Paper 140

A Demonstration and Primer of Modern Handling Qualities Characteristics Using a Highly Augmented Wi-Fi Controlled Rotorcraft

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Abstract

Training engineers in rotary wing handling qualities test techniques has been conducted for over sixty years, with mixed levels of success. Limitations such as aircraft availability, weather and proximity of those aircraft to adequate classroom assets have combined to make the evolution of both "hands-on" and theory-based training difficult and expensive. The risk of locating non-aviators in close proximity to flight controls was considered unacceptable; leaving out important training that should be required of all flight test engineers. Even when this risk was mitigated, the cost of merging all that is required to deliver good training becomes so expensive that only a few of any organization's staff received the training needed. In fact, in the history of the U. S. Army Aviation Engineering Directorate, only two engineers have attended the United States Naval Test Pilot School. This paper proposes a unique approach to providing a primer to handling qualities testing and reporting. Rather than using expensive aircraft or simulators; a small Wi-Fi controlled quad rotor aircraft is used. All training is conducted within the confines of a classroom and a small gymnasium. This approach dramatically improves the level of "hands-on" training experienced by each student, and the cost is reduced to a small initial investment in equipment along with recurrent instructor and classroom cost.

INTRODUCTION

This training approach is built around a highly augmented, quad rotorcraft named the Parrot AR Drone™. The AR Drone™ opens new doors for flight test training featuring:

- Automatic takeoff and landing.
- Altitude and heading hold.
- Roll/pitch/yaw damping.
- Look forward and look down video cameras allowing real time viewing from the pilot's station.
- Extremely low rotor velocities and mass.
- Wi-Fi control with multiple surrogate capability.

This system also takes the seasoned rotorcraft pilot out of his/her normal cockpit environment and exposes them to innovative new inceptors…namely the iPad™, iPhone4™ and iPod™. The AR Drone™ that was used for the development of this training course has 5 hours of flight time, without damage. If, while being flown manually by a student, the controls are released, the AR Drone™ will automatically transition to a safe hover mode while maintaining the last altitude. It will remain in this state until the operator provides commands, the aircraft battery reaches a low voltage condition or an emergency cutoff command is sent.

This paper addresses the various phases of an aircraft evaluation in the order that would typically take place in an actual rotorcraft handling qualities evaluation.

SYSTEM DESCRIPTION

AR DRONE ™

The AR Drone™, depicted in Figure 1, (from vendor's website), is a quad rotor unmanned air vehicle originally designed to be controlled by the iPhone 4™, iPod Touch™ or either of the two existing iPad™ models. It is controlled via an ARMS 468 Mhz microprocessor with 128Mbytes of Double Data Rate RAM (DDR). The flight control software is Linux-based and the source code is available for modification by users. Thus the inner control loops are automatic, providing heading, altitude and position hold along with rate damping about the x, y and z axes. The operator simply provides outer loop control via a Wi-Fi link. The limit of Wi-Fi range, unfortunately, varies greatly with the environment.

Figure 1, AR Drone (Sketch courtesy of Parrot)

The AR Drone™ is constructed of carbon fiber tubes and high impact resistant plastic foam. The basic dimensions are 20.7 inches long and 20.3 inches wide. All flight control and flight thrust are provided via four high-performance propellers, each driven through gear reduction by 15 watt brushless motors.

The flight control system uses MEMS accelerometers, rate gyros and an ultrasonic range finder. The yaw rate gyro is a higher level of precision when compared to the pitch and roll rate gyros in order to provide a pseudo-heading hold capability.

Two cameras are also incorporated into the AR Drone™. A vertical camera pointed nadir, is used to assist in position hold longitudinally and laterally by driving the optical velocity vector [1] to zero. This camera is a 64 degree diagonal, color camera with a video rate of 60 frames per second (fps). The second camera is positioned on the longitudinal axis of the aircraft; pointed forward. It is based on a 93 degree, wide angle, 15 fps, color video camera and is used to detect targets using color patterns between 30 cm and 5 meters. When video targets are used on known dimensions, range is also provided. The AR Drone ™ can also stalk these targets; whether they are moving or stationary.

Controls and Display

Two Apple™ devices were used as the primary controllers for the development of this demonstration/primer in handling qualities.

The first generation Apple ™ iPad ™, was used initially, while the author awaited the release of the iPhone 4™. With the large display, the iPad™ quickly became the primary display, while the iPhone 4™ was relegated the duties of controlling the rotorcraft. Figure 2, Display Comparison, gives a comparison of the size and the primary "aviator" display of the Drone Ace application.

Figure 2, Display Comparison (U.S. Army Photograph)

While the iPad™ display is considerably larger than that of the iPhone, the virtual control sticks, used by all three of the applications were evaluated, and the weight of the iPad™ make its use as a controller more difficult. This device was subsequently attached to an adjustable table with the viewing angle adjustable by the operator. The iPhone™ was held in a fixture for some tests requiring precise inputs, such as Trimmed Flight Control Positions (TFCPs), but it was handheld for most test flights.

Controller Applications

The Flight Record™ application offers the user pitch, roll and yaw control, with all of the "automatic modes."

Drone Control™ offers much more display data for post-flight use. The ability to shoot a date/time stamped sequence of photos during a maneuver at up to 2 frames per second aids in post flight analysis. It also can record ground speed Vx, vertical speed Vz and altitude. Graphs of these are available in a navigation data folder after each flight and this data can be transferred to a laptop using the shared files mode of iTunes™ in a comma-separated variables format.

Drone Ace™ may be the most useful of all current applications for flight test technique training. It overlays altitude, pitch and roll attitudes in the video for use during the flight test. This application allows recording of video with data overlay and audio.

MANUAL FLIGHT CONTROL EVALUATION

COCKPIT EVALUATION

Classical cockpit evaluation is a detailed examination of the field of view, flight control locations, force/displacement characteristics and the locations of all switches. [2] Within the scope of this demonstration/primer, the controls are the touch controls embedded in the three applications loaded on the Apple™ devices. Figure 3 shows a typical cockpit layout.

Figure 3, "Cockpit" Layout (U.S. Army Photograph)

The flight control/display screens given in each application are shown in Figures 4 through 7.

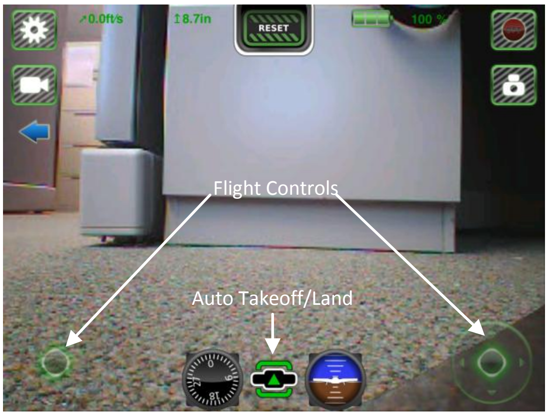


Figure 4, FlightRecord™ Display (U.S. Army Photograph)

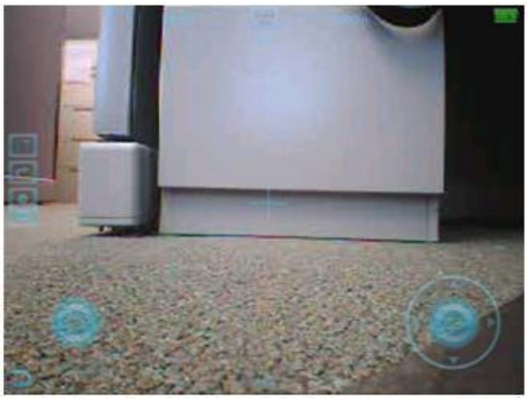


Figure 5, Drone Control™ Display (U.S. Army Photograph)

Figure 6, Drone Ace Aviator™ HUD (U.S. Army Photograph)

Figure 7, Drone Ace Minimal HUD (U.S. Army Photograph)

The field of view of each camera is verified in the demonstration through the use of a protractor and string. The string is drawn from the protractor axis and contacted on a wall with the video camera active, allowing the student to note the edges of the field of view and the subtended angle. The same is repeated for the nadir camera by placing the grid board on the floor. The altitude measurement accuracy of the ultrasonic altimeter is evaluated using a tape measure, monofilament line and a turning pulley. The monofilament line is attached to the center of the lower surface of the AR Drone™, thru the turning pulley at the floor. The tape measure case is mounted in a manner that would allow easy viewing. Then the Drone is powered up, the Drone Ace™ application is started and the displayed altitude is compared to the tape measure. The data is taken twice from the floor to the maximum length on the tape. See Figure 8 for typical results.

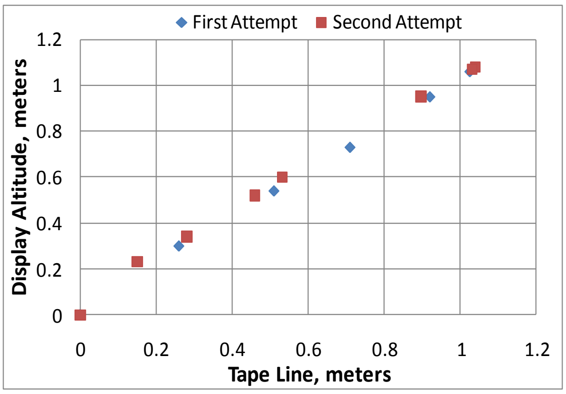


Figure 8, AR Drone™ Altitude Accuracy

Flight Cards and Setup

Each "test flight" is flown to a flight card. Specific parameters are required for each test flight and these are entered after the initial Wi-Fi link is made with the AR Drone™. This routine is conducted before each test flight, adding a certain amount of similarity to full-scale flight testing where fly-by-wire flight controls might be reconfigured before each test flight. This further emphasized time management through the use of proper flight test cards and procedures. A typical setup menu for the Flight Record™ application is shown in Figures 9, 10 and 11.

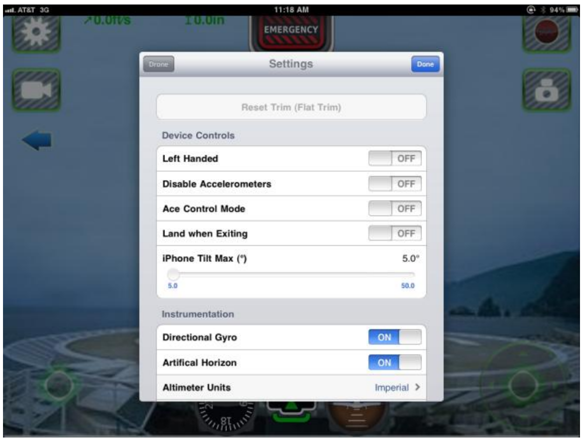


Figure 9, Flight Record™ Setup, page 1 (U.S. Army Photograph)

Figure 10, Flight Record™ Setup, page 2 (U.S. Army Photograph)

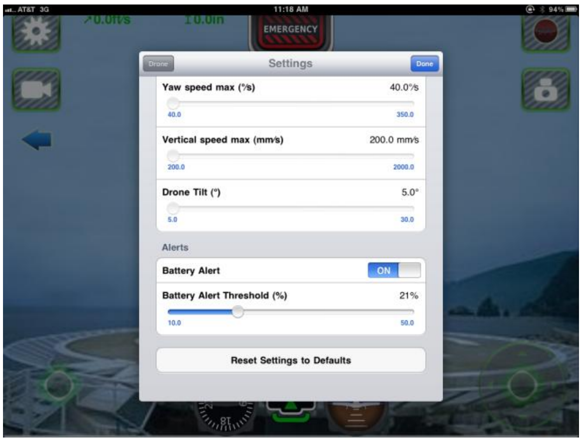


Figure 11, Flight Record™ Setup, page 3 (U.S. Army Photograph)

CONTROL FORCE EVALUATION

Control force is not a function of the input to the controller applications used with the AR Drone™; thus, the evaluation of acceleration-based (iPhone 4™ accelerometer outputs) control input is demonstrated. Breakout will appear as the first change in the least significant decimal place of the attitude displays.

The accelerometer/attitude output of the iPad™ and iPhone4™ are compared using an application called Tiltmeter™. The method of comparison is to stack the iPhone4™ on top of the iPad™ and running the Tiltmeter ™ application on each.

This provides the student some idea of the level of detail required to determine whether the "cockpit" controls would pass an ADS-33 flight control characteristics requirements; thus introducing the student to his first handling qualities specification. Figures 12 and 13 illustrate the results of this analysis.

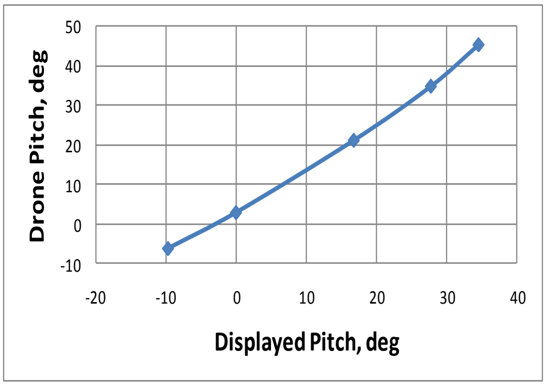


Figure 12, Pitch Attitude Calibration

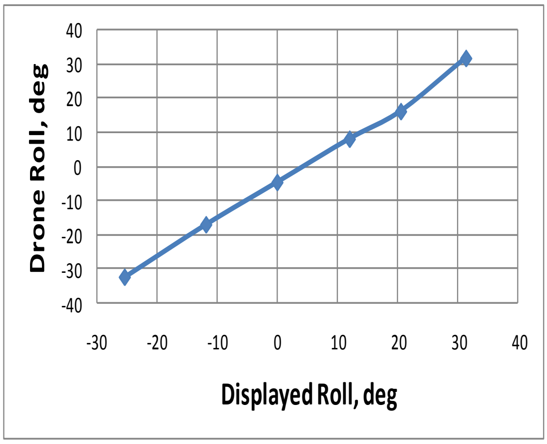


Figure 13, Roll Attitude Calibration

TRIMMED FLIGHT CONTROL POSITIONS

Trimmed flight control position (TFCP) tests are conducted using two different methods.

The first method consisted of testing the Drone™ attitude limits in the flight setup page before each flight. Starting with small pitch and roll angle settings, flight control inputs were made using each inceptor set (iPad™, iPhone™ 4), with output measured visually and with the post-flight data from the Drone Ace™ and Drone Control™ software. See Table 1for details of the flight control applications used for this demonstration. The inceptor is displaced well beyond the maximum input setting and the response is noted. Three axis velocities and altimeter data are also extracted into spreadsheet format. This data, along with the calibration data from the "cockpit" evaluation, allow a fairly comprehensive understanding of flight control authority to be determined. Table 1 shows the information available with each application, both on-screen and post flight in the form of video, audio and data.

Controller Application	In-flight Cueing						Available Post-flight			
Attributes	Alt	θ	φ	ψ	Vx	Vz	Data	Photo	Video	Audio
Flight Record	X			X	X			X	X	X
Drone Control					X	X	X	X		
Drone Ace	X	X	X	X			X	X	X	X

Table 1, Controller Application Attributes

The second method of demonstrating or conducting TFCP testing is using a control fixture to enable the operator to apply preselected control input; a method used quite frequently in full-scale aircraft handling qualities testing. Then, as discussed above, the output is noted visually and recorded for post flight analysis as shown in Figure 14.

This is followed immediately by some mission suitability testing outside in real wind/turbulence conditions, where the flight controls are first set to levels that are inadequate for the conditions...leading to loss of control and either an automatic landing, manual landing or emergency landing.

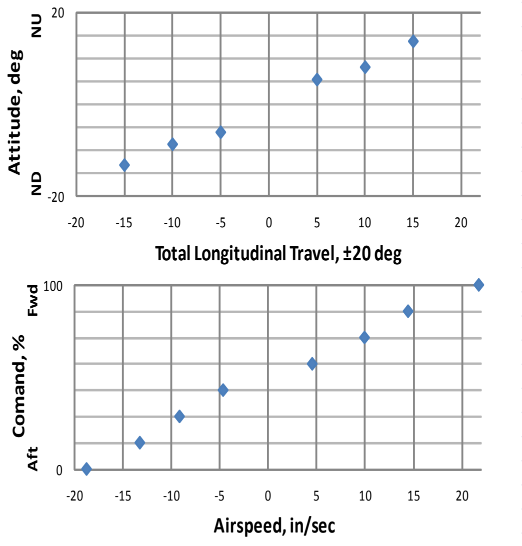


Figure 14, Trimmed Flight Control Positions

Static Stability

Static stability test techniques are demonstrated and practiced by masking the nadir camera to remove the optical velocity from the automatic hover mode and then trimming the aircraft to a known, non-zero attitude of interest before takeoff. Once airborne the inner loop of the onboard flight controls flies the aircraft to the preset trim attitude. The static stability of the aircraft about this trim point can then be tested by going to manual controls, departing from the trimmed flight control position and returning to trim by releasing the controls back to automatic. Because this aircraft has attitude command as its primary mode, static stability is not actually tested; but the method of testing is proper.

Handling Quality Ratings (HQRs)

By running U.S. Army experimental test pilots through the Automatic Flight Controls and Mission Task Element sections of the course, accepted Handling

Quality Ratings will be developed for the AR Drone™ in accordance with the Modified Cooper Harper Chart shown in Figure 15. These HQR's will be used as a baseline for each mission or maneuver element as part of the demo/primer course, allowing instructors with more technical flight control background than flight experience to provide the training…further reducing the cost to teach. Useable Cue Environment is also evaluated using the scoring criteria of Figure 16 and 17 [4].

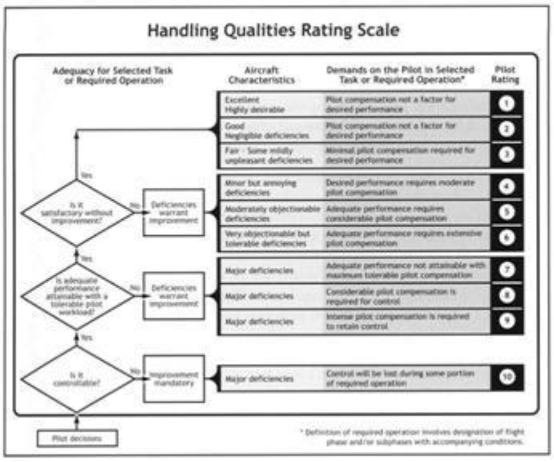
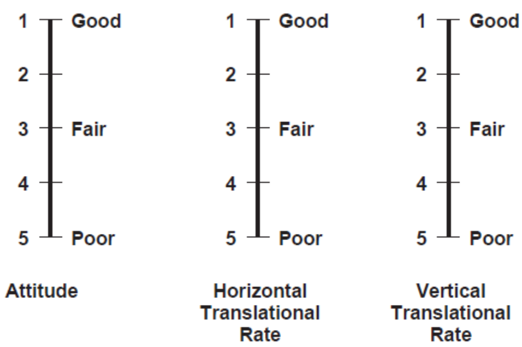


Figure 15 Cooper-Harper Scale



Pitch, roll and yaw attitude, and lateral-longitudinal, and vertical translational rates shall be evaluated for stabilization effectiveness according to the following definitions:

Good : Can make aggressive and precise corrections with confidence and precision is good.

Fair : Can make limited corrections with confidence and precision is only fair.

Poor: Only small and gentle corrections are possible, and consistent precision is not attainable.

Figure 16, Visual Cue Rating (VCR) Scale

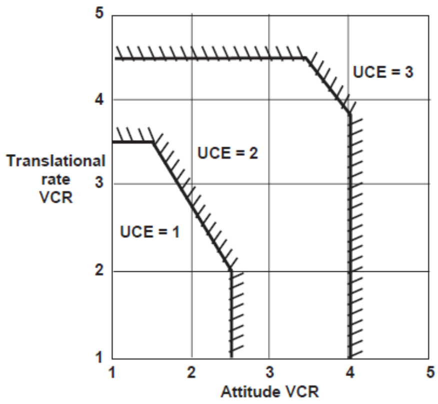


Figure 17, Usable Cue Environments for VCRs

The limited video field of view, flight control input delays and video latency make the AR Drone™ an excellent training aide for training in Useable Cue Environment testing.

Automatic Flight Control Modes Evaluation

The Drone has five automatic modes, in addition to strong stability augmentation in all three axes.

Altitude Hold

Altitude hold is evaluated at various altitudes to determine accuracy with respect to altitude and the stability of this hold mode. A sample graph, generated automatically in the Drone Control™ application, is shown in Figure 18.

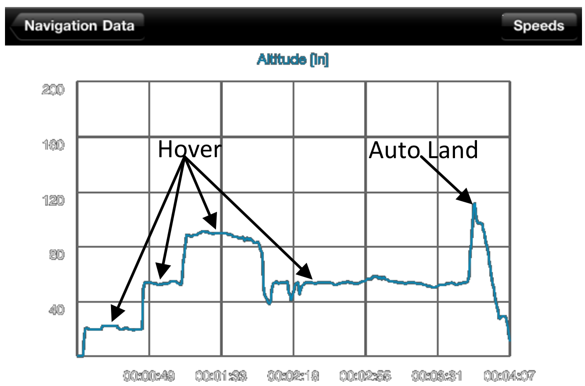


Figure 18, Sample Altitude Hold Data

Heading Hold

Heading hold is evaluated in no-wind conditions and with wind and gust. Testing to date verified that the aircraft does not have true heading hold, but instead has a very accurate directional rate gyro and drives all yaw-rate quickly to zero. Thus, for short periods of time (measured in seconds), the aircraft appears to have a heading hold mode.

Turn Coordination

Turn coordination is tested at various forward speeds and roll attitudes to determine if the yaw rate approximately zeroes out the lateral accelerations. A chart of angle of bank and ground speed versus turn rate can be used as a crude method of testing for proper turn coordination. The AR Drone™ aircraft used in the class will have 3-axis accelerometer sensors with a data recorder and telemetry to further enhance this type of training.

Automatic Takeoff

The AR Drone™ is programmed to perform and automatic takeoff to hover/position hold with a pre-assigned altitude of approximately 20 inches as shown in the first hover plotted in Figure 18. After the setup menu has been reviewed to verify the parameters for a specific flight test, the takeoff button on the touch screen is depressed and approximately 7 seconds later the aircraft is in a hover, stabilized in all three axes.

Automatic Landing

Automatic landing can occur in three specific scenarios with the AR Drone™.

- Exiting the controller application due to a phone call or for any other reason.
- Reaching a preset battery level.
- Pressing the landing touch icon on the display.

Upon initiation the aircraft begins a descent at a constant rate to approximately six inches, where the four motors are commanded to cut off. Though vertical rate of descent cannot be modified during the descent, longitudinal and lateral translation can be effected.

Mission task Evaluation

Early in the development of this demonstration/primer, it became apparent that though all of the ADS-33 Mission Task Elements can be evaluated, some provide a better training opportunity for the student than others. The pirouette is particularly difficult and more humbling than applicable. Below are the descriptions of two MTEs that appear more appropriate for this primer.

Hover

This MTE checks the ability to transition from translating flight to a stabilized hover with precision and with a reasonable amount of aggressiveness. It consists of approaching a hover point on a 45 degree relative heading at a ground speed that is scaled off the requirements for the scout/attack or cargo/utility aircraft. The student can execute this maneuver by simply flying the AR Drone™ while viewing it directly or by using both the cameras and direct viewing. Altitude hold and pseudo-heading hold can be used to greatly assist in this MTE and show the student how upper-level flight control modes can greatly improve rotorcraft performance.

Vertical Maneuvering

This ADS-33 Mission Task Element (MTE) is used by scout/attack unmasking and remasking, with an aiming task in the unmask phase. For cargo/utility helicopters the MTE is used to assess the heave axis controllability with precise station keeping.[4] Heading and pitch attitude are considered key parameters that required advanced flight controls. They are required to acquire, designate and launch weapons successfully. For a quad rotor aircraft, such as the AR Drone™, this maneuver might not be difficult, but as the rate of climb and descent is increased, even the AR Drone™ exhibits some heading hold limitations.

Conclusions

This paper has discussed a handling qualities demonstration/primer course built around a highly augmented, low cost UAV that reduces risk to both testers and property, and dramatically reduces training costs. Every MTE in ADS-33, including external cargo can be evaluated. For low airspeed handling qualities and automatic flight control modes, this approach gives the student outstanding insight into the planning, execution and reporting of classic handling qualities test techniques. The automatic hover that occurs anytime the student releases the flight controls removes most of the requirement for prior flight experience for student and instructor.

References

[1] Anon., "Rotary Wing Stability and Control", USNTPS-FTM-No. 107, December 31, 1995.

[2] Cooper, George E.; Robert P. Harper, Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", NASA TN-D-5153, April 1969.

[3] Parrot™ AR Drone™ user's manual, web-based, http://ardrone.parrot.com/parrot-ar-drone/usa/

[4] Anon., "Handling Qualities Requirements for Military Rotorcraft", Aeronautical Design Standard, ADS-33E-PRF, March 21, 2000.