Design, construction and modelling of a low cost, miniature UAV using machine vision

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Abstract

The price barrier for the implementation of UAVs commercially is substantial, limiting growth in this area. This paper presents results from a project aimed at developing light-weight and low-cost systems for the on-board control of a small scale commercially available helicopter, targeted at the low-end of the market. This would allow UAVs to be used by relatively untrained operators.

The control system consists of two major streams, a vision system for high-level control and a low-level attitude control system. The vision system has been developed using a combination of a blackfun processor and an inexpensive cmos camera to implement colour segmentation algorithms. The attitude control system is developed using Fleck wireless sensor nodes developed at CSIRO. These inexpensive nodes perform sensing and control of the helicopter for data acquisition purposes. Flight data has been used to identify and verify a dynamic model of the helicopter.

1 Introduction

Helicopters are a very versatile aerial vehicle. Their ability to hover and achieve vertical take off are traits that make them suitable for many tasks including photography, surveillance and search. A full sized manned helicopter however requires approximately $4000 per hour to run [Burke]. In order to make the usefulness of helicopters more accessible, smaller unmanned versions are being created.

UAVs eliminate the human element, allowing versatile designs which would be impossible with a human crew. UAVs also offer the potential of lower operating costs and are capable of undertaking high risk missions. The development of vision systems for UAVs is a growing research area with contributions from a large number of research institutions.

The CSIRO Micro-Heli project is intended to fill a void in the UAV development community for a very small scale, fully self contained hovering rotorcraft platform. Such a platform has been designed using external processing and sensing equipment [Gurdan, Stumpf *et al.*] as well as in larger and easer to control helicopters [Bhandari, Colgren *et al.*]. A small integrated platform however, will allow the inexpensive creation of a number of micro-scale UAVs as platforms for future experimentation.

The system presented here is targeted at small, low-cost platforms with the aim of opening up the commercial UAV market to ‘everyday’ applications. The entire flight system weighs in at less than 1kg and at a cost of under $1500, which includes the helicopter (an Align T-REX450s) and the vision and control systems.

In brief, the helicopter control platform is a lightweight system which is able to receive servo signals, control servos, read sensors and communicate to a wireless base station for data collection and development.

The vision system is intended to provide high level control of the helicopter based on vision data from a camera. The system has been developed to calculate helicopter position and yaw relative to a ground based target. Colour segmentation has been used in conjunction with a colour based target for computational efficiency.

2 Literature Review

Helicopter stabilization has been achieved on larger scale UAVs [Bhandari, Colgren *et al.*] however this project has been designed to achieve stabilization on a commercially available model electric helicopter of less than 1 kg. The small scale of this particular helicopter presents some interesting problems in terms of carrying capacity and control dynamics; however it will also provide a lower cost solution for an aerial platform.

UAV development is increasingly reliant on vision systems to provide automation. Vision systems are capable of identifying targets, avoiding obstacles and providing a fixed reference to the surrounding environment. Many existing vision systems developed for micro UAVs rely on off-board processing which relies on a wireless connection between the vehicle and base station. A key aspect of the vision system discussed in this paper is that all processing is done on-board. This means that the system is capable of truly autonomous operation without relying on a connection to a base station.

The implementation of an on-board vision system is severely limited by payload capability and power supply. These limitations require the use of an embedded DSP microcontroller.

Since the vision system is used in the real time control of a micro UAV it is essential that helicopter position and velocity is updated as fast as possible. Optic flow can be used to calculate ground speed, however the process can be computationally expensive. A review of fast optic flow algorithms [Ortiz and Neogi] implemented on a 2GHz computer using a 320x240 colour BMP image shows processing time in excess of 0.2 seconds and up to 1.4 seconds. Instead, the system developed in this paper relies on straightforward colour segmentation which is used to determine both position and velocity in a computationally efficient manner.

Colour segmentation has been used in the RoboCup domain where real time performance and speed is critical [Wasik and Saffiotti]. Colour segmentation has been used as it is computationally efficient and produces effective results in a controlled environment. A method of colour segmentation known as seeded region growth (SRG) has been successfully implemented on mobile robots [Aziz, Shafik *et al.*]. The aim of the developed vision system is to use a variety of colour segmentation methods to develop a fast and robust system to determine position on the target platform.

3 Physical Systems

The aircraft used for this research is the Align T-rex 450s, see Figure 1. This hobby helicopter has a main blade span of approximately 70cm and is driven by a brushless electric motor. The power for the entire system comes from a single 11.4V hobby Li-Po battery which is regulated for the various components. For controlling the pitch of the main rotor and flybar, this helicopter uses a 3 axis swash-plate.

Figure 1 - Align T-rex 450s Helicopter

The actuation of the various helicopter components is performed by 9g hobby servo motors. These servos are rotary actuators that act over a range of +/-90 using a PWM signal. There are 4 such actuators on the helicopter as well as a motor speed controller which also uses a PWM input for speed control, resulting in a total of 5 input variables that are required to control the helicopter.

4 Electronic Systems

The electronic systems used to control the helicopter can be separated into two distinct sections; helicopter control and the vision system. Each is discussed in the following sections. Figure 2 shows the control electronics on the left, vision DSP on the right and the camera in the centre of the undercarriage assembly.

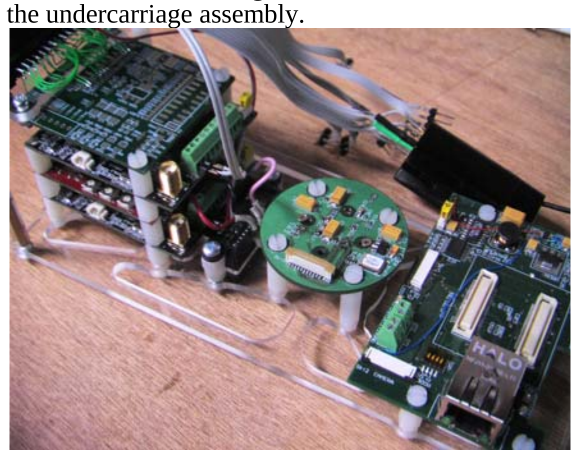

Figure 2 – Electronic Systems

Helicopter Control System

The embedded systems used for this project are the Fleck nodes developed by CSIRO [Sikka, Corke *et al.*].These sensor nodes integrate an Atmel microcontroller, wireless communication and various add-on capabilities into a small package. For this project a total of 3 Flecks are used. Two Flecks are onboard the helicopter with one performing the real time control of the helicopter and outputting the servo PWM signals while the other collects flight data. This flight data is sent to a third base node which relays the information to a PC for logging and debugging purposes.

In order to control the helicopter, certain real time data is required. The CSIRO IMU add-on board for the Fleck is used to obtain acceleration data and thus roll and pitch angles. A sharp GP2YA02YK range sensor is used to collect height information. Finally the vision system is used in combination with the attitude and height data to provide a relative position to a ground target.

To find a model for the system using system identification, pilot input data is required. For this purpose the inputs received by the helicopter from the standard hobby radio control were logged by the onboard Fleck and transmitted real time with the measured roll, pitch and position data. One of the hobby radio switch channels is used as a manual/auto switch allowing changeover from manual to automatic control of the helicopter. This allows an operator to perform takeoff then switch to automatic flight mode and then back to manual control for landing or in case of emergency.

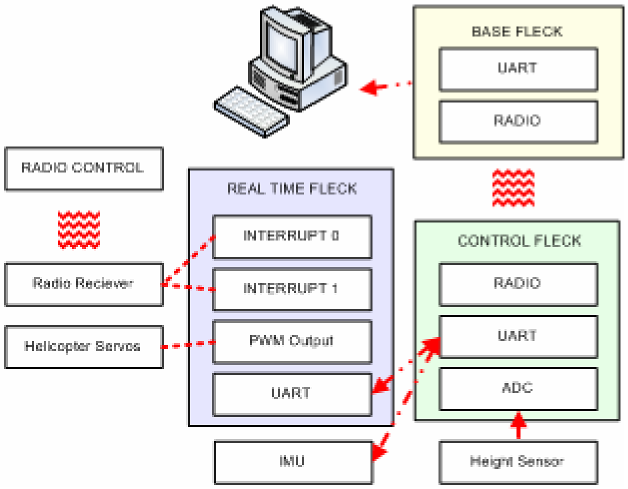

Figure 3 – Electronic systems flow diagram

Vision System

The Blackfin DSP microcontroller and Omni Vision colour camera have been selected as the platform for the development of the vision system. The Blackfin is connected with the helicopter control system using a serial interface. The helicopter control system provides roll and pitch angles and distance to ground. The vision system provides helicopter position and velocity information to the helicopter control system.

The camera used is a 1.3MegaPixel RGGB/YUV camera; however the present camera model is limited to RGGB output.

An Ethernet connection is used to send video and data packets to a desktop PC for debugging and development. Figure 4 shows the hardware setup for the vision system.

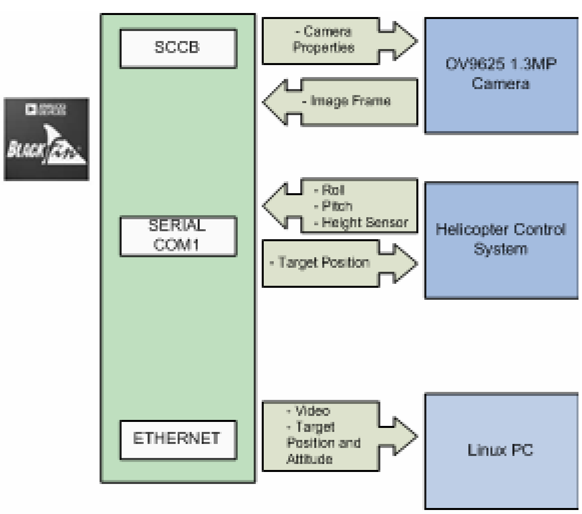

Figure 4 - Vision System Hardware Overview

5 Software Overview

Helicopter Control System

The Helicopter control software runs on three Fleck sensor nodes. The Control Fleck runs various threads which collect the sensor data from sensors as quickly as the data is available. A constant time interrupt runs a thread which then performs the control calculations. These control signals are then sent to the Real Time Fleck for output to the actuators. The Real Time Fleck is run purely on interrupts in order to receive the pulses from the pilot control and output the required servo pulses to control the helicopter.

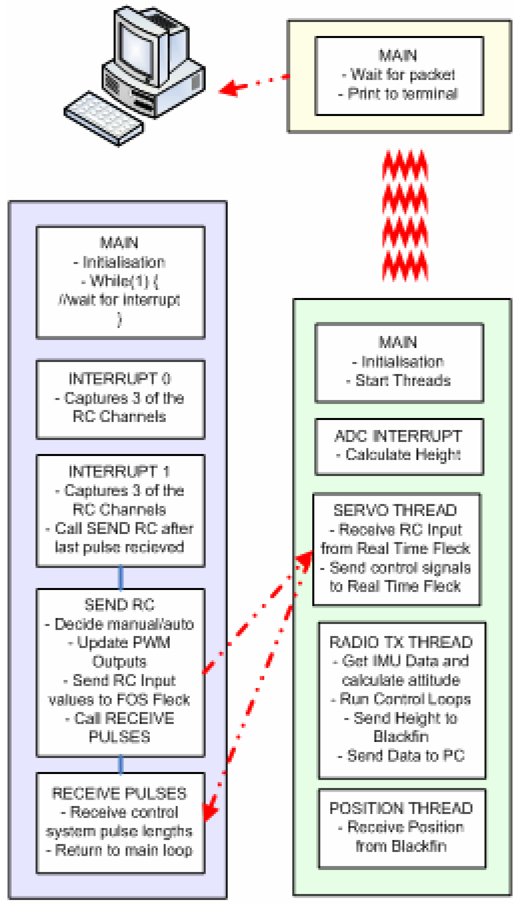

Figure 5 – Fleck Software Layout

Vision System

The software for the vision system is implemented under the uClinux operating system. uClinux provides all the basic functionality of the linux operating system, and also allows for the inclusion of libraries developed for other linux based applications. The vision software developed has the ability to read an image from the camera using the SCCB interface and process the image. The system is capable of sending the image, and other data, over Ethernet to a desktop PC for the purposes of development and debugging. This would not be used during actual flight as there is no wireless ethernet connection to a ground station. The software is also capable of serial connections on two ports.

Presently the system consists of one main thread. This thread reads an image, performs processing on the image, sends the processing or unprocessed image and position information over Ethernet and sends control data to the helicopter control system via serial interface. Figure 6 shows the flow of the vision system software.

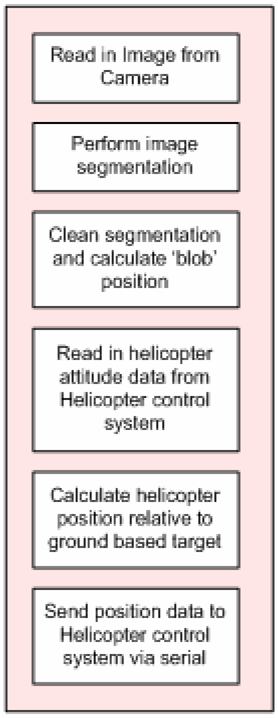

Figure 6 – Flow of Vision System Software

Calculation of Vehicle Position

The position of the vehicle is calculated using a colour based target at a known position on the ground. The target consists of two coloured blobs with one larger than the other as shown in Figure 11. The image is segmented based on colour to produce a binary image. This binary image is labelled to obtain the two largest blobs, which, if the system is correctly trained, will correspond to the target blobs. The centroid of these blobs can then be calculated.

The position of the target in the image frame is now known. The roll, pitch and range to ground in the z axis of the helicopter is known from the helicopter control system. The properties of the camera can then be used to convert image coordinates into 3D camera coordinates providing the distance to the target is known. The series of transformation matrices and vectors can be used to determine the position of the target in level helicopter coordinates from the image coordinates.

Segmentation Techniques

A variety of segmentation techniques have been developed to obtain maximum speed and segmentation quality. Colour segmentation is undertaken in the YUV colour space so that a simple lookup table can be used to specify a colour. Segmentation techniques include:

1. Full Segmentation
   This technique is relatively simple and involves comparing the colour component (U and V) of each pixel to the specified look up table. If the colour of the pixel falls within the lookup table the pixel is turned on.

2. ROI (Region of Interest) Segmentation
   The method of segmentation involves segmentation around a region where the target was last positioned. This means that the system looks for the target around the region where it was last positioned. This is reasonable since it can be assumed that the target velocity in the image frame is limited. This method of segmentation requires the position of the target which can be found from the previously segmented image.

3. Sub-sampled Region Segmentation
   This method involves breaking the image into a number of rectangular sections. The centre pixel of each section is segmentated, and if it is on the whole section is segmented.

4. SRG (Seed Region Growth) Segmentation
   The image is first sub-sampled and segmented to produce seeds.

A range of binary morphology operations have been implemented in conjunction with image segmentation to produce a clean image.

6 Results

Flight Data Collection

In order to create a model of the helicopter dynamics using model identification methods, a set of inputs and outputs are required. The inputs to the helicopter system are the stick controls of the human pilot, and the outputs that were recorded were the roll and pitch angles.

One of the major problems associated with data collection on a helicopter platform is the aggressive vibrations caused by blade flap in the rotating blades. This vibration introduces significant noise into the data collected from movement sensors. This noise is very visible in the data collected from onboard the helicopter via the IMU sensors in Figure 7. The first plot is the roll and pitch values as calculated from the onboard accelerometers while the second set of data has been filtered using a 48 tap Parks McClellan FIR filter designed to remove the blade flap frequency.

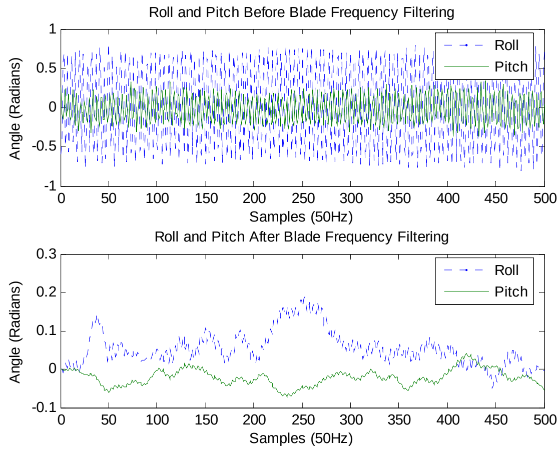

Figure 7 – Roll and Pitch Data (filtered)

A plot of a typical set of input data is shown in Figure 8. The first plot shows the actual data obtained from the radio receiver while the second plot is the same data filtered using the above low pass filter to ensure that any delay introduced by the filter affected the input and output data sets identically.

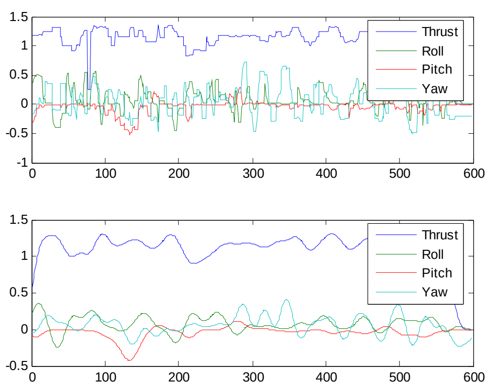

Figure 8 – Pilot Control Signals (filtered)

Model Identification

In order to help in the design of a control system a model of the helicopter was required. The input and output data previously recorded was loaded into Matlab where the system identification toolbox was used to develop a model mapping the input to the output data.

The inputs given were the pilot Thrust, Roll, Pitch and Yaw control signals with the outputs being the roll and pitch of the helicopter. This model is easily expandable to allow the inclusion of more data sources such as position and angular velocity when this data is available. The model has the following format where 'u' is a vector of inputs and 'y' is a vector of outputs and 'x' represents the current state of the system.

$$x(n+1) = Ax(n) + Bu(n)$$
$$y(n) = Cx(n)$$

$$A = \begin{pmatrix} 1.0103 & 0.0841 & 0.0842 & -0.2087 & 0.0899 & -0.1735 \\ 0.0828 & 0.9889 & -0.1296 & 0.3625 & 0.1951 & 0.1683 \\ 0.2843 & -0.5469 & 0.2676 & 1.0611 & -0.1630 & -0.3265 \\ 0.1884 & -0.1926 & -0.8248 & 0.2495 & 0.1603 & -0.3738 \\ -0.0584 & -0.1895 & 0.0043 & 0.2148 & 0.7656 & 0.1111 \\ 0.0820 & -0.1048 & -0.0314 & -0.1145 & -0.0664 & 0.5901 \end{pmatrix}$$

$$B = \begin{pmatrix} 0.0660 & -0.9181 & 0.3341 \\ -0.1285 & 1.2653 & -0.4305 \\ -0.1448 & 4.2635 & -1.8346 \\ 0.7300 & -2.1225 & 0.1433 \\ -0.1031 & 0.9765 & -0.3199 \\ 0.0959 & -0.4310 & 0.0611 \end{pmatrix}$$

$$C = \begin{pmatrix} 1.3638 & -0.3767 & 0.0826 & -0.1560 & 0.1280 & -0.1549 \\ -0.3865 & -0.4288 & 0.0554 & 0.0273 & -0.0317 & 0.0506 \end{pmatrix}$$

The model presents a reasonable correlation with the measured roll and pitch angles when it is applied to the training data Figure 9.

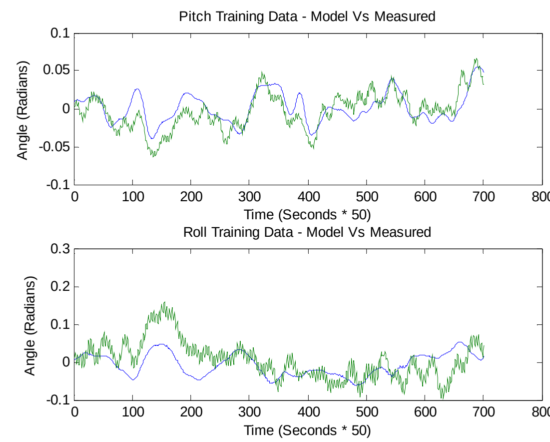

Figure 9 – Training of Helicopter Model

In order to verify the accuracy of the model a second set of flight data was used and the outputs of the model compared to the actual flight recordings Figure 10. The output of the model on verification data is correlated with the actual data, just as well as the output of the model usign training data is correlated with actual data.

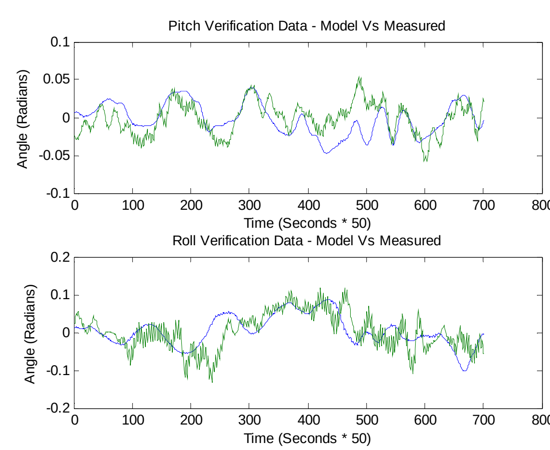

Figure 10 - Verification of Helicopter Model

It is expected that a helicopter control system will be able to be designed and tested around this plant model. Thus allowing control loop parameters to be roughly tuned before any automated flight testing is carried out.

It is important to note that a helicopter is not a linear system such as the one that has been used for the identification algorithm. Helicopter dynamics are a multi-input multi-output nonlinear system [Shim, Jin *et al.*], it is hoped however that this linear approximation will provide enough correlation with the actual flight dynamics to allow a control system to be developed.

The current system software has been designed with a PID control system where four PID loops are used for basic stability. One loop is to control the thrust of the helicopter while the other three loops control the attitude parameters roll pitch and yaw. The PID method of control was chosen due to the efficient processing and ease of implementation. Following verification of control system parameters using the identified model, flight tests to gauge stability and the effectiveness of this approach to helicopter stabilisation will be performed.

Vision System Verification

The vision system can be configured to 'track' any colour using a look up table. The results in this section use the target shown in Figure 11 and detect the colour green. For the purposed of development and debugging the system draws a cross on the two largest blobs and sends the images to a desktop PC where they can then be viewed. An example image is shown in Figure 11.

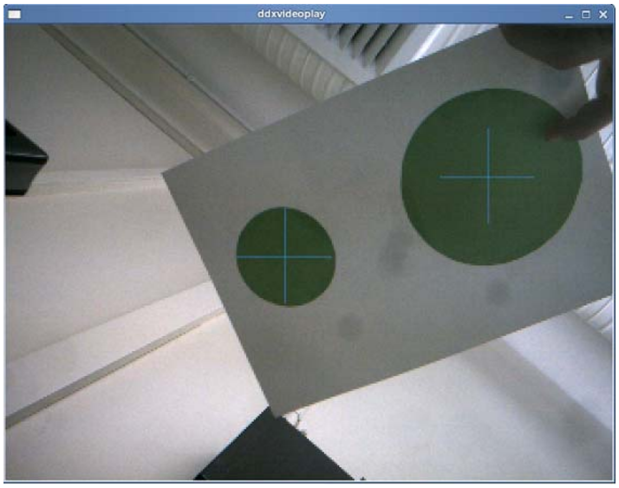

Figure 11 – Example Image

Figure 12 shows a comparison between various methods of segmentation implemented on the Blackfin DSP.

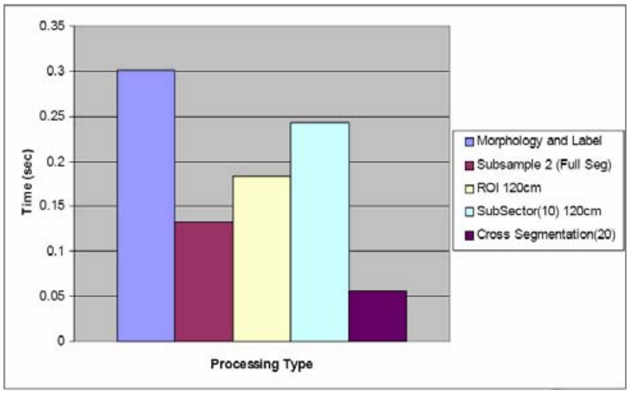

Figure 12 – Comparison of Segmentation Techniques

The vision system aims to provide information on the position of the helicopter from a ground based target. The CSIRO AVS, or Air Vehicle Simulator [Usher, Winstanley *et al.*] has been used to verify this data against actual position data. The AVS is able to position a payload, in this case the helicopter, to any 3D position in the workspace. Figure 13, Figure 14 and Figure 15 show a comparison between the AVS actual position and the position calculated from the vision system. Note that the vision system does not incorporate roll and pitch angles for these results. To date the system with roll and pitch angle incorporation has not been tested.

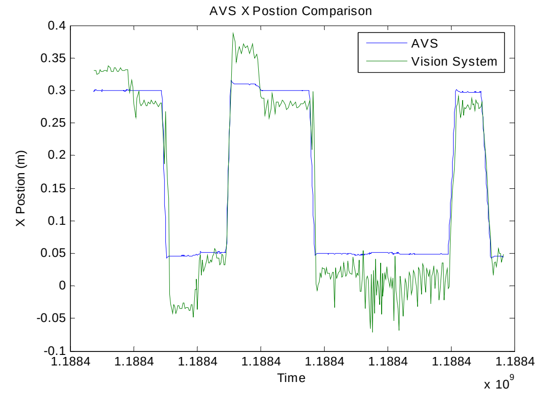

Figure 13 - X Position Comparison

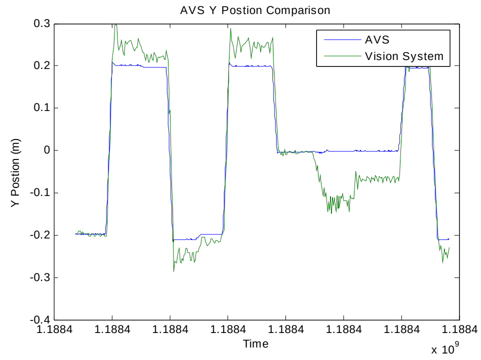

Figure 14 - Y Position Comparison

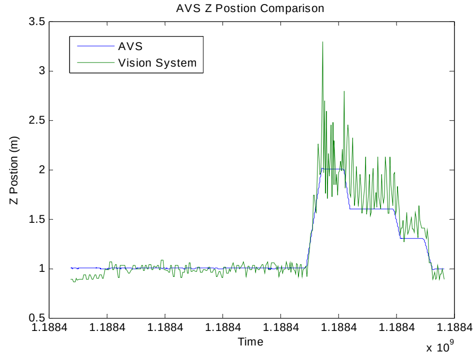

Figure 15 - Z position Comparison

7 CONCLUSIONS

Helicopter System

The physical helicopter system is a solid foundation for a small scale UAV development platform. The electronics have proved to be very reliable during flight testing and have provided a simple to adjust platform for future experimentation. The wireless Fleck sensor nodes allow real time data to be streamed and displayed on a nearby computer while all control processing is completed onboard the helicopter.

Model ID

It appears that a model can be created using the system identification toolbox within Matlab however more flight data variables are required to fully represent the dynamics of the helicopter. Initiatives are currently underway to add gyroscopic and positional data to this model to improve its accuracy. It is hoped that the addition of this data will produce a model with sufficient accuracy for a control algorithm to be designed.

Vision System

Although testing and development of the system are incomplete, there exists enough data to indicate that the algorithms implemented, although simple, will be sufficient for onboard control. These image processing algorithms enable the system to calculate the vehicle position from a ground based colour target. The system provides position information at a rate of 5-10Hz. Although untested this update rate should allow for the implementation of a PD (proportional and differential) position control system.

The next steps are to improve the model of the helicopter in order to allow the development of attitude control. Vision system integration will provide data for high level position control.

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