurations using AVUS (Air Vehicles Unstructured Solver),” *22nd Applied Aerodynamics Conference and Exhibit*, AIAA 2004-5452, 2004

[7] Rasmussen, S. J. and Chandler, P. R., “MultiUAV: A Multiple UAV Simulation for Investigation of Cooperative Control,” *Proceedings of the Winter Simulation Conference*, 2002