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Toward Developing MTEs for Multirotor sUAS in Controlled Wind Conditions

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Unmanned aircraft systems are quickly becoming a ubiquitous presence in military and civilian life. Developers are demanding they be allowed in the National Airspace System. This includes myriad small unmanned aircraft systems that seek to use the uncontrolled airspace at altitudes below 500 ft. Methods to verify, validate, and certify these aircraft for safe introduction into the airspace, especially for beyond line of sight operations, as well as the communication infrastructure to support them are slow to develop for a number of reasons. One such is that little to no experimental data of these aircraft performing well-defined tasks with well-defined requirements is available with which to support the development of these methods and processes. To this end, a study was conducted to support the effort to develop, test, and validate tasks for small unmanned aircraft systems in off-nominal conditions. This study focused on multirotor aircraft free flying four defined tasks—precision hover, lateral sidestep, vertical reposition, and landing—in controlled wind conditions generated in the NASA Langley Research Center 14x22-ft subsonic wind tunnel. Two pilots flew two multirotor aircraft through a series of tasks at constant windspeeds ranging from 0 mph to 25 mph. Performance assessments signaled that the pilots could fly the tasks and meet most performance requirements. Increased windspeed resulted in performance degradation as expected. Pilot feedback suggested that the course layout can be improved to facilitate longitudinal visual cueing. Results indicated that the foundation of these tasks and the process by which they were tested in off-nominal conditions is sound.

I. Nomenclature

H	=	Hover
L	=	Landing
LaRC	=	Langley Research Center
LS	=	Lateral Sidestep
MTE	=	Mission Task Element
NASA	=	National Aeronautics and Space Administration
STI	=	Systems Technology, Inc.
sUAS	=	small Unmanned Aircraft Systems
VR	=	Vertical Reposition

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II. Introduction

The presence of small unmanned aircraft systems (sUAS) is quickly becoming ubiquitous in both military and civilian life. In particular, a number of civilian applications of sUAS in low-altitude airspace are being developed, including cargo delivery, infrastructure monitoring, precision agriculture, search and rescue, etc.[1,2] As these programs progress and look toward integrating into this airspace, it is necessary to consider the future interactions with current users of that airspace (e.g., general aviation aircraft, helicopters, gliders, balloons, parachutists) and how to uphold the current level of safety of these operations.

Current users of this airspace require line of sight and consistent communication between themselves to avoid adverse interactions and ensure the safety of everyone. UAS operations that are autonomous and/or beyond line of sight must integrate into this communication flow; however, there is currently no automation infrastructure in place to facilitate UAS operations and communication in uncontrolled airspace. To fill this void, NASA has instituted the NASA Unmanned Aircraft System (UAS) Traffic Management (UTM) Project.[3]

> "The UTM system will enable safe and efficient low-altitude airspace operations by providing services such as airspace design, corridors, dynamic geo-fencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning, re-routing, separation management, sequencing, spacing, and contingency management. UTM is essential to enable the accelerated development and use of civilian sUAS applications. In its most mature form, the UTM system will be developed using autonomicity characteristics, which will include self-configuration, self-optimization, and self-protection."[1]

An initial step in realizing this system is to better understand the sUAS to be operating within by formally defining mission task elements (MTEs) and their associated requirements for nominal and off-nominal flight. It is through these MTEs that the performance of the sUAS will be formally assessed and thereby performance in off-nominal conditions may be compared. From there, handling qualities[4] and risk may be more thoroughly assessed, and safety assured.

To this end, a study was conducted to support the ongoing effort to develop, test, and validate MTEs for sUAS, specifically multirotor aircraft, in off-nominal conditions. The off-nominal conditions comprised a controlled wind environment generated in the NASA LaRC 14x22-ft subsonic wind tunnel. Two multirotor aircraft were free flown in the wind stream in March 2019—a feat that has never been accomplished with a multirotor aircraft, and the last fixed-wing free flight in this wind tunnel occurred in the 1990s—and exercised through a common set of multirotor MTEs that were first introduced in Ref. 5. This builds upon a similar study conducted in nominal conditions in the NASA LaRC Autonomy Incubator.[6] It is intended that the evaluations described herein will serve to vet the MTEs and the process by which they are developed and tested as well as to document off-nominal system performance of the selected vehicles.

This paper discussing this flight testing in controlled wind conditions is organized as follows. The low speed MTEs developed for multirotor aircraft performance assessment are described in Section III. The setup for testing in controlled wind conditions is outlined in Section IV. The flight test protocol is summarized in Section V. Results and discussion are presented in Section VI followed by the conclusions in Section VII.

III. Mission Task Elements

The current philosophy of STI and NASA LaRC for the testing and certification process of multirotor sUAS is to define the tasks as mission-oriented Mission Task Elements (MTEs).[5] This leverages categorizing segments of the mission into specific tasks. It is intended that the MTEs be specified in detail, including performance requirements. Flight phase categories are defined in terms of the level of *precision* and *aggressiveness* required of the UAS. Four categories of MTEs using these terms for flight phase include:

1. *Non-Precision, Non-Aggressive* – Non-precision tasks that require only a moderate amount of remote pilot or autonomous system control fall in this category.
2. *Non-Precision, Aggressive* – This category includes the large amplitude maneuvering MTEs that emphasize control power over crisp dynamics. Moderate- and large-amplitude maneuvering requirements are of primary interest for these MTEs. This category invokes some of the existing control power criteria as well as other agility criteria.
3. *Precision, Non-Aggressive* – This category includes tasks where considerable precision is required, but without the aggressive control activity. The dynamic response requirements for these tasks are less stringent than for *Precision, Aggressive*, but significantly greater than for *Non-Precision, Non-Aggressive*.

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4. *Precision, Aggressive* – This category includes precision tasks, where an extremely crisp and predictable response to control inputs is required. The results of not achieving the required precision are usually significant in terms of accomplishing the mission or safety of flight.

A. Types of Tasks

For the purposes of the study conducted for this program, a set of four Precision, Non-Aggressive MTEs were developed as a basis upon which to build and refine: 1) Precision Hover, 2) Lateral Sidestep, 3) Vertical Reposition, and 4) Landing. The objectives, task setup, and requirements are loosely inspired by MTEs for fixed-wing aircraft and rotorcraft[7] as well as experience of the STI and LaRC team. Testing and data analysis for this study discussed herein as well as future testing and analysis will likely indicate that refinements need to be made to more appropriately guide the nominal system performance of multirotor sUAS in wind.

B. Precision, Non-Aggressive MTEs

1. Precision Hover MTE

Objectives

- Evaluate ability to transition from translating flight to a stabilized hover over a target hover zone with precision and a reasonable amount of aggressiveness.
- Evaluate ability to maintain precise position, heading, and altitude over the target.

Description

The MTE will start 25 ft aft of the hover board and approximately 15 ft left or right of the hover board center. From this starting point, the vehicle will maneuver at a constant altitude of approximately 5 ft and a speed of approximately 5 kts to the precision hover point that is 25 ft aft of the hover board center. Attain a stabilized hover in the defined target hover zone marked by the hover board. Maintain the stabilized hover at the 25 ft aft location in front of the hover board for the time duration specified in the performance requirements. Repeat as needed.

The center of the hover board will be placed 5 ft above and 25 ft in front of the hover point marker at ground level. The hover board will have distinct boundaries indicating desired and adequate performance requirements.

Desired Performance

- Attain stabilized hover from the lateral sidestep before exiting the desired region of the hover board.
- ≥30 sec of stabilized hover in desired region.
- ±1 ft altitude deviation from hover board center.
- ±1 ft lateral deviation from hover board center.
- ±1 ft longitudinal (fore/aft) deviation from hover point.
- ±5° heading deviation from target or hover board.
- No undesirable motions (bobble, overshoots/undershoots) that impact task performance during the transition to hover or stabilized hover.

Adequate Performance

- Attain stabilized hover from the lateral sidestep before exiting the adequate region of the target and hover board.
- ≥30 sec of stabilized hover in adequate region.
- ±2 ft altitude deviation from hover board center.
- ±2 ft lateral deviation from hover board center.
- ±2 ft longitudinal (fore/aft) deviation from hover point.
- ±10° heading deviation from target or hover board.
- No oscillations that impact system stability of safety of flight during the transition to hover or stabilized hover.

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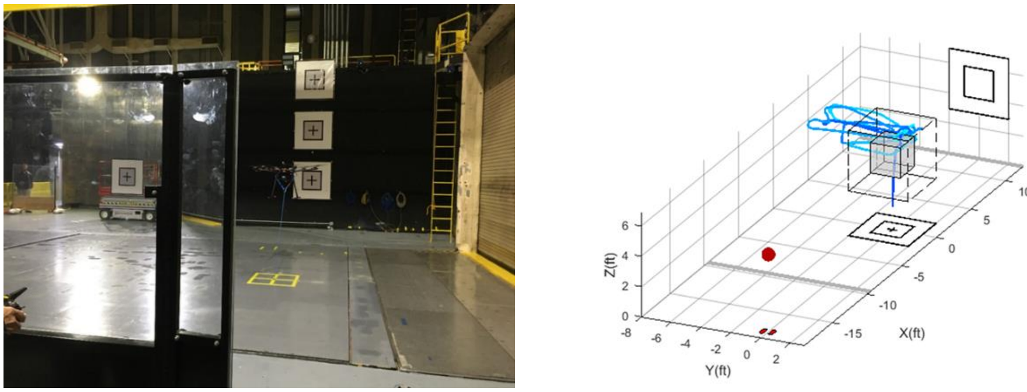

Figure 1: Precision Hover

2. Lateral Sidestep MTE

Objectives

- Assess roll axis and heave axis response during moderately aggressive maneuvering.
- Identify undesirable coupling between the roll controller and the other axes.

Description

From a stabilized hover at an altitude of 5 ft with the longitudinal axis of the multi-rotor sUAS oriented 90 degrees to a reference line marked on the ground, initiate a lateral acceleration to approximately 5 kts groundspeed followed by a deceleration to laterally reposition the vehicle to a stabilized hover 12.5 ft left of the starting point as indicated by another ground marker all while maintaining the initial heading throughout the maneuver. The acceleration and deceleration phases shall be accomplished as single smooth maneuvers. The reposition capture is complete when a stabilized hover is achieved as indicated by the vehicle position in front of the hover boards, left or right depending on course position.

The center of the (left and right) hover boards will be placed 5 ft above ground and approximately 25 ft apart laterally, equally spaced left and right of the starting point. (In the NASA LaRC Autonomy Incubator, the starting point was 20 ft aft of the precision hover board.) The hover board will have distinct boundaries indicating desired and adequate performance requirements.

Desired Performance

- ±1 vertical deviation from hover board center at each capture point.
- ±1 ft lateral deviation as indicated by the hover board center at each capture point.
- ±1 ft longitudinal (fore/aft) deviation from ground marker.
- ±5° heading deviation from reference heading.

Adequate Performance

- ±2 vertical deviation from hover board center at each capture point.
- ±2 ft lateral deviation as indicated by the hover board center at each capture point.
- ±2 ft longitudinal (fore/aft) deviation from ground marker.
- ±10° heading deviation from reference heading.

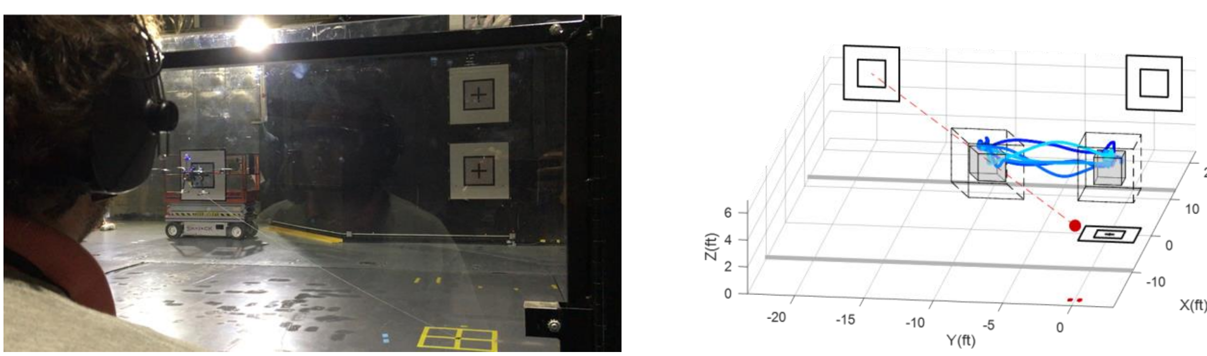

Figure 2: Lateral Reposition (mini course)

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3. Vertical Reposition MTE

Objectives

- Evaluate heave damping, i.e., the ability to precisely control and stop a vertical rate.
- Evaluate vertical control power.
- Identify undesirable coupling between collective and the pitch, roll, and yaw axes.

Description

From a stabilized hover at an altitude of 5 ft, initiate a vertical ascent of at least 10 ft and stabilize for 5 seconds at an altitude of at least 15 ft using an available landmark to stabilize vertical position. Descend back to the initial hover position in front of the hover board (5 ft altitude and 25 ft aft of the hover board center) and stabilize for at least 5 seconds. Maintain initial heading and longitudinal/lateral position throughout the maneuver. Repeat as needed.

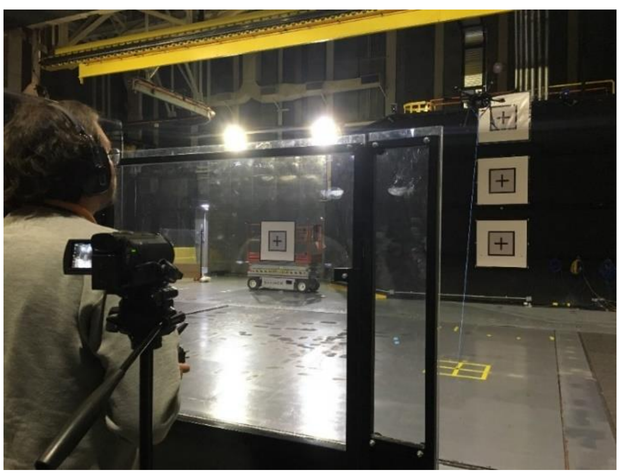
The center of the hover board will be placed 5 ft above and 25 ft in front of the hover point marker at ground level. The hover board will have distinct boundaries indicating desired and adequate performance requirements.

Desired Performance

- ±1 vertical deviation from start/finish altitude as indicated by the hover board center.
- ±1 ft lateral deviation as indicated by the hover board center.
- ±1 ft longitudinal (fore/aft) deviation from ground marker.
- ±5° heading deviation from ground marker.

Adequate Performance

- ±2 vertical deviation from start/finish altitude as indicated by the hover board center.
- ±2 ft lateral deviation as indicated by the hover board center.
- ±2 ft longitudinal (fore/aft) deviation from ground marker.
- ±10° heading deviation from ground marker.



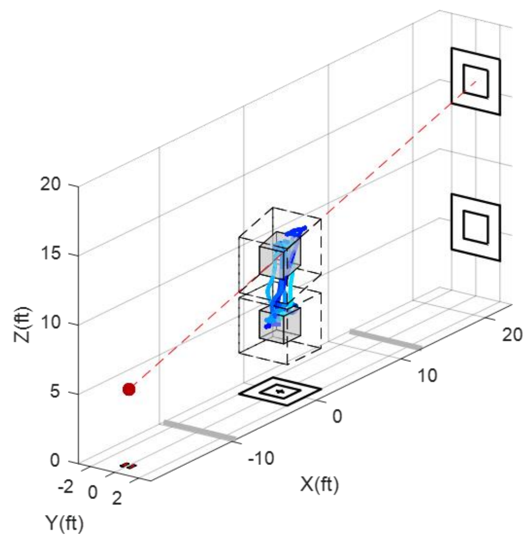


Figure 3: Bob-up/Down (Vertical Altitude Change)

4. Landing MTE

Objectives

- Evaluate precision control of multi-rotor position during final descent to a precision landing point.

Description

From an initial altitude of greater than 10 ft as indicated by a hover board or other appropriate landmark, maintain an essentially steady descent to a prescribed landing point as marked on the ground by a landing marker while maintaining a reference heading. It is acceptable to arrest the sink rate momentarily to make last-minute corrections before touchdown.

Desired Performance

- ≤2 fps vertical speed at touchdown.
- ±1 ft longitudinal (fore/aft) deviation from landing marker.
- ±1 ft lateral deviation from landing marker.
- ±5° heading deviation from landing marker.
- Smooth, continuous descent with no undesirable motions that may impact task performance.

Adequate Performance

- ≤4 fps vertical speed at touchdown.
- ±2 ft longitudinal (fore/aft) deviation from landing marker.
- ±2 ft lateral deviation from landing marker.
- ±10° heading deviation from landing marker.
- No system oscillations during landing maneuver.

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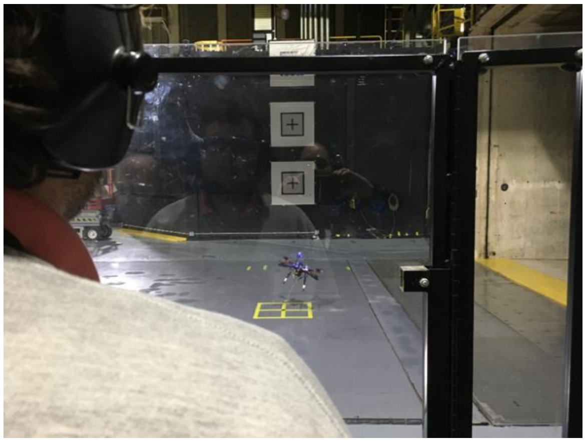

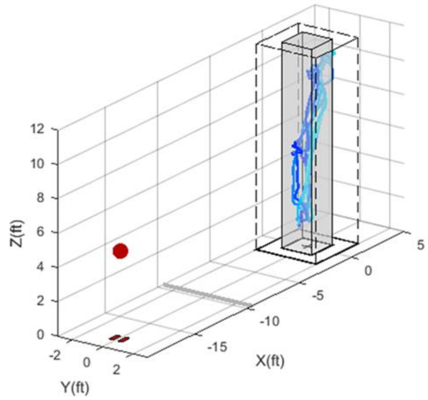

Figure 4: Landing

IV. Testing in Controlled Wind Conditions

A. NASA Langley 14x22-ft Subsonic Wind Tunnel

The multirotor MTE development and refinement in a controlled wind environment was conducted indoors in the NASA Langley 14x22-ft Subsonic Wind Tunnel. The test section is 14x22 ft with a control room just off the test section with a view through a plexiglass panel. To ensure the safety of the personnel positioned within the test section as well as the vehicle and tunnel, there were plexiglass panels behind which the personnel stood during testing, and the sUAS was affixed to the floor of the test section via a retracting 3/16-in cable.

Figure 5: 14x22-ft Subsonic Wind Tunnel

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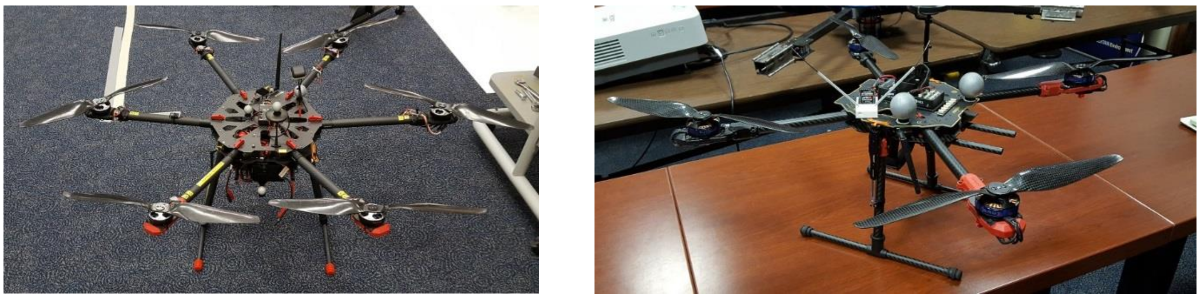
B. Test Aircraft

Two aircraft were used for this test for both the checkout and the evaluation test phases: a Tarot X6 hexacopter (Figure 6a) and a Tarot 650 Sport quadcopter (Figure 6b). These aircraft are owned and maintained by NASA LaRC and flown for many programs on campus.

The Tarot X6 is a 960 class hexacopter with 11-in. props, 5008 340kV motor, and 15-min flight time. The Tarot 650 Sport is a 650 class quadcopter with 10-in. props, 4114-320kV motor, and 12-min flight time. Both aircraft are outfitted with standard Pixhawk autopilots. Vicon tracking nodes were affixed to the aircraft for precision, indoor position and attitude tracking. For safety purposes, a 13-ft tether was attached to each aircraft with small weights on the end. This tether was fed through a hole in the wind tunnel floor and acted as a retractable safety line.

The battery packs are mounted to the bottom of the central node of the aircraft. For all of the MTEs, the pilots used these packs as their reference point when flying, meaning the pilot attempted to fly the battery pack within the desired regions as indicated by the hover boards described in the next section.



a) Tarot X6 b) Tarot 650 Sport

Figure 6: Multirotor Test Vehicles

C. Course Layout

The course was defined by a set of hover boards that served as visual cues for the desired and adequate performance bounds for the tasks (see Figure 7). The inertial (0,0,0) point of the space was defined as the hole in wind tunnel floor through which the safety tether fed. This point was 11.5 ft back from the leading edge of the wind tunnel test section and 18 in. right of center when facing the wind tunnel mouth. A ±1-ft box was marked by tape around this point.

The center of the hover boards marked by a "+" indicated the (0,0) point of the performance bound. The inner box indicates a ±1-ft bound, and the outer box indicates a ±2-ft bound. Three boards were affixed to the wall directly across from the pilot and in line with the (0,0,0) point to mark the hover course (bottom board only), the right capture of the lateral sidestep course (bottom board only), the vertical reposition course (top and bottom boards), and the landing course (top board only). The hover board for the left capture of the lateral sidestep course was mounted to a crane. This crane was positioned such that a large enough sidestep was performed but did not force the pilot to fly the aircraft at the full length of the safety tether.

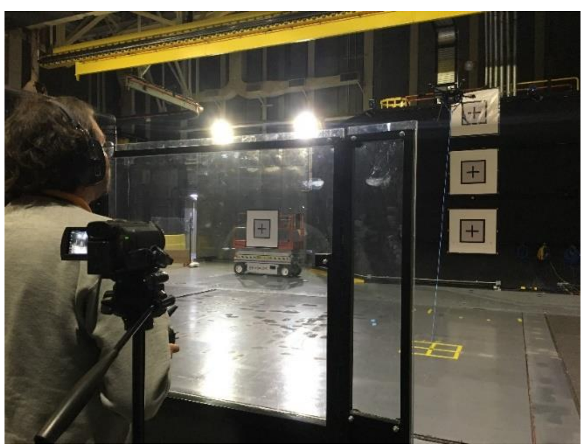


Figure 7: MTE Course Layout

D. Data Collection

Three sources of data were collected for these tests: Vicon, Pixhawk, and video. A Vicon system was installed in the open test section of the wind tunnel along the perimeter of the test area shown in Figure 7. The Vicon system was a Vantage V5, which utilizes five cameras with 5-megapixel resolution at 2000 Hz to achieve high precision position and attitude tracking. This data was used for performance assessment of the wind tunnel tests.

The Pixhawk autopilots installed on the aircraft record GPS, IMU, pilot command, and control deflection data. The GPS data were not accurate for these tests in the indoor wind tunnel and cannot be used to measure performance. The IMU, pilot command, and control deflection data will be valuable in understanding the pilot-vehicle system and how that affects performance, but that discussion is outside the scope of this paper.

Two videos were recorded for all flights. One camera was set up just behind the shoulder of the pilot behind the blast screen with a view of the whole course. This angle captured pilot perception and line-of-sight. The second camera was set up ~40 ft downstream of the pilot with a view of the whole course. These videos served to verify run log information, pilot visual cues, and pilot comments recorded during the tests.

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V. Flight Test Summary

The wind tunnel entry consisted of one day of checkout testing and two days of evaluations. The checkout testing consisted of several tasks:

- Installing the Vicon system and ensuring it was not unduly affected by the wind tunnel when in operation.
- Marking the (0,0,0) point on the floor of the wind tunnel.
- Positioning hover boards to define the course layout within the constraints of the wind tunnel and safety requirements.
- Testing each aircraft with the safety tether affixed and marking the tether in 3-ft sections for additional cueing.
- Testing each aircraft with the wind tunnel on with speeds up to 15 mph.

It was during the wind on tests that an interesting phenomenon occurred. The standard method of flying multirotor aircraft with Pixhawk autopilots is in Altitude Hold mode as this usually decreases pilot workload. When this wind tunnel runs at low speeds, such as 5 mph, there is some swirling of the air along the boundaries of the tunnel. These swirls cause local changes in barometric pressure. The Altitude Hold mode uses barometric pressure as its feedback signal. This caused the aircraft motors to surge rhythmically as the autopilot attempted to maintain altitude, which induced a marked increase in pilot workload. It was quickly determined that flying in the wind tunnel with Altitude Hold mode was not conducive to this testing, so Stability Hold mode was used for all evaluation testing.

The evaluation consisted of testing the four MTEs at six windspeeds with two pilots and two aircraft. The full test matrix is listed below in Table 1. Flight time was constrained by the batteries on the aircraft. Therefore, the test procedure was designed accordingly. For each flight, the wind tunnel was brought up to the speed at which the tasks were to be flown. The first pilot took off and performed three hover MTEs, three lateral sidestep MTEs, three vertical reposition MTEs, and three landing MTEs. After the last landing, the first pilot disarmed the aircraft and handed the controls to the second pilot. The second pilot armed the aircraft, took off, and performed the same sequence of MTEs. After the last landing, after ~10 minutes of total flight time, the aircraft was disarmed, and the wind tunnel was shut down. The spent battery was replaced with a fresh one, and the process was repeated at the next test point. The same procedure was followed for both aircraft.

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Table 1: Test Matrix

Aircraft	Pilot	Windspeed (mph)	MTEs
Tarot X6	1	0	H, LS, VR, L*
Tarot X6	2	0	H, LS, VR, L
Tarot X6	1	5	H, LS, VR, L
Tarot X6	2	5	H, LS, VR, L
Tarot X6	1	10	H, LS, VR, L
Tarot X6	2	10	H, LS, VR, L
Tarot X6	1	15	H, LS, VR, L
Tarot X6	2	15	H, LS, VR, L
Tarot X6	1	20	H, LS, VR, L
Tarot X6	2	20	H, LS, VR, L
Tarot X6	1	25	H, LS, VR, L
Tarot X6	2	25	H, LS, VR, L
Tarot 650 Sport	1	0	H, LS, VR, L
Tarot 650 Sport	2	0	H, LS, VR, L
Tarot 650 Sport	1	5	H, LS, VR, L
Tarot 650 Sport	2	5	H, LS, VR, L
Tarot 650 Sport	1	10	H, LS, VR, L
Tarot 650 Sport	2	10	H, LS, VR, L
Tarot 650 Sport	1	15	H, LS, VR, L
Tarot 650 Sport	2	15	H, LS, VR, L
Tarot 650 Sport	1	20	H, LS, VR, L
Tarot 650 Sport	2	20	H, LS, VR, L
Tarot 650 Sport	1	25	H, LS, VR, L
Tarot 650 Sport	2	25	H, LS, VR, L

*H = Hover, LS = Lateral Sidestep, VR = Vertical Reposition, L = Landing

VI. Results and Discussion

For brevity, results that exemplify performance of each MTE and summary results are presented. Representative tasks at 5 mph and 25 mph are highlighted because they best show the effect of the controlled wind environment. Performance of the tasks did not change significantly from 0 to 5 mph while there was noticeable degradation in performance as windspeed increased to 25 mph. Runs for Pilot 1 flying the Tarot X6 are shown for the hover, lateral sidestep, and vertical reposition examples as he tended toward calm purposefulness in his piloting style with this aircraft regardless of windspeed and thus yielded clean results. The landing example is for Pilot 2 as Pilot 1 chose not to attempt landings at 25 mph. These examples set the basis for the discussion in the subsequent subsection. From this collection of data, it is possible to assess the performance of each MTE and determine if and how the MTEs should be improved.

The full NASA report, reduced data, and raw data is available in Ref. 8. From this collection of data, it is possible to assess the performance of each MTE and determine if and how the MTEs should be improved.

A. Performance Metrics

Based on the MTE definitions in Section III.B, performance metrics can be defined based on the vehicle's position (i.e., X, Y, and Z coordinates), attitude (i.e., roll, pitch and heading angles), and velocity depending on the MTE. Since the Vicon data does not include velocity, it was derived by differentiating aircraft position. Performance metrics include % Desired performance and % Adequate performance.

This metric is calculated by assessing each data point over the test performance range or scoring to determine if it falls within the desired or adequate bounds and dividing the number of points within each by the total number of data points. If the pilot keeps the aircraft within the desired bounds more than 50% of the time for the task, then the overall task performance is considered desired. If less than 50% is within the desired bounds, but more than 50% is within the adequate bounds, then task performance is adequate. If less than 50% is within the adequate bounds, then the pilot fails in task performance.

In the plots in the following subsection, the desired performance region is defined by an opaque grey region outlined in solid black lines, the adequate performance region is defined by dashed lines, the flight data is shown in blue, and the performance test range or scoring region for the run is defined by dashed red lines.

B. MTE Example Results

1. Precision Hover

To execute the precision hover task, pilots were instructed to start the vehicle and begin hovering at 5 feet. The pilot then executed a step to the left while maintaining the longitudinal position and altitude. The pilot immediately stepped the vehicle back to the original lateral position and hovered above the origin for 5-10 seconds. This MTE was repeated three times before proceeding to the next MTE (see example in Figure 1).

A comparison of X position, Y position, altitude or Z position, and heading for the hover MTE performed at a windspeed of 5 mph and a windspeed of 25 mph is shown in Figure 8. The primary task for this MTE was to capture and hold a stable Y and Z position in front of the pilot. The secondary task was to maintain X position and heading.

From this example, it is easy to pick out the three hover tasks completed by this pilot in the Y position data in Figure 8c and d, the first of which is indicated by the dashed red lines. Qualitatively, there is slightly more activity in these states for the hover MTEs performed at the higher windspeed, but the pilot was generally able meet the performance requirements.

This observation is supported by the performance data listed in Table 2 and Table 3 for the indicated run. The pilot had desired performance in both the primary task and secondary task for both windspeeds. However, there is a significant decrease in % Desired in X position and heading at the 25-mph windspeed. This is attributed to the lack of sufficient cueing for longitudinal position and heading on the test course. It is challenging to maintain these states with the available cues at the relatively lower workload of the lower windspeed. The higher windspeed increased pilot workload according to pilot comments and the aircraft attitudes not shown here (namely roll attitude), which resulted in less attention paid to the secondary task.

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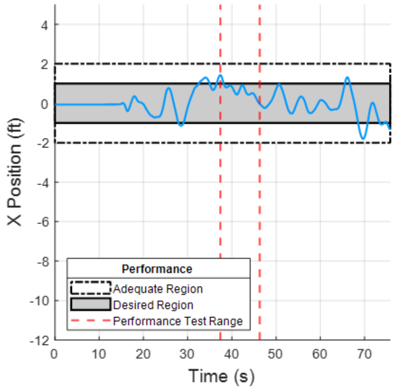
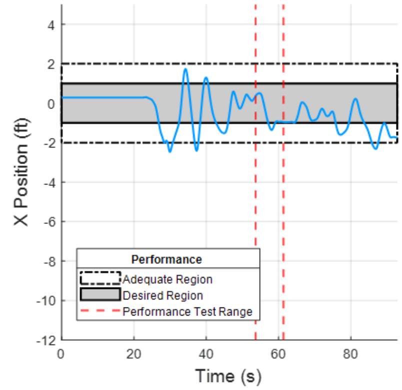
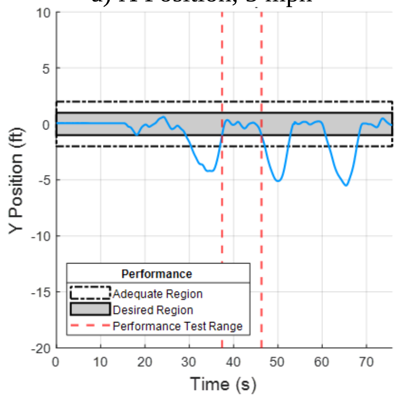


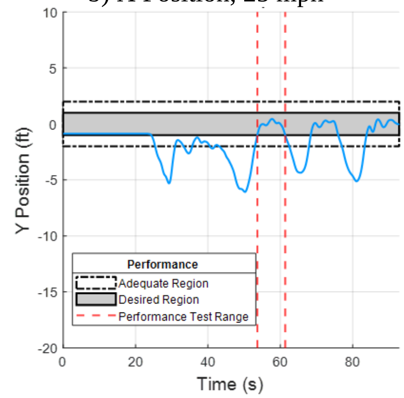
a) X Position, 5 mph



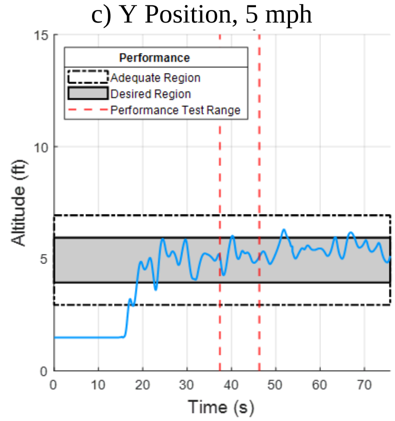
b) X Position, 25 mph



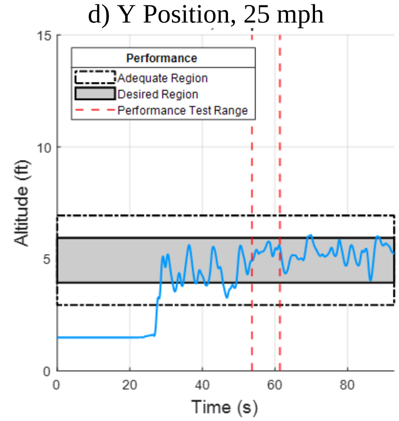
c) Y Position, 5 mph



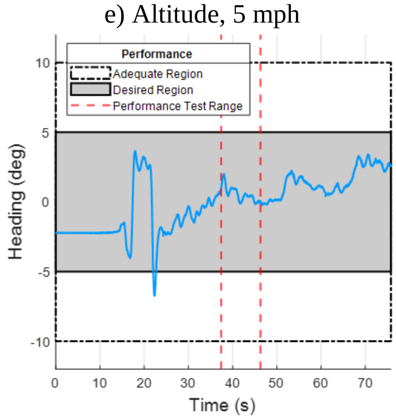
d) Y Position, 25 mph



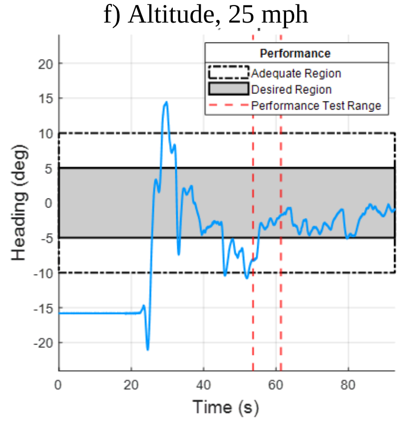
e) Altitude, 5 mph



f) Altitude, 25 mph



g) Heading, 5 mph



h) Heading, 25 mph

Figure 8: Hover MTE Example

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Table 2: Hover Performance, 5 mph

Windspeed: 5 mph	Vehicle: Tarot X6	
Run: 2	Desired (%)	Adequate (%)
X Position	91.63	100.00
Y Position	99.94	100.00
Z Position	94.44	100.00
Heading Angle	100.00	100.00

Table 3: Hover Performance, 25 mph

Windspeed: 25 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	75.45	100.00
Y Position	99.94	100.00
Z Position	100.00	100.00
Heading Angle	80.13	100.00

2. Lateral Sidestep

For the lateral sidestep MTE, the pilots were instructed to fly the vehicle laterally in one direction, capture and hold a static position, then sidestep in the other direction to capture and hold the original position. The pilot first flew the aircraft to the hover board directly in front of him and in line with the takeoff point and then sidestepped towards a hover board to the left of the takeoff point resulting in a roughly 10-ft sidestep. The lateral sidestep was then repeated three times (see example in Figure 2). Each capture lasted 5-10 seconds with the test director counting to five as aural cue of time in position.

A comparison of X position, Y position, altitude or Z position, and heading for the lateral sidestep MTE performed at a windspeed of 5 mph and a windspeed of 25 mph is shown in Figure 9. Similar to the hover MTE, the primary task for this MTE was to capture and hold a stable Y and Z position, and the secondary task was to maintain X position and heading.

From this example, it is again easy to pick out the three sidestep tasks completed by this pilot in the Y position data shown in Figure 9c and d, of which the third left sidestep is indicated by the dashed red lines. Qualitatively, the right step, for which the capture hover board is directly in front of the pilot, is performed more cleanly than the left according to these two subfigures. There is an offset in X position and more deviation in altitude for the 5-mph case. This could be due to the pilot focusing largely on maintaining lateral position especially at the left hover board and not correcting for the offset.

For the 25-mph case, the pilot doesn't appear to be able to capture hover board when sidestepping left well. A probable cause of this issue is the pilot's perspective of that hover board (refer to Figure 1). An offset in X position is difficult to perceive at that angle, thus making it possible that the pilot believes he has captured the hover in the desired region based on his line of sight. When Y position is corrected for this X offset, as shown in Figure 10, his performance appears to be well within the adequate performance bounds if not the desired performance bounds.

These observations are reflected in the performance data listed in Table 4 and Table 5 for the indicated run. Heading and Z position have desired performance for both windspeeds. The pilot failed X position performance for the MTE flown at 5 mph with a 23.9% Adequate. The Y position performance increased significantly for both windspeeds with a change from an adequate performance of 69.53% Adequate to a desired performance for the MTE performed at 25 mph.

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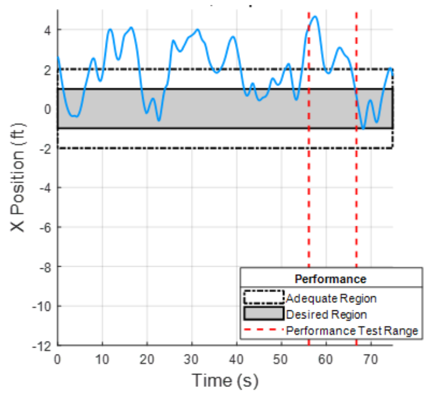
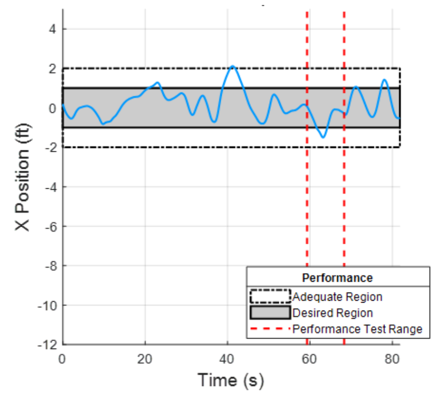
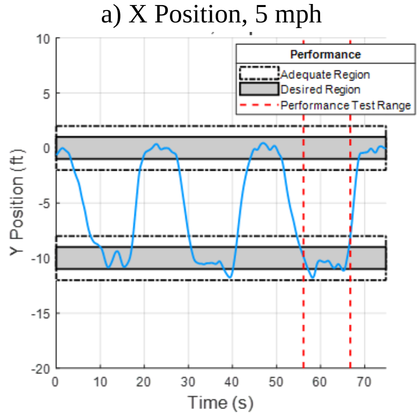


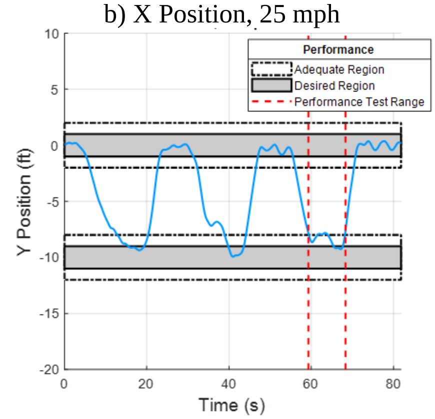
a) X Position, 5 mph



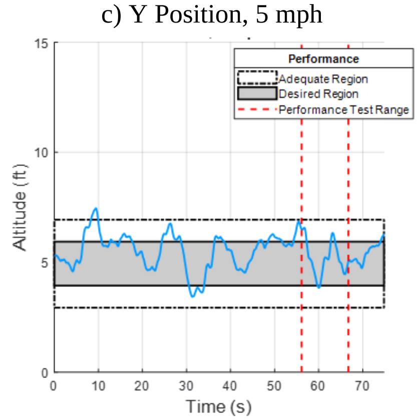
b) X Position, 25 mph



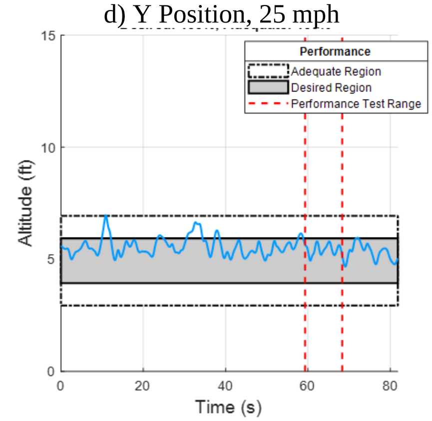
c) Y Position, 5 mph



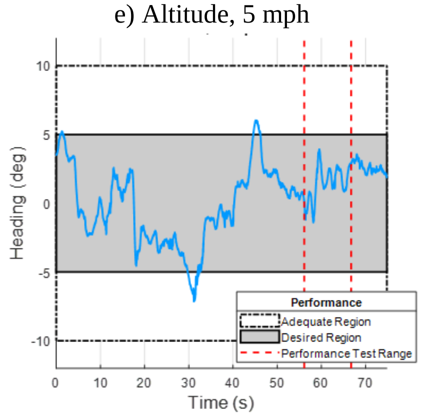
d) Y Position, 25 mph



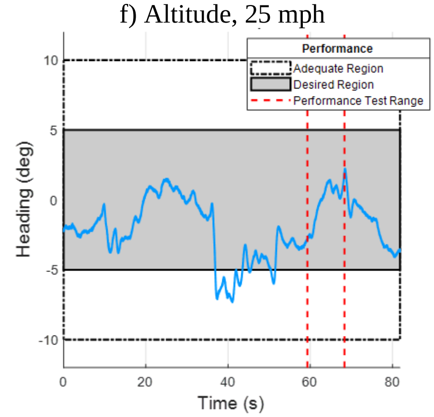
e) Altitude, 5 mph



f) Altitude, 25 mph



g) Heading, 5 mph



h) Heading, 25 mph

Figure 9: Lateral Sidestep MTE Example

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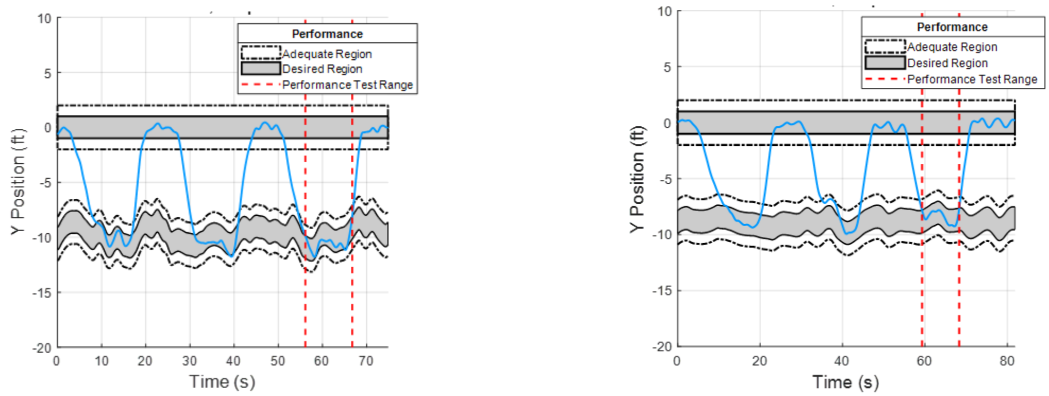


a) 5 mph b) 25 mph

Figure 10: Lateral Sidestep Corrected Y Position

Table 4: Lateral Sidestep Performance, 5 mph

Windspeed: 5 mph	Vehicle: Tarot X6	
Run: 1	Desired (%)	Adequate (%)
X Position	2.78	23.90
Y Position	74.82	100.00
Y Position (Corrected)	93.40	100.00
Z Position	74.59	100.00
Heading Angle	100.00	100.00

Table 5: Lateral Sidestep Performance, 25 mph

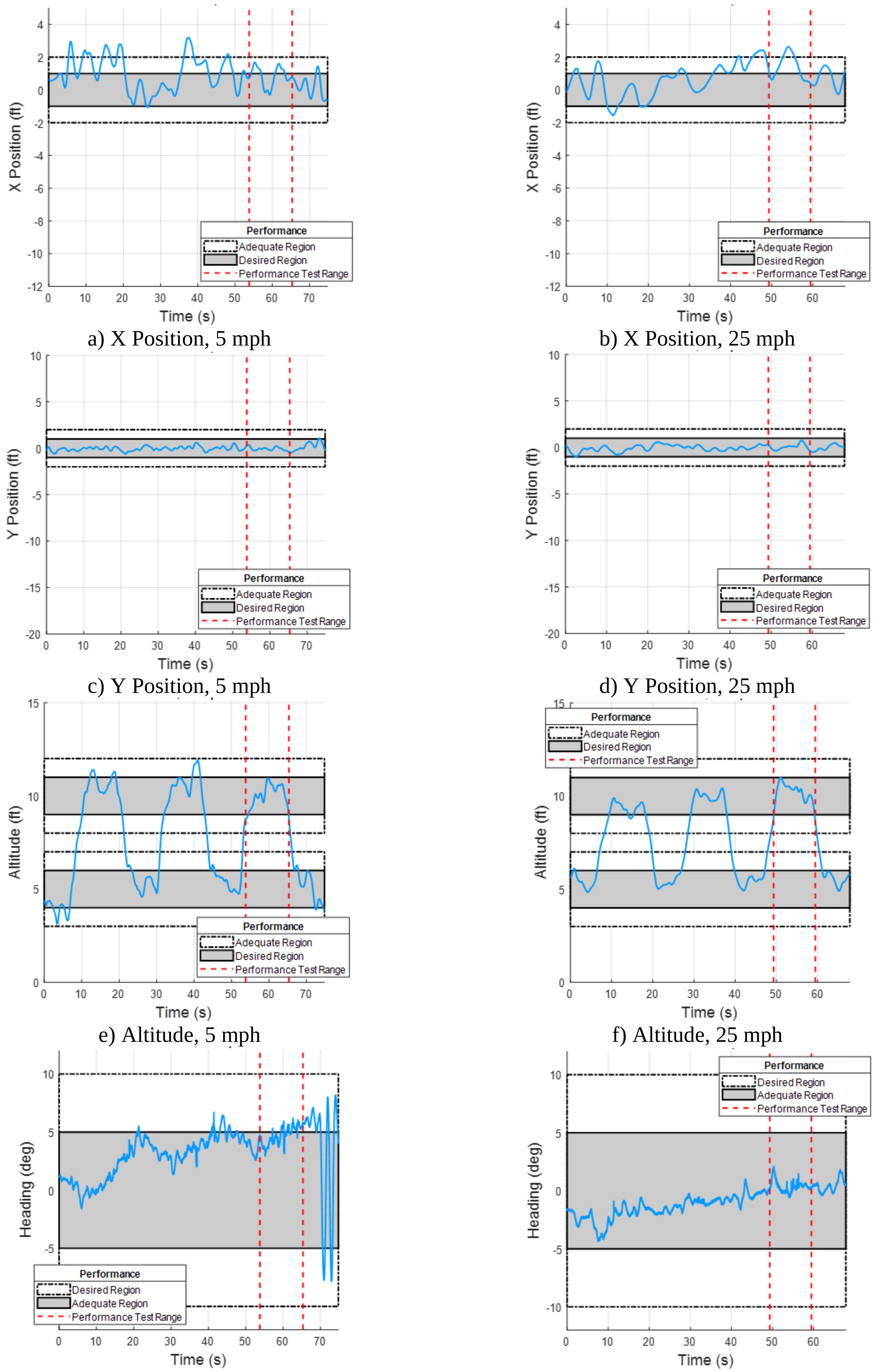
Windspeed: 25 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	71.25	100.00
Y Position	24.60	69.53
Y Position (Corrected)	100.00	100.00
Z Position	100.00	100.00
Heading Angle	100.00	100.00

3. Vertical Reposition

For the vertical reposition MTE, the pilots were instructed to takeoff and stabilize in a hover for 5 seconds relative to the hover board directly in front of him. The pilots were then instructed to fly the vehicle up to a hover board placed ~10 feet above the lower hover board. Due to the perspective of the pilot, this placed the aircraft ~10 ft above the ground. As such the requirement for the MTE was modified to 10 ft above the ground from the original 15 ft. This also kept the upper capture point well within the wind tunnel test section, which is 14 ft in height. Once at this altitude the pilot stabilized the vehicle in a hover for 5 seconds as counted by the test director and then descended back to the original hover (see example in Figure 3).

A comparison of X position, Y position, altitude or Z position, and heading for the vertical reposition MTE performed at a windspeed of 5 mph and a windspeed of 25 mph is shown in Figure 11. Again, the primary task for this MTE was to capture and hold a stable Y and Z position, and the secondary task was to maintain X position and heading.

From this example, the three vertical reposition MTEs completed by this pilot can be deduced from the Z position data shown in Figure 11e and f, of which the third ascending vertical reposition is indicated. Maintaining X position and heading appears to be a challenging secondary task for this MTE. Y position is generally maintained well, and the descending vertical reposition is a more cleanly performed task in altitude performance as is expected from previous observations.



a) X Position, 5 mph
b) X Position, 25 mph
c) Y Position, 5 mph
d) Y Position, 25 mph
e) Altitude, 5 mph
f) Altitude, 25 mph
g) Heading, 5 mph
h) Heading, 25 mph

Figure 11: Vertical Reposition MTE Example

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However, like the left lateral sidestep, the ascending vertical reposition in which the upper hover board is used as the visual cue for position capture and hold appears more challenging. The altitude of the vehicle was highly influenced by the longitudinal position of the vehicle and the pilot's line of sight (refer to Figure 3) much like the lateral position was influenced for the lateral sidestep MTE. An offset in X position is difficult to perceive at that angle, thus making it possible that the pilot believes he has captured the hover in the desired region based on his line of sight. When Z position is corrected for this X offset, as shown in Figure 12, the pilot's performance appears to be well within the adequate performance bounds if not the desired performance bounds for both cases, though this does not appear to have had as significant an effect as the did the Y position correction for the lateral sidestep MTE performance.

These observations are reflected in the performance data listed in Table 6 and Table 7 for the indicated run. Heading and Y position have desired performance for both windspeeds. The pilot barely achieved desired performance in X position at 5 mph with a 53.4% Desired, and he only achieved adequate performance in X position at 25 mph with a 71.23% Adequate. For both windspeeds, the corrected Z position resulted in a slightly worse performance metric, decreasing from 93.2% to 88.78% Desired for the 5-mph case and from 96.44% to 92.68% Desired for the 25-mph case. This suggests that the pilot is better able to regulate X position for this MTE and a correction in Z position performance is not required.

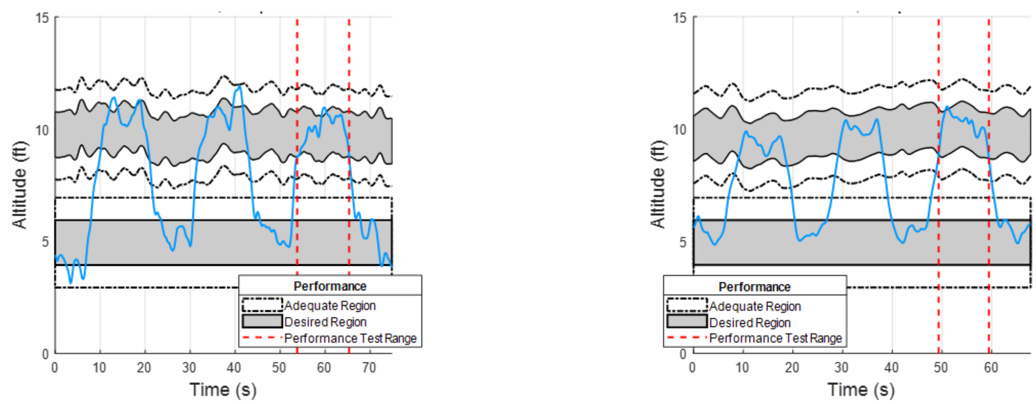

Figure 12: Vertical Reposition Corrected Z Position

Table 6: Vertical Reposition Performance, 5 mph

Windspeed: 5 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	53.40	100.00
Y Position	100.00	100.00
Z Position	93.20	100.00
Z Position (Corrected)	88.78	100.00
Heading Angle	60.29	100.00

Table 7: Vertical Reposition Performance, 25 mph

Windspeed: 25 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	38.95	71.23
Y Position	100.00	100.00
Z Position	96.44	100.00
Z Position (Corrected)	92.68	100.00
Heading Angle	100.00	100.00

4. *Landing*

To execute the landing task, pilots were instructed to fly the vehicle above 10 ft, then gently land the vehicle at the same spot from which they took off, minimizing lateral and longitudinal deviations (refer to Figure 4). They were also required to limit vertical velocity at touchdown to ≤ 2 ft/s. Each pilot executed this MTE three times per windspeed per vehicle (see example in Figure 4). There was no requirement to capture or maintain a certain altitude as the focus was on the landing position.

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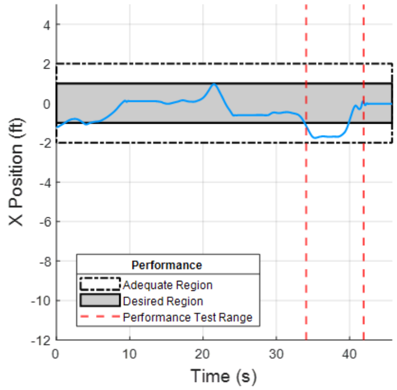
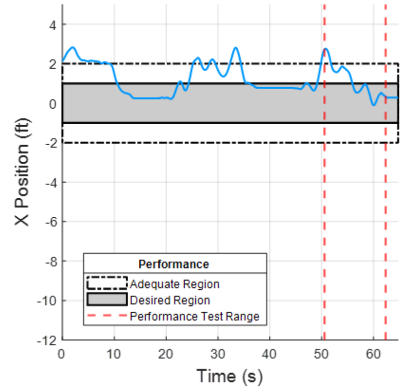
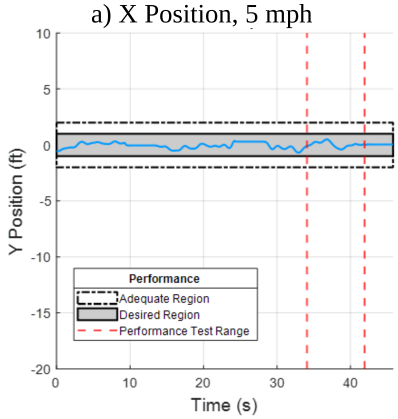


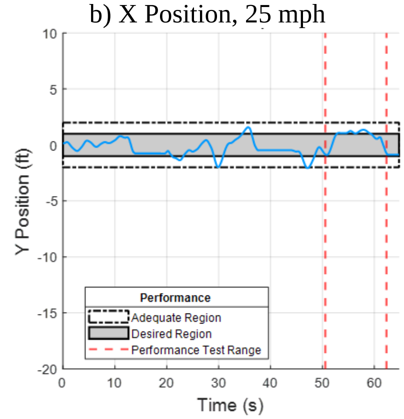
a) X Position, 5 mph



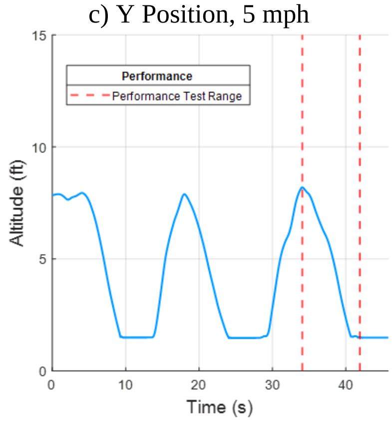
b) X Position, 25 mph



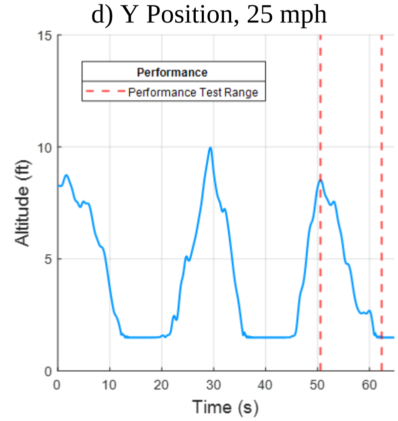
c) Y Position, 5 mph



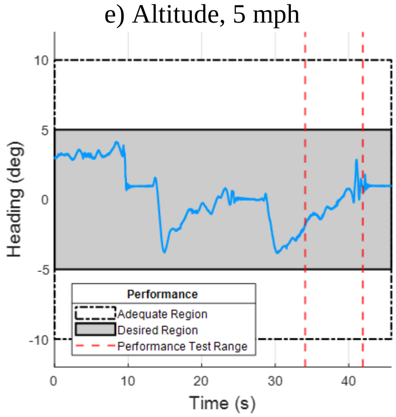
d) Y Position, 25 mph



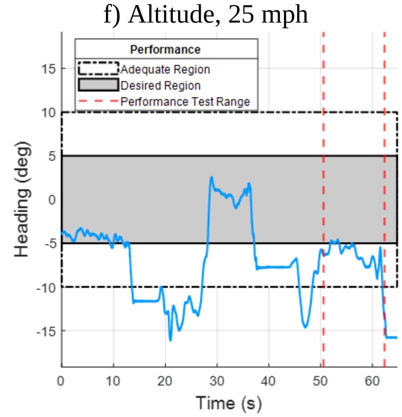
e) Altitude, 5 mph



f) Altitude, 25 mph



g) Heading, 5 mph



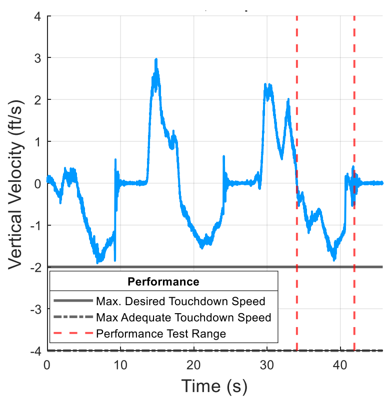
h) Heading, 25 mph

Figure 13: Landing MTE Example

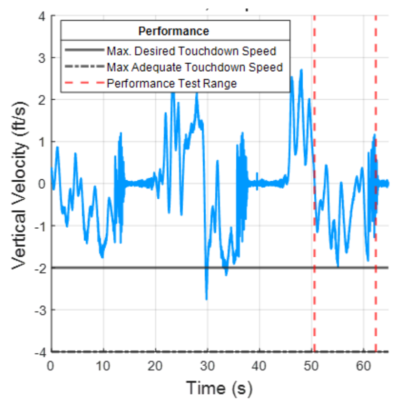
A comparison of X position, Y position, altitude or Z position, and heading for the landing MTE performed at a windspeed of 5 mph and a windspeed of 25 mph is shown in Figure 13. Vertical velocity is shown in Figure 14. The primary task for this MTE is maintaining X and Y position while modulating vertical velocity. The secondary task was to maintain heading.

From this example, each landing MTE can be determined from the altitude of the aircraft. The beginning of the task is roughly an apex in Z position, and the ending is when altitude is steady at roughly the height of the battery pack of the aircraft. Qualitatively, there are stark differences between the MTE performance for the two windspeeds. In general, the states of the aircraft in 5 mph are smoother than in 25 mph winds. This is especially stark in the vertical velocity, though the pilot does keep the vertical velocity below the 2 ft/s requirement. X position is difficult to maintain in the descent at both windspeeds, but maintaining Y position and heading significantly degraded at windspeed of 25 mph.

These observations are supported by the performance data listed in Table 8 and Table 9. X position performance is only 26.0% and 54.5% Desired for the 5-mph and 25-mph cases, respectively. For the 5-mph case, Y position, vertical velocity, and heading were all perfectly maintained within the desired performance bounds. For the 25-mph case, Y position and heading were only maintained within the adequate performance bounds and had 44.31% and 12.48% Desired performance, respectively.



a) 5 mph



b) 25 mph

Figure 14: Landing Vertical Velocity

Table 8: Landing Performance, 5 mph

Windspeed: 5 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	26.00	100.00
Y Position	100.00	100.00
Landing Speed	100.00	100.00
Heading Angle	100.00	100.00

Table 9: Landing Performance, 25 mph

Windspeed: 25 mph	Vehicle: Tarot X6	
	Desired (%)	Adequate (%)
X Position	54.50	89.43
Y Position	44.31	100.00
Landing Speed	100.00	100.00
Heading Angle	12.48	96.43

C. Summary Results and Discussion

The average % Desired performance of each MTE performed at each windspeed by both pilots on both aircraft are illustrated in the subfigures of Figure 15.

For the Hover MTE in Figure 15a and b, the pilots had consistently high performance scores for altitude and lateral position (red and blue symbols in Figure 15, respectively). For these two performance measures, the pilots maintained an adequate performance for all maneuvers performed and almost always met the desired performance requirements

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as well. The most difficult task was maintaining the aircraft's longitudinal position in the desired region. They also struggled to keep the heading angle within the desired bounds, especially at higher windspeeds.

In general, the pilots flew better with the Tarot X6 aircraft. There was more dispersion in the % Desired for the pilots' performances with the Tarot 650 Sport with more of the metrics falling below the 50% threshold to be deemed an Overall Desired performance. In addition, there were two metrics for the pilots' performances with the Tarot 650 Sport that fell below the 50% threshold in % Adequate as well.

For the Lateral Sidestep MTE, both pilots excelled at maintaining a desired lateral position for each Sidestep maneuver as indicated by the consistently high % Desired in Figure 15c and d. Although both pilots rarely maintained smooth altitude tracking, they were consistent at keeping the aircraft within the adequate bounds throughout the maneuvers. They consistently maintained a % Desired performance above 80% for both aircraft save for a couple test points, as seen in Figure 15. However, the pilots struggled to maintain longitudinal positioning within the desired bounds (black symbols in Figure 15) and only achieved an Overall Desired performance for ~50% of the test points. The pilots had moderate success maintaining the aircraft's heading angle within the desired bounds and achieved an Overall Desired performance for 65% of the test points.

Comparing the two vehicles, the only significant difference in performance is the heading angle. Considering the heading performance data shown in Figure 15c and d, the average % Desired for the Tarot X6 are consistently higher than those for the Tarot 650 Sport. With the Tarot 650 Sport, the pilots only achieved an Overall Desired for heading angle in 47% of the test points. With the Tarot X6, the pilots achieved an Overall Desired performance for heading angle in 87% of the test points. Pilot 2 appeared to struggle even more with the Tarot 650 Sport with several average % Desired for heading angle below 10%.

For the Vertical Reposition MTE in Figure 15e and f, both pilots excelled at maintaining a desired lateral position (blue symbols in Figure 15) for the duration the vertical reposition maneuvers for both aircraft. For all but one test point the average % Desired for Y Position is 100.00%. The pilots also consistently maintained altitude within the desired performance bounds, achieving an average Overall Desired performance for the Z Position for all of the test points. This suggests that the effects of longitudinal position on altitude for the Vertical Reposition MTE are not as significant as for Y Position in the Lateral Sidestep MTE.

As with the Lateral Sidestep and Hover MTEs, the pilots struggled to maintain a steady longitudinal position within the desired performance bounds. The pilots only had an average Overall Desired performance in X Position for 55% of the test points. Pilot 2 again struggled with heading angle and had an average Overall Desired performance in heading angle for only 50% of the test points, while Pilot 1 had an Overall Desired performance for all of test points. Like the Lateral Sidestep MTE, most of Pilot 2's heading angle struggles were while flying the Tarot 650 Sport.

Finally, for the Landing MTE in Figure 15g and h, controlling the vertical velocity when landing was fairly easy for the pilots with both vehicles. The performance assessment of landing vertical velocity is a discrete metric in which the pilot had Desired, Adequate, or Failed performance. For these data, the failure condition does not appear because the pilots achieved desired performance for all maneuvers and never exceeded the 4-ft/s failure limit.

The pilots once again performed poorly with regard to longitudinal position during this MTE. The pilots achieved an average Overall Desired performance in longitudinal position for 72% of the test points. Pilot 1 was less capable that Pilot 2 in maintaining longitudinal position and only achieved an average Overall Desired performance in longitudinal position for 67% of the test points. The pilots had greater success in maintaining their heading angle during this MTE and were able to maintain an average Overall Desired heading angle performance for all but four of the test points. There was no apparent difference in performance measures between the two aircraft.

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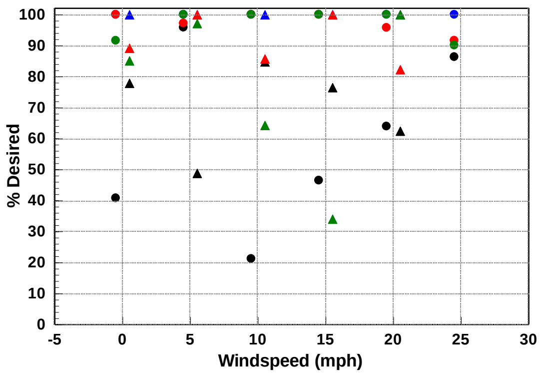
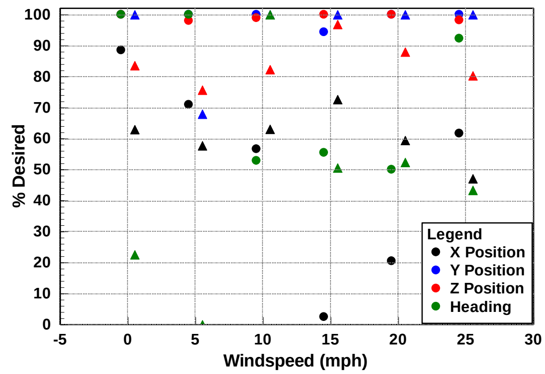
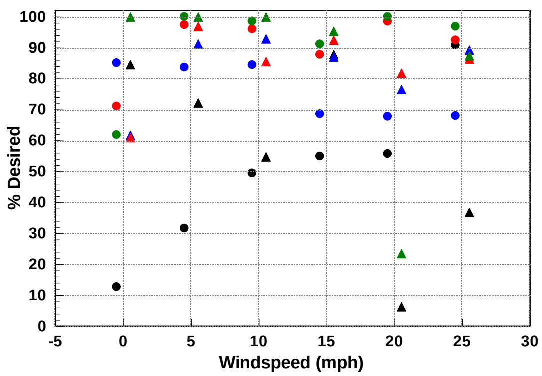


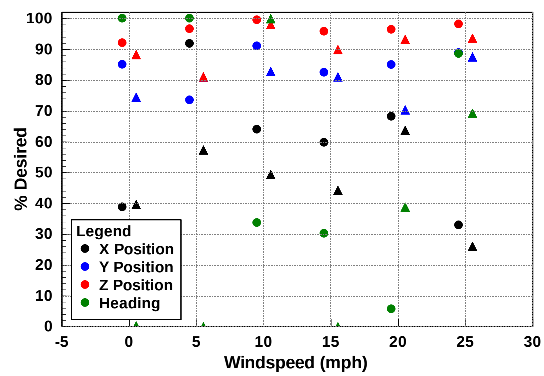
a) Hover, Tarot X6



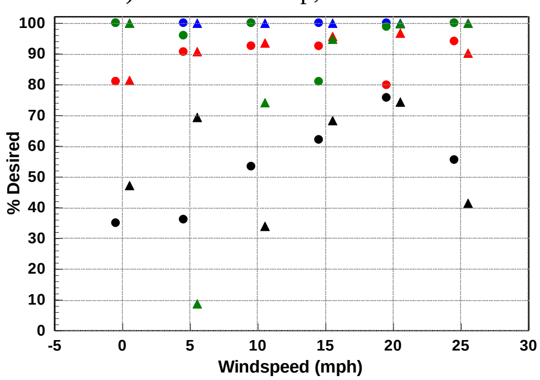
b) Hover, Tarot 650 Sport



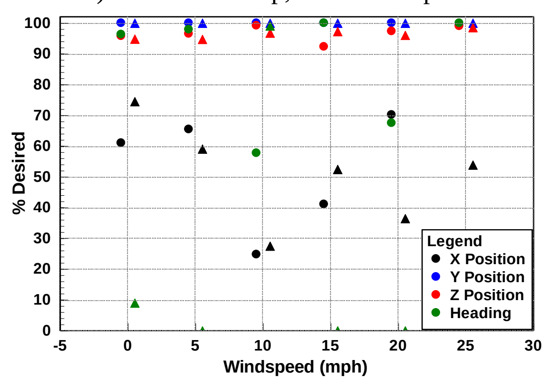
c) Lateral Sidestep, Tarot X6



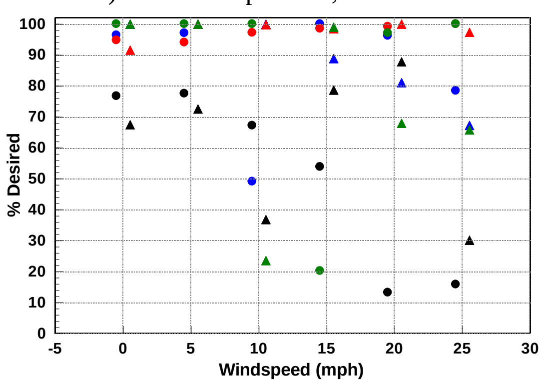
d) Lateral Sidestep, Tarot 650 Sport



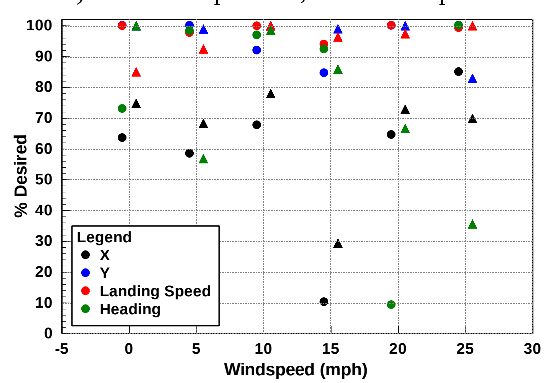
e) Vertical Reposition, Tarot X6



f) Vertical Reposition, Tarot 650 Sport



g) Landing, Tarot X6



h) Landing, Tarot 650 Sport

Figure 15: Average % Desired Performance (● - Pilot 1, ▲ - Pilot 2)

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VII. Conclusions

The purpose of this flight test in controlled wind conditions was to determine the effectiveness of the mission-oriented approach as a means to define sUAS off-nominal performance. NASA LaRC's 14x22-ft subsonic wind tunnel was employed to generate the controlled wind conditions in which small multirotor UAS were free flown. The MTEs evaluated in the test program were precision hover, lateral sidestep, vertical reposition, and landing. Two multirotor aircraft were flown by two pilots through these MTEs at six windspeeds ranging from 0 mph to 25 mph. Performance metrics constituted % Adequate and % Desired measures based on requirements defined in the MTE descriptions. From the qualitative results that included pilot debrief questionnaires and the quantitative task performance results from the Vicon data, it was clearly demonstrated that the MTEs met the defined objectives. Aggregate results show that pilot performance does not vary inversely with increasing windspeed, which indicates the validity for these MTE's in controlled wind environment. Pilot feedback rated the MTEs as effective for simulating operational tasks.

From this study, several conclusions can be drawn. The general procedure utilized for this test to evaluate small multirotor aircraft through a set of precision non-aggressive MTEs within the constraints of the wind tunnel test section and safety requirements is sound. The pilots were generally able to perform the MTEs with at least adequate performance, though performance degraded at the higher windspeeds. This suggests that upper wind limits could be defined for this size aircraft. The pilots often had difficulty maintaining X position within the performance bounds due to inadequate longitudinal visual cueing especially at higher windspeeds. Pilot feedback suggested that better longitudinal cueing is required. However, an alternative conclusion is that longitudinal cueing in a real world environment will likely be even less clear, therefore certifying agencies must either not consider that important or not allow piloted sUAS in environments in which precise longitudinal positioning is required.

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