Helicopter Automation Using a Low-Cost Sensing System

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Abstract

This paper details the design of an autonomous helicopter control system using a low cost sensor suite. Control is maintained using simple nested PID loops. Aircraft attitude, velocity, and height is estimated using an in-house designed IMU and vision system. Information is combined using complimentary filtering. The aircraft is shown to be stabilised and responding to high level demands on all axes, including heading, height, lateral velocity and longitudinal velocity.

1 Introduction

This paper discusses the design of a helicopter automation system using simple PID control and low cost modules for state estimation. Helicopter automation is a challenging problem, given both the time varying nature of the dynamics due to environmental conditions, and the effect of aircraft vibration on both sensor readings and general avionics integrity. These problems are exacerbated in small size aircraft such as our Xcell-60 (see Figure 1), where vibration isolation is more difficult, and the sensor options are limited to those possessing both low weight and low power consumption characteristics. It is also important that their cost has a comparable scale to that of the aircraft; i.e. one hundred thousand dollars worth of sensors on a five thousand dollar aircraft reduces the practical impact of such a system to market.

A diverse range of control has been applied to helicopter automation, including gain scheduling [13], linearization feedback [7, 10], fuzzy control [14, 4], neural networks [10, 2], and simple PID [12, 1, 15]. While all have demonstrated successful flight control on experimental small size platforms, PID continues to dominate most small scale helicopter control due to its simplicity, and ease of design in the absence of any form of aircraft model.

Most automation systems make use of expensive inertial and DGPS systems ([8, 5, 9, 6]. In particular, expensive RTK positioning systems such as the Novatel RT2 Millenium provide accurate position (<2cm error) and velocity estimation at 10Hz update. Such accurate velocity

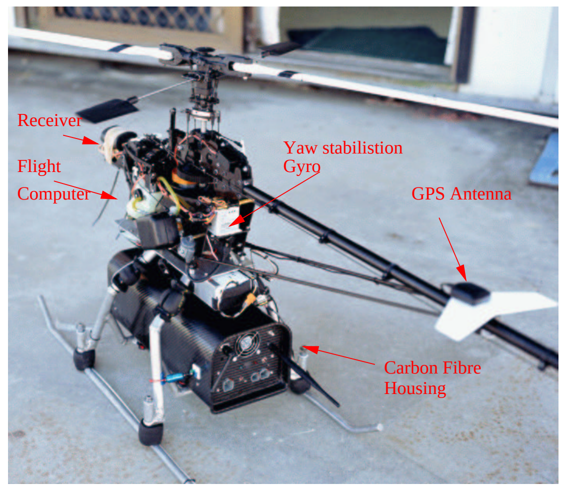


Figure 1: *Xcell 60 Helicopter Platform*

estimates greatly simplify the automation problem. In fact, while it is true that helicopters are non-linear, time varying, coupled plants, it is the problem of sensing aircraft state that is the real challenge for small size helicopter control. With accurate sensing, well tuned decoupled PID controllers can provide levels of control upon which meaningful missions can be executed.

2 Flight Vehicle

The flight vehicle is an XCell-60 commercially available RC helicopter fitted with custom avionics. This vehicle replaces the JR Ergo-60 used during our early experiments. The XCell-60 uses a petrol rather than methanol engine, resulting in lower engine speed and hence less vibration. The petrol engine also provides around twice the lift capacity and almost three times the flight duration. Flight duration on a single tank of fuel is approximately 18 minutes. The aircraft has a main rotor diameter of approximately 1.5 meters, total length of 1.8 meters,and weighs around 8kg including avionics. The majority of the avionics are located in a carbon fiber housing mounted beneath the helicopter using springs and dampers for vibration isolation. More robust landing gear has also been designed to absorb the inevitable heavy landings during prototyping. The aircraft with modified undercarriage stands approximately 0.6 meters tall.

3 Avionics and Sensors

The main computer used for data logging and control is a Pentium III 733MHz based PC104 stack equipped with wireless ethernet, frame grabber, and camera multiplexing board used for fusing images from multiple cameras. The onboard sensors include IMU running at 50Hz, stereo vision running at 5Hz, and DGPS running at 1Hz. DGPS is not used at this stage, as it was intended that all low-level stabilising control (height and velocities) be conducted in a fully self-contained manor. It is intended that DGPS will then be used purely for waypoint positioning. The main computer interacts with the control servos via a flight (safety) computer located in the aircraft's nose. This safety computer acts both as a signal router, and facilitates manual override using fail-safe relays. Thus all computers, including itself, can be locked out during an emergency. This is discussed in more detail in [11, 3].

The IMU weighs around 65g and is 50mm cubed. A combination of rate gyros, accelerometers, and magnetometers are used to generate roll,pitch and heading estimates. The complimentary filtering technique is used for data fusion. All filter processing is performed on-board the unit. This is also discussed in more detail in [11, 3].

The stereo vision system is combined with the IMU rates and acceleration measurements to estimate aircraft velocities [x,y,z] and height. The actual image processing techniques employed are described in [11, 3], as to is the complimentary filtering used for fusing the lateral/longitudinal information sources. Until recently, however, vertical velocity and height estimation had been performed using only visual information. Vertical velocity and height estimation now fuses vision with accelerometer data using complimentary filters. The complimentary filter structure is shown in Figure 2. Stage-1 provides vertical velocity estimates, while Stage-2 provides height estimates. The differential of the vision-based height estimate is used as the 5Hz reference signal to Stage-1, with the accelerometers providing 50 Hz interpolation updates. The estimated vertical velocity is then used as the 50Hz interpolation update source to Stage-2, with vision-based height estimates acting as the 5Hz reference. A comparison of the raw vision, and complimentary filter vertical velocity and height estimates is shown in Figure 3.

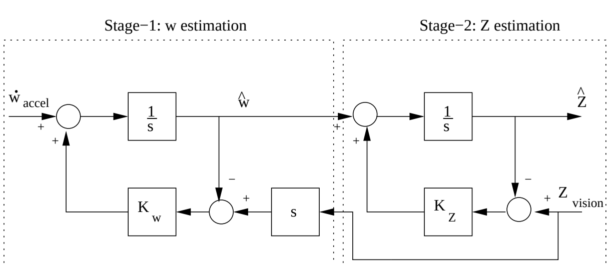
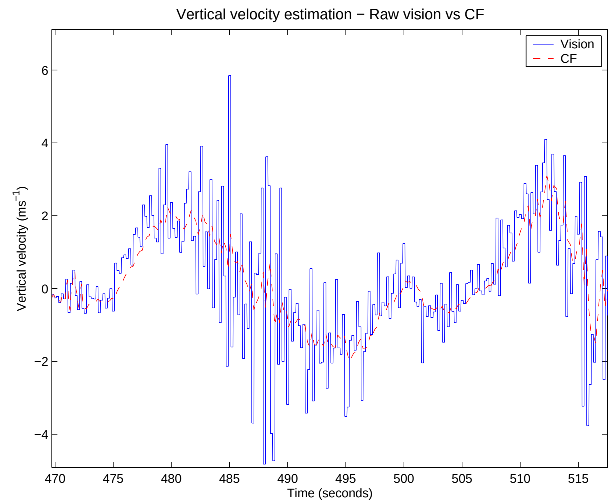
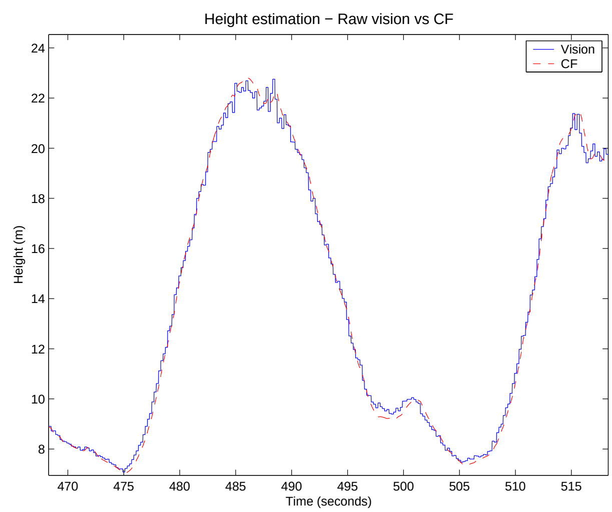


Figure 2: *Vertical complimentary filter.*



(a) w estimate



(b) Z estimate

Figure 3: *Comparison between raw vision and complimentary filter Z and w estimates.*

4 Engine Governer

The first thing that must be automated is throttle control. If the pilot still has throttle authority, then they could still directly manipulate the aircraft height, even if the height automation system (demanding collective pitch) is engaged. A purely feedforward approach which maps the relationship between throttle and collective pitch stored in the handset is unacceptable, since the pilot needs to tweak these settings at the start of each flight day. Feedback control using an RPM sensor coupled with a feedforward term from the collective pitch to improve regulation response has been found to be most effective. This structure is shown in Figure 4.

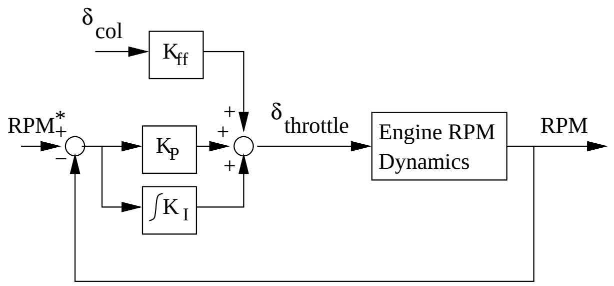


Figure 4: *Engine governer.*

5 Attitude Control

Heading (ψ), roll (ϕ) and pitch (θ) control is implemented using simple PI modules; their generic structure is shown in Figure 5.

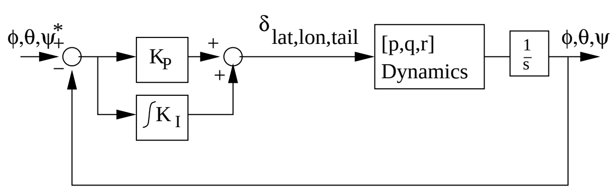


Figure 5: *Attitude control modules.*

The integral compensates for two types of variance. The first and most simple source is that associated with aircraft maintainence resulting in control linkage length changes, and hence servo positions for trimmed flight; this variation occurs between flights. The adaptation for this type of variation can be seen in Figure 7 where there is initially a large SSE which is then removed by the integral action. The second source of variation, dependant on the axis in question, occurs continuously throughout a flight. In the case of the yaw axis, the required rudder input to counter the torque induced by the main rotor changes under varying rotor loads. In the case of the roll and pitch axes, the second source of variation is wind magnitude and direction changes altering the flapping characteristics of the dynamics; this variation occurs during a flight. The tracking performance of the heading, roll, and pitch modules is shown in Figures 6, 7 and 8 respectively.

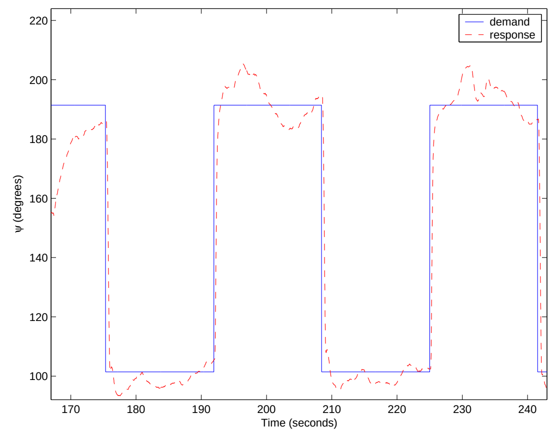


Figure 6: *Heading tracking.*

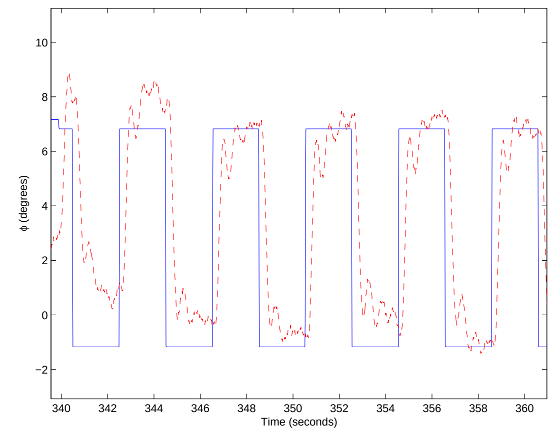


Figure 7: *Roll tracking.*

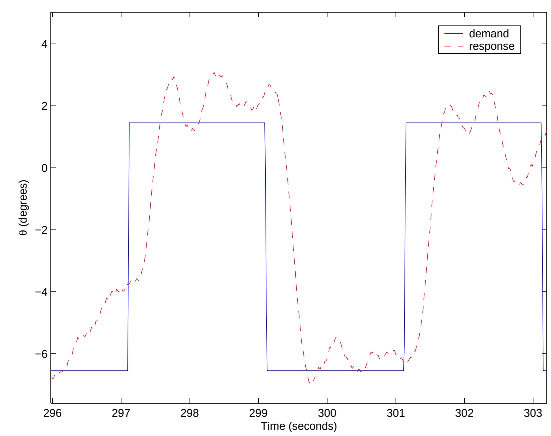


Figure 8: *Pitch tracking.*

6 Horizontal Velocity Control

Each axis of velocity control is implemented using the two level, nested loop structure shown in Figure 9. Lateral

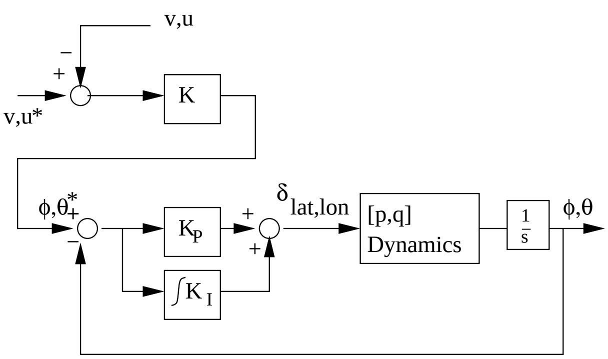


Figure 9: *Horizontal control modules.*

velocity (v) errors are used to generate roll demands for the roll (ϕ) control module, while longitudinal velocity (u) errors are used to generate pitch demands for the pitch (θ) control module. Integral should also be added to the outer velocity loop to compensate for the varying attitude-to-horizontal acceleration relationship resulting from varying wind conditions. This is intended to be the next step in our control testing.

The lateral and longitudinal velocity control tracking is shown in Figures 10 and 11. Also shown is the demand tracking of the inner attitude loops.

7 Vertical Control

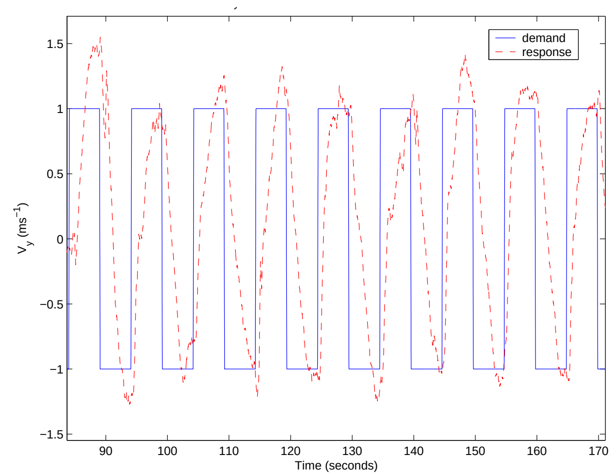
Vertical control either takes the form of vertical velocity regulation or height regulation. The vertical velocity control uses PI feedback. For height control both the use of proportional control to send velocity demands to the nested vertical velocity loop as shown in Figure 12-(a), and stand-alone PID control shown in Figure 12-(b) are being investigated. The integral action in both cases compensates for linkage changes during maintainence, and for changes in the heave dynamics due to wind gusts.

At present, only vertical velocity PI control and height control results using the stand-alone PID module are available. Testing of the nested structure is continuing over the coming week. The tracking of the vertical velocity control module responding to user specified velocity demands is shown in Figure 13. The tracking of the height control module responding to user specified height demands is shown in Figure 14

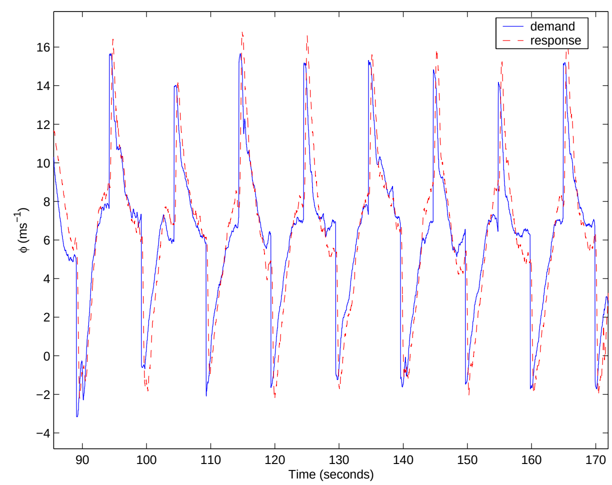
8 Conclusions

This paper has presented the design of a helicopter automation system using low-cost avionics, and a simple control approach. Sensing is conducted using custom inertial and vision modules. The use of cheap sensing distinguishes this project from others which use expensive inertial/GPS modules. Heading, roll, pitch, 3-axis velocity, and height regulation have all been demonstrated. While further tuning of the control parameters is likely to see an improvement in tracking performance, all axes are stable, providing an airborne platform base with which more advanced experiments can be conducted. This completes stage one of the project.

The next intended stage is comprised of several streams. These include sensing reliability and contingencies for individual sensor outages, forward flight, take-off and land-

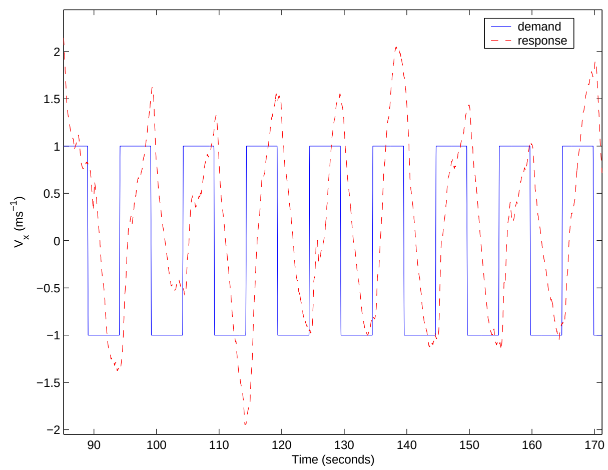


(a) Velocity tracking

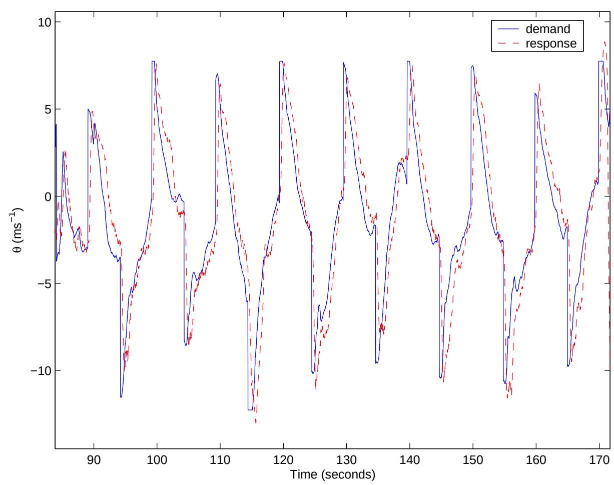


(b) Corresponding Roll tracking

Figure 10: *Lateral velocity tracking*

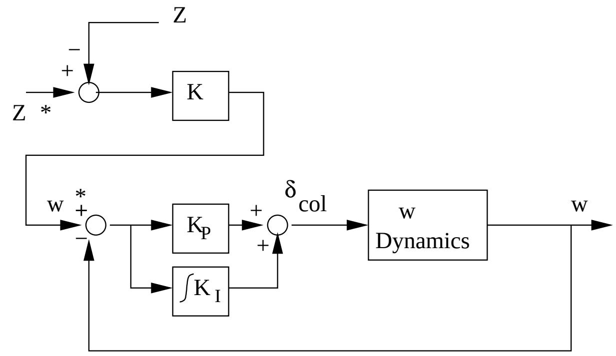


(a) Velocity tracking

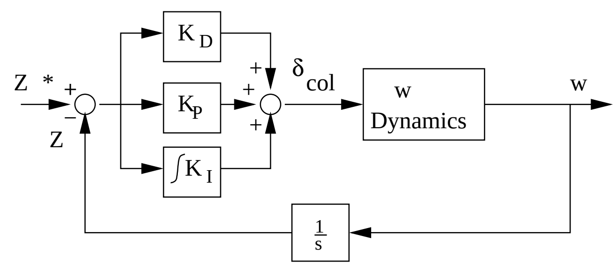


(b) Corresponding Pitch tracking

Figure 11: *Longitudinal velocity tracking*



(a) Nested loop structure.



(b) Stand-alone PID.

Figure 12: *Vertical control module.*

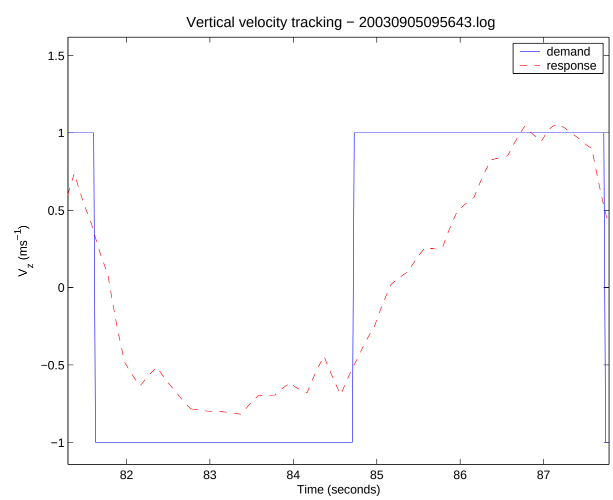


Figure 13: *Vertical velocity tracking.*

ing, and aggressive manuevers. Work into achieving take-off and landing, and performing aggressive manuvers has already begun, and we should see results before the end of the year.

Acknowledgments

The authors would like to thank the whole automation team for their invaluable assistance and support. In particular, Craig Worthington, Les Overs, Stuart Wolfe, Steven Brosnan, Pavan Sikka, Graeme Winstanley, Mathew Dunbabin, Elliot Duff, and our pilot Fred Proos.

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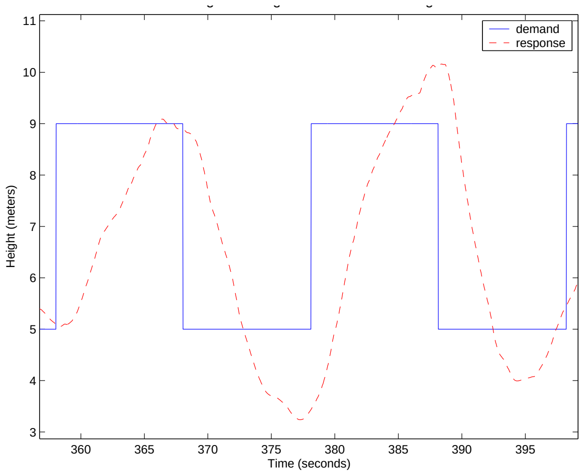

Figure 14: *Height tracking.*

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