Guidance, Navigation, Control, and Operator Interfaces for Small Rapid Response Unmanned Helicopters

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Abstract

This paper focuses on the development of small rapid response reconnaissance unmanned helicopters (1 to 3 kg, electric), for use by the military in urban areas and by civilian first responders, in terms of system architecture, automation (including navigation, flight control, and guidance), and operator interface designs. Design objectives include an effective user interface, a vehicle capable of smooth and precise motion control, an ability to display clear images to an operator, and a vehicle that is capable of safe and stable flight.

Introduction

Small electric helicopters, Figure 1, have been developed for hobbyists with impressive payload and endurance – at very small sizes (including outdoor suitable vehicles at less than 1 kg) and low cost. These small aircraft have relatively low noise, and are a minimal hazard to people to due a relatively small amount of energy in the rotor, compared to typical helicopters and other VTOL platforms. Compared to existing small unmanned aircraft, a helicopter offers stop and stare capability, and the ability operate at low level and within urban areas. Compared to existing VTOL systems (such as ducted fans), they tend to be quieter, lower-weight, less expensive, can handle more wind, and have a greater endurance.

Figure 1, Small Electric helicopters (1 to 3 kg) have the potential to be effective platform for urban combat surveillance and for first responders given their relative safety, if related guidance, navigation, and control issues can be addressed.

This paper focuses on the development of small rapid response reconnaissance unmanned helicopters (less than 4kg, electric) for use by the military in urban areas and by civilian first responders, Figure 1. Issues relating to system architecture, automation (including navigation, flight control, and guidance), and operator interface designs are explored. The following missions were considered in this study:

- Obtain Information for planning: entry points, escape routes, locations of threats and civilians
- Check area immediately prior to and during forced entry
- Locate threatening individuals
- Inspect suspicious vehicle, inspect suspicious object
- Follow/chase individuals who are on foot
- Find an escape route in real time
- Inspect otherwise inaccessible objects/structures
- Document incident location for evidence

Design objectives include an effective user interface, a vehicle capable of smooth and precise motion control, an ability to display clear images to an operator, and a vehicle that is capable of safe and stable flight.

System Architecture Options

Existing small unmanned aircraft are flown in a variety of different ways, from pure manual flight by an operator seeing the vehicle from the ground (the manner in which hobbyists fly model airplanes) to highly autonomous systems where high-level plans are provided prior or during a mission. Options for configuring the proposed small rapid response helicopters in terms of operator input are explored in Table 1. Keep in mind that multiple automation configurations might be possible within a single design. To enable non-line-of-sight operation, to achieve minimal operator training, and (most importantly) enable the most effective ability to quickly obtain desired images from the onboard camera the remainder of this paper will emphasize velocity/position control – typically through joystick inputs to change the camera view in a manner similar many video game interfaces. Enabling waypoint operations as another option is a relatively trivial extension to the capability to do velocity/position control, and so it is anticipated that systems such as these would have that option for operator control also.

Table 1: Pros and cons of selected methods for operator control of a small rapid response unmanned helicopter; emphasis of remainder of paper is on the velocity/position control of the camera position with option to fly waypoints.

Operator Control Configuration	**Pros**	**Cons**
Pure manual as seen externally	▪ Avionics very simple, immediate start-up ▪ Traditional method for flight of model aircraft, legacy method	▪ Requires non-trivial training ▪ Non-line-of-sight flight impossible
Pure manual through onboard video	▪ Avionics very simple, immediate start-up (note: need onboard video anyway)	▪ For the operator: difficult to the point of being impractical
Stability augmentation or Attitude command through onboard video	▪ Relatively simple avionics	▪ Requires non-trivial training
Velocity/position control through onboard video	▪ Least training required for operator of any listed here ▪ Typically highest performance in terms of quickly obtaining desired images, particularly at unprepared sites	▪ Requires measurement of velocity, relatively complex avionics ▪ Longer start-up time (e.g., GPS lock)
Waypoints/routes	▪ For prepared sites (where coordinates are previously surveyed), enables high-level commands to be used by operator (e.g., go look at a specific window). ▪ Useful for “return to base” and lost communication procedures	▪ Requires measurement of position, relatively complex avionics ▪ Longer start-up time (e.g., GPS lock) ▪ Can be awkward to get desired video at unprepared sites

Related to the choice of method for the operator to control the flight path is the choice of method for obstacle avoidance. A summary of the choices for method is given in Table 2. At the very small sizes explored in this paper, choices of existing obstacle avoidance sensors are extremely limited. As a result, the emphasis of the remainder of the paper will be on operator performing the obstacle detection task (which does go well with operator input being velocity/position control). However, sensor technologies to enable small aircraft and VTOL aircraft to have automated obstacle detection are an important area of active research, and so changes are anticipated in this area in the future.

Table 2: Choices for obstacle avoidance; emphasis of this paper will be on operator performing obstacle avoidance through high-level position/velocity commands utilizing the onboard video

Obstacle Avoidance	Pros	Cons
Operator as seen externally	▪ No sensors required ▪ Traditional method for flight of model aircraft, legacy method	▪ More training required ▪ Non-line-of-sight flight impossible
Operator as seen through onboard video	▪ No sensors required (note: need onboard video anyway)	▪ Onboard video must be usable for both collision avoidance and obtaining useful images – a problem when want to fly in a different direction than what one needs to look at or use a narrow field-of-view zoom
Automatic obstacle avoidance	▪ Potentially safest (automatic avoidance could be seen as augmenting operator avoidance)	▪ Availability of suitable sensors at this size

The architecture that is being emphasized in this paper requires onboard video to be used for collision avoidance, flight path control, and to obtain the desired surveillance images (purpose of the mission). This “triple use” may lead to excessive compromise of the video signal design for some applications, but seems appropriate when the extremely small size important. Simulation and flight test experimentation revealed that a fixed camera with approximately a 60-80 degree wide field of view mounted to point out the front of the aircraft and tilted down so that the horizon is just visible at the top of the image (pointing down 15-20 degrees) was good compromise of these three purposes. Since the vehicle would normally be at a higher altitude that what it is looking at and not directly above it, this eliminated the need for a tilt mechanism or the need for the operator to worry about the tilt of the camera. This field of view was sufficient for obstacle avoidance even without a pan or tilt mechanism. It is also found that the small size and low noise of these aircraft makes it practical to approach the object being viewed rather than requiring a zoom to smaller field-of-view, which eliminates some further complexity and weight.

Guidance, Navigation, and Control

Here, a custom avionics system was utilized to perform onboard guidance, navigation, and control functions[1]. This includes a sixteen state Extended Kalman Filter (EKF) that uses data from the onboard sensors to generate a navigation solution that closely estimates the state of the system[2]. The EKF serves several important functions including: 1) estimating the orientation of the system from accelerations and angular rates, 2) removing process and measurement noise from the measurements, 3) providing state estimates at 100 Hz, even though most sensor measurements are taken at a much slower rate, and 4) blending GPS and pressure altitude data. Of particular challenge here is obtaining good estimates with the relatively poor inertial measurement performance obtained on such a small vibrating platform. The states in the navigation filter include: four quaternion components, three position states, three velocity states, and six accelerometer and gyro biases.

The guidance and flight control architecture is shown in Figure 2. It includes a dynamic inverse inner loop (attitude) and outer loop (position/velocity). The outputs of the outer loop inverse law represent the desired values of attitude and angular rate, which are fed to the inner loop. The inner loop inversion is based around an invertible, linear helicopter model.

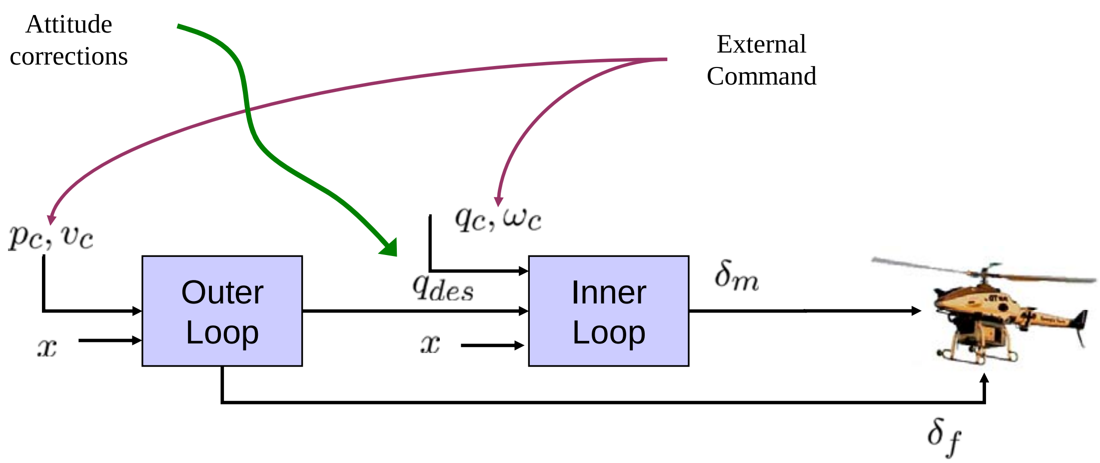

Figure 2: Guidance and control architecture utilizes position, velocity, and attitude commands from trajectory generator (generated from joystick inputs or from specified waypoints) as external input. An outer loop utilizes force control (collective) and inner-loop commands (attitude) to achieve desired position/velocity. An inner loop utilizes moment controls (cyclic and tail rotor) to achieve that command.

Operator Interface

Given the importance of the onboard video for the prescribed mission of the proposed systems described in this paper, and the additional burden of having the operator use this same imagery for obstacle avoidance, it was chosen to center the operator interface around the video. To that end, all required display and many of the input elements are on the video itself, Figure 3. A map display is also normally utilized to display the same information in what is often a more useful way (i.e., relative to map features).

The display elements include:

- Aircraft attitude (particularly heading)
- Aircraft position and altitude
- Aircraft speed
- Battery voltage
- Status of communication between control station and helicopter
- Status of navigation system
- Mode of guidance system (joystick vs. waypoints)
- Predicted path of current set of waypoints
- Fault indicators (low battery, GPS lock)

Input elements include:

- Adjust commanded velocity/position with joysticks, Figure 4
- Initiate rotor spin up, take-off, and shutdown after landing with joystick buttons
- Enter waypoints, engage flight of waypoints (mouse or stylus)
- Adjust map display, center, zoom, overlays (mouse or stylus)

Figure 3: Prototype Operator Interface during flight testing in urban area (Left) video with overlaid status information (Right) map display; All important display elements are on the video (status panel on bottom, key numerical values on upper left, compass display at center).

Figure 4: Typical of the operator input devices used in this work: Two two-axis joysticks on the device are used to allow the operator to adjust move the camera view up/down, left/right, and forward/backward; and to turn left/right. Letting go (centering) both sticks results in hover at the current location.

Flight Test Results

A series of flight tests were conducted to verify the functionality of this class of rapid response helicopter. This includes approximately 20 flight test days with the Logo-based aircraft and approximately 20 flight test days with the T-Rex-based aircraft, Figure 5.

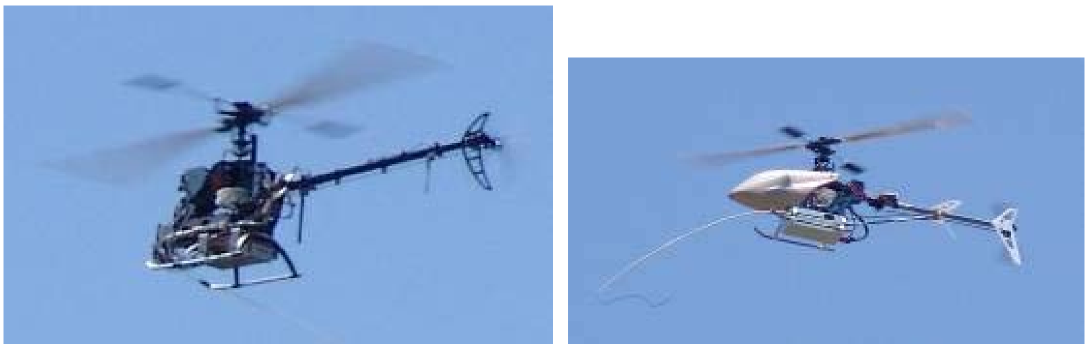

Figure 3: Two types of aircraft were utilized for testing and development under this project, (Left) a 3 kg system based on the Mikado Logo 14 hobby helicopter, (Right) a 1 kg system based on the Align T-Rex 450 hobby helicopter, the latter in cooperation with Adaptive Flight, Inc.

The first type of test was to verify the guidance, navigation, and control system as designed and implemented/installed. Some of those results are briefly summarized here. Figures 5-7 shows results for single a test sequence of the T-Rex-based aircraft, which includes hover and then a shortly spaced series of relatively aggressive maneuvers in each direction. The maneuvering segment represents the operator attempting to precisely get a desired image or to maneuver quickly among closely spaced obstacles. Figure 5 shows the roll and pitch attitude, clearly delineating the hover segment (first 35 seconds) from the maneuvering segment. The roll and pitch attitudes peak around 15-20 degrees, indicating relatively short/quick maneuvers – particularly when one also considers Figure 6, showing the horizontal velocity never exceeding approximately 10 ft/sec.

Figure 6 and 7 show horizontal and vertical tracking performance respectively. They indicate that it is practical to operate within 10 feet horizontally and 5 feet vertically of obstacles under these conditions, which is consistent with the conclusion that perhaps flying closer to objects of interest can be utilized rather than camera zoom, depending on other considerations. The plots show estimated position, and it should be noted that horizontal position estimate performance is limited in this case by the performance of GPS, and so can be expected to slowly drift approximately 15-20 feet horizontally. This implies that one must remain further from obstacles if one is not going to be vigilant about staying clear of obstacles (such as an extended hover while operator performs another task). This is much less of an issue in the vertical, where barometric altimetry is utilized.

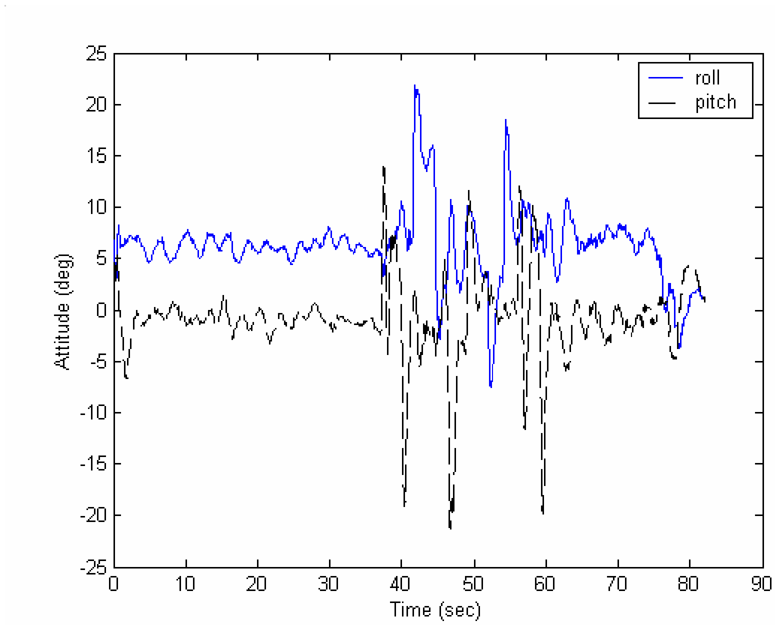

Figure 5: Roll and pitch attitude angles of the T-Rex based aircraft during a period of stable hover, and then during some precise/rapid repositioning. Note roll and pitch angles reach peak values of 15-20 degrees, indicating relatively aggressive tracking of commands.

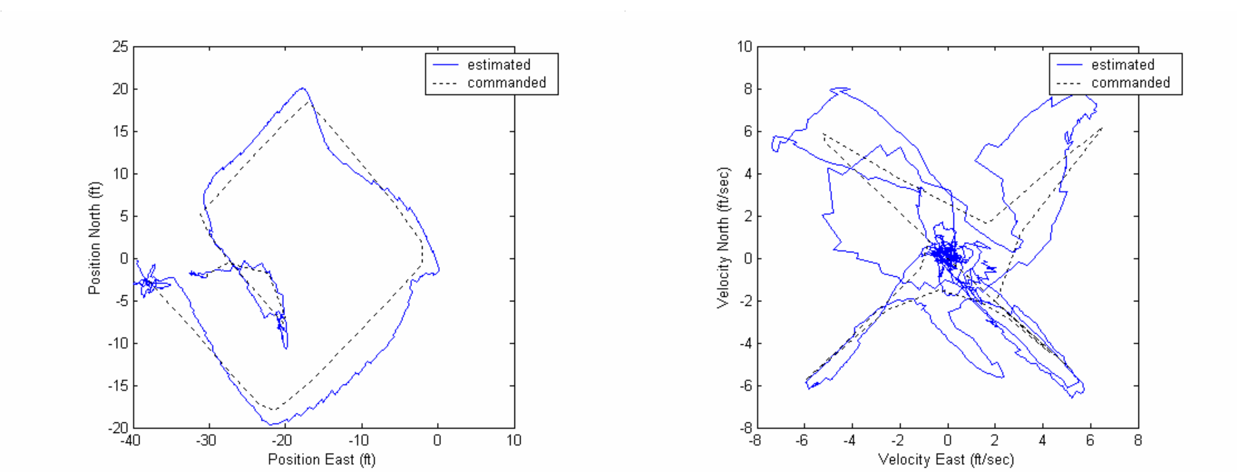

Figure 6: Horizontal position and velocity (estimate and command) corresponding to same flight condition as Figure 5; note: "commanded" velocity is effectively a feed-forward term, and is modified to enable tracking commanded position. Performance indicates that it is practical to maneuver with approximately 10 feet of obstacles even with these relatively aggressive and closely-spaced maneuvers.

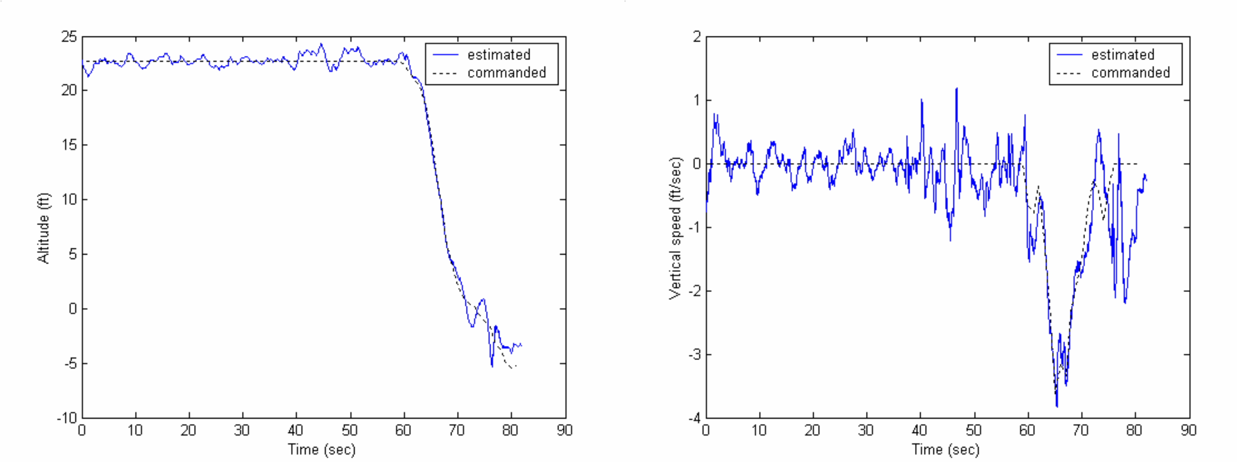

Figure 7: Altitude and vertical speed (estimate and command) corresponding to same flight condition as Figure 5 and 6; note: "commanded" vertical speed is effectively a feed-forward term, and is modified to enable tracking commanded altitude.

In addition to guidance, navigation, and control verification flights, a number of flights were conducted to evaluate in a more operational context. This enabled additional verification and iteration of the operator interface concept. These results are summarized in the following paragraphs, with some conclusions and in some cases links to video clips.

American Helicopter Society Redstone Chapter "1st Responder Competition, in Huntsville, Alabama: The Logo-based system was flown several times performing a simulated First Responder mission. This was simulated by placing numbers on windows of a large building. The operator utilized the helicopter system to, from a remote location, circumnavigate the building reading those numbers. The competition score was determined by accuracy of number reading and speed, among other criteria.

The T-Rex-based system was flown several times at the McKenna urban training site within Ft. Benning, Georgia. This facility is utilized to train military personnel for urban operations. The system was operated from within one building, and utilized to fly between buildings, below wires, and simulate inspection of items in the area. System was operated for extended periods without line-of-sight. The T-Rex-based system was also flown at three different law enforcement facilities in Georgia and Alabama to demonstrate similar operations.
External: http://uav.ae.gatech.edu/videos/x070622a1_downStreetUnderWires.wmv (6.7Mb)
External: http://uav.ae.gatech.edu/videos/x070622a2_downStreetUnderWires.wmv (4.2Mb)
Onboard: http://uav.ae.gatech.edu/videos/x070622a1ob_mckenna_uncompressed.avi (1.3Gb)
Video Description: These videos are of one of the Hornet Micros flying at the McKenna Military Operations in Urban Terrain (MOUT) training location in Ft. Benning, Georgia.

Two T-Rex-based systems were flown at the Association for Unmanned Vehicle Systems, International (AUVSI) exhibit practice and show at Webster Field in Maryland. Show included flight to 200 feet, inspecting car, looking into window, following a group to a car, chasing a car, and two aircraft operations.

External: http://uav.ae.gatech.edu/videos/hx070806a1_auvsiWholeThing.wmv (126Mb)

Onboard: http://uav.ae.gatech.edu/videos/hx070806a1ob_auvsiWholeThing_uncompressed.avi (2.2Gb)

Video Description: These videos are from two Hornet Micro UAS aircraft flying at the AUVSI exhibit at Webster Field, Maryland in August of 2007. You see both aircraft perform a demonstration mission. There is a takeoff/landing, climb to 200 feet for a "look around" above the field, descent to inspect a car, inspecting a building, and a simulated car chase.

Conclusions

The developments described here have resulted in a practical unmanned helicopter as small as 1kg, with the tremendous advantages of cost, (lack of) noise, and safety that come with this small size. The systems are capable of performing effective short-range surveillance missions in an urban area. The systems are able to obtain images similar to unmanned airplanes when they are operated at relatively short ranges and low altitude. The same systems are also able to obtain images similar to what is possible with unmanned ground vehicle when operated outdoors. As a result, it is anticipated that these types of systems can be utilized to fill the significant surveillance "gap" between ground-based systems/observers and existing aircraft.

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