Single-Hertz Single-Antenna GPS-Driven Attitude Warning System

Final Report

16.621

Fall 2001

Author: William Buford

Advisor: Prof. Hansman Partner: Matthew Lockhart

11 DEC 2001

Contents

List of Figures

List of Tables

1 Abstract

This paper describes the implementation and testing of an aircraft attitude warning system based upon pseudo-attitude. Pseudo-attitude consists of flight path and pseudo-roll angles calculated from GPS velocity measurements. A computer was used to monitor pseudo-attitude and provide a verbal warning to the pilot in case of dangerous flight conditions. In flight testing, the warnings did not affect pilot reaction times in recovering from divergent attitudes but were effective in preventing divergence in the absence of other attitude information.

2 Introduction

2.1 Motivation

Aircraft accidents continue to happen on a disturbingly regular basis. A significant number of these accidents are attributed to the pilot's lack of situational awareness. No particular limitation of man or machine is reached. The pilot is simply ignorant of the danger to his aircraft. A potential solution for this problem is the use of artificial awareness aids, often provided through the use of computers. A computer driven warning system for aircraft attitude could increase pilot situational awareness of dangerous situations; however, traditional aircraft attitude indicators are entirely analog devices and thus not well suited for digital monitoring.

2.2 Prior Work

During PhD research in the Department of Aeronautics and Astronautics at MIT, Richard Kornfeld developed a system known as pseudo-attitude. Pseudo-attitude utilizes aircraft velocity information from a GPS receiver to calculate flight path and pseudo-roll angles, which are analogs of pitch and roll as measured by conventional attitude indicators.

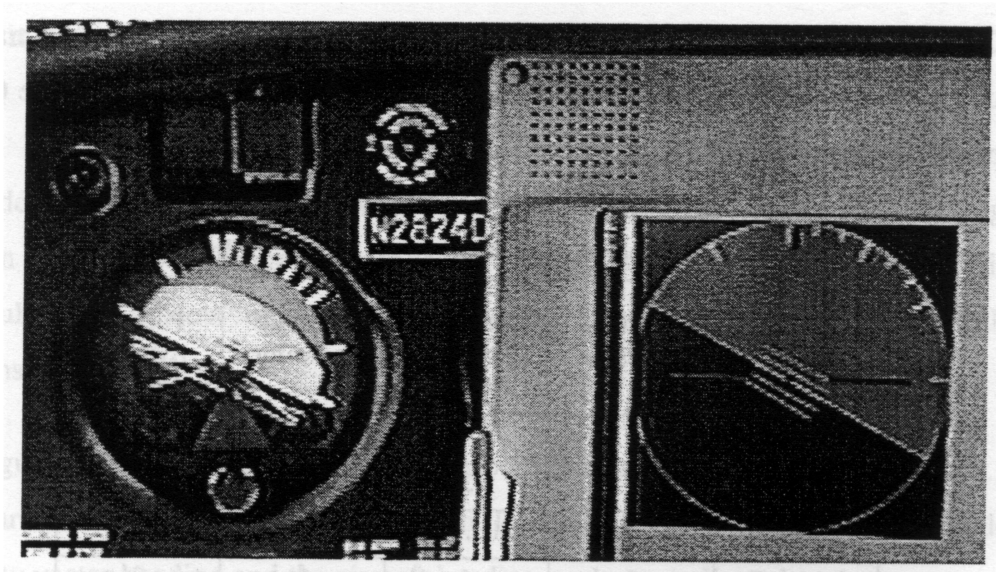


Figure 1. Traditional attitude indicator juxtaposed with a computer generated pseudo-attitude display.

Flight testing in the course of Kornfeld's research showed that pseudo-attitude was sufficiently accurate to completely replace conventional attitude indicators. Many applications for a digital attitude system exist, but the system as originally implemented is not particularly well suited for many of these applications. The original system employed a receiver with a 10 Hz update rate, the rapid update rate being necessary to avoid lags in pilot input. In addition, the original software included filtering routines not strictly necessary for the determination of pseudo-attitude.

2.3 Objectives

The objectives of this project were to implement a pseudo-attitude system utilizing a commercial off-the-shelf GPS receiver and use this system to test the utility of a verbal attitude warning system.

Much of the impetus for this project arose from the vast array of potential applications for pseudo-attitude systems and a desire to make these applications more straightforward. It was hoped that a simple implementation could serve as a jump off point for further research or encourage others to explore further uses.

Ideas for the attitude warning system sprang from one of Kornfeld's suggestion that pseudo-attitude could be used to supplement existing cockpit instrumentation. Verbal warnings could serve to alert the pilot to a dangerous situation of which he would otherwise be unaware, or act as an additional vote in cases of ambiguity with the instruments. The use of verbal audio warnings also suggested an architecture that could be readily integrated into existing aircraft, many of which already have a 1 Hz GPS receiver for navigation. The incorporation of pseudo-attitude warnings could potentially increase pilot situational awareness without crowding instrument panel real estate or requiring extensive modifications to flight hardware.

3 Technical Approach

3.1 Theory

Pseudo-attitude has at its core two vector equations derived by Kornfeld.

Flight path angle is the difference between the velocity vector and the local horizontal reference, and is given by

$$\gamma = \operatorname{atan}\left(\frac{-v_{gD}}{\sqrt{v_{gN}^2 + v_{gE}^2}}\right) \quad (1)$$

Flight path angle is not a measure of pitch but a direct indication of the path of travel of the aircraft. It is offset from pitch by the angle of attack of the wings.

Pseudo-roll is derived by taking the compliment of the angle between the components of the lift and gravity vectors that are perpendicular to the velocity vector.

$$\tilde{\phi} = \operatorname{asin}\left(\frac{\tilde{\mathbf{l}} \cdot \tilde{\mathbf{p}}}{|\tilde{\mathbf{l}}| \cdot |\tilde{\mathbf{p}}|}\right). \quad (2)$$

The **l**, **p**, **g**, **a**, and **v** represent lift, the local horizontal reference, gravity, acceleration, and velocity respectively. For a further derivation, see Ref [1].

3.2 Hardware

Velocity information was provided by a Garmin eTrex GPS receiver. This unit is a single Hz system intended for recreational use by backpackers and outdoorsmen. It is widely available and retails for less than \$ 120. Velocity measurements are rated to be accurate to within 10 cm/sec. The unit's ASCII text-out output mode was utilized in conjunction with a serial cable adaptor to export velocity data to the computer.

An Intel Pentium based laptop running the Linux operating system was used to perform the pseudo-attitude calculations and implement the warning system.

A standard RS-232 serial cable connected the GPS to the laptop. The system as tested is shown in figure 2.

Figure 2. Test Rig: View of the system as flown.

3.3 Software

The system software was implemented in approximately 250 lines of PERL. A full cycle of the code ran in significantly less than one second, resulting in generation of pseudo-attitude nearly instantaneously, albeit only once per second. This meant that there were no significant sensing and processing delays, although it would be possible for high frequency oscillations to escape the notice of the system. Most high frequency oscillations in attitude are very small, and thus the system's limitations did not hamper the testing we performed.

The GPS receiver in its text-out mode automatically transmits position, velocity (in North, East, Down coordinates), and time information over the serial cable to the computer at a rate of 1

Hz. The incoming data is parsed to extract the velocity and time information. The two most recent velocity measurements are backdifferenced to calculate aircraft acceleration, and the current velocity and acceleration are used to calculate pseudo-attitude as discussed above. The pseudo-attitude is then compared to limits established when the script is run. Should the pseudo-attitude exceed the limits, an appropriate warning message is selected and played.

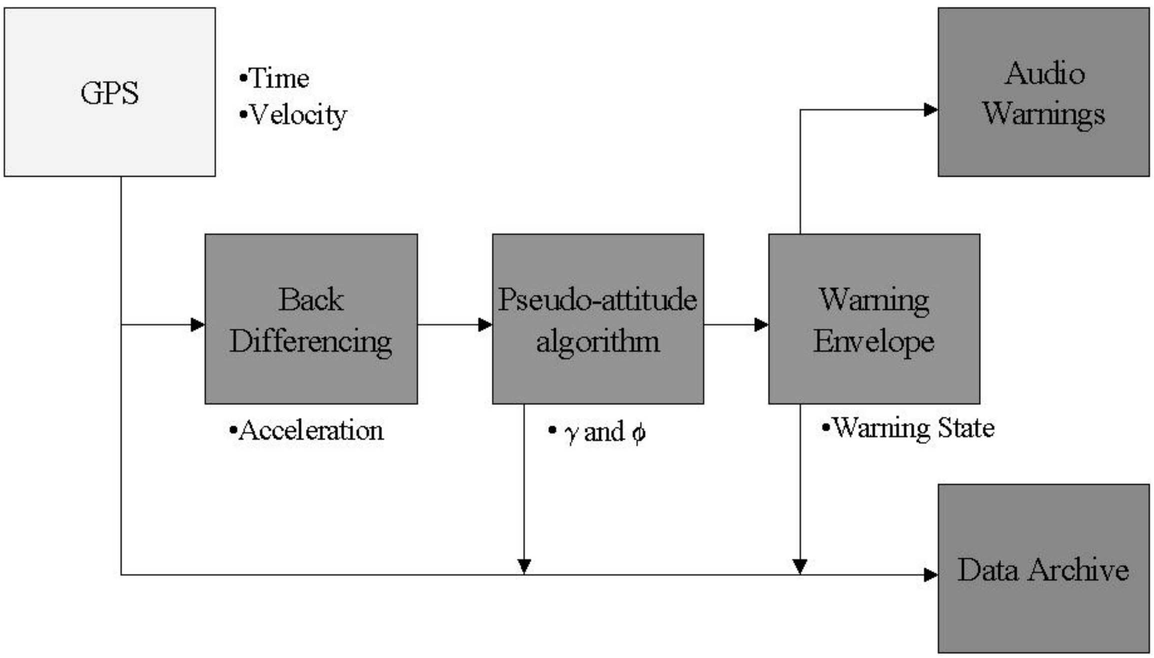
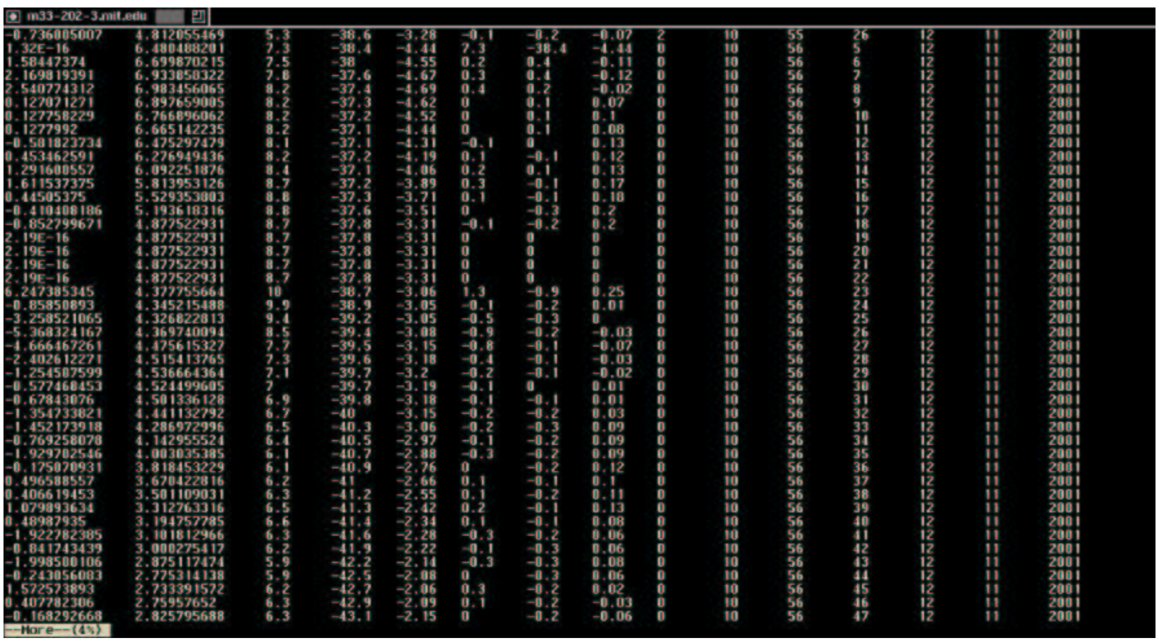


Figure 3. Flowchart of Data Through the System: GPS supplies velocity and time. The computer calculates, acceleration, pseudo-attitude, warning state. It then plays the appropriate warning message if any. All data is then archived to a text file.

Warning messages were stored as .au files. There were a total of eight warning messages, corresponding to the eight possible warning states: climb, dive, left turn, right turn, and combinations of these. Each of the warning messages is approximately three seconds in length. When a warning message is triggered, the warning envelope logic is disabled for three seconds to prohibit overlapping audio messages.

Velocity, acceleration, flight path angle, pseudo-roll angle, warning state, and time were all written into a text file as they were generated.


m33-202-3.mit.edu

-0.736005007	4.812055469	5.3	-38.6	-3.28	-0.1	-0.2	-0.07	2	10	55	26	12	11	2001
1.32E-16	6.480488201	7.3	-38.4	-4.44	7.3	-38.4	-4.44	0	10	56	5	12	11	2001
1.58447374	6.699870215	7.5	-38	-4.55	0.2	0.4	-0.11	0	10	56	6	12	11	2001
2.169819391	6.933858322	7.8	-37.6	-4.67	0.3	0.4	-0.12	0	10	56	7	12	11	2001
2.540774312	6.983456065	8.2	-37.4	-4.69	0.4	0.2	-0.02	0	10	56	8	12	11	2001
0.127071271	6.897659005	8.2	-37.3	-4.62	0	0.1	0.07	0	10	56	9	12	11	2001
0.127758229	6.766896062	8.2	-37.2	-4.52	0	0.1	0.1	0	10	56	10	12	11	2001
0.1277992	6.665142235	8.2	-37.1	-4.44	0	0.1	0.08	0	10	56	11	12	11	2001
-0.581823734	6.475297479	8.1	-37.1	-4.31	-0.1	0	0.13	0	10	56	12	12	11	2001
0.453462591	6.276949436	8.2	-37.2	-4.19	0.1	-0.1	0.12	0	10	56	13	12	11	2001
1.291600557	6.092251876	8.4	-37.1	-4.06	0.2	0.1	0.13	0	10	56	14	12	11	2001
1.611537375	5.813953126	8.7	-37.2	-3.89	0.3	-0.1	0.17	0	10	56	15	12	11	2001
0.44505375	5.529353803	8.8	-37.3	-3.71	0.1	-0.1	0.18	0	10	56	16	12	11	2001
-0.410408186	5.193618316	8.8	-37.6	-3.51	0	-0.3	0.2	0	10	56	17	12	11	2001
-0.852799671	4.877522931	8.7	-37.8	-3.31	-0.1	-0.2	0.2	0	10	56	18	12	11	2001
2.19E-16	4.877522931	8.7	-37.8	-3.31	0	0	0	0	10	56	19	12	11	2001
2.19E-16	4.877522931	8.7	-37.8	-3.31	0	0	0	0	10	56	20	12	11	2001
2.19E-16	4.877522931	8.7	-37.8	-3.31	0	0	0	0	10	56	21	12	11	2001
2.19E-16	4.877522931	8.7	-37.8	-3.31	0	0	0	0	10	56	22	12	11	2001
6.247385345	4.377755664	10	-38.7	-3.06	1.3	-0.9	0.25	0	10	56	23	12	11	2001
-0.85850893	4.345215488	9.9	-38.9	-3.05	-0.1	-0.2	0.01	0	10	56	24	12	11	2001
-3.258521065	4.326822813	9.4	-39.2	-3.05	-0.5	-0.3	0	0	10	56	25	12	11	2001
-5.368324167	4.369740094	8.5	-39.4	-3.08	-0.9	-0.2	-0.03	0	10	56	26	12	11	2001
-4.666467261	4.475615327	7.7	-39.5	-3.15	-0.8	-0.1	-0.07	0	10	56	27	12	11	2001
-2.402612271	4.515413765	7.3	-39.6	-3.18	-0.4	-0.1	-0.03	0	10	56	28	12	11	2001
-1.254507599	4.536664364	7.1	-39.7	-3.2	-0.2	-0.1	-0.02	0	10	56	29	12	11	2001
-0.577468453	4.524499605	7	-39.7	-3.19	-0.1	0	0.01	0	10	56	30	12	11	2001
-0.67843076	4.501336128	6.9	-39.8	-3.18	-0.1	-0.1	0.01	0	10	56	31	12	11	2001
-1.354733821	4.441132792	6.7	-40	-3.15	-0.2	-0.2	0.03	0	10	56	32	12	11	2001
-1.452173918	4.286972996	6.5	-40.3	-3.06	-0.2	-0.3	0.09	0	10	56	33	12	11	2001
-0.769258078	4.142955524	6.4	-40.5	-2.97	-0.1	-0.2	0.09	0	10	56	34	12	11	2001
-1.929702546	4.003035385	6.1	-40.7	-2.88	-0.3	-0.2	0.09	0	10	56	35	12	11	2001
-0.175070931	3.818453229	6.1	-40.9	-2.76	0	-0.2	0.12	0	10	56	36	12	11	2001
0.496588557	3.670422816	6.2	-41	-2.66	0.1	-0.1	0.1	0	10	56	37	12	11	2001
0.406619453	3.501109031	6.3	-41.2	-2.55	0.1	-0.2	0.11	0	10	56	38	12	11	2001
1.079893634	3.312763316	6.5	-41.3	-2.42	0.2	-0.1	0.13	0	10	56	39	12	11	2001
0.48987935	3.194757785	6.6	-41.4	-2.34	0.1	-0.1	0.08	0	10	56	40	12	11	2001
-1.922782385	3.101812966	6.3	-41.6	-2.28	-0.3	-0.2	0.06	0	10	56	41	12	11	2001
-0.841743439	3.000275417	6.2	-41.9	-2.22	-0.1	-0.3	0.06	0	10	56	42	12	11	2001
-1.998500106	2.875117474	5.9	-42.2	-2.14	-0.3	-0.3	0.08	0	10	56	43	12	11	2001
-0.243056083	2.775314138	5.9	-42.5	-2.08	0	-0.3	0.06	0	10	56	44	12	11	2001
1.572573893	2.733391572	6.2	-42.7	-2.06	0.3	-0.2	0.02	0	10	56	45	12	11	2001
0.407782306	2.75957652	6.3	-42.9	-2.09	0.1	-0.2	-0.03	0	10	56	46	12	11	2001
-0.168292668	2.825795688	6.3	-43.1	-2.15	0	-0.2	-0.06	0	10	56	47	12	11	2001

--More--(4%)

Figure 4. Sample Output: Flight path angle, pseudo-roll angle, velocity acceleration (in NED coordinates), warning state, date and time are all logged.

In addition to the system's automatic data logging, the capacity also existed to insert manual time hacks into a separate file for use in timing the various phases of flight testing.

4 Experimental Procedure

Preliminary system verification was conducted in a GMC Jimmy on the streets of Boston and Cambridge. This was done to assure that data was flowing through the entire system, and the car was able to generate velocities sufficient to activate the warnings. The system responded as anticipated, issuing correct warnings for sloping roads and turns, logging data, and accepting manual time hacks.

Flight testing was conducted in a Piper Arrow four-seat aircraft, with a safety pilot and test subject in the front seats at the controls, and two test coordinators in the rear seats to operate the laptop, coordinate the test runs, and take data.

Figure 5. Test Coordinators: Hard at work taking data.

Two sets of tests were conducted. The first examined recovery from unusual flight attitudes, and the second looked at the pilot's ability to control the aircraft based solely on verbal warnings from the system.

All flight tests were performed with the test subject's vision restricted to the instrument panel through the use of a hood.

4.1 Recovery Testing

For the recovery tests, the test subject was asked to recover from an unusual attitude to steady, level flight. These tests conducted both with and without the benefit of informational warnings from the system. The system was set to issue warnings at +/- 30 degrees pseudo-roll and +/- 10 degrees flight path angle.

For each run, the test pilot looked down at his lap as the safety pilot performed a brief slewing maneuver to disorient the test subject. The safety pilot then placed the aircraft into the specified attitude from the test card (shown in Tables 1 and 2), transferring control to the test pilot when the system registered a warning state, at which point a warning statement would be issued. For the first series of tests, the warning consisted only of the spoken word "warning," while the second series of tests employed warning statements that provided information as to the nature of the unusual attitude such as "Right turn." The test subject then looked up, assumed control of the aircraft, and recovered as quickly as possible to level flight. The length of time from the initial registering of the warning state and the return to level flight was recorded for each run.

Tables 1. Recovery Testing Maneuvers.

Maneuver Sequence 1

1. CLIMB
2. DIVE & ROLL RIGHT
3. CLIMB & ROLL LEFT
4. DIVE & ROLL LEFT
5. ROLL LEFT – CONSTANT ALTITUDE
6. CLIMB & ROLL RIGHT
7. ROLL RIGHT – CONSTANT ALTITUDE
8. DIVE

Maneuver Sequence 2

1. DIVE
2. ROLL LEFT – CONSTANT ALTITUDE
3. DIVE & ROLL LEFT
4. CLIMB & ROLL RIGHT
5. CLIMB & ROLL LEFT
6. ROLL RIGHT – CONSTANT ALTITUDE
7. DIVE & ROLL RIGHT
8. CLIMB

4.2 Divergence Testing

The second series of testing, the test subject would be asked to maintain steady, level flight in the absence of attitude information except for the system warnings. This testing would be carried out in two runs. For both test runs, the instrument panel was covered, and the test subject was essentially flying blind. This condition would simulate failure of cockpit instrumentation or distraction of the pilot. Divergence was defined as +/- 30 degrees pseudo-roll or +/- 10 degrees flight path angle. For the test case with informational warnings, these warnings would be issued at half the failure criteria, +/- 15 degrees pseudo-roll or +/- 5 degrees flight path angle

For the duration of flight testing, the system archiving function was active and recorded flight path and pseudo-roll angles, velocity, acceleration, warning state, and time. Additional time hacks were logged to assist in post-processing of the data.

5 Results

Due to scheduling constraints and mechanical issues with the aircraft, testing was performed with only one test subject rather than the planned four. Additionally, an incompatibility with the power conservation function caused the laptop to drop its audio drivers, thus necessitating the issuance of warnings over the intercom by one of the test coordinators. This added a lag to the delivery of warnings to the pilot of somewhere between 0 and 1 seconds.

Throughout the flight test, the system's calculated pseudo-attitude tracked very closely with observed attitude, which is consistent with Kornfeld's original findings.

Flying unusual attitudes with restricted vision proved to be more physiologically demanding than originally anticipated, and the recovery testing was cut short for the comfort of the test subject. Table 2 shows the performed maneuvers, the recovery times for each maneuver, and the average time and standard deviation for each run.

Table 2. Recovery maneuvers performed and associated times, averages, and standard deviations.

Test Sequence	Maneuver	Time to Recovery (sec)	Average/ Std Dev
1	CLIMB	2	
	DIVE AND ROLL RIGHT	6	
	CLIMB AND ROLL LEFT	6	
	DIVE AND ROLL LEFT	10	
	ROLL LEFT AT CONSTANT ALTITUDE	15	8 / 4.6
2	DIVE	6	
	ROLL LEFT AT CONSTANT ALTITUDE	8	
	DIVE AND ROLL LEFT	14	
	CLIMB AND ROLL RIGHT	15	12.3 / 3.8

The test subject wavered between the 15 degree roll warning limits, but avoided the test's failure limits. Each time the subject received a warning, he was applied corrective action to return to a flight attitude closer to level. Figure 6 shows the flight path angle and pseudo-roll angle over the two and a half minutes of testing.

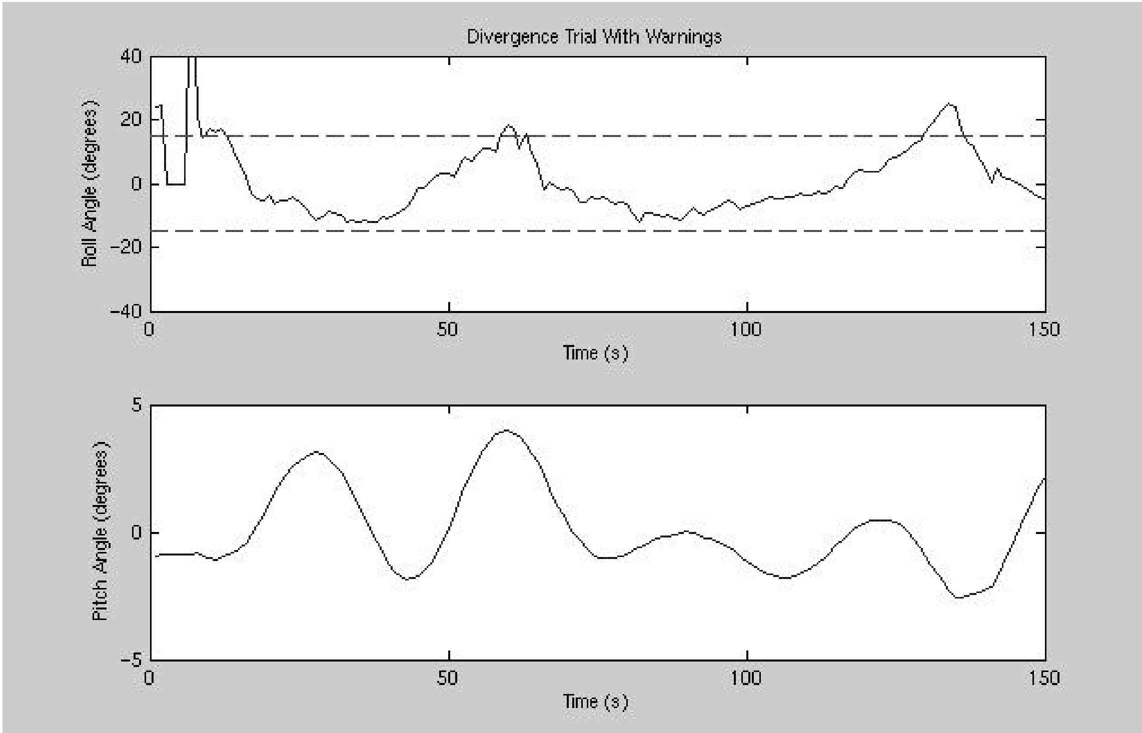


Figure 6. Flight path and pseudo-roll angles for the divergence test case with informational warnings.

The second divergence test case was conducted with no warnings of any kind. The test subject's only source of attitude was his innate ability to sense the motion of the aircraft via the inner ear. Under these conditions, the aircraft steadily increased in right bank over the course of the test, ultimately reaching the 30 degree failure criterion 63 seconds into the test. Figure 4 shows the flight path angle and pseudo-roll angle over the 63 seconds of testing.

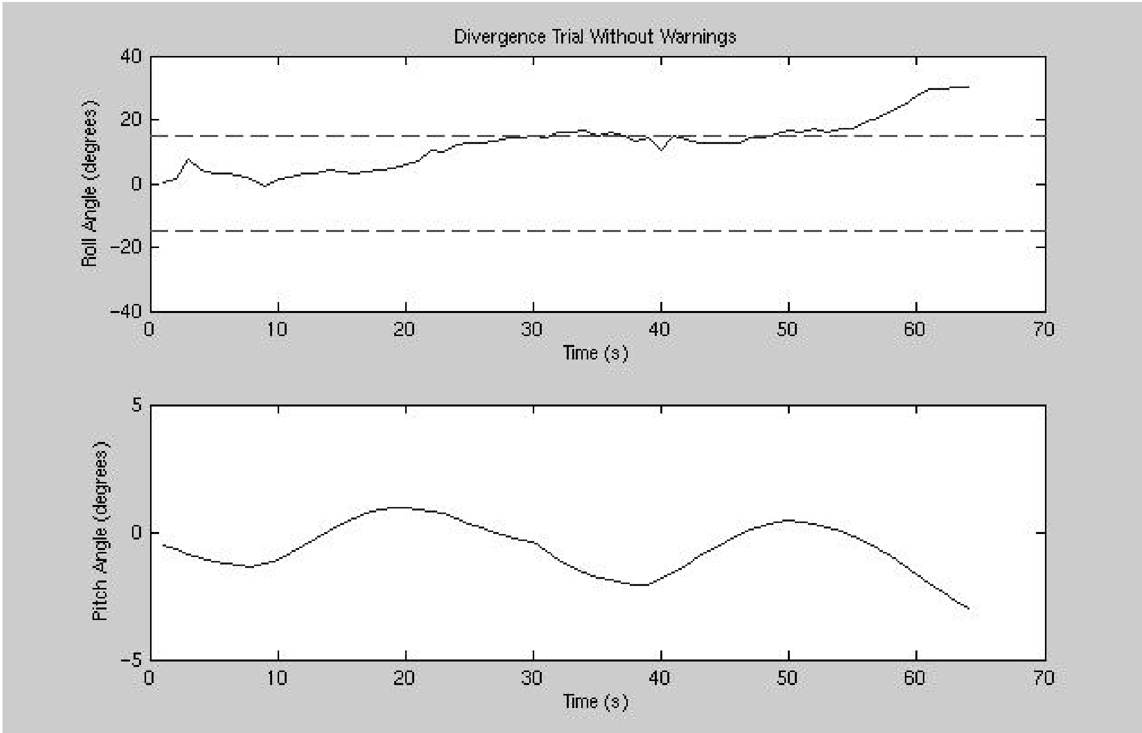


Figure 7. Flight path and pseudo-roll angles for the divergence test case with no warnings.

6 Conclusions

The 1 Hz pseudo-attitude system was successfully implemented. The computer-calculated pseudo-attitude tracked very closely with the aircraft's attitude indicator. The flight path angle showed an offset from pitch, corresponding to the angle of attack of the aircraft's wings, and this confirms Kornfeld's findings in this regard. The pseudo-roll angle did not differ from actual roll to any observable degree.

The use of the verbal warnings did not produce any improvements in the recovery time from unusual attitudes. Two factors may account for this. As previously noted, the test subject became increasingly airsick as the testing continued; and the testing with informational warnings occured after the testing with simple warnings. It seems more likely though, that no amount of additional testing would produce different results given the current test protocol, which called for the instruments to remain uncovered. Thus, as soon as the test subject assumed control of the aircraft, he had full use of the instruments including the attitude indicator. For a pilot with any degree of experience, the time needed to process the visual information of the attitude indicator is likely to be less than or equal to the three seconds it takes the system to issue the verbal warnings. This was corroborated by test pilot's subjective opinion of the system's utility.

The divergence cases indicate that a pseudo-attitude system can indeed be used to prevent divergence in cases of instrument failure or pilot distraction. In both divergence cases, pseudo-roll oscillated sinusoidally with a period of roughly 60 seconds. This corresponds to the fugoid mode of the aircraft, and is not believed to have been the result of any test subject control inputs. More interesting is the roll angle. In the case without warnings, the aircraft diverged steadily over the entire test run. For the case with warnings, the test subject was issued situational warnings at 60 and 130 seconds, following which he took corrective action to return the aircraft to a wings level attitude. In neither case did he have any internal indication of the divergence. The aircraft's motion was too subtle for him to detect. Figure 8 shows a comparison of pseudo-roll angle for the two runs.

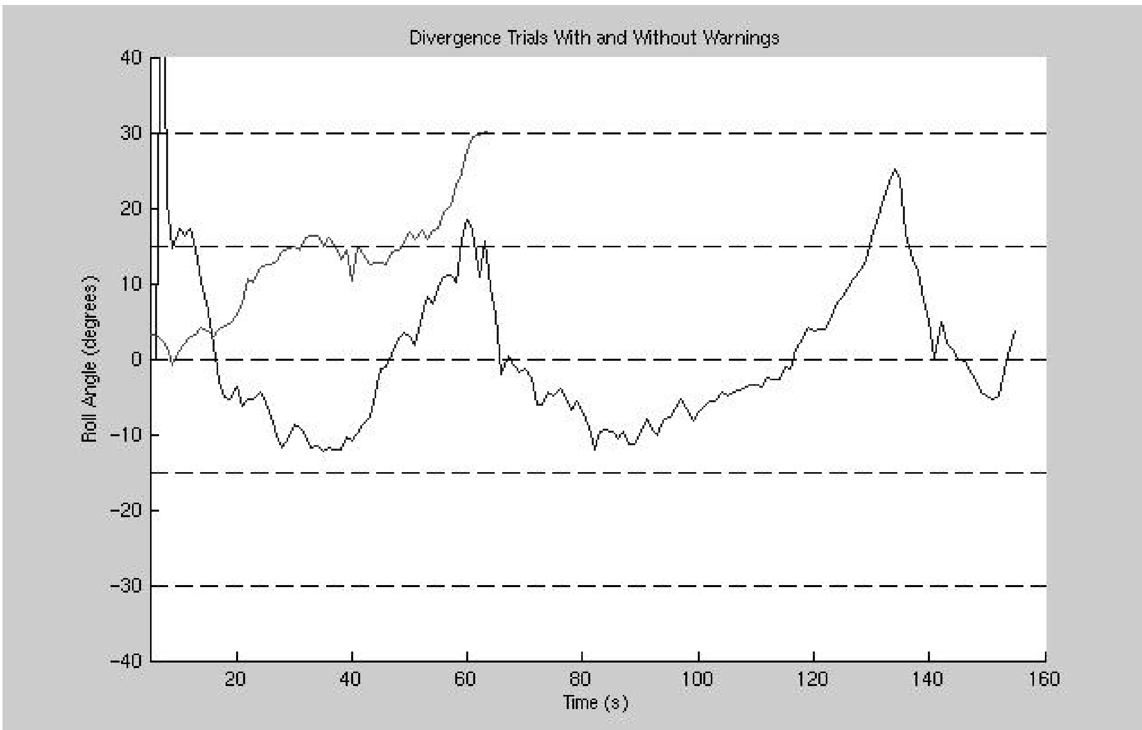


Figure 8. Pseudo-roll angles for both divergence cases.

These data demonstrate that the use of pseudo-attitude as a backup indicator for aircraft (a use proposed by Kornfeld) is a very viable application. The test subject also expressed a desire for a backup visual system in addition to the audio.

Figure 9 shows a graph of all data points taken over the course of approximately 35 minutes of flight time. Also shown in dashed lines are the divergence limits used for most of the testing. Recorded pseudo-attitude exceeded these limits for less than 1% of the time in flight path angle and less than 5% of the time in pseudo-roll. The unusual attitude testing accounts for a significant portion of this time outside the limits.

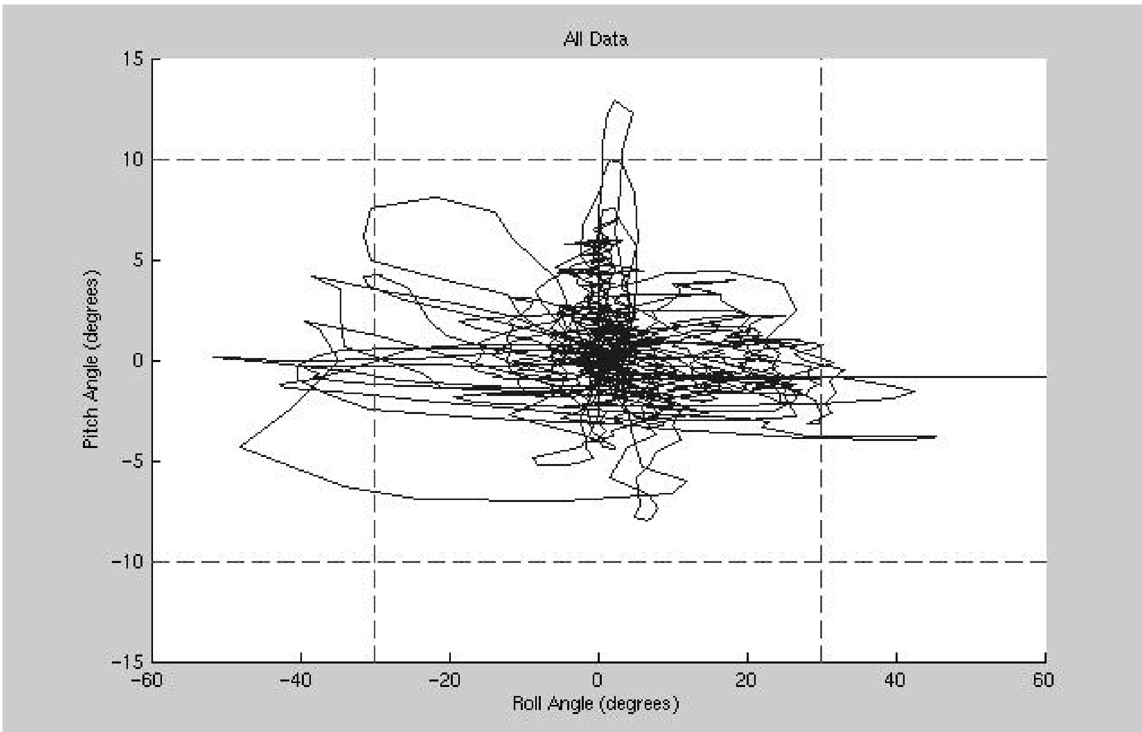


Figure 9. Plot of all data points collected during flight. Dashed lines indicate the warning limits for the recovery test cases.

In order to bring the warning system up to full operational readiness, further work must be done to refine the concept of what a safe flight attitude is. The possibility of having varying levels of warnings, differing with phase of flight, particular pilots, visibility conditions, and altitude all could be investigated further.

Perhaps more importantly, this system was implemented with a minimum of hardware and software. Low cost, low power, low mass pseudo-attitude systems such as the one implemented for this research make available position, velocity, acceleration, and attitude from a single source. This implementation demonstrates the feasibility of a multitude of other applications, from the backup instrumentation tested here to primary navigation, autopilot, or autonomous guidance systems.

7 Acknowledgements

The author would like to thank Richard Kornfeld whose development of the pseudo-attitude system allowed this research to be attempted in the first place.

The author would also like to thank his lab partner Matt Lockhart, advisor Prof. R. J. Hansman, test subject, and the .62x staff for their concern and guidance.

Thank you to Rodin Entchev for the use of the GPS, Sarah Dagen for the loan of her laptop, and Jennie Cooper for the use of her car. Thank you also to Veronica Sara Weiner for recording the voice warnings.

References

1. Kornfeld, R.P., Hansman, R.J., and Deyst, J.J., "The Impact of GPS Velocity Based Flight Control on Flight Instrumentation Architecture," Report No. ICAT-99-5, June 1999.

2. Kornfeld, R.P., Hansman, R.J., and Deyst, J.J., "Preliminary Flight Tests of Pseudo-Attitude Using Single Antenna GPS Sensing," 17th Digital Avionics Systems Conference, Seattle, WA, Oct. 31 - Nov. 6, 1998.

3. Kornfeld, R.P., Hansman, R.J., and Deyst, J.J., "Single-Antenna GPS-Based Aircraft Attitude Determination," Navigation,, Vol. 45, No. 1, Spring 1998, pp. 51-60.

4. Kornfeld, R.P., Hansman, R.J., and Deyst, J.J., "Single Antenna GPS Information Based Aircraft Attitude Redundancy," 1999 American Control Conference, San Diego, CA, June 2-4, 1999.

5. Sanders, M.S. and McCormick, E.J. Human Factors in Engineering and Design, McGraw-Hill, Inc. New York, 1993.

6. Stokes, A., Wickens, C., and Kite, K., Display Technology: Human Factors Concepts, Society of Automotive Engineers, Inc., Pennsylvania, 1990.