Wind Gust Alerting for Supervisory Control of a Micro Aerial Vehicle

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Abstract—In this paper we present a method for estimating wind gusts and a corresponding display for increasing the situational awareness of a minimally trained operator controlling a Micro Aerial Vehicle (MAV). Our method utilizes statistical correlations between MAV controller output and prior wind conditions to predict the presence of a gust in the current flight environment. The findings show that the effect of wind gusts on the MAV are significantly correlated to the rate of increase and duration of a gust rather than the magnitude of the gust. The primary benefit of this method is the simplicity of identifying wind gusts without additional sensors and without performing additional maneuvers. This technique enables existing vehicles to incorporate wind conditions into their operator displays without vehicle modification and without dedicating computation resources to flight modeling. In contrast to traditional wind indicators, our display presents wind information in the form of a warning metric rather than a wind velocity vector.

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[1] 978-1-4244-7351-9/11/ $26.00 ©2011 IEEE.
[2] IEEEAC Paper #1418, Version 1, Updated 20/10/2010.

1. INTRODUCTION

As Micro Aerial Vehicle (MAV) systems become cheaper and more readily accessible, the range of situations in which they have been successfully used continues to expand. Autonomous or partially autonomous air vehicles capable of assisting humans in exploring and mapping unknown environments can significantly improve the execution of Intelligence, Surveillance, & Reconnaissance (ISR) tasks [1]. In order for a MAV to operate effectively in unknown outdoor environments, the vehicle must be able to deal with varying weather conditions such as wind gusts. Most MAVs can self-stabilize and hold a commanded position by using control loops that process Global Positioning System (GPS) and Inertial Measurement Unit (IMU) data. Despite this automation, high wind speeds can cause loss of control, posing a danger to the vehicle as well as to persons or objects in the vicinity. In particular, sudden wind gusts can affect a vehicle faster than its control system can mitigate the error.

In response to this potential problem, we set out to develop an alerting system such that a novice MAV user (i.e., an operator who is not a trained pilot) would be notified when wind gusts could cause a loss of control. The definition of a wind gust, according to National Oceanic and Atmospheric Administration (NOAA), is "a sudden, brief increase in speed of the wind [where] the peak wind speed reaches at least 16 knots and the variation in wind speed between the peaks and lulls is at least 9 knots" [2]. Given that MAVs typically weigh on the order of 1 kilogram, they are susceptible to much smaller wind increases as compared to typical Unmanned Aerial Vehicles (UAVs). As a result, our gust detector needs to be able to

Table 1. Subset of the Beaufort Scale.

Level	**Wind speed** (knots)	Wind speed (m/s)	Descriptor
0	<1	<0.3	Calm
1	1-3	0.3-1.59	Light Air
2	4-6	1.6-3.4	Light Breeze
3	7-10	3.4-5.4	Gentle Breeze
4	11-16	5.5-7.9	Moderate Breeze

identify gusts with smaller magnitudes.

To delineate categories of wind strength, we use the Beaufort scale [3], which categorizes wind strength on a scale from 0-12, as partially represented in Table 1. We are primarily concerned with Levels 0-4, as MAVs are not typically capable of steady operation in higher wind gust conditions.

Several techniques have been used for wind detection and estimation in MAV systems. One common wind estimation strategy relies on optical flow techniques, where perceived motion in a video image is used to determine the sideslip angle of the aircraft. The sideslip angle is then used in conjunction with the vehicle's heading to calculate the current wind speed and direction [4]. Another technique involves estimating the wind speed and direction by combining groundspeed measurements from GPS and IMU data, airspeed measurements from a pitot-static tube system, and relative wind direction measurements from wind vanes [5]. However, the payload capacity of our MAV is very limited, so reducing the need for extra sensors allows for more useful, mission-specific payloads or allows for additional flight time.

An important aspect of our approach to gust detection relies on the concept that we do not need to fully characterize the speed or direction of the wind. Although the operator must have some knowledge of the wind conditions, the device will autocorrect for position deviations caused by wind, so the operator only needs to know whether the conditions are within the limits set by the autocorrection capabilities of the vehicle. This simplification of information aligns with our intention for this device to be operable by persons without extensive pilot training. Previous work [1] demonstrated a person's ability to pilot a MAV in an indoor environment and complete an ISR task using a mobile device after only 3 minutes of training. In order to extend this work so that novice operators can control the MAV in unknown, outdoor environments, we need to increase the operators situational awareness about the local wind conditions without increasing cognitive workload. Consequently we are only attempting to convey to the operator whether the wind conditions are relevant to the operator interaction with the device. Two relevant categories of gusting behavior were identified by our experiences operating our MAV system: 1) The wind could be detrimental to the operation of the vehicle, and 2) Wind gusts could stress the vehicle beyond the compensation limits of the off-the-shelf autopilot and pose a threat to the vehicle's continued operation.

The paper details the statistical methods used to determine the correlation between wind gusts and the position of the MAV, explains the logic necessary to determine if the current wind condition presents a danger, and describes the interface through which this information will be presented to the operator.

2. METHOD

The experiment was completed in two parts: data collection and statistical analysis. The data collection took place over the course of 2 weeks in varying wind conditions. All data were collected on an open athletic field without tall buildings in the immediate vicinity. The MAV continuously logged new position data for the commanded waypoint and current position every 2 seconds throughout the duration of the flight. For each flight, the MAV was sent a single waypoint command. This allowed us to capture steady-state position data rather than the transient behavior of moving between waypoints.

For our test platform, we used an Ascending Technologies Hummingbird, a commercially available quadrotor helicopter. The Hummingbird vehicle is approximately half a meter in diameter with a carbon fiber, balsa, and magnesium frame. The onboard hardware consists of a GPS system, an IMU sensors, a gyroscope, an altimeter, a magnetometer, a Radio Control (RC) receiver, an XBee radio unit, and two onboard microprocessors for the flight control software included with the device. The control software attempts to maintain level flight by resisting any uncommanded changes in attitude, and will attempt to maintain position when commanded to fly to a waypoint. The only source of localization data in this experiment is the reported GPS coordinates from the Hummingbird. This system is powered by a 3-cell Lithium Polymer battery and can attain flight times of up to 15 minutes with a payload of up to 200g. The wind speed measurements were obtained using a ground-based Kestrel 4000 Weather Meter. The Kestrel logged the current wind speed every 2 seconds. The Kestrel could only record the magnitude of the wind, not the direction, and was positioned to be in the direction of the prevailing wind for each flight.

For the data analysis, we inferred the wind conditions through a statistical analysis of the difference between the measured positions of the MAV and the commanded waypoints. Since the MAV does not have any anemometers or other instruments to directly measure the speed or direction of the wind, wind conditions must be estimated based on the logged position data. Using the fused GPS and IMU data, best estimates of latitude, longitude, and height for the current location of the MAV were recorded. These values, in conjunction with the recorded wind speed measurements, were used to calculate six parameters, defined below.

1) Gust Magnitude: the difference between the lull wind speed and the peak wind speed
2) Gust Time: The time it takes the wind speed to change from lull to peak
3) Gust Rate of Increase: (1) divided by (2).
4) Step distance: The distance traveled on one 2-second interval during the gust
5) Path distance: The summation of the distances traveled during the gust on each 2 second interval
6) Distance to origin: The maximum difference between the distances from the origin

3. RESULTS

The data used to determine a correlation between wind speed and the error distance between the measured position of the MAV and the waypoint command were taken from three flight tests on different days with variable wind conditions. The MAV's location as recorded over the course of each flight with respect to the commanded waypoint (in blue) is shown in Figure 1.

Figure 1 presents the path of the MAV for each of the three flights. All three flights show an offset between where the vehicle should have been hovering and where it is actually hovering. This offset is due to a combination of GPS error, which can be as high as 5 meters, the accuracy with which the control algorithms maintain position, and drift due to wind.

Figures 2-4 display the wind speed, the error distance, and the step distance for each of the three flights. The error distance is defined as the linear distance between the commanded waypoint and the MAV's actual position.

Using the data presented in the three graphs, a statistical analysis was performed to determine correlations between wind speed, the error distance, and the step distance. The analysis was applied to the regions highlighted in a dashed box in the graphs, which correspond to regions of low gust (where the wind increase was between 0.9 m/s and 1.59 m/s in keeping with Table 1), and to the regions highlighted in black, which corresponds to medium gust (where the wind increase was between 1.6 m/s and 3.4 m/s). We defined these regions based on the levels designated by the Beaufort scale which correspond to light air and light breeze respectively.

For each of the two gust levels, the statistical analysis was performed by calculating the Pearson correlation and the significance level between the wind and position parameters defined earlier, as indicated in Tables 2 and 3. Table 2 displays the results of the statistical analysis for the low gust level with 24 observations each. Table 3 displays the results for the medium gust level with 12 observations each.

Table 2. Statistical analysis for wind differences between 0.9 m/s and 1.59 m/s. Shaded cells indicate significant values where $p \leq .055$.

		Gust Magnitude	Gust Time (s)	Gust Rate of Increase (m/s^2)
Step Distance	Pearson Corr.	0.397	0.412	-0.154
	Sig. Level	0.055	0.045	0.473
Path Distance	Pearson Corr.	0.37	0.683	-0.483
	Sig. Level	0.075	0.000	0.017
Distance to Origin	Pearson Corr.	0.13	0.632	-0.611
	Sig. Level	0.545	0.001	0.002

Table 3. Statistical analysis for wind differences between 1.6 m/s and 3.4 m/s. Shaded cells indicate significant values where $p \leq .055$.

		Gust Magnitude	Gust Time (s)	Gust Rate of Increase (m/s^2)
Step Distance	Pearson Corr.	-0.572	0.566	-0.773
	Sig. Level	0.052	0.055	0.003
Path Distance	Pearson Corr.	-0.339	0.724	-0.69
	Sig. Level	0.281	0.008	0.013
Distance to Origin	Pearson Corr.	-0.111	0.273	-0.303
	Sig. Level	0.731	0.391	0.339

4. DISCUSSION

There are several statistically significant correlations present in both levels of gusting conditions that inform our understanding of gust dynamics and the quadrotor's behavior. First, we can see that the maximum distance traveled along the path of the vehicle during a gust is positively correlated with the total gust time for both weak and moderate gusts ($p<.000$ and $p<.008$, respectively). This confirms our expectations that longer gusts increase the displacement of the quadrotor more than shorter gusts. We also note that the correlation between the path distance metric and the rate of increase of the gust is negative for both gust categories ($p<.017$ and $p<.013$, respectively), which shows that weaker, longer gusts have a bigger effect on the displacement of the quadrotor than stronger, shorter gusts. This result makes sense given what we know about the attitude stabilization behavior of the vehicle. It appears that rapid gusts of wind induce more roll and pitch in the vehicle than more slowly building gusts. Given that the relative sensitivity of the on-board gyroscopes is much greater than the accuracy of the GPS and IMU fused localization data, it appears that a sudden shift in angular position is counteracted by the attitude stabilization control loop more quickly than a slowly drifting motion is counteracted by the position control loop.

It is important to note the inherent noise and uncertainty in the system. As shown in Figure 1, there is an average offset of 1 to 2 meters from the commanded waypoint on any given trial. The cause of this is not fully understood, but can be partially explained by the limited accuracy of GPS, which is only guaranteed to within about 5 meters. Figures 2-4 also show that during the entire holding pattern the quadrotor was moving 1 meter per second on average, a behavior that is observed

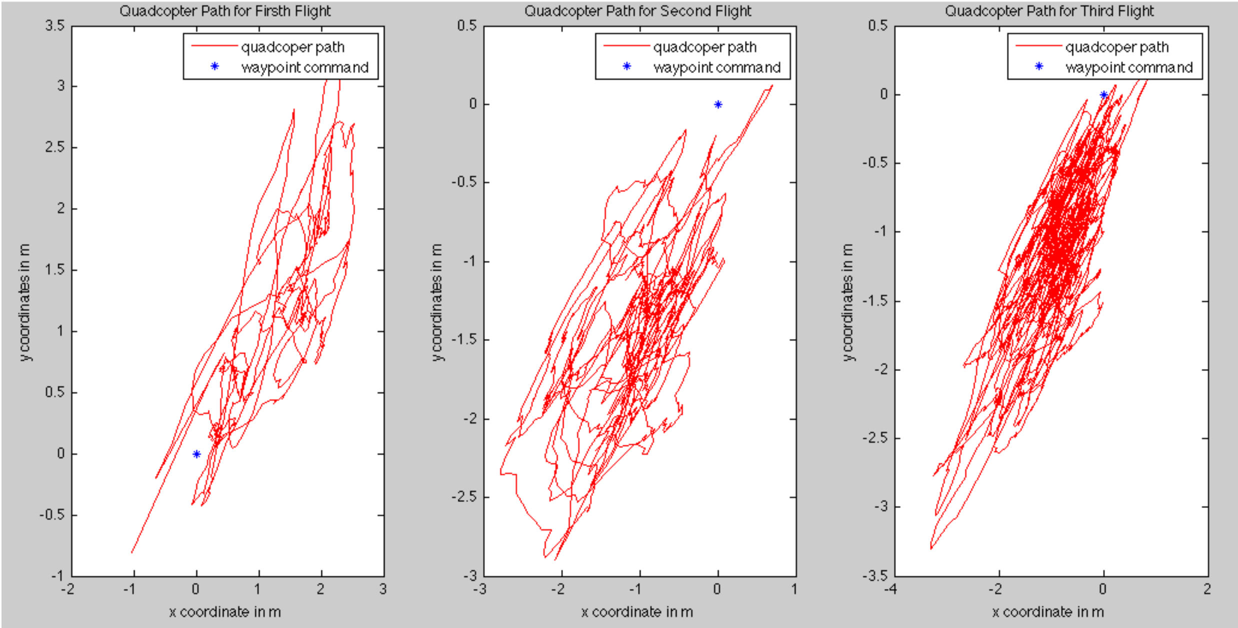

Figure 1. Path of the MAV during each flight

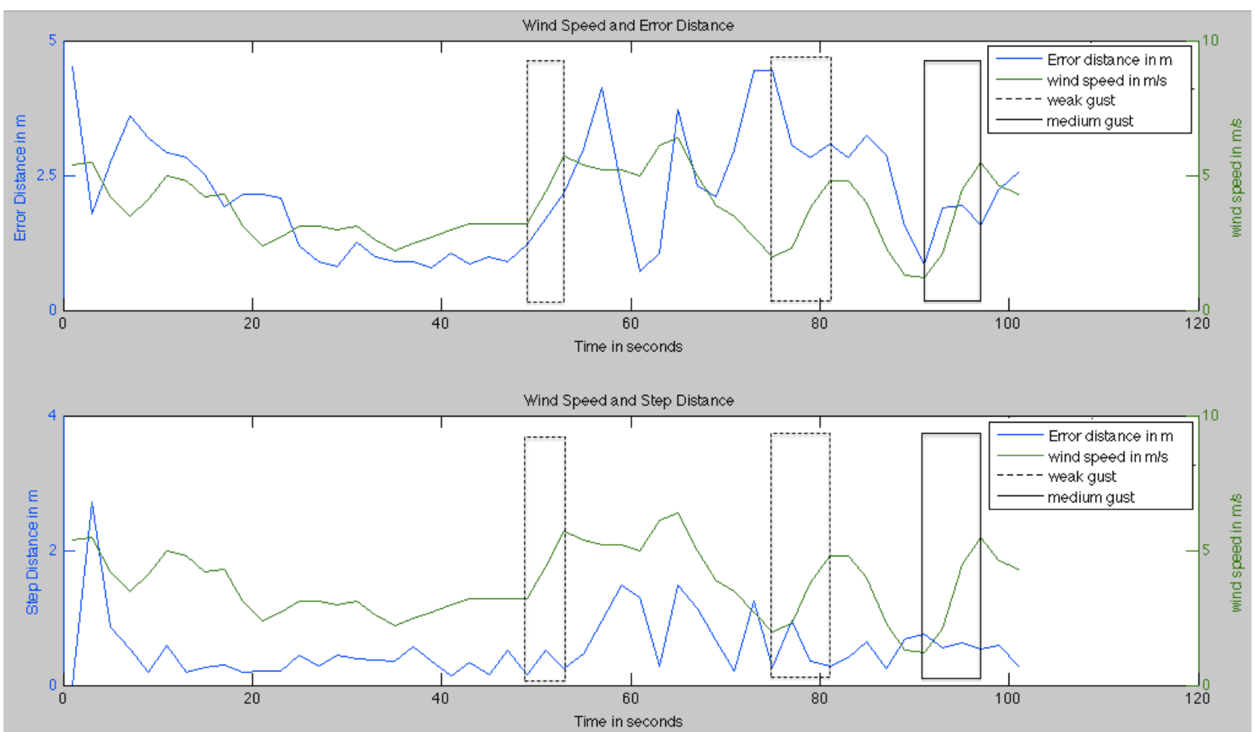

Figure 2. Wind speed, error distance and step distance versus time for the first flight

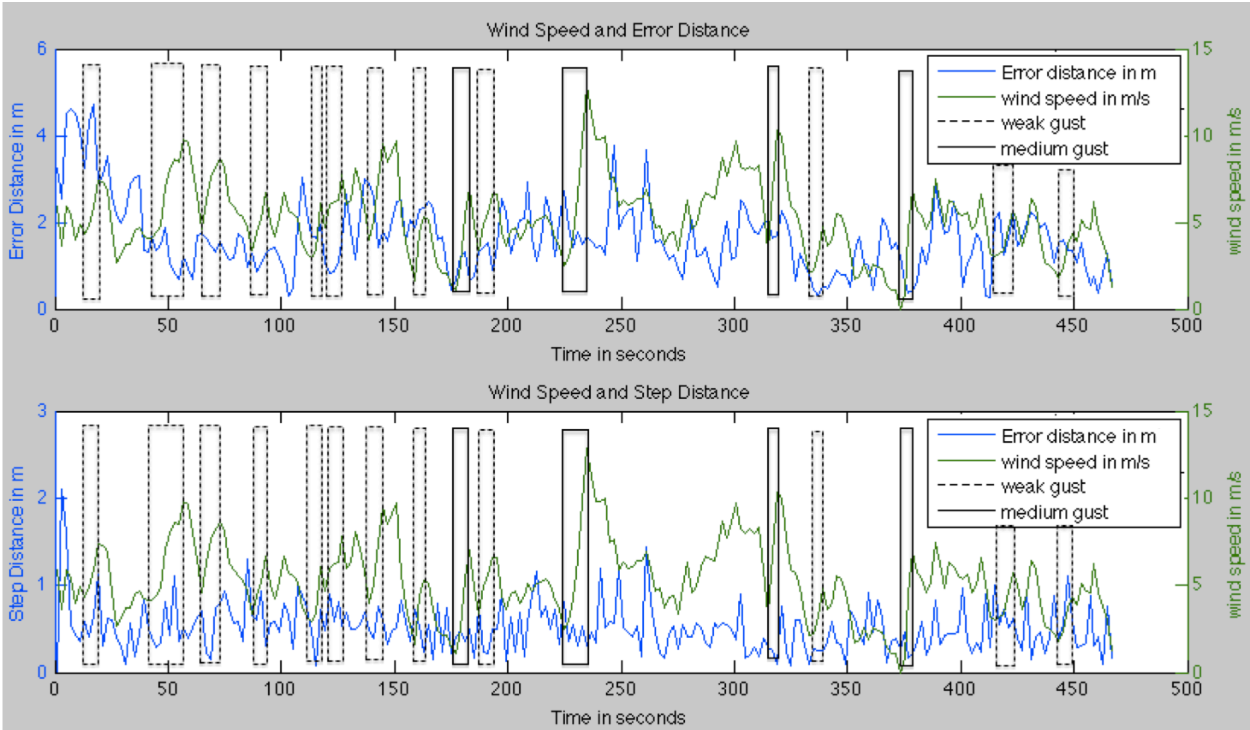

Figure 3. Wind speed, error distance and step distance versus time for the second flight

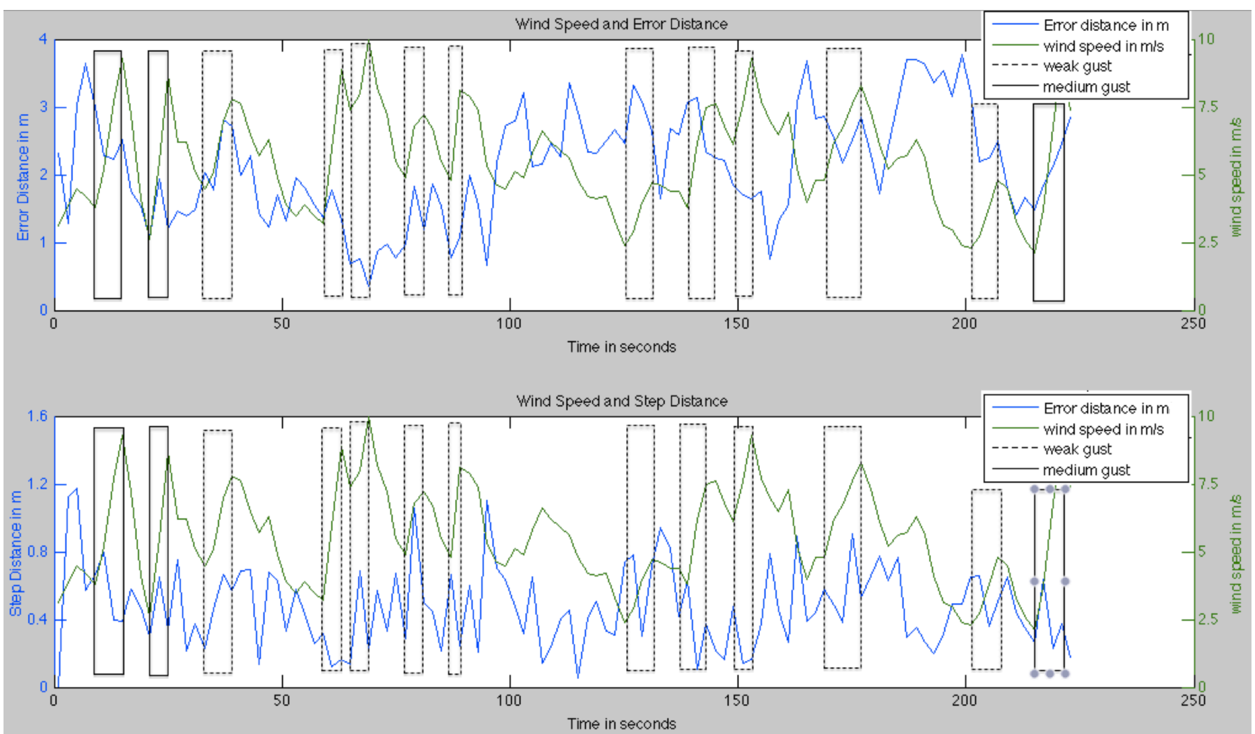

Figure 4. Wind speed, error distance and step distance versus time for the third flight
GPS

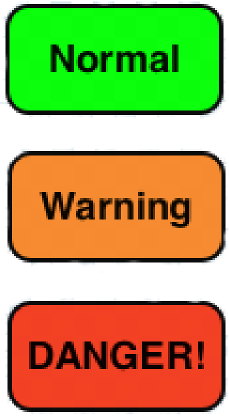

Figure 5. Alert icons for each wind condition.

Figure 6. Indicator as presented to the operator on the iPhone display.

even in situations with virtually no wind.

Based on the limited test flights and the lack of conformance of local weather to experimental plans, all three flights took place during calm conditions and at no point were the wind conditions above the limits of the vehicle. Thus future work is needed to collect more data at higher wind gust levels to better characterize the quadrotors response to larger wind gusts and determine when the operator needs to receive a recommendation to land.

5. Design

To present results of our proposed real-time onboard wind analysis to an operator, we created a three-level indicator to display the state of wind conditions. The indicator used to alert the operators of unstable flying conditions has three color-coded levels: Normal (green), Warning (orange), and Danger (red). This indicator is a simple colored icon in the corner of the screen of our mobile interface on an iPhone with short text displayed inside the icon, as shown in Figure 5.

Normal indicates that there is little to no wind that will compromise the stability of the MAV's flight and is hidden by default. Warning, the next level, is a notice to the operator that there is significant wind that could affect the flight of the MAV. The highest level, Danger, indicates that the operator should land the MAV immediately as the wind speeds could cause the MAV to fly with undesirable behavior that could result in a crash. The indicator is located on the iPhone display as shown in Figure 6. Because the MAV can compensate for steady wind, a wind gauge that represented the wind speed and direction was unnecessary since the operator only needs to know when the wind poses a relevant danger. Thus, the simple, three-color indicator is sufficient to alert the operator to whether or not the MAV is capable of stable flight in the current conditions. We are currently tuning these thresholds based on the previously discussed data and future data that will be gathered.

6. Conclusions

From this study we have shown that the position stability of a MAV with respect to wind gusts can be analyzed through different distance measures, and is strongly influenced by the length of wind gusts and the rate of increase, not necessarily by the magnitude of the gust. In addition, weaker and longer gusts have a greater effect on the displacement of the MAV than shorter, stronger gusts. We have shown it is possible to formulate a detection algorithm, which uses these observations about gust effects to predict the danger posed to MAV systems by current wind conditions, but more data is needed for further validation.

Acknowledgments

This research was sponsored by Boeing Research and Technology.

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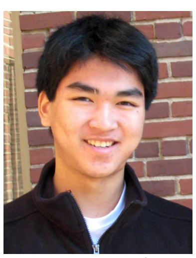
BIOGRAPHY

Manal Habib is a senior at MIT, majoring in Aeronautics and Astronautics. As an undergraduate researcher at the Humans and Automation Lab, Manal works on implementing a LIDAR into a Micro Aerial Vehicle (MAV) to provide a map of the environment, ensuring that the MAV can avoid obstacles. Outside of classes, Manal likes to participate in karate, taekwando, running, swimming, and skiing. In the future, Manal plans to further pursue her interest in both becoming a skydiver and a private pilot. Already a world traveler, she is always ready for a new global adventure. Manal plans to continue her studies in aeronautics and astronautics at the graduate level and would like, someday, to be an astronaut.

Paul Quimby is a Bachelor's degree candidate in the MIT Department of Electrical Engineering and Computer Science. His research with HAL focuses on developing the infrastructure for Human-Computer Interaction experiments involving Micro Aerial Vehicles. Paul also pursues studies in philosophy, while enjoying vocal performance and technical theater as an officer of the MIT Gilbert and Sullivan Players.



Stephen Chang is a Bachelor's degree candidate in MIT's Department of Electrical Engineering and Computer Science. At HAL, he works on visualization of unexplored environments through unmanned micro aerial vehicle control and iPhone development. Outside of classes, Stephen enjoys playing viola in MIT's Emerson Music program, Chamber Music Society, and just hanging out with friends.

Kimberly Jackson graduated from MIT in June 2010 with a Bachelor's degree in Aerospace Engineering and is now a Master's student in the Humans and Automation Lab. Her current research involves operator interaction with Micro Aerial Vehicles in unknown environments and intuitive visualization of LIDAR data.

Mary (Missy) Cummings received her B.S. in Mathematics from the United States Naval Academy in 1988, her M.S. in Space Systems Engineering from the Naval Postgraduate School in 1994, and her Ph.D. in Systems Engineering from the University of Virginia in 2003. A naval officer and military pilot from 1988-1999, she was one of the Navy's first female fighter pilots. She is currently an Associate Professor in the Aeronautics & Astronautics Department at the Massachusetts Institute of Technology. Her previous teaching experience includes instructing for the U.S. Navy at Pennsylvania State University and as an assistant professor for the Virginia Tech Engineering Fundamentals Division. Her research interests include human interaction with autonomous vehicle systems, modeling human interaction with complex systems, decision support design for time-pressured, uncertain systems, and the ethical and social impact of technology.