Original Article

Institution of MECHANICAL ENGINEERS

Journal of AEROSPACE ENGINEERING

Proc IMechE Part G:
J Aerospace Engineering
0(0) 1–11

DOI: 10.1177/0954410012440663
uk.sagepub.com/jaero
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Experimental method for studying gust effects on micro rotorcraft

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Abstract

Micro rotorcraft have a great potential for both civilian and military applications, but for successful deployment, they must operate robustly in real-world environments including flight in winds. Due to their small size, common wind fields in and around buildings can represent a large percentage of the vehicle's full flight envelope resulting in highly non-linear motion. An experimental method has been developed to evaluate the capabilities of micro rotorcraft in realistic wind conditions to aid in the design and evaluation of these vehicles. A synthetic wind generation system is used to create repeatable and controllable gust excitations, and a motion capture system is used for precise measurement of vehicle response. Performance metrics associated with the accuracy of position tracking and angular rate excursions are proposed to quantify vehicle capabilities at different excitation levels for design assessment and cross-platform comparison. To demonstrate the experimental method, test results are shown to evaluate the capabilities of a micro coaxial helicopter in realistic winds as a function of gust excitation level and vehicle size. For this example system, light wind gusts degrade hover hold accuracy by a factor of 3 compared to a situation with quiescent winds.

Keywords

Rotorcraft, gusts autonomous, control

Date received: 24 January 2011; accepted: 7 February 2012

Introduction

With the increasing availability and functionality of small electronics today, more efforts are being focused on the design, fabrication, and operation of micro rotorcraft on the scale of tens of grams. It is envisioned that these vehicles will operate indoors in relatively small complex spaces and outside near the ground among buildings and other structures. The small size, relative covertness, and high maneuverability of micro rotorcraft make them ideal for a plethora of applications in both the civilian and military sectors.[1,2] However, the aerodynamic velocity field near the ground, around buildings and trees, and inside buildings is notoriously complex with mean winds varying spatially and temporally with features such as shears, vortices, separated and reattached flows, and recirculating eddies.[3–6] Even seemingly benign indoor environments can appear gusty to micro rotorcraft where flows caused by pressure differences, temperature gradients, and air ventilation systems have magnitudes measured as high as 5.0 m/s.[4,5,7] These wind velocity perturbations can be on the same order of magnitude as the maximum flight speed of the vehicle leading to stall, large roll/pitch/yaw angle perturbations, and even loss of control.

Full-scale piloted rotorcraft are required to operate in moderate to serve turbulence during hover and low-speed tasks such as nap-of-the-earth flight and around ship decks.[8] Wind gusts and turbulence velocities experienced by rotorcraft blades differ drastically from velocities experienced at non-rotating fixed points, such as the center of gravity or the rotor hub, due to the periodic motion of blades through the turbulence patch.[9] Studies have shown that at low advance ratios and gust wavelengths, the atmospheric turbulence seen at a rotor blade has significantly higher frequency content than at a non-rotating point on the vehicle, resulting in changes to the rotor dynamics

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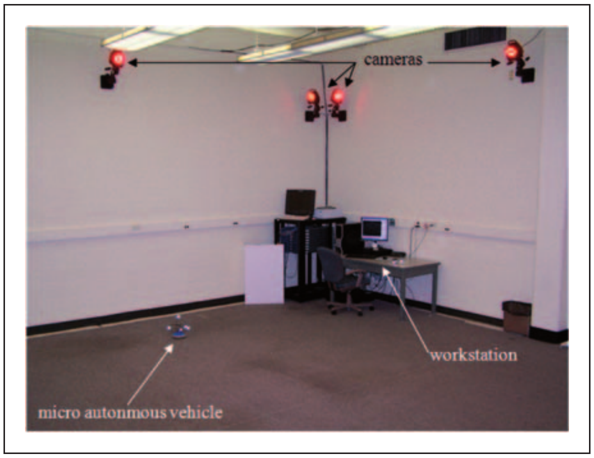

Figure 1. Georgia Tech IFF with VICON motion capture system.

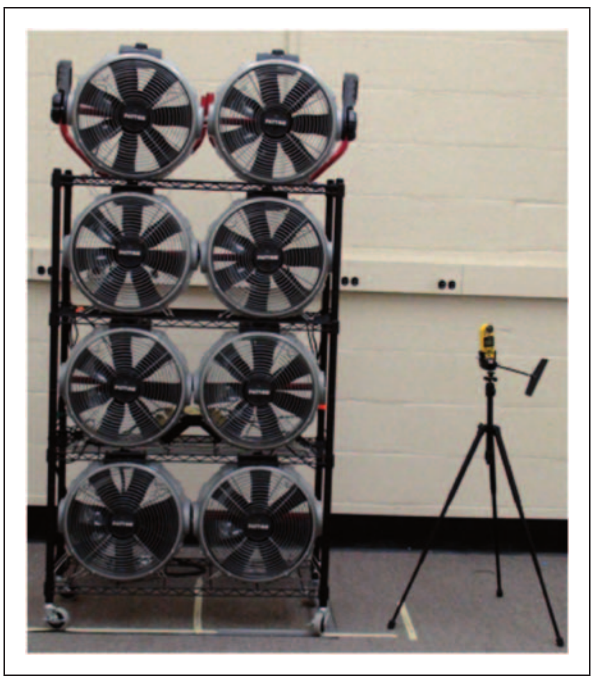

Figure 2. Synthetic gust generation equipment: fan bank and pocket wind meter.

that must be accounted for to accurately model vehicle motion.[9,10] While most of the existing literature of rotorcraft response to gusts has been simulation based, a few basic flight test experiments have been performed to determine control sensitivity and disturbance rejection requirements of rotorcraft, as well as to develop and improve simulation models.[11,12] A study of a tilt-rotor vehicle operating near and on a ship deck demonstrated that active digital flight control technologies have the potential to improve handling qualities and operational effectiveness in complex environments

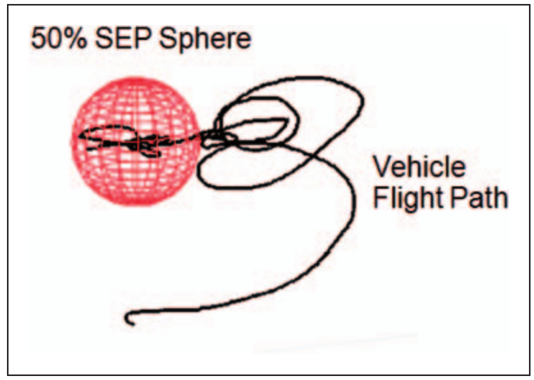

Figure 3. Illustration of SEP for a hover flight test. SEP: spherical error probable.

Figure 4. Micro coaxial helicopter hovering in the IFF.

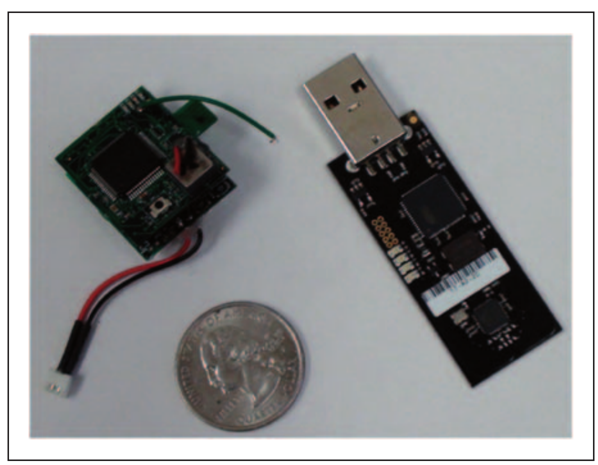

Figure 5. GINA 2.0 mote (left) and base station (right).

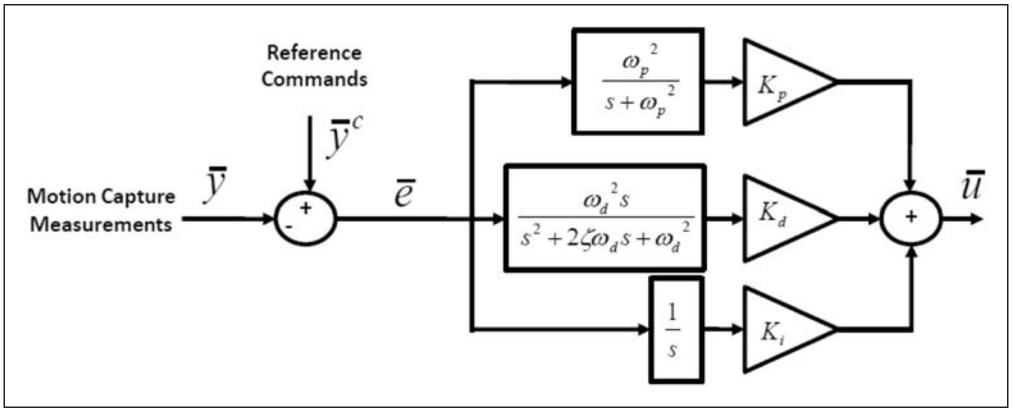

Figure 6. Autonomous control algorithm block diagram.

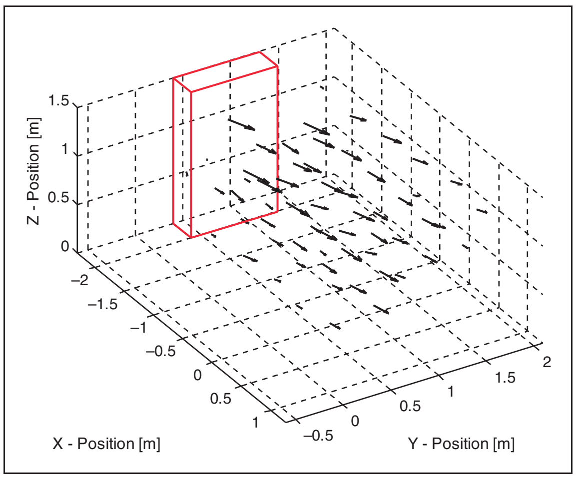

Figure 7. Flow visualization for the hover experiments; mean velocity field with the fan bank outlined.

such as an unsteady turbulent ship wake.[13] Some experimental testing of fixed-wing micro-air vehicles in gust environments has been performed in low-speed wind tunnels. These wind tunnels have been built or modified with active grids and other methods to generate turbulence, shears, and other relevant gust environments.[5,14] Even with a substantial literature base on larger rotorcraft, there is little quantitative information on the response of micro rotorcraft operating in wind gusts. An exception is the work by Rezgui et al.[15] who considered useful design modifications of a coaxial helicopter (200 g, 350 mm rotor diameter) to improve stability and controllability in wind gusts and turbulence. Based on qualitative pilot feedback, changes including moving the center of gravity forward and increasing the size of the vertical fin allowed the vehicle to be manually flown in slow ramping gusts up to 4 m/s in strength.[15]

Given the relatively large lack of quantitative data in the existing literature on micro rotorcraft performance in gusts, this study seeks to start to fill this void by proposing an experimental method to systematically assess the capabilities of these vehicles in a simple and concise manner. In this method, a set of experiments are performed inside a motion capture facility with gust generation capability. Since micro rotorcraft most commonly operate near hover, the proposed experiments are focused on the hover flight regime. A set of metrics are proposed to adequately capture vehicle performance, and each experiment is repeated a sufficient number of times so that statistics can be generated. The experimental method is demonstrated by considering the response of a micro coaxial helicopter operating in a gusty environment. This includes experiments of autonomous hover in increasing wind levels and a study of hover performance for coaxial helicopters of different sizes. The article begins with descriptions of the experimental method including the hardware and analysis metrics. This is followed by accounts of the experiments on coaxial helicopters.

Experimental method

This experimental method is designed to quantitatively characterize the response of a micro rotorcraft platform to relevant wind gusts and turbulence. The following section provides information on the major equipment and processes used to achieve this goal. This includes a gust generation system, the motion capture facility where all experiments were performed, and a description of the proposed performance metrics.

Motion capture system

The Indoor Flight Facility (IFF) at Georgia Tech consists of a 12 camera VICON motion capture system (Figure 1). The infrared cameras use three-dimensional (3-D) optical position analysis to calculate the position of spherical retro-reflective markers to

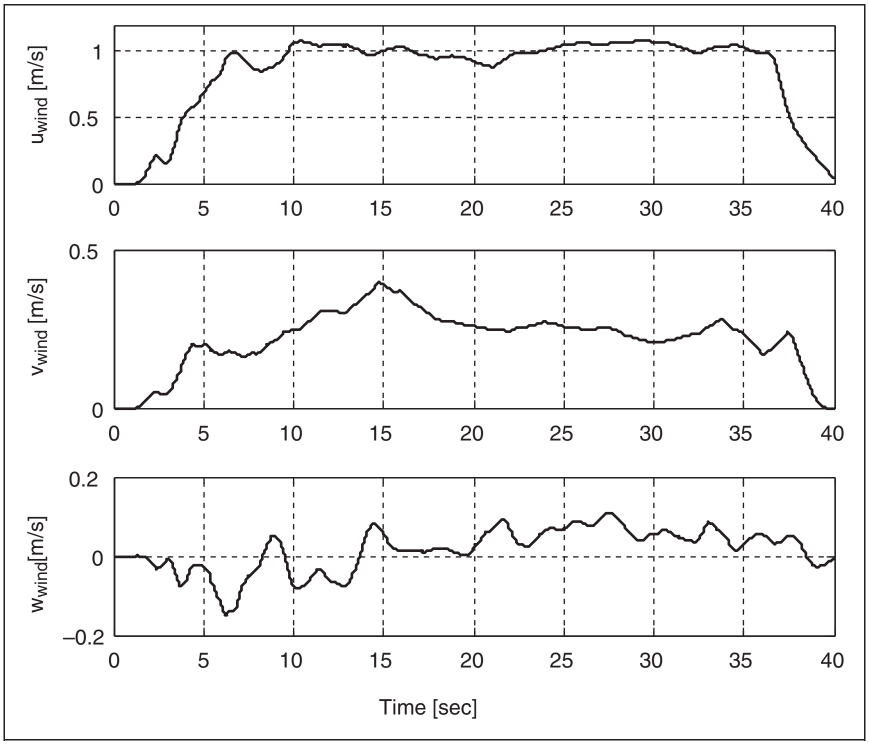

Figure 8. Estimated time histories for the inertial wind vector components at the vehicle for a fan setting of 1.0 m/s.

Table 1. Mean and SD of wind magnitude and direction at the commanded hover position for each wind level.

	Magnitude (m/s)		Direction (°)	
Wind level	Mean	SD	Mean	SD
1	0.0	0.0	N/A	N/A
2	0.6895	0.0388	14.2895	0.8671
3	1.0684	0.0873	7.6053	1.9248
4	1.5500	0.0647	8.4474	5.2848
5	2.0216	0.0750	6.7210	3.2984

within 1 mm accuracy.[16,17] In real time, the marker positions are used to calculate vehicle position and attitude. Using filters, state derivatives can be calculated allowing real-time full-state feedback for the vehicle. This system allows the flexibility and space to construct realistic environments and study micro rotorcraft response in such conditions.

Synthetic gust generation

A synthetic gust generator was constructed (Figure 2) to generate repeatable wind conditions. It is composed of a bank of eight commercial floor fans connected to a single variable transformer which enables the speed of all eight fans to be controlled simultaneously. Pocket wind meters are used to measure wind speed and direction (Figure 2). These sensors use a digital anemometer to measure wind speed and a weather vane combined with a magnetometer to measure wind direction. The wind field is sampled at 2 s intervals and the data are logged internally. In order to characterize the wind field, measurements of wind velocity are taken at a set of discrete points in space using the motion capture system to measure sensor location.

Performance metrics

An important attribute of micro rotorcraft is the ability to precisely hover which enables operation in tight complex urban environments. The spherical error probable (SEP) is defined as the radius of a sphere centered at a commanded hover position that encircles 50% of the trajectory during a gust event (Figure 3). The SEP provides a simple metric to assess position hold capabilities of a rotorcraft platform when excited by disturbances.

Angular vibrations caused by wind disturbances affect attitude hold accuracy, as well as degrade the data quality from onboard sensors. The angular velocity root mean square (AVRMS) is a simple measure of the variation of the magnitude of the angular velocity from the mean value during a flight event

$$\mathrm{AVRMS} = \sqrt{\overline{|\omega|}^2 + \sigma^2_{|\omega|}} \tag{1}$$

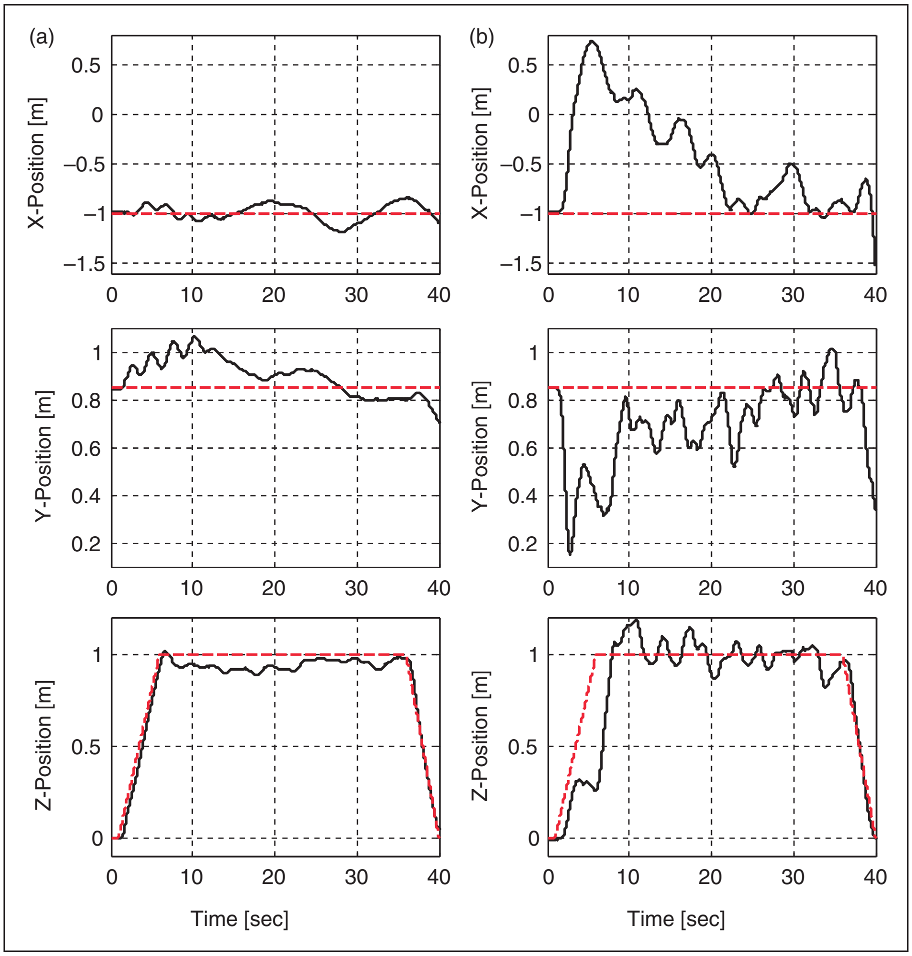

Figure 9. Example time histories of vehicle position in hover. The state measurements are shown as solid lines and the commanded positions are shown as dotted lines in (a) 0.0 m/s wind and (b) 2.0 m/s wind.

where $\overline{|\omega|}$ is the mean angular velocity magnitude and $\sigma_{|\omega|}$ its SD. The AVRMS metric captures attitude response and is useful in understanding the attitude error during flight and the limiting conditions for different sensor suites on a micro rotorcraft platform. The SEP and AVRMS metrics are calculated for each flight event, and the results of multiple flight tests are used to estimate the mean values at each wind level with 95% confidence.

Coaxial helicopter experiments

Employing the experimental method described above, two experiment sets were carried out to capture the hover hold performance of a micro coaxial helicopter as gust levels and platform size were increased. The following section provides information on the experiments performed, the hardware, and results.

Autonomous hover experiment

As noted above, the ability of a micro rotorcraft to hold position in hover can be extremely important in narrow complex urban environments. The nominal aircraft used for this experiment is a micro coaxial helicopter (Figure 4). This vehicle weighs 55 g and has a main rotor diameter of 175 mm with two blades per rotor. The rotorcraft's two counter rotating rotors are driven by electric motors. Thrust is controlled by changing the speed of each rotor simultaneously while yaw control is achieved through changing the speed of each rotor differentially. A swash plate attached to the lower rotor is connected to two servo motors for cyclic pitch control, and the upper rotor is connected to a stabilizer bar which improves lateral and longitudinal stability. The micro coaxial helicopter is powered by a LiPo battery and has an approximate maximum forward flight speed

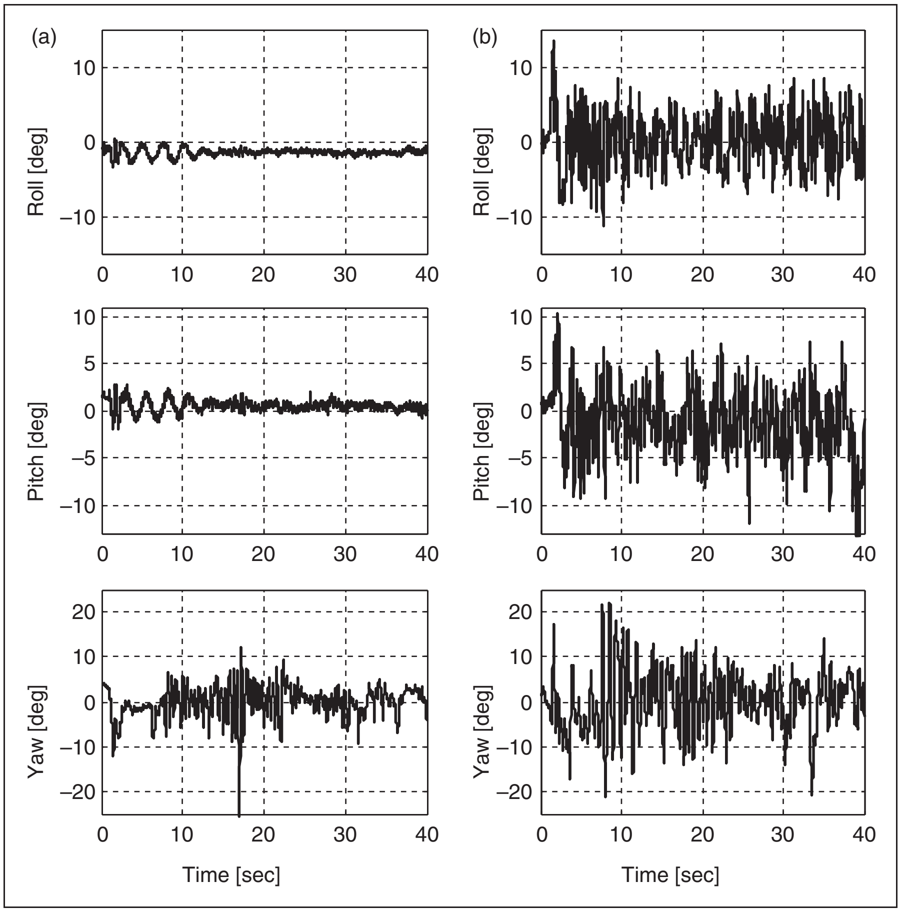

Figure 10. Example time histories of vehicle attitude in hover: (a) 0.0 m/s wind and (b) 2.0 m/s wind.

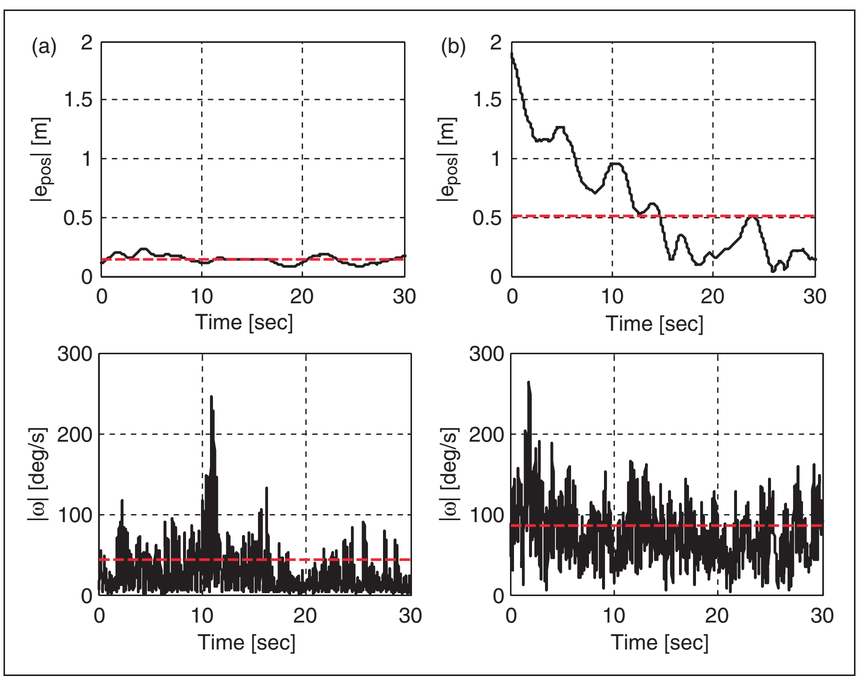

Figure 11. Example time histories of position error and angular velocity magnitudes: (a) position error in 0.0 m/s wind, SEP = 0.142 m; (b) position error in 2.0 m/s wind, SEP = 0.506 m; (c) angular velocity in 0.0 m/s wind, AVRMS = 42.7°/s; and (d) angular velocity in 2.0 m/s wind, AVRMS = 84.5°/s.

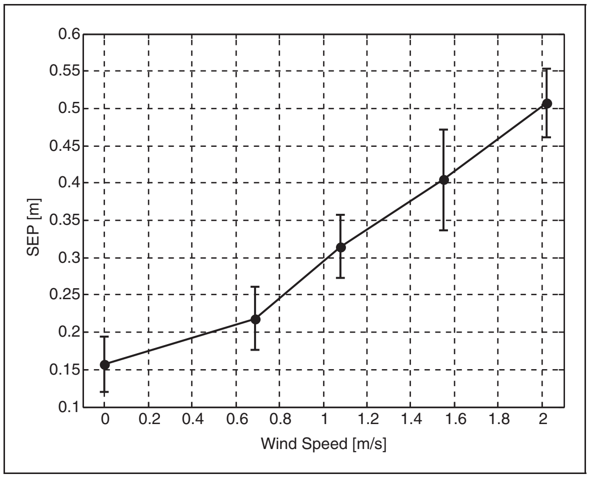

Figure 12. Average SEP for increasing wind levels. SEP: spherical error probable.

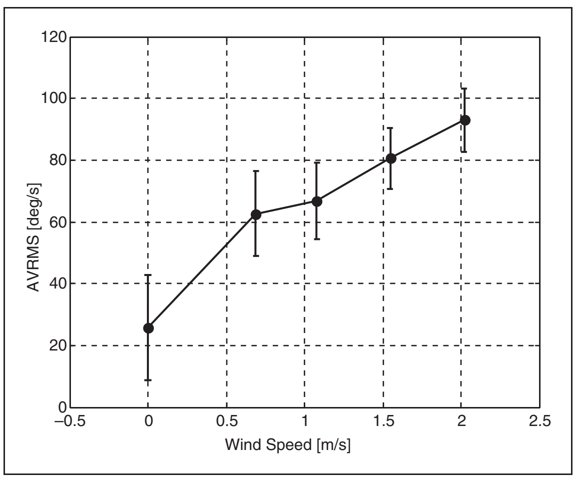

Figure 13. Average AVRMS for increasing wind levels. AVRMS: angular velocity root mean square.

of 4.0 m/s. As seen in Figure 4, the helicopter is outfitted with spherical retro-reflective markers for use in the motion capture system and also had a tail rotor which is not controllable. The micro coaxial helicopter has also been outfitted with a wireless IMU circuit card developed by the University of California, Berkeley (Figure 5).[18] This mote provides wireless communication as well as control of servos and motors. Information is transmitted to and from the vehicle using a USB base station.

A proportional–integral–derivative (PID) controller was chosen as a simple architecture to assess baseline performance. Figure 6 shows a block diagram of the control algorithm used for the autonomous flight experiments. Position and attitude measurements from the motion capture system are processed in real time. Control inputs are then calculated based on the measurements and state commands—position (x, y, z) and heading angle (ψ)—and discrete filters were used to calculate the derivative and integral feedback. In the proposed operational environment for micro rotorcraft—close around buildings and indoors—the wind field is expected to be highly variable both spatially and temporally. Thus, the flight regime of a vehicle has the potential to change rapidly and often. Rotorcraft of this size cannot measure wind fields directly. With this in mind, the controller gains are tuned for robust performance around hover and slow forward flight with no adjustment in flight. It was observed that fine tuning gains for one flight regime resulted in poorer performance in other conditions even in the slowly varying fields used in these experiments.

For autonomous hover experiments, the vehicle took off in little to no wind and then rose into the full flow created by the synthetic gust generation system, where it was commanded to hover for 30.0 s before landing. The flow field was measured at 108 spatial points for 2 min each, and the mean wind magnitude and direction are visualized in Figure 7. The wind magnitude is zero at the ground, increases with altitude, and decreases downstream (x-direction), and the flow was approximately 1.5 m wide (y-direction). The wind vector at the vehicle is estimated through 4-D interpolation, using the gust time history data from the spatial points and the measured vehicle position from flight test data (Figure 8). The wind magnitude was estimated to change from 0 to 1.0 m/s in less than 5.0 s. The wind magnitude and direction were measured at the commanded hover position for all wind levels, and the mean and SDs are presented in Table 1. The SDs were found to be small compared to the mean values. Therefore, the wind gust field at a particular point in space is largely quasi-steady with small fluctuations in time. Strong spatial wind gradients persist at the edges of the gust generator so the helicopter experiences time-dependent gusts caused by its ascension through the gust field. This velocity field simulates a simple version of expected real-world conditions in and around buildings, such as flight around a corner of a building or across an open window or air vent.

Figures 9 and 10 present time histories of vehicle position and attitude for flights in wind levels of 0.0 and 2.0 m/s. These figures illustrate the basic behavior of the vehicle when entering a small gust. At first, the helicopter is pushed downwind (positive x-direction) before the controller compensates and the vehicle returns closer to the commanded hover position. Significant orientation excursions are experienced in 2.0 m/s wind. Figure 11 shows the

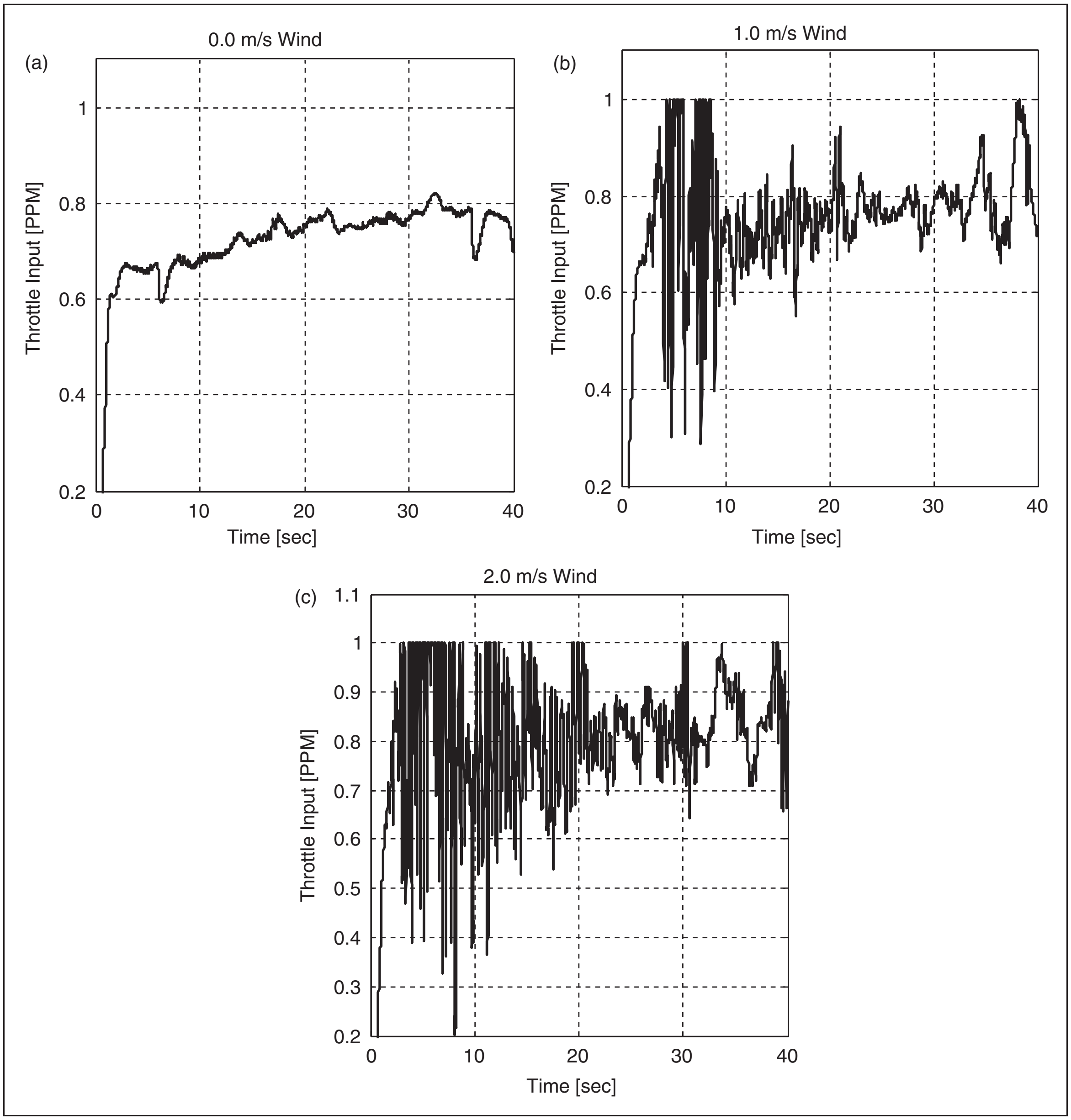

Figure 14. Example time histories of throttle control inputs at different wind levels: (a) 0.0 m/s wind; (b) 1.0 m/s wind; and (c) 2.0 m/s wind.

magnitudes of position error and angular velocity for 0.0 and 2.0 m/s wind levels used to calculate SEP and AVRMS for each flight test. As expected, SEP and AVRMS are significantly higher in 2.0 m/s wind. Figure 12 shows the average SEP values at each wind level tested, and as expected, the ability of the vehicle to maintain hover at a commanded position decreases as the wind level increases—with the SEP at 2 m/s wind at least three times larger than the SEP with zero wind. The AVRMS is three times larger at 2.0 m/s wind than in no wind (Figure 13). These much larger levels of angular disturbance degrade onboard sensor quality.

Significant increases in throttle input magnitude and frequency are required at higher wind levels (Figure 14). This suggests increased power consumption which reduces endurance of the vehicle, even in slowly varying gusts. Also, for 1.0 and 2.0 m/s wind levels, the throttle input saturates at the upper limit. This is shown in Figure 15 where the actual saturated control input is compared to the desired control input computed by the autopilot. For a 2.0 m/s wind level, the throttle input calculated by the autopilot is almost twice the limit. The roll, pitch, and yaw control inputs show similar increases but do not saturate at any wind level.

Vehicle size experimental study

The ability to accurately predict the performance and response of new micro rotorcraft designs can be improved by understanding how these qualities trend with vehicle size. To this end, four commercial coaxial helicopters were manually hovered in increasing wind levels. The helicopters were purchased from the same company and are similar in design and construction (Figure 16). The total weight and rotor diameter for each helicopter is shown in Figure 17. To compare the control responsiveness of the helicopters, a characteristic response time was calculated for each helicopter's four control channels. Using the motion capture system to record vehicle response, step inputs in control are used to fit a first-order transfer function[19] (Figure 18). The characteristic response time is calculated as the time constant of the transfer function, and the resulting response times are presented in Table 2. For each flight test, the same hover experiment was used as described above, and the average SEP and AVRMS values were calculated from all flight tests and then non-dimensionalized by the helicopter rotor diameter for comparison. The wind speed is also non-dimensionalized by the helicopter's rotor inflow velocity in hover.

$$\nu_i = \sqrt{\frac{T}{2\rho A}} \tag{2}$$

where T is the helicopter's thrust in hover and A the rotor disc area.

Flight tests were performed at four increasing wind levels for each helicopter. The maximum wind speed tested for each helicopter was based on the pilot's opinion on conditions for safe operation. Larger helicopters are able to fly safely in winds close to 2.5 m/s while the smaller helicopters could only operate in winds of 2.0 m/s (Table 3). While the micro coaxial helicopter (175 mm rotor diameter) is greatly affected by the 2.0 m/s gusts, resulting in SEP that is 2.5 times larger than in zero wind, the wind had little effect on the largest coaxial helicopter (457 mm rotor diameter) (Figure 19). AVRMS shows similar trends with the wind levels of 2.5 m/s having little affect on angular velocity (Figure 20). Workload to fly the micro helicopter is significantly greater than that of the larger helicopters. A comparison of the characteristic response times for each helicopter

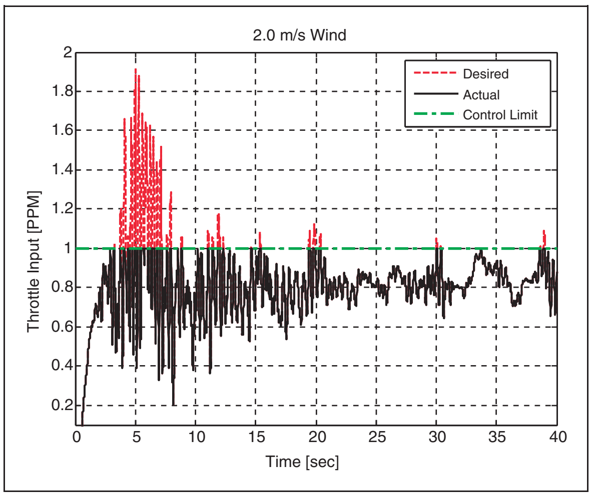

Figure 15. Example time history of desired and actual throttle input in 2.0 m/s wind.

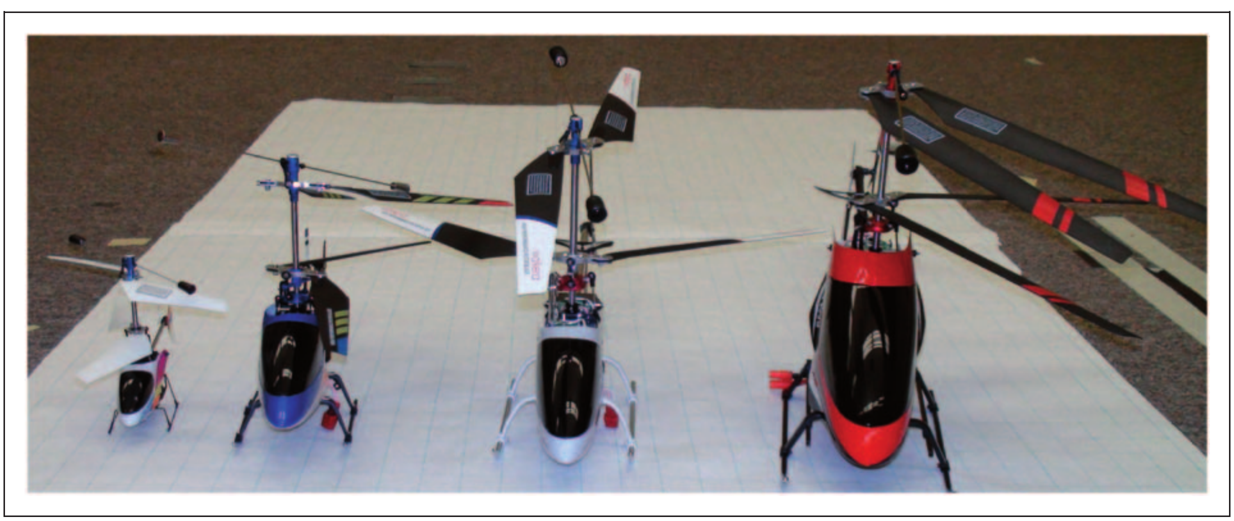

Figure 16. Coaxial helicopters used in the sizing study. Left to right: 5G6 (175 mm rotor diameter, 55 g total weight), 5#10 (348 mm, 195 g), 53-8 (450 mm, 365 g), and Lama 400 (497 mm, 580 g).

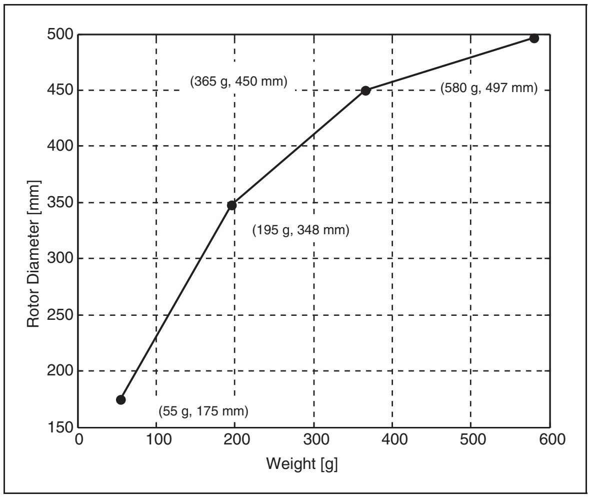

Figure 17. Rotor diameter with respect to weight for each coaxial helicopter used in the sizing study.

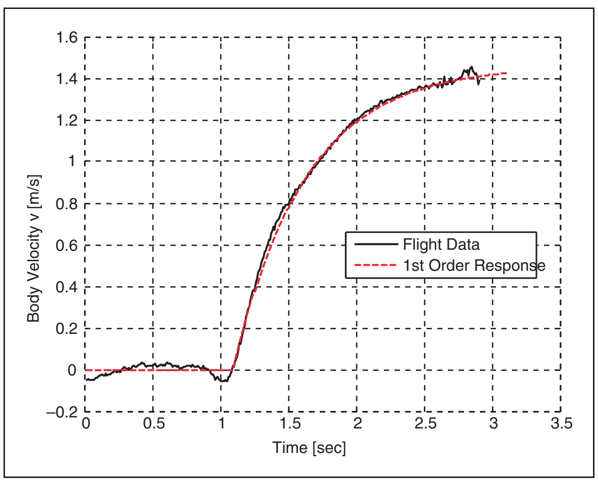

Figure 18. Example characteristic time response flight test for *y* control channel. Both measured flight data (solid line) and the fitted first-order transfer function response (dotted line) are shown. The characteristic time response was found to be 0.54 s.

Table 2. Characteristic response times of each coaxial helicopter used in the sizing study.

Helicopter	Rotor diameter (mm)	Weight (g)	Control channel characteristic response time (s)			
			x	*y*	*z*	Yaw
5G6	175	55	0.37	0.45	1.20	0.58
5#10	348	196	0.43	0.42	0.98	0.13
53-8	450	365	0.79	0.48	1.12	0.23
Lama 400	497	580	1.07	1.60	1.14	0.25

Table 3. Maximum wind speed tested for each coaxial helicopter used in the sizing study.

Helicopter	Rotor diameter (mm)	Weight (g)	Maximum wind speed (m/s)
5G6	175	55	2.0
5#10	348	196	1.9
53-8	450	365	2.5
Lama 400	497	580	2.6

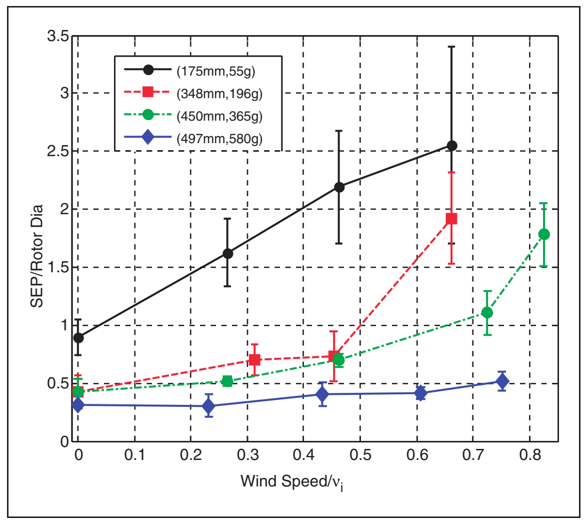

Figure 19. Non-dimensionalized average SEP for each coaxial helicopter.
SEP: spherical error probable.

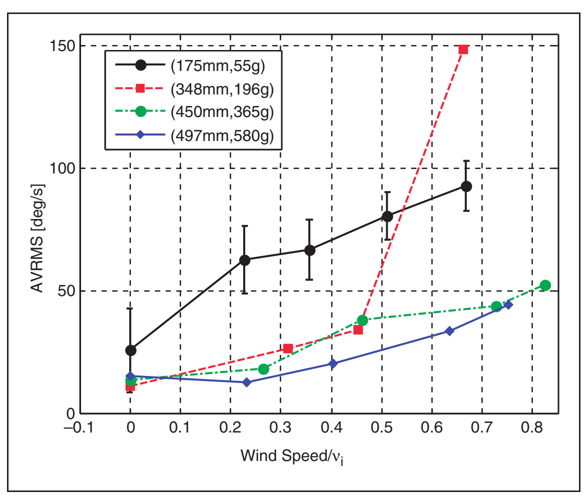

Figure 20. Average AVRMS for each coaxial helicopter.
AVRMS: angular velocity root mean square.

(Table 2) shows very little correlation between control characteristic response time and hover performance in gusts. This indicates that the ability of larger helicopters to hold position in wind gusts and turbulence is more likely related to maximum thrust available and vehicle inertia rather than control response time.

Conclusions

An experimental method has been created and exercised to quantitatively assess the performance of micro rotorcraft in realistic wind velocity fields. A synthetic gust generation system is used to create realistic winds, and digital anemometers are employed to measure wind magnitude and direction at discrete spatial points. A motion capture system measures vehicle position and attitude during flight tests after which measures of position accuracy and attitude error are calculated to quantify vehicle performance. This provides a straightforward methodology to assess the capability of micro rotorcraft to fly in realistic wind gust fields. Synthetic gust generation provides repeatability, and the position and attitude metrics provide simple comparisons between design iterations of the same vehicle as well as between different vehicle platforms and sizes. Using this methodology, micro coaxial helicopters were flight tested as a function of gust level and vehicle size. As wind levels increase, and vehicle size decreases, vehicle performance degrades substantially. The experimental methodology demonstrates the sensitivity of micro rotorcraft to small wind disturbances and provides a means to quantify performance improvements.

Funding

This work was funded by the US Army Research Laboratory as part of the Micro Autonomous Systems Technology (MAST) program.

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