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Fixed Wing UAV Navigation and Control through Integrated GNSS and Vision

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With the rapid deployment of Unmanned Airborne Vehicles (UAVs) into new applications, the pressure to extend the capabilities of current platforms is increasing. Increased capabilities, however, should preferably not come at the cost of increased aircraft size. In order to strive towards a more capable platform, the UAV must become increasingly aware of its current state (control, navigation and health) and surroundings (location of other aircraft, airspace boundaries, weather and terrain). This paper reports on the results of research into providing a new level of situational awareness to the UAV that is low in cost and complexity. In particular the paper investigates the unique benefits that can be obtained from the integration of a GNSS sensor and a forward-looking vision sensor. The motivation for this investigation is the belief that both GNSS and vision will be integral features of future UAV avionics architectures: GNSS to provide basic aircraft navigation; and vision to provide for obstacle, and aircraft collision avoidance. This paper will present results showing that when single-antenna GNSS measurements are combined with information derived from optical flow techniques, a number of unique synergies emerge. Sensor accuracies and simulated flight control results are presented based on a comprehensive Matlab® Simulink® model which creates an optical flow stream based on the simulated flight of an aircraft. The paper establishes the promise of this novel integrated GNSS/Vision Sensor Suite approach for use as a complete UAV sensor package, or as a backup sensor for an inertial navigation system.

I. Introduction

THIS paper presents an integrated GNSS and Vision based Sensor Suite (GVSS) for navigation and control of a fixed-wing UAV. Vision-based sensors are a logical sensory component for a UAV as they can enable the UAV to mimic many of the processes performed by a human pilot. However, vision alone does not provide enough information to meet the needs of a modern UAV.

Horizon detection and tracking using standard cameras has been explored for UAV applications. Researchers at the University of Florida, for example, have developed a horizon detection and tracking method that uses a statistical approach to determining the separation between the sky and ground[1]. Causey successfully implemented this method for control in an autopilot for a micro UAV[2]. The horizon detection methods have the limitation that they can only resolve pitch and roll, not yaw. Another limitation is that the horizon must be in view and generally level (i.e. no dominant obstacles on the horizon such as trees or mountains).

Extensively studied biologically inspired technologies for UAV applications are Elementary Motion Detectors (EMD) which are found on most flying insects. Barrows has successfully demonstrated the use of this technology

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for close proximity object detection for collision avoidance and also altitude control[3-5]. These systems have the limitation that they require specialist hardware and have a restricted range.

Chahl and Srinivasan have carried out research into the use of biologically inspired vision techniques using sensors that model insect ocellus and can measure polarization patterns[6]. Related to this research is the work that has been carried out in the area of optic flow for UAV applications. Successful implementations of systems utilising optic flow for applications such as terrain following in UAVs have been demonstrated[7].

While optic flow offers great promise it is very difficult to reliably uncouple the translational flow from the rotational flow without knowledge of the rotation. Traditionally an inertial package is used for this purpose. This research has developed a novel method of using a single antenna GNSS sensor to estimate the rotational flow.

The methods used in this research to provide GNSS derived rotational estimates are based in part on the work done by Kornfeld, Hansman, and Deyst[8,9], who introduced the notions of pseudo-roll and pseudo-pitch. They used the prefix "pseudo" for quantities obtained or derived from GPS measurements. The "pseudo" prefix is used in a similar manner throughout this paper.

II. Research Overview

The broad objective of this research is to investigate the unique synergies that exist between GNSS and vision for fixed wing UAV navigation and control. Encompassed in this broad objective are two central areas of focus for the research:

1. Investigate the fusion of GNSS and vision techniques
    a. Develop a novel sensor suite concept focusing on reducing size, mass and cost over traditional sensor suites with the same capability
    b. Utilise GNSS to aid in vision based attitude determination
    c. Evaluate the performance of the novel sensor suite concept
2. Increase the robustness of the vision system
    a. Employ biologically inspired techniques
    b. Remove the need for horizon detection and tracking for attitude determination

The outcome of this research will be an optimised sensor for a fixed wing UAV capable of being utilised for:

- Standalone navigation and control
- Sensor redundancy
- Sensor health monitoring

The motivation for the use of GNSS is the fact that, due to continuing advances, GNSS is becoming an essential sensor for the majority of UAV applications. The motivation for the use of vision is founded on the need for UAV platforms to provide forced landing identification and collision detection capabilities. A human pilot uses vision as the key sensor for performing these tasks, and therefore it is logical that the UAV adopt a similar approach. The choice of these two types of sensors allows implementation of the concepts presented in this paper with minimal additional hardware.

This paper illustrates that in principal, this simple combination of GNSS and vision is sufficient to provide the desired information about the current state of the UAV and its surroundings for navigation and control purposes.

III. Sensor Technologies

The technologies utilised in GNSS and Vision based Sensor Suite (GVSS) include only two components: a single antenna GNSS receiver; and a camera. The role of each of the individual sensors in the overall GVSS is explained in the subsections below.

A. GNSS Sensor Utilization

It is imperative for the safe navigation of a UAV that the absolute position, velocity and time are known at any given instant. This knowledge is readily obtainable from a single antenna GNSS sensor. A GNSS sensor is well within the size, mass, power and cost limitations that are usually imposed on UAV platforms.

In addition to the absolute positioning gained from the GNSS sensor, accurate Doppler based velocity and derived acceleration measurements are also utilized to provide an estimate of the Euler angles and rates. It should be noted however that the Euler angles and rates derived from the GPS velocity relate directly to the attitude of the velocity vector and not to that of the UAV. Although this attitude information is not the final result, it is an integral part of the process required to achieve the final result

B. Vision Sensor Utilization

Vision based sensors are a logical sensory component for a UAV as they can enable the UAV to mimic many of the processes performed by a human pilot. There have been several different approaches to utilising vision for UAV navigation sensors but the one chosen for this research is the biologically inspired optic flow. Optic flow calculations can be carried out on a standard image stream so that no specialised hardware is necessary.

The optic flow derived from the vision stream, in the GVSS, is utilised to determine the direction of the velocity vector in relation to the body frame of the UAV. The optic flow information is also used to estimate the distance to objects in the field-of-view.

C. GNSS and Vision Sensor Integration

The GNSS and vision sensor combination lends itself to the derivation of many parameters useful for UAV navigation and control. The GVSS would possess a size, mass and cost specification that is lower than that of a suite of traditional sensors capable of providing the same level of information. GPS is used to derive the attitude of the velocity vector of the UAV and vision to translate this attitude into the UAV body frame attitude. This forms the basis of the GVSS.

IV. Sensor Architecture

The GVSS has a complex flow of data and processing which is illustrated in Fig. 1 and described in general in the following sections. For a more thorough description please refer to Ref. 10.

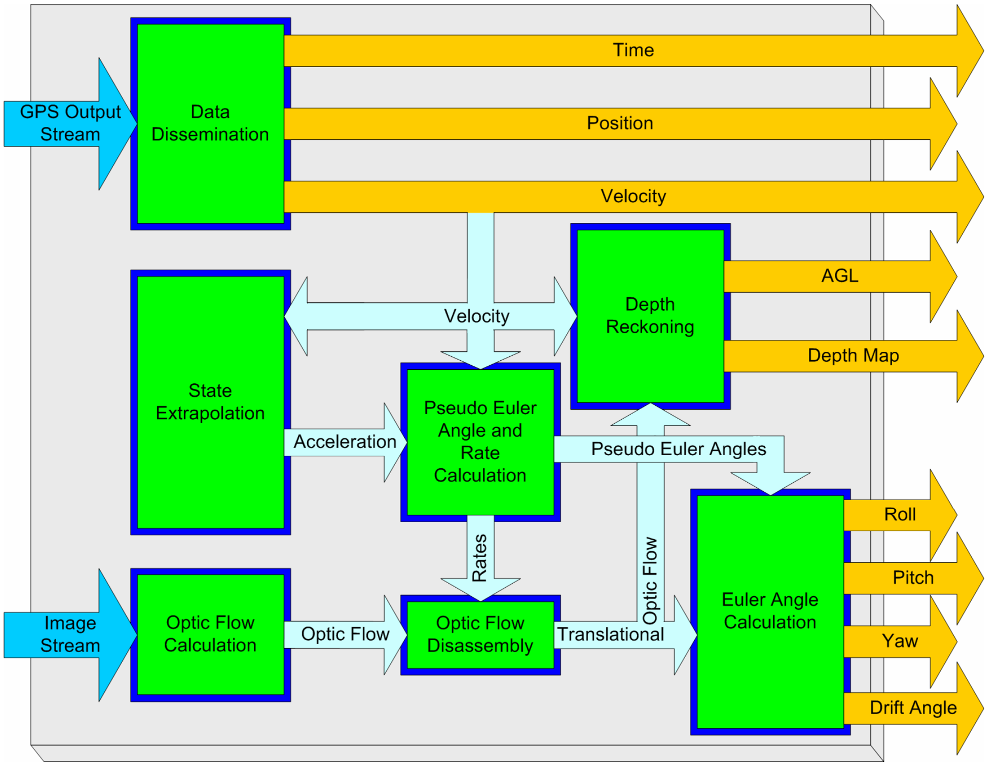


Figure 1 Sensor Architecture

A. Attitude Calculation

The process of attitude calculation takes place with two major steps. Firstly there is an initial attitude calculation of the velocity vector which is derived from GPS measurements. Secondly, there is a correction to this with the velocity vector offset from the body axis which is derived from the optic flow. An overview of the steps involved is described in the following sections.

1. *GNSS Attitude Calculation*

The GNSS measurements are used to obtain approximations of the three Euler parameters, roll, pitch and yaw. The approximations are referred to respectively as the pseudo-roll, pseudo-pitch and pseudo-yaw. Euler and body rates are also calculated from the GNSS measurements. These calculations are based on the principal that during coordinated flight, distinct relationships exist between the velocity and acceleration as measured by a GPS receiver and the Euler angles. The calculated pseudo-roll closely follows that of the actual roll. The pseudo-pitch is directly related to the pitch of the aircraft with an offset due to the angle of attack and any wind induced effects. The components that make up the pitch and yaw are illustrated in Fig. 2 and Fig. 3 respectively.

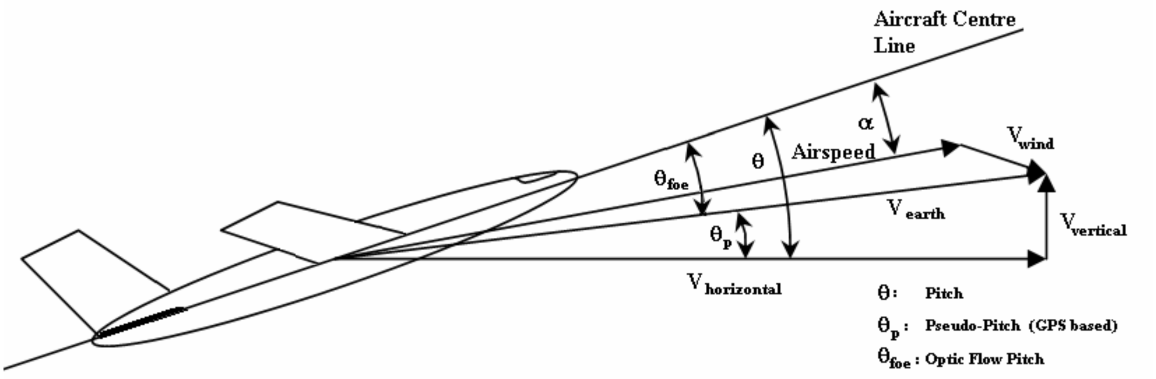


Figure 2 Pitch Components

The pseudo-yaw contains an offset due to sideslip and wind effects, but it directly relates the yaw component of the aircraft velocity vector with respect to the horizontal plane of the north east down (NED) coordinate system.

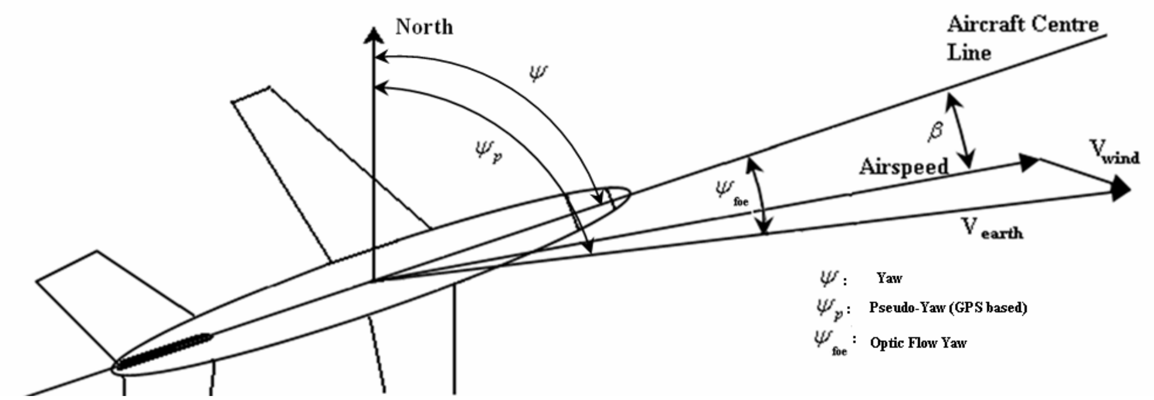


Figure 3 Yaw Components

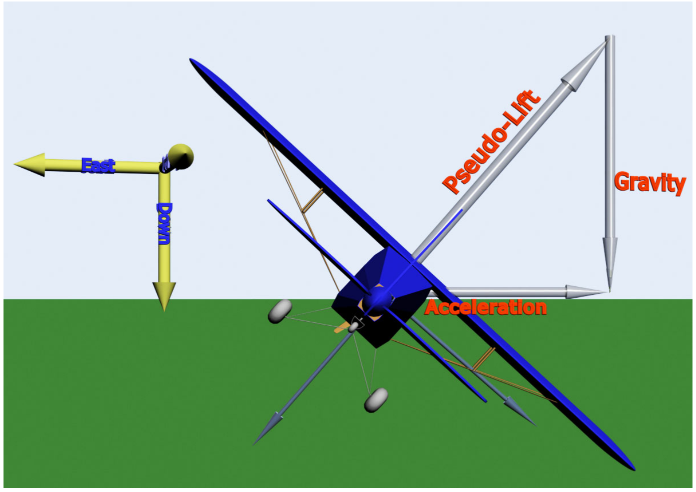


Figure 4 Determination of Pseudo-Lift

The pseudo-roll is calculated from the pseudo lift vector which is based on the combination of the gravity vector and a component of the GPS based acceleration vector as illustrated in Fig. 4. The pseudo-roll is the complement of the angle between the pseudo lift vector and the local horizontal reference.

By using the components of acceleration and gravity that lie in the plane normal to the velocity vector, along with the assumption of coordinated flight (velocity vector aligned with the aircraft's x axis), we can determine the acceleration force in an approximated y-z plane of the aircraft body frame. This is the pseudo lift vector and it will lie in the approximated y-z aircraft body frame. It represents the direction of the total lift forces acting on the aircraft normal to the body x axis.

The direction of the pseudo lift is dictated by the roll angle of the aircraft and thus provides roll angle information.

2. *Visual Attitude Offset Calculation*

The vision based pitch and yaw offsets are calculated from the location of the focus of expansion (FOE) in the image stream. Optic flow can be used to locate the direction of travel by the FOE but only after the rotational components of motion are removed. The optic flow is an accumulation of six individual components, three components each of rotational and translational motion as illustrated in Fig. 5.

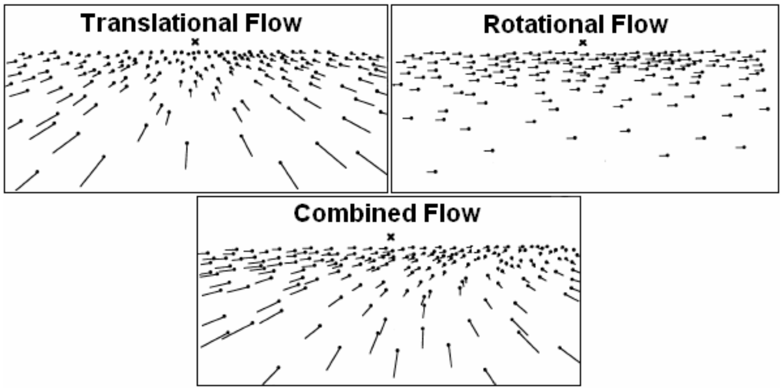


Figure 5 Optic Flow Component Example[11]

The extraction of all 6 of these components is necessary for the accurate interpretation of the optic flow data. The dominant component of the optic flow will be the translation along the aircraft x axis (i.e. the direction of flight). With knowledge of the pseudo rates, the rotational components of the optic flow can be removed leaving only the translational motion. Figure 6 illustrates the different components of the rotational optic flow and their combined effect.

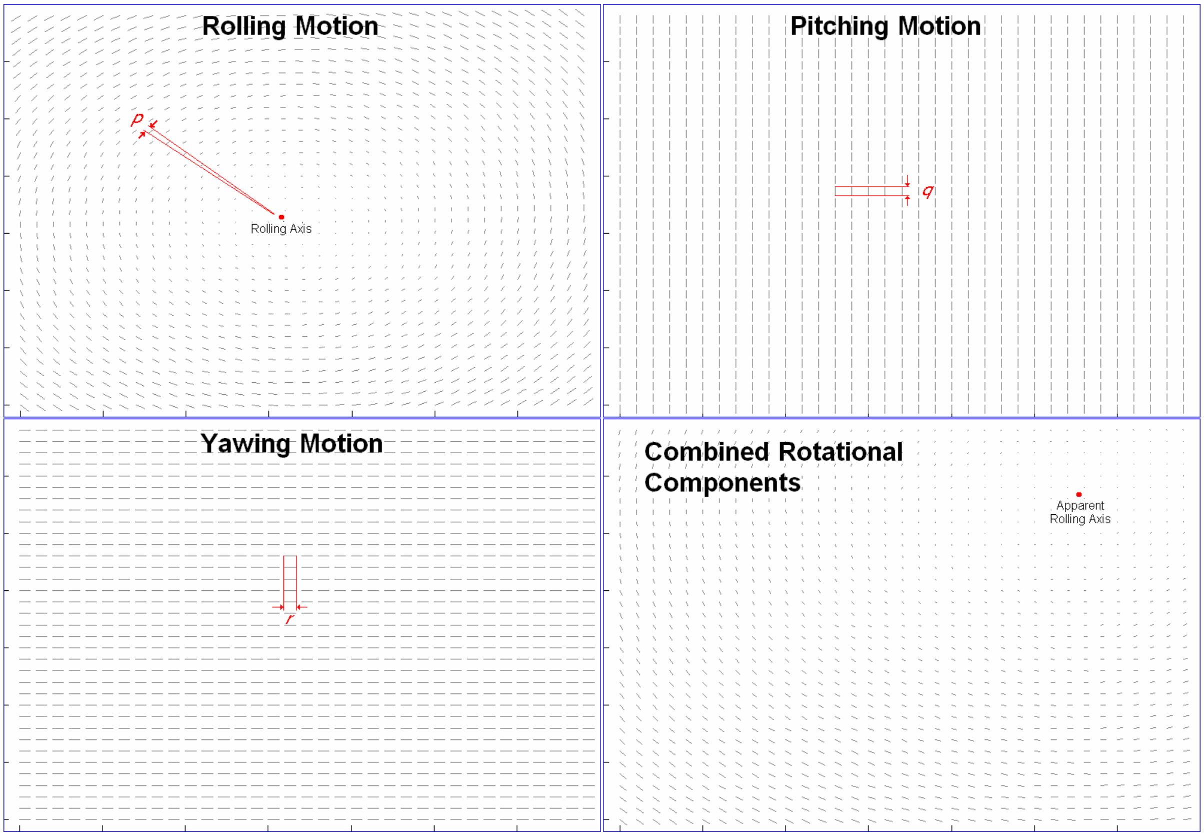


Figure 6 Rotational Optic Flow

The rotational components of the optic flow are independent of the distance to the object from which the optic flow is being generated. The images shown are a simplified model that does not include the effects of the curvature of the field-of-view (FOV) and lens distortion. The camera is orientated coincident with the aircraft x axis of the aircraft.

The translational optic flow FOE gives the offset of the direction that the aircraft is pointing relative to its actual velocity and thus allows for calculation of the pitch and yaw offsets as shown in Fig. 7.

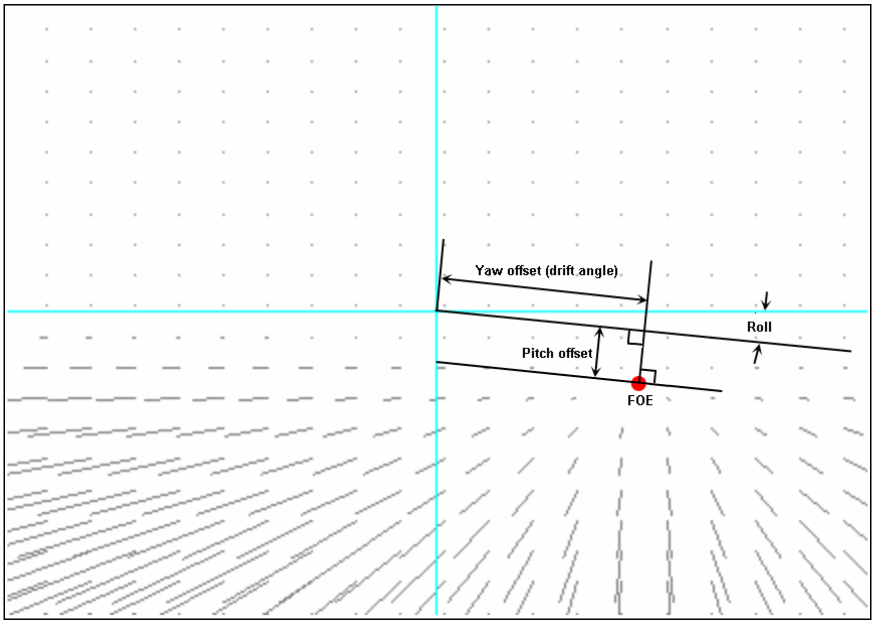


Figure 7 Velocity Vector Offset

Pitch offset is calculated by measuring the distance of the FOE from the centre of the FOV normal to the roll angle. The optic flow yaw offset is calculated by measuring the distance of the FOE from the centre of the FOV tangential to the roll angle.

3. *Attitude Calculation*

The final pitch and yaw angle calculations are the GPS derived pseudo attitude combined with the vision offsets as measured from the translational optic flow. Simulation testing (presented in Section VI) shows the pseudo-roll to differ very little from the true roll. Accordingly, the pseudo-roll is accepted as the true roll.

B. Depth Reckoning

Knowledge of velocity magnitude and direction with respect to the translational optic flow map allows for a calculation of the distance to objects in the FOV. This comes about by the direct relationship between the length of the optic flow line, velocity magnitude, angle of the measurement from the velocity direction and the distance to the object producing the optic flow.

1. *Depth Map Calculation*

The velocity and line of sight direction of the image plane pixels are determined utilising the velocity magnitude from the GPS and the velocity direction from the FOE of the translational optic flow. This information, along with the translational optic flow map, is then utilised to determine the distance to objects giving a depth map of the objects in the FOV.

2. *Height Above Ground Level Estimation*

An estimation of the height above ground can be made using knowledge of the camera orientation and the distance to the objects in the field of view. This estimation is based on the assumption that the ground is generally level.

By calculating the angle, λ, between the local horizon and the line of sight vector of a distance measurement, one can estimate the height above ground level (AGL), as shown in Fig 8.

Note that the AGL estimation process described above is subject to the assumption of level surroundings. This is considered to be a minor limitation because the process would primarily be utilised during the takeoff and landing phases of flight, and the surrounding airfield typically is level.

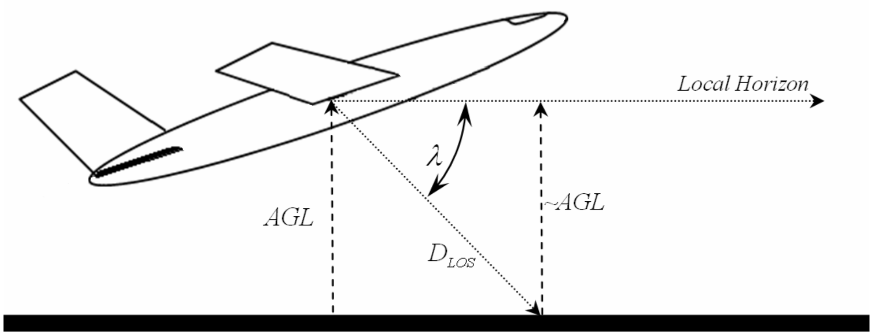


Figure 8 AGL Estimation

V. Simulation Environment

To facilitate concept validation, algorithm development and testing, a comprehensive simulation environment has been developed. This environment is implemented in Matlab® Simulink® and is separated into two major sections: aircraft simulator; and sensor simulator.

C. Aircraft Simulator

The aircraft simulator comprises several models as described below,

- Aircraft Model – a six degrees of freedom flight model that provides the simulated state of an aircraft based on the AeroSim block set[12]
- Control Model – provides the control inputs for the aircraft model
- Flight Management Model – provides the control model with the current waypoint information
- Terrain Model – provides a map of distances to the ground in camera pixel coordinates
- Vision Model – provides an optic flow map including errors associated with the optic flow calculation process
- GPS Model – provides the position and velocity that has been degraded to match what would be output from a GPS receiver

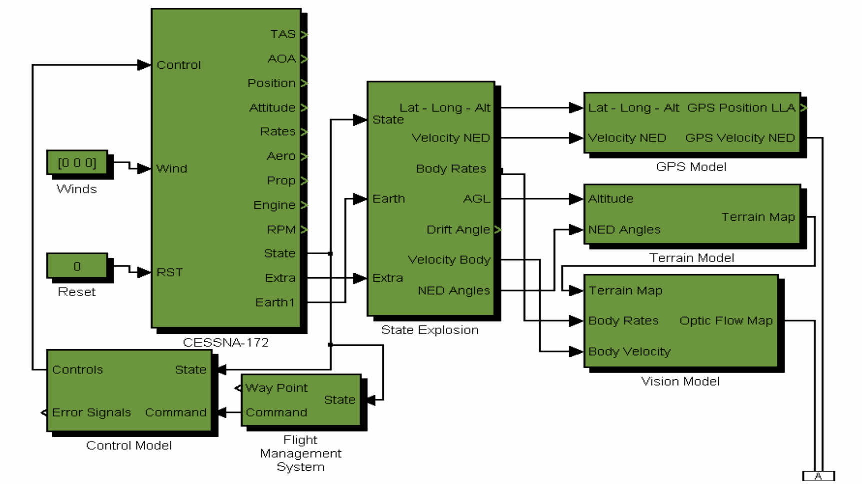


Figure 9 Aircraft Simulator

The aircraft simulator as illustrated in Fig. 9 is designed to closely model a real aircraft and its sensors. The GPS and vision models simulate the errors that are typically found in the output of the relevant sensor.

D. Sensor Simulator

The simulated GVSS implementation is as illustrated in Fig. 10. Inputs to the GVSS model are GPS velocity and optic flow maps.

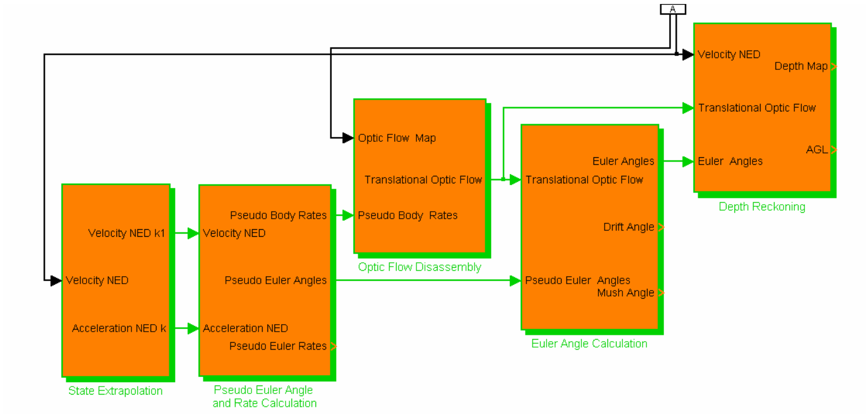


Figure 10 GVSS Simulator

VI. Simulation Test Results

Simulation of an extreme flight condition was undertaken to assess the viability of the GVSS concept and to test its robustness. Figure 11 presents the pitch angle in degrees for an aircraft that was commanded to increase its angle of attack to a point where a stall would occur and then recover normal flight.

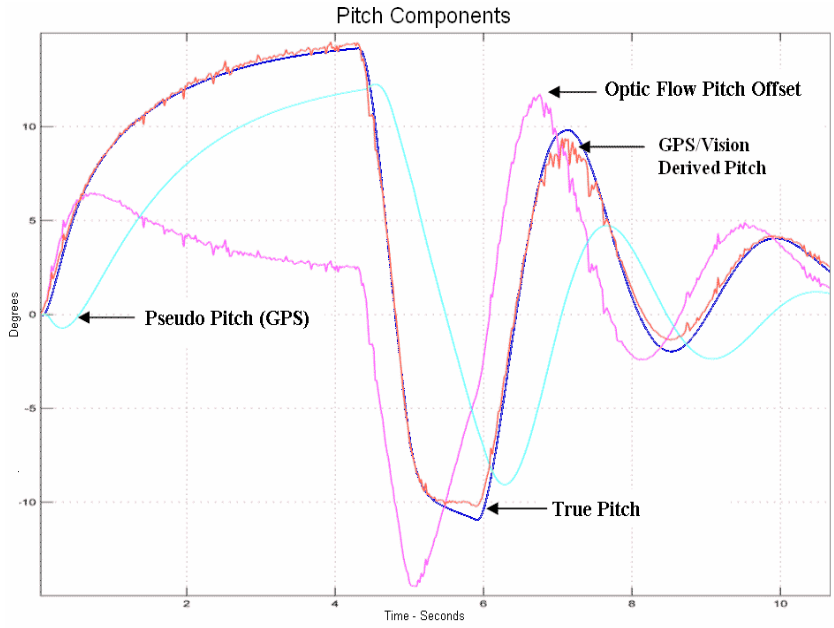


Figure 11 Pitch Angle

As can be seen the *Pseudo Pitch* that is derived purely from the GPS measurements provides a very rough estimate of the pitch angle, with inaccuracies occurring due to a failure to account for the angle of attack of the aircraft. Understandably there is a lag induced in the pseudo-pitch due to the inherent lag in the velocity measurements from the GPS receiver. The *Optic Flow Pitch Offset* is derived from the offset of the FOE from the centre of the image plane normal to the roll angle. The line labelled *GPS/Vision Derived Pitch* is a combination of the pseudo-pitch and optic flow pitch offset. This is an output from the GVSS. As can be seen it is a close approximation to the true pitch angle even under the extreme condition of a stall.

Results presented below are based on simulated flights using a flight plan with five waypoints, and with the distance between each waypoint being approximately 2.16 nm [4 km]. A reference flight path has been generated using the flight plan and control of the aircraft with error free values. This has been done to enable a performance metric to be calculated.

Testing of the GVSS for control purposes has been conducted with the aircraft flying the same flight plan as used for the reference flight path. Throughout the duration of the test flight, the flight management system and the flight controller received input from the GVSS. Thus control of the aircraft was based solely on the output of the GVSS. The performance evaluation of the GVSS is made by comparing the GVSS controlled flight path against the reference flight path.

Table 1 Simulation Flight Parameters

Parameter	Value
Optic flow density	45 x 45
Camera field of view	90 x 90 deg
Flight length	330 sec
Optic flow error	± 2.5 deg

Summarised in Table 1 are the key simulation parameters used in gaining the results for the GVSS controlled flight. The optic flow error consists of a random degradation of the angle of the flow lines bounded by ± 2.5 degrees. This is an error which is typical for the optic flow algorithm used[13].

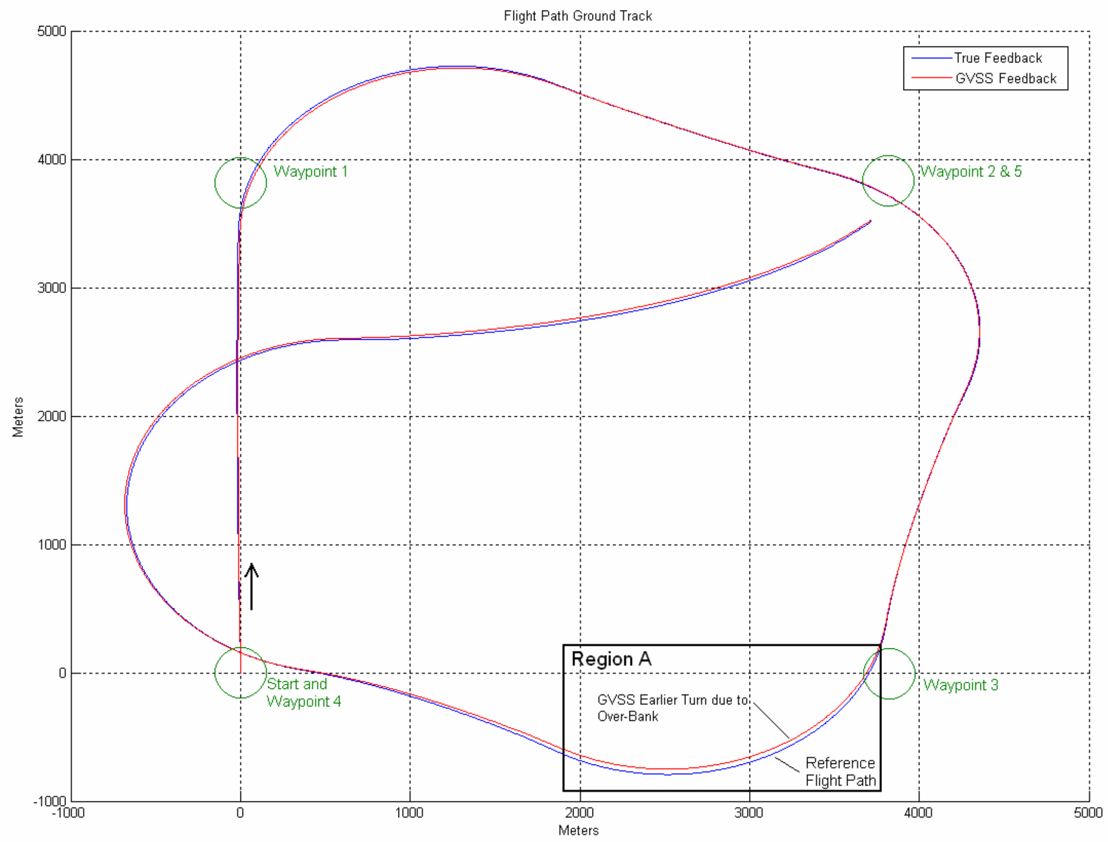


Figure 12 Flight Path Ground Track Comparison

The ground track of the GVSS controlled flight and the reference flight is illustrated in Fig. 12. A summary of the three dimensional deviations between the two flights paths is presented in Table 2.

Table 2 Flight Path Deviation

Parameter	Value
Mean	42.649 m
Standard Deviation	26.561 m

The ground tracks are very close with slight deviations occurring during the turns as shown in 'Region A' of Fig. 12. This can be explained by the delay of the GVSS output which causes the aircraft to over-bank compared with the reference flight. This overbanking is illustrated in Fig. 13 which displays the true roll angle, for the reference and GVSS controlled flights, for the entire duration of the flights. The true roll angle for the GVSS controlled flight leads that of the reference flight upon leaving a waypoint (i.e. when a bank is initiated).

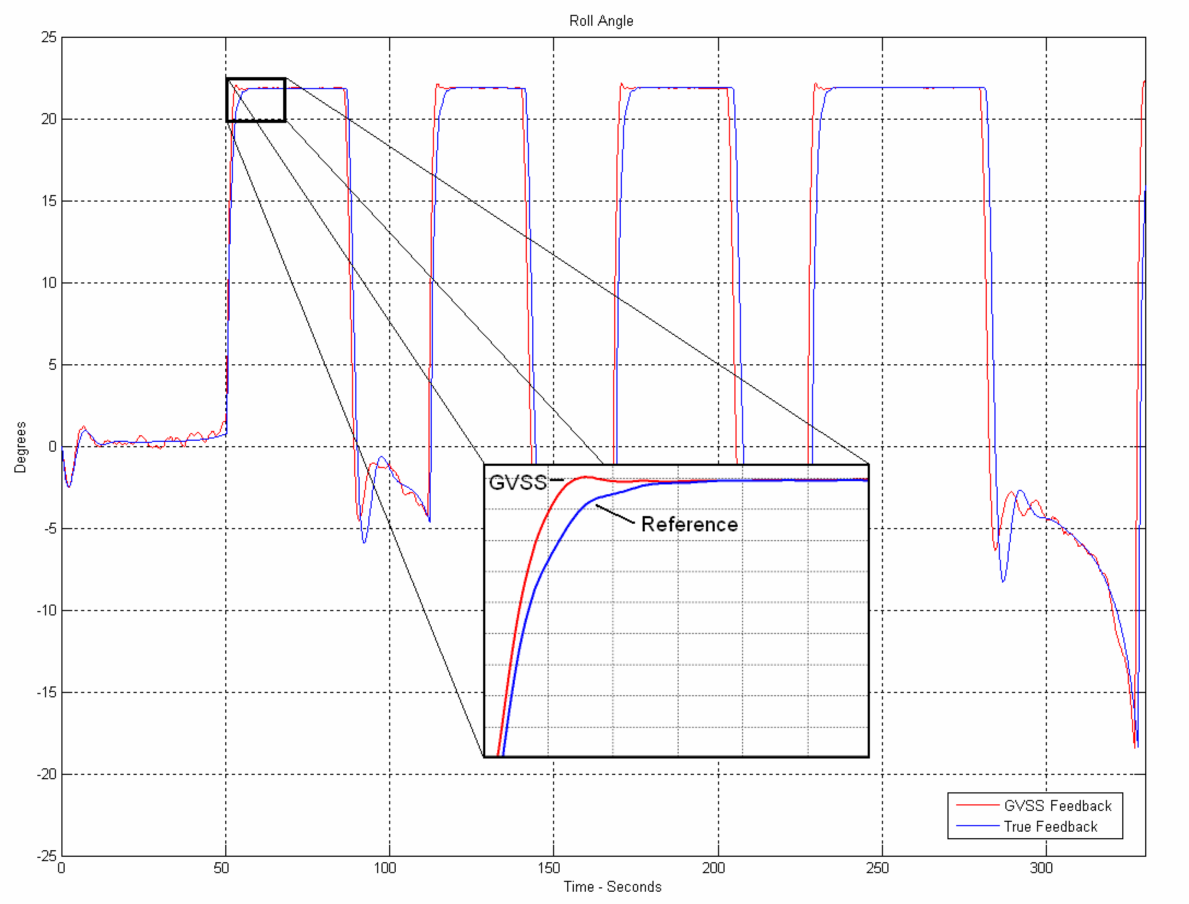
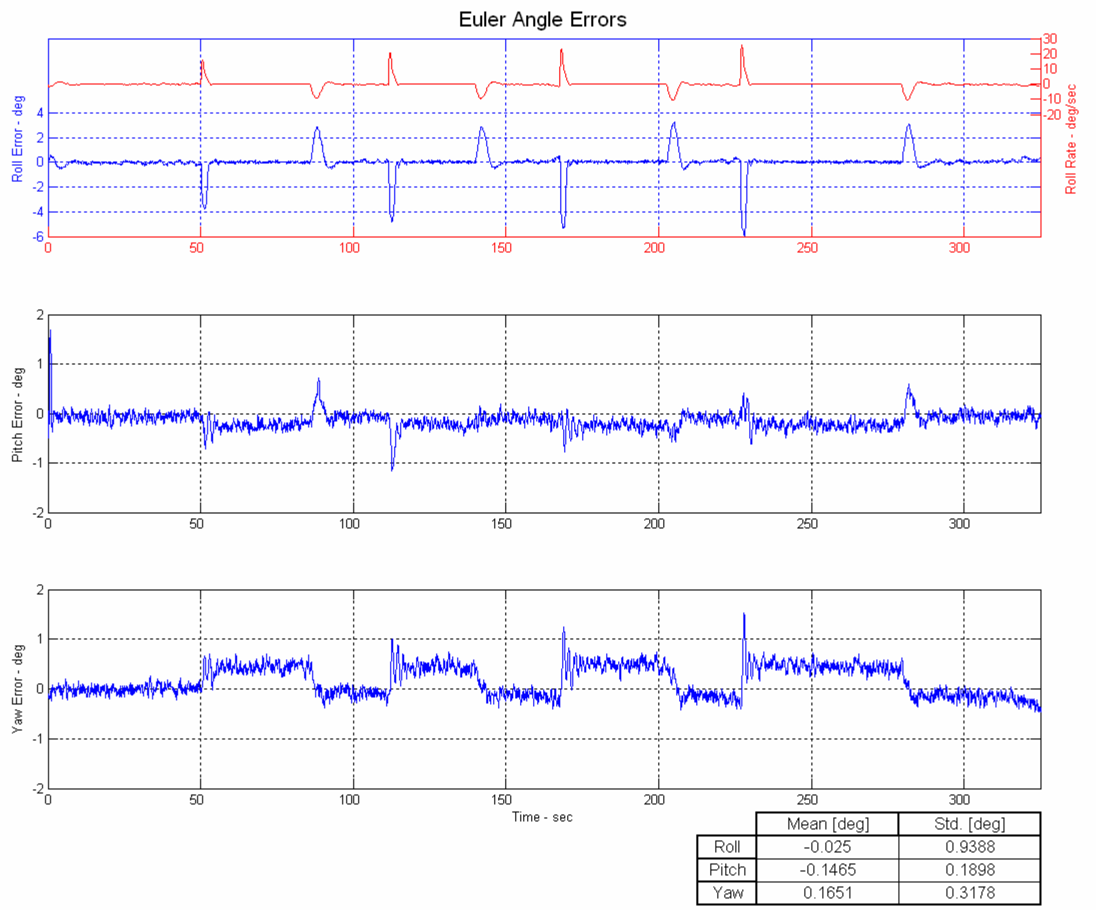


Figure 13 True Roll Angle Comparison

Examining the Euler angle error of the GVSS output reveals the cause of the leading, over-bank response of the GVSS controlled flight. As shown in Fig. 14 there is a sizeable error in the GVSS roll angle during periods of increased roll rates. This error is due to the lag of the GVSS attitude estimates compared to the true values. This lag in roll angle estimate causes the flight controller to further increase the aileron deflection to achieve the desired roll, resulting in an overbanked response.



	Mean [deg]	Std. [deg]
Roll	-0.025	0.9388
Pitch	-0.1465	0.1898
Yaw	0.1651	0.3178

Figure 14 Euler Angle Errors (GVSS vs True)

As can be seen from the roll error in Fig. 14, the overall error is small, with the exception of some noticeable spikes. The roll is calculated independent of the optic flow measurement and is thus based purely on the GPS. The spikes of error occur in periods of increased roll rate as previously discussed. As the GPS velocity and derived acceleration measurements are subject to the small delays inherent in GPS receivers, this error is unavoidable.

The pitch error as shown in Fig. 14 is a distribution bounded by approximately ± 0.5 degrees of error. The error consists mainly of noise generated by the optic flow pitch offset derivation. There are three main sources of error in calculating the optic flow offset and they are as follows:

1. The deliberate introduction of error in the optic flow during generation of the simulated optic flow map. This is done to provide a better representation of what would be calculated from an actual image stream.
2. The use of pseudo-rates for removing the rotational components of the optic flow. The only rate measurement available is derived from the GPS and therefore contains error. Due to the dominate proportion of the optic flow being translational flow and more specifically translational flow in the x body direction, the rotational components are adequately removed with the pseudo rates for this application. The error that exists due to this is not able to be mitigated.
3. The algorithm for the estimation of the FOE is a rudimentary implementation of a weighted line intersection voting routine. This error can be reduced through a filtering regime based upon knowledge of the maximum rates that the UAV would encounter as well as past FOE values.

The yaw angle error as shown in Fig. 14 has the same characteristics found in the pitch error. This is a result of the same error sources affecting pitch, also affecting yaw. Additional to this common error is an offset in the yaw associated with the roll angle of the UAV. This is an error in the FOE identification algorithm. This error will be rectified to totally decouple the two Euler components in the near future.

Based upon the results for the GVSS Euler angles and controlled flight, it can be concluded that the concept presented is capable of providing a level of accuracy sufficient for UAV navigation and control.

VII. Future Directions and Conclusion

The core objective of this research is to investigate the synergies that exist between GNSS and vision for fixed wing UAV navigation and control applications. This paper has presented the research conducted to date in this field. The proposed research is unique in several aspects, enumerated below:

1. The use of GNSS and biologically inspired techniques (i.e. optic flow) to derive the velocity vector with respect to the UAV body frame.
2. The use of GNSS derived attitude to decouple the rotational and translational components of optic flow
3. The use of a vision based attitude sensor without the need for horizon detection and tracking
4. The use of a GNSS/Vision attitude sensor providing roll, pitch and yaw

With the fusion of GNSS and vision, an unprecedented level of functionality can be achieved for a given size, mass and cost. There are key problem areas that have been overcome to make the proposed GVSS viable. GNSS can provide an estimate of the attitude, but only of the velocity of the aircraft and not of the aircraft body frame itself. Optic flow can provide a link between the attitude of the aircraft and its velocity. It is this combination that provides the complete attitude information.

Horizon detection and tracking is the traditional approach to attitude determination with a vision sensor but its shortcomings are that the horizon needs to be in the field of view and must be level. The method described in this paper removes these restrictions, providing a more robust attitude measurement than simple horizon detection and tracking.

Optic flow is not usually used in airborne environments as the translational and rotational motions are difficult to decouple without knowledge of one of them. The use of the GNSS derived attitude provides rotational motion estimates enabling this problem to be overcome.

The translational optic flow is used to determine the direction of travel of the aircraft with respect to the aircraft body axes. This translational flow provides information to determine two parameter sets: the velocity vector pitch and yaw offsets with respect to the aircraft body frame; and the calculation of the distance to the object from which the optic flow measurement was derived. Distance calculation from optic flow measurements is a function of the velocity and the angle of the measurement off the velocity vector. The angle can be determined from the translational optic flow itself leaving the velocity magnitude unknown. This problem is overcome with use of the velocity magnitude from the GNSS sensor.

It is this synergy of the GNSS and vision throughout the GVSS that facilitates the determination of the wide variety of information.

The results presented for attitude show that estimates can be obtained within the simulation environment of less than one of degree error in the mean and standard deviation. This in turn enables the aircraft to fly the same flight path, using the GVSS, as one using true data with a 3D track error of only 43 meters mean and 27 meters standard deviation.

Further development of the GVSS is continuing with the intent to be able to provide estimates of glide angle, time to touchdown and touchdown position estimation. The inclusion of airspeed in the GVSS is being investigated with the expectation that this will allow the derivation of the wind vector, angle of attack and angle of sideslip.

This paper has presented a novel combination of GNSS and vision for UAV navigation and control. The synergies that exist between these two sensors and the information that can be exploited has been explored and presented. The motivation for this research has been the belief that both GNSS and vision will be integral features of future UAV avionics architectures, GNSS for basic aircraft navigation and vision for obstacle, and aircraft collision avoidance.

The GVSS concept has been implemented into a simulation environment and the results have been presented in this paper. The simulation results show promising potential for the GVSS for use in fixed wing UAV navigation and control applications.

This design has the potential to be superior to other vision based methods used for UAV applications in terms of accuracy, robustness and available information

Acknowledgments

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