Correction of Pseudo-Attitude Information and Partial Panel Flight Test in General Aviation Aircraft

by

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S.B., Mechanical Engineering (2001)

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science at the

Massachusetts Institute of Technology

September 2002

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ABSTRACT

This thesis explores the concept of pseudo-attitude, an aircraft attitude display generated from single antenna Global Positioning System (GPS) velocity information. A group of researchers developed the baseline pseudo-attitude system at MIT in 1999. In one possible application, pseudo-attitude is intended as a backup attitude display in the event of primary attitude indicator failure. The impact of a failed primary attitude display in general aviation is discussed, as is basic instrument flying.

Since the original MIT system is based on an assumption of coordinated flight, the system produced accurate aircraft roll angles during coordinated maneuvers, but failed to predict actual aircraft roll attitudes in uncoordinated maneuvers. Further, the baseline system produced flight path angle information, but could not produce aircraft pitch information. This study focuses on aircraft maneuvers that generate false attitude cues within the baseline system. The coordinated flight assumption is relaxed and two accelerometers and additional algorithms are added to the system to produce corrected roll angle and pseudo-pitch. Both the baseline system and the sensor-augmented system are compared directly to Attitude Heading and Reference System (AHRS) flight test data, post-processed in computer simulations. Additionally, a preliminary flight test is performed in which partial panel flying is compared to flight with reference to the pseudo attitude system. AHRS data is compared to pseudo-attitude data for a variety of simple maneuvers, and Cooper-Harper evaluation results are presented for each flight scenario.

Results indicate that during severely uncoordinated flight, RMS roll error improved from 10.14 to 0.63 degrees using the sensor augmented system. The discrepancy between flight path angle and aircraft pitch improved from 3.8 degrees to 0.12 degrees in straight and level flight utilizing pseudo-pitch in place of flight path angle. It should be noted that each method of correction can be used independently or together to correct pseudo-attitude.

Cooper-Harper results from the preliminary real-time flight test are favorable, showing a preference for pseudo-attitude over partial panel flying.
Acknowledgements

Foremost, I would like to thank the Avidyne Corporation for their financial and intellectual support on this project, namely Mark Krebs, Paul Stoltz, and Mike Morgan for their direct assistance with project plans, logistics, and the development of concepts, as well as Kathy Stoltz for making my stay in Boulder possible. Working at Avidyne was by far my most enjoyable experience in industry to date.

My parents of course deserve special thanks for their continuous concern and support. I would be truly blessed to become half the parent when I finally have children. Thanks to my brother, Clay, for constant inspiration.

I would like to thank the U.S. Navy for providing me the time and money to pursue my education at MIT; LT Eric Whitman deserves special mention for his role in helping me to improve my graduate program and get back on track. You made a huge difference in my life, Slim. I look forward to an exciting career flying with guys like you.

At MIT and around Boston, I would like to thank Professors James Kuchar, Thomas Sheridan, and Martin Culpepper for their help and wisdom. I would like to thank all the brothers of Phi Gamma Delta, especially my pledge brothers in the class of 2001. Thanks to my countless friends at Berklee College of Music and elsewhere, especially Craig Lawrence, Hylah Hedgepeth, and Tracy Sampedro, for providing me an escape from the rigors of academia.

Finally, in Boulder, I would like to thank Anne Wellnitz and her roommates for a warm Colorado welcome, and for making my last summer as an MIT student a constant joy.
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1 Introduction/Overview

1.1 Background

In recent years, Global Positioning System (GPS) technology has emerged as a source of high-quality, low-cost position and velocity information for the consumer market. GPS chip production has reached a level at which the principle of economy of scale applies, while GPS system accuracy has reached a level comparable to that previously only available with inertial navigation systems (INS). Thus, GPS technology has recently been adapted to many applications, most notably in the context of this work as a source of velocity data for novel aircraft instrumentation architecture.

1.1.1 Standard Flight Instruments

Traditionally, general aviation relies on six main flight instruments that permit aircraft to be flown in Instrument Meteorological Conditions (IMC), where reference to outside visual cues is impossible due to obscured visibility. The six instruments include the airspeed indicator, the attitude indicator, the altimeter, the turn coordinator, the heading indicator (HI), and the vertical speed indicator (VSI). The primary reference used during Instrument Flight Rules (IFR) flying is the attitude indicator, as it serves as the most direct replacement for reference to the real world outside cues used by the pilot. Figure 1.1 depicts the instruments.

Figure 1.1: Standard Flight Instruments – (clockwise from upper left) Airspeed Indicator, Attitude Indicator, Altimeter, Vertical Speed Indicator, Heading Indicator, Turn Coordinator
In general aviation, the six flight instruments can be categorized as gyroscopic instruments and pressure instruments. Gyroscopic instruments can be further subdivided into vacuum driven and electrically driven, while pressure instruments can be subdivided into pitot and static pressure.

The altimeter and VSI operate from measurements of static pressure, while the airspeed indicator uses ram or pitot pressure compared to static reference pressure in order to measure speed through the air.

The turn coordinator actually contains two instruments in one. An electrically driven rate gyro measures the rate of turn, and the inclinometer below indicates whether the aircraft is slipping or skidding in the turn based on the specific lateral acceleration using a moving ball in a tube. The two white marks below the wing tips are timing marks. When the wing tip within the instrument is aligned with the mark and the ball in the inclinometer is centered, it will take two minutes to complete a 360-degree turn.

Finally the attitude indicator and the HI operate using vacuum pump driven gyroscopes. Each gyroscope rotates at high speed on very low friction bearings. When each is rotating normally, it resists changes in direction. The HI is manually set to match the magnetic compass heading, and remains fixed in space due to gyroscopic principles, allowing the compass card in the instrument to indicate the correct heading as the aircraft changes direction. The attitude indicator indicates the pitch and roll angles of the aircraft making similar use of gyroscopic principles, this time in two axes. It is gimbaled to permit rotation about the lateral axis indicating pitch attitude, and about the longitudinal axis to indicate roll attitude. The miniature wings attached to the case remain parallel to the wings of the aircraft. The horizontal white line across the face of the attitude indicator represents the horizon, the upper field (usually colored blue) the sky, the lower, the ground. When in a left turn, the blue portion of the ball will have rolled to the right, as though the pilot were looking at the horizon over the nose of the aircraft during the turn. The instrument is powered by suction generated by a vacuum pump through a closed system. The air flowing through the instrument case moves vanes attached the gyroscope, causing the gyroscope to spin and the instrument to operate.
1.1.2 Attitude Indicator Failures
The vacuum system is critical to the operation of the attitude indicator, however failures of the system occur with regularity. The Aircraft Owner and Pilot Association (AOPA) Air Safety Foundation found 40 accidents from 1983 through 1997 involving vacuum pumps (Marsh, 1999). Thirteen listed a broken vacuum pump as the cause of the accident, while the rest listed the failed pump as one factor contributing to the accident. Four of the 40 accidents caused no injuries, three resulted in minor injuries, and one led to serious injuries, while 32 of the accidents resulted in fatalities.

Scenarios involving failed attitude indicators are numerous in general aviation. The pilot of a Cessna P210 and his friends were killed in February of 1999 after the aircraft’s two vacuum pumps failed (Marsh, 1999). The pilot had told controllers at one point that he thought he had just been in a spin, and later that he had done a roll. He had a backup electrically driven attitude indicator, but he reported that it did not seem to be in agreement with the aircraft’s compass. A witness saw a wing separate from the aircraft after it emerged from the base of a high overcast, indicating high load factor maneuvers. Obviously from these reports, the pilot was extremely disoriented, and was having considerable difficulty flying from a partially failed instrument panel.

Even experienced pilots are not immune to loss of control after a vacuum system failure. An Airline Transport Pilot flying a Piper Seneca II over Oregon crashed in a steep, nose-down attitude during a no-gyro approach (Marsh, 1999). The pilot had 6,500 hours total time and 500 in type. Another pilot with 1,270 hours total time and 256 hours of instrument time was killed along with his passengers when he was unable to control a Beech B55 Baron following vacuum system failure. The pilot told Air Traffic Control (ATC) just before the crash that he was "in trouble, in a dive." Flight conditions included low ceilings, poor visibility, snow, and turbulence (Marsh, 1999).

1.1.3 Instrument Flying
During IFR flight, the pilot relies primarily on the six main instruments described above. If any of the instruments should fail, the pilot must diagnose the failure, ignore the failed instrument, and fly with reference to the remaining functional instruments. This type of flying is known as partial panel flying. Pilots occasionally practice this type of flying during flight with another pilot in the cockpit, where the safety pilot or instructor will
cover the “failed” instrument with a placard while the subject will attempt to fly by cross-checking the remaining instruments to maintain appropriate altitude, heading, turn rate, or whatever maneuver the pilot is attempting to perform. The task is made more difficult by simulating IFR conditions through the use of a “hood” which allows the pilot to see only the instrument panel.

In a real IFR scenario, the pilot must identify the failed instrument on his own. The pilot accomplishes this by scanning the instruments regularly, and verifying that they are all in agreement. For example, in a coordinated, level, standard rate turn to the right, the pilot would see a right bank angle of approximately 15 degrees displayed on the attitude indicator with a slightly positive pitch attitude in order to maintain level flight. The HI would be turning counterclockwise at the rate of one half revolution per minute. The turn coordinator would show the ball centered in the inclinometer with the instrument “wings” aligned with the right tick mark. The VSI would show zero vertical speed, and the altimeter would indicate constant altitude. Airspeed would remain basically constant depending on the pilot’s power and pitch inputs. Figure 1.2 depicts the standard instrument display for this maneuver.

![Figure 1.2: Level Standard Rate Turn to the Right](image)

If the aircraft were descending at constant airspeed while turning, the HI, the airspeed indicator, and turn coordinator would show similar indications. The attitude indicator would still show approximately 15 degrees of bank. The VSI would indicate a negative
value, and the altimeter would indicate decreasing altitude. Figure 1.3 depicts the instrument display.

![Figure 1.3: Descending Standard Rate Turn to the Right](image)

If the attitude indicator had failed in either scenario, the pilot might still guess that his aircraft is banked, and thus turning, based on the rotation of the HI and the turn indication from the turn coordinator. Although with a failed attitude indicator, the pilot could only guess at the actual attitude of the aircraft. Thus, flying from a partial panel can quickly become more difficult than flying from a fully functional panel. Figure 1.4 depicts a possible display scenario for a failed attitude indicator. All instruments except the attitude indicator indicate a descending right turn with increasing airspeed.

![Figure 1.4: Possible Indication of Failed Attitude Display](image)
A variety of instrument crosschecks are easily imagined, with any given instrument failed. If any instrument seemed to be in disagreement with the others based on the crosschecks, the pilot could guess that the instrument has failed and perform other checks to verify failure.

Additionally, because an actual vacuum pump failure can cause the attitude indicator to fail slowly as the angular speed of the gyroscope spinning on low friction bearings eventual goes to zero, the instrument failure can be extremely difficult for the pilot to resolve (Marsh 1999). A failed gyro will eventually indicate a descending bank to either the left or right even if the aircraft is in level flight attitude. A pilot attempting control inputs to correct the indicated attitude from the failed display might put the aircraft into an extreme nose up and banked attitude, which would be a perfect condition for a stall followed by a spin. In this case of attitude indicator failure, another attitude instrument such as pseudo-attitude to aid in the crosscheck would be extremely helpful to the pilot.

1.2 Thesis Motivation

1.2.1 Baseline Pseudo-Attitude
A group of researchers developed a system at MIT in 1999 that utilizes GPS velocity information to synthesize aircraft attitude information at a fraction of the cost of traditional INS attitude systems (Kornfeld, 1999). The system has been termed pseudo-attitude because aircraft orientation is inferred from GPS velocity information and a simple computer algorithm, rather than measured with traditional INS sensors.

The synthesis of the pseudo-roll and pseudo-pitch angles will be described in greater detail in Chapter 2.

This thesis was motivated by a need to assess the performance of a pseudo-attitude system intended for commercial application in general aviation. The focus of the assessment was the examination of scenarios where the pseudo-attitude system might give false or misleading attitude information to the pilot.

Pseudo-attitude synthesis as previously developed at MIT is based on an assumption of coordinated flight (zero lateral acceleration), which simplifies the translation of the
appropriate velocity vector components into an estimate of the aircraft’s roll angle. This assumption does not always represent reality, especially in scenarios of aircraft slip, skid, and other unusual attitudes. Further, Kornfeld’s pseudo attitude utilizes the flight path angle of the aircraft rather than the aircraft’s pitch attitude. These two indications provide completely different information to the pilot. Flight path angle indicates the vertical motion of the aircraft’s center of gravity up or down with reference to the local horizontal plane, while pitch angle indicates the aircraft body’s angular rotation about the wing axis. Both will be discussed in more detail in later chapters.

1.2.2 Need for Corrected Pseudo Attitude Angles
Pilots flying under visual flight rules (VFR) use the horizon and visual cues outside the cockpit as their primary attitude reference. In the event of instrument meteorological conditions (IMC), a pilot must rely instead on his primary attitude indicator for reference. Because instrument rated pilots are trained to use the attitude indicator as their primary instrument during IMC conditions, having a reliable system and a redundant backup display are important to the improved safety of general aviation.

Beyond the basic need to assess the baseline pseudo attitude system, this thesis was further motivated by a need to correct the pseudo-roll and flight path angle attitudes in order that pseudo attitude more closely resemble traditional attitude. With pseudo attitude displaying roughly the same information as traditional attitude indicators, the pilot could more easily interpret a pseudo attitude display were it serving as a backup to the traditional display.

1.2.3 Maneuvers Generating False Pseudo-Attitude Indication
Three basic aircraft maneuvers exist that generate false attitude cues in the baseline pseudo-attitude system: slip, skid, and any configuration where the aircraft’s pitch attitude differs significantly from its flight path angle, including take off, slow flight, and stalls, among others. Definitions of pitch attitude and flight path angle are given in Section 2.2.

Figure 1.5 depicts a brief overview of coordinated as well as skidding and slipping turns. The turn coordinator indication is shown to further illustrate the point. In a coordinated turn, the pilot sets a desired roll angle, creating a horizontal component of lift that causes
the aircraft to turn. The pilot provides adequate rudder input to balance the centrifugal force of the turn with the horizontal component of lift. The turn coordinator shows the ball centered in the inclinometer. In a skidding turn, the pilot provides excessive rudder input, forcing the aircraft to turn faster than normal for the given roll angle. This causes the centrifugal force to exceed the horizontal component of lift. The inclinometer shows the ball pushed to the outside of the turn, opposite of the excessive rudder input. In a slip, the pilot provides inadequate rudder input, causing the horizontal component of lift to exceed the centrifugal force. The ball falls to the inside of the turn, as do the occupants of the aircraft.

![Simple Overview of Coordinated and Uncoordinated Turns](image)

In the case of slip and skid, the baseline pseudo-attitude system generates false roll angle information because lateral forces acting on the aircraft are no longer balanced. This will be discussed in further detail in Chapter 3, and a correction will be proposed utilizing information from a single accelerometer.

Now considering aircraft pitch, we see an immediate discrepancy between actual aircraft pitch attitude and pseudo-attitude generated flight path angle. Figure 1.6 shows the difference between the two angular measurements. Flight path angle \( \gamma \) indicates the aircraft's trajectory (\( v \) in the diagram) up or down from a local horizontal plane. Pitch \( \theta \) indicates the angle of the aircraft's longitudinal axis (\( x \) in the diagram) relative to the
same horizontal reference. Anytime the aircraft’s center of gravity moves in a direction other than along its longitudinal axis, the pitch angle and the flight path angle will not be equal. In general, the larger the aircraft’s angle of attack, the larger the discrepancy between pitch and flight path angle.

1.2.4 Vestibular Illusions

When subject to the variety of forces of flight without reference to outside visual cues, a pilot’s vestibular system may send misleading cues to the brain, resulting in vestibular illusions. Several different illusions can occur in this system when a pilot has no outside visual cues for reference. This section contains several examples of false vestibular cues to the pilot. Since the brain can deceive the pilot, he must rely on his instruments, especially the attitude indicator, which is the only direct indication of the aircraft’s attitude relative to the horizon.

The vestibular system consists of the vestibule and three semicircular canals located in the inner ear. The vestibule perceives gravity and linear acceleration. A gelatinous substance within the vestibule is coated with tiny grains of limestone, which shift causing hair cells to send nerve pulses to the brain for interpretation. The semicircular canals are oriented in three planes to sense pitch, roll and yaw. Each canal is filled with fluid. When the body moves, the canal moves but the fluid lags behind, causing hair cells to send impulses to the brain, which it interprets as motion about an axis (Jeppesen, 1998).

The most basic vestibular illusion occurs during a prolonged constant rate turn. When the turn is initiated, the hair cells within the semicircular canal are deflected by the fluid motion, providing an accurate sensation of the rotational acceleration. The fluid eventually reaches equilibrium with the canal during the prolonged turn, causing a false
sensation of no motion in the direction of the turn (Jeppesen, 1998). Without reference to outside visual cues or without properly functioning instruments, the pilot might not sense the bank angle or the turn. If the rate of turn then decreases, the pilot might receive a false sensation of a turn in the opposite direction as the fluid in the semicircular canal decelerates.

These factors in combination with a loss of altitude in a prolonged constant rate turn may be interpreted by the pilot as a wings level descent. The pilot might add elevator backpressure, increasing the rate of the turn and thus the rate of altitude loss. A recovery to wings level attitude may produce a sensation of a turn in the opposite direction, possibly causing the pilot to reenter the spiral. This is known as a graveyard spiral (Jeppesen, 1998).

A coriolis illusion occurs during a constant rate turn if the pilot tilts his head down rapidly. The head movement puts fluid in motion in more than one semicircular canal. This may create an overwhelming sensation of rotating, turning or accelerating in a completely different plane. Attempts by the pilot to maneuver the aircraft to stop the sensation may result in a dangerous unusual attitude (Jeppesen, 1998).

A somatogravic illusion occurs during level accelerations or decelerations of the aircraft. A rapid acceleration in level flight will create the illusion of a nose-high pitch attitude, possible causing the pilot to initiate a dive. Rapid deceleration, such as quickly retarding the throttle, may produce the opposite effect. The pilot may sense a dive, and raise the nose, possibly resulting in a stall (Jeppesen, 1998).

The various vestibular illusions in aviation require the pilot to reference visual cues, either outside the cockpit or from the aircraft instruments. Without a properly functioning attitude indicator, the pilot could fall victim to these scenarios.

1.3 Thesis Objectives

The objectives of this thesis include the assessment of a baseline pseudo-attitude system, which uses a zero sideslip assumption, in flight scenarios expected to introduce false attitude cues the system. The system will be assessed by direct comparison of roll and
pitch data gathered from a gyroscopic system compared to the GPS-based pseudo attitude roll and pitch data. Comparisons will be made utilizing existing INS attitude and GPS flight test data in computer simulations running the pseudo-attitude algorithm.

As an improvement to the baseline, the system will be augmented with wing-axis accelerometer data in order to reduce the magnitude of false roll attitude cues. Additionally, pseudo-pitch will be developed utilizing GPS velocity information and an additional accelerometer. Again roll and pitch data gathered from an air data system will be compared directly to the GPS-based pseudo attitude data within a computer simulation running the pseudo-attitude algorithm, this time for the sensor-augmented system.

Kornfeld proved in his study that a pseudo attitude system can work in flight, but his results showed discrepancies between actual aircraft attitude and indicated pseudo attitude during uncoordinated maneuvers. Additionally, flight path angle output from the system, never matched pitch attitude information in flight scenarios. By considering certain flight scenarios wherein the baseline pseudo-attitude system disagrees with traditional attitude information, the sensor augmented pseudo attitude system proposed in this study is intended to prove that these discrepancies can be reduced with two low-cost sensors. Again, comparisons between the baseline and augmented systems will be made utilizing computer simulations of post-processed flight test data.

The ultimate goal of this project is to confirm that the augmented pseudo-attitude display system produces roll and pitch information comparable to traditional INS systems. Additional experiments in this study will include a preliminary examination of the augmented system tested by pilots in real time flight. Comparisons will be made between partial panel flying without reference to either traditional or pseudo attitude and partial panel flying without reference to traditional attitude, but with reference to pseudo attitude. The performance will be based on objective and subjective measures.

1.4 Organization of Thesis

This thesis is divided into 7 chapters, including this introduction. Chapter 1 provides background and motivation for the study. Chapter 2 provides an overview of the theory behind pseudo-attitude synthesis. Included in Chapter 2 are discussions of the coordinate
reference frames and the methodology behind calculating pseudo-attitude roll and flight path angles from GPS velocity information.

Chapter 3 describes MATLAB simulations that were conducted from existing 1 Hz GPS flight test data. The simulations focused on a baseline pseudo-attitude system similar in function to Kornfeld's original pseudo-attitude system. Chapter 4 describes a pseudo-roll angle correction accomplished through the incorporation of wing-axis accelerometer data, as well as the development of pseudo-pitch using similar methodology.

Chapter 5 describes the preliminary real time flight test designed to compare partial panel flying (failed attitude indicator) to flight with reference to pseudo attitude in place of the traditional attitude indicator. Included are flight test protocols, objective flight test results, and results from Cooper-Harper evaluations for each scenario. Chapter 6 briefly covers preliminary estimates concerning product architecture and costs. Chapter 7 covers conclusions and a summary of findings.
2 Overview of Pseudo-Attitude Synthesis

2.1 Coordinate Frames

Based on the pseudo attitude development by Kornfeld, the following coordinate frames are important (Kornfeld, 1999):

- The NED frame $F_{NED}$ is fixed to the earth. Its origin is instantaneously fixed to the center of gravity of the aircraft. The axes are aligned with the directions of North, East, and local vertical (Down). For the purpose of this thesis, the earth is assumed flat locally, and $F_{NED}$ is treated as an inertial reference frame, in which accelerations are measured. The velocity of the aircraft, as measured by GPS, is denoted $v_{gps}$, and is expressed in NED coordinates as components: $v_{gpsN}$, $v_{gpsE}$, $v_{gpsD}$.

- The aircraft body frame $F_B$ is fixed to the aircraft body, and its axes are aligned along the roll ($x_b$), pitch ($y_b$), and yaw ($z_b$) axes of the aircraft. As depicted in figure 2.1, the roll axis extends from the aircraft’s nose, the pitch axis extends out the right wing, and the yaw axis extends out of the belly of the aircraft.

![Aircraft Body Axes and Pseudo-Attitude Angles](image)

Figure 2.1: Depiction of Aircraft Body Axes and Pseudo-Attitude Angles for flight path angle ($\gamma$) and roll ($\phi$) (Kornfeld, 1999)

Unlike traditional attitude, which is referenced from the aircraft body axis relative to the $F_{NED}$ frame, pseudo attitude is referenced from the aircraft’s velocity vector. Figure 2.1 depicts the aircraft body coordinate frame, an arbitrary aircraft velocity vector $v_{gps}$, and the pseudo-pitch and pseudo-roll angles, denoted $\gamma$ and $\phi$ respectively.
2.2 Pseudo Attitude Synthesis

Based on Kornfeld’s development, pseudo-attitude is referenced from the aircraft’s velocity vector $v_{gps}$ with respect to the ground. Pseudo attitude consists of the aircraft’s flight path angle and roll angle. The flight path angle, or pseudo-pitch, is given by

$$\gamma = \tan^{-1}\left(\frac{-v_{gpsD}}{\sqrt{v_{gpsN}^2 + v_{gpsE}^2}}\right)$$  \hspace{1cm} (2.1)

The angle is measured between the local $F_{NED}$ horizontal plane and the aircraft’s velocity vector. As seen in Figure 2.2, this differs from the Euler pitch angle which is measured between the local $F_{NED}$ horizontal plane and the x axis of the aircraft body. Flight path angle provides a direct indication of the vertical trajectory of the aircraft, where a positive $\gamma$ indicates a climb and a negative value indicates descent. This relationship holds for values common in general aviation, i.e. in quadrants one and four of the Cartesian plane. In the case of inverted flight, a positive value for $\gamma$ still indicates climb and a negative value still indicates descent. In the case of perfectly vertical flight, the relationship reaches a singularity; however this scenario is uncommon in general aviation.

The synthesis of pseudo-roll is slightly more involved. As a first assumption, coordinated flight of the aircraft is assumed, meaning lateral accelerations along the $y_b$ axis are set to zero. For the majority of aircraft maneuvers, this assumption holds, but in later chapters, this assumption will be relaxed, and side accelerations will be considered.
We begin by calculating the acceleration vector based on the aircraft's velocity vector \( \mathbf{v}_{gps} \). The acceleration is given by

\[
\mathbf{a} = \frac{d\mathbf{v}_{gps}}{dt}_{NED}
\]

the time derivative of the velocity vector.

Then we calculate the component of the aircraft acceleration in the direction of the velocity vector, or the projection of \( \mathbf{a} \) onto \( \mathbf{v}_{gps} \).

\[
\mathbf{a}^t = \frac{\mathbf{a} \cdot \mathbf{v}_{gps}}{|\mathbf{v}_{gps}|^2} \cdot \mathbf{v}_{gps}
\]

(2.3)

Subtracting \( \mathbf{a}^t \) from \( \mathbf{a} \) gives the component of the aircraft acceleration normal to the velocity vector:

\[
\mathbf{a}^n = \mathbf{a} - \mathbf{a}^t
\]

(2.4)

Similar to equation 2.3, we calculate the component of the gravitational acceleration in the direction of the velocity vector, or the projection of \( \mathbf{g} \) onto \( \mathbf{v}_{gps} \).

\[
\mathbf{g}^t = \frac{\mathbf{g} \cdot \mathbf{v}_{gps}}{|\mathbf{v}_{gps}|^2} \cdot \mathbf{v}_{gps}
\]

(2.5)

Subtracting \( \mathbf{g}^t \) from \( \mathbf{g} \) gives the component of the gravitational acceleration normal to the velocity vector:

\[
\mathbf{g}^n = \mathbf{g} - \mathbf{g}^t
\]

(2.6)

Using vector addition (see Figure 2.3), we see that the aircraft's lift vector is the following:

\[
\mathbf{l} = \mathbf{a}^n - \mathbf{g}^n
\]

(2.7)
Figure 2.3: Vector Diagram of Relevant Forces in Pseudo Attitude Synthesis

Now we define a reference vector in the horizontal plane of $F_{NED}$ by crossing the local gravitational acceleration vector with the aircraft velocity vector:

$$h = g \times v_{gps}$$

(2.8)

Finally, pseudo-roll $\phi$ is defined as the arcsine of the normalized dot product of the lift vector and the reference vector:

$$\phi = \sin^{-1} \left( \frac{1 \cdot h}{|1| \cdot |h|} \right)$$

(2.9)

This relationship holds for values common in general aviation, i.e. in quadrants one and four of the Cartesian plane. A positive value for $\phi$ indicates a right-hand bank, while a negative value indicates a left-hand bank. In the case of inverted flight, the correlation is reversed.
3 Baseline Pseudo-Attitude Accuracy from Flight Data

3.1 Algorithms

A simple MATLAB algorithm was written to calculate the pseudo-attitude angles based on the synthesis described in the previous chapter. All MATLAB scripts can be viewed in the appendix.

A second script was written to make use of flight test data available from a corporate sponsor. The MATLAB script plots pseudo-attitudes as well as Attitude Heading Reference System (AHRS) attitudes (from gyroscopic sensors) for direct comparison.

3.2 Results

3.2.1 Baseline Pseudo-Roll

1 Hz GPS data from several flight tests were compared to AHRS data using the previously described MATLAB script for the baseline system. Figure 3.1 depicts pseudo-roll and AHRS roll data from one segment of the flight test data. The plot shows a coordinated left bank of 30 degrees followed by straight and level flight initiated at approximately 3000 seconds into the test. At 3035 seconds, the pilot rolls into a coordinated 30 degree right bank, and then again to straight and level. The RMS error between pseudo-roll and AHRS roll angles for this segment of the test is 0.89 degrees.
3.2.2 Baseline Flight Path Angle

From the same flight test, GPS based flight path angle is compared to AHRS pitch data. Figure 3.2 depicts a period of basically straight and level flight at constant trim. Note that the oscillations are only on the order of 1 to 2 degrees. Note also that a constant offset exists between flight path angle and aircraft pitch. This indicates a constant trim scenario where the aircraft maintains approximately level flight – indicated by basically zero flight path angle – while the aircraft itself is pitched nose up by approximately 4 degrees – indicated by 3.87 degrees RMS error between flight path angle and pitch.
Figure 3.2: Flight Path Angle (solid) and AHRS Pitch (dashed) for Constant Trim

3.2.3 Aircraft Trim

Figure 3.3 depicts the period of flight following takeoff. The AHRS data indicates decreasing pitch as the pilot trims the aircraft from takeoff trim to level trim attitude. Similar to the data in Figure 3.2, there exists an offset between the two data sets. The RMS error calculated for this segment is 6.87 degrees. In the next chapter, the concept of pseudo-pitch will be introduced to greatly reduce this discrepancy.
3.2.4 Uncoordinated Maneuvers

Figure 3.4 depicts maneuvers designed to yield false roll information from the baseline pseudo-attitude algorithm. These maneuvers include cross-coupled controls, yielding basically zero pseudo-roll angles, while the AHRS data shows non-zero roll. Also shown is a 360-degree skid turn, showing non-zero pseudo-roll and basically zero AHRS roll. The RMS error calculated for this segment of the flight test is 10.14 degrees.
3.2.5 Stalls

Figure 3.5 depicts AHRS pitch and Flight path angle data for two stalls – power-on and power-off. In a power-on stall the pilot applies full power, and increases aircraft pitch until the stall angle of attack is achieved. This is similar to what might occur during takeoff if the pilot increases pitch to the point of stalling the aircraft. A power-off stall occurs when the pilot reduces power to idle, then increases aircraft pitch to the point of stall. This can occur during landing maneuvers when the pilot reduces power for the landing descent. Note that during the power-off stall, pitch and FPA disagree by as much as 17.4 degrees and for approx 13 seconds the aircraft has a positive pitch though FPA is negative, which could lead a pilot into aggravating the stall. This points to the possible hazards in displaying flight path angle rather than pitch information on the attitude display.
3.2.6 Low-Pass Filter

Because the level of noise present in the pseudo-roll data is greater than the nominal flight noise present in the AHRS data, the effect of a simple low pass filter placed on the pseudo-roll data was briefly examined. The filter was intended to smooth the pseudo-roll data for display in a real-time display application. The filter was of the form:

\[ y(n+1) = e^{-\frac{t}{\tau}} \cdot y(n) + (1 - e^{-\frac{t}{\tau}}) \cdot x(n) \]  \hspace{1cm} (3.1)

Where \( x \) is the input of the system, \( y \) is the output, \( T \) is the sample period and \( \tau \) is the time constant.

Figure 5.3: Flight Path Angle (solid) and AHRS Pitch (dashed): Power-On and Power-Off Stalls
Figure 3.5 shows the effect of the filter. The sample rate for the data was 1 Hz and the time constant for the filter was set to two seconds, yielding a ratio of $T$ over $\tau$ of 0.5. The
low pass filter succeeds in visibly smoothing the noise in the pseudo-roll data, but results in a lag in the pseudo-roll response approximately equal to the time constant. Results from a study performed by Kornfeld show that display update rates below 2 Hz are undesirable for aircraft control, thus indicating that a display lag of more than approximately 0.5 seconds is also undesirable. Although a two second lag in pseudo-roll response is too long to achieve proper aircraft control, given a higher update rate from the GPS receiver, a faster time constant could be employed to reduce the data lag. Given the same ratio of $T$ over $\tau$, GPS data would need to update at a rate of at least 4 Hz. Such capability is commercially available.
4 Pseudo-Attitude Roll Angle Correction and Pseudo-Pitch Development

4.1 Motivation

As seen in the test data in Figure 3.4, uncoordinated aircraft maneuvers produce discrepancies between the calculated pseudo-roll angle and the roll angle measured by the AHRS system. Additionally, the flight path angle calculated by the baseline system shows a roughly constant offset from the AHRS pitch data given the same trim configuration. With additional information from a single low-cost accelerometer, the simple pseudo-attitude system can be augmented such that the pseudo-roll and flight path angles are corrected and the discrepancies between pseudo-attitude and traditional attitude are greatly reduced.

4.2 Synthesis of Roll Angle Correction

By taking measurements in flight from a single accelerometer, mounted to measure accelerations in the direction of the aircraft wing-axis (yb), the calculation of the pseudo-roll angle can be modified and a more accurate pseudo-roll angle can be determined. However, some approximations are necessary.

The single accelerometer mentioned above measures in the y-axis of the aircraft reference frame. As seen in chapter 2, all vectors used to calculate pseudo-roll are measured in a plane perpendicular to the velocity vector of the aircraft. In order to use the accelerometer data, we must translate the data as measured in the body reference frame of the aircraft into a vector that lies within the plane perpendicular to the aircraft’s velocity vector.

As a first approximation, we simply assume that the measured acceleration vector actually lies in the plane perpendicular to the velocity vector. For small angles of \( \beta \) (sideslip angle), this assumption is valid since the cosine of a small angle is approximately 1. Second, we must calculate the direction of the acceleration vector within that plane. In the previous calculation of pseudo-roll, we assumed zero lateral acceleration. We also assumed correctly that the lift vector of the aircraft is
perpendicular to the aircraft’s wingspan, allowing us to infer the pseudo-roll angle of the aircraft directly from the lift vector.

In an uncoordinated flight scenario using the zero lateral acceleration assumption, we actually end up with two non-coincident “lift vectors” - the actual lift vector and the pseudo-lift vector inferred from the GPS data. Because these vectors are not coincident, an error exists between the actual roll angle and the pseudo-roll angle.

In order to correct this error in pseudo-roll, we must create an acceleration vector that represents the lateral acceleration of the aircraft within the plane perpendicular to the aircraft’s velocity vector. Since we know that the accelerometer is taking data along the actual wing axis of the aircraft, we also know that the actual lift vector of the aircraft is perpendicular to that acceleration measurement by definition. From this information, we can draw the following picture:

![Figure 4.1: Vectors and Angles Used in Roll Angle Correction](image)

where $\phi$ is the pseudo-roll angle, $\tilde{\phi}$ is the corrected roll angle, $\varepsilon$ is the error between the two angles, and $a_y$ is the acceleration measured from the wing axis accelerometer. Since the two lift vectors and the acceleration vector form a right triangle, we can write the following expression:

$$\varepsilon = \sin^{-1} \left( \frac{|a_y|}{| |} \right)$$

(4.1)

Now we can directly subtract this error from our previous calculation of pseudo-roll to find the corrected roll angle.
\[ \tilde{\phi} = \phi - \varepsilon \] (4.2)

### 4.3 Synthesis of Pseudo-Pitch

Similar to the case of pseudo-roll correction, information from a single accelerometer can be utilized to create pseudo-pitch. This time the accelerometer is mounted in the \( x_b \) direction of the aircraft body frame. Since GPS data is given in the \( F_{NED} \) coordinate frame, we must attempt to make the two coordinate systems coincident.

Conveniently, pseudo-attitude is based on a point mass model of the aircraft, meaning that the velocity and acceleration information from GPS indicates the motion of the aircraft's center of gravity – or more accurately the motion of the GPS antenna. This means that the lift vector calculated from GPS information is coincident with the lift vector of the aircraft in its own body reference frame, allowing translation of body accelerations into the \( F_{NED} \) coordinate frame. Figure 4.2 depicts the important variables. The lift vector of the aircraft in both reference frames is depicted by \( l_{body} \). This vector is assumed to be perpendicular to \( x_b \). As before, \( l \) represents the component of lift within the plane perpendicular to the velocity vector \( v_{gps} \) of the aircraft. The flight path angle is represented by \( \gamma \) and the pitch angle is represented by \( \theta \), while \( \alpha \) represents angle of attack.

![Figure 4.2: Variables for Pseudo-Pitch Synthesis](image)
Similar to the assumptions made for pseudo-roll correction, if we assume that the aircraft’s lift vector is perpendicular to the wing chord – as viewed in the x-z plane of the aircraft (from the side) – we can then reference the aircraft’s body attitude within the $F_{\text{NED}}$ coordinate frame.

Recalling from the synthesis of pseudo-roll, certain vector projections onto $v_{\text{gps}} - a^t$ and $g^t$ of $a$ and $g$ respectively – were subtracted in order to determine the lift vector $l$ lying within the plane perpendicular to $v_{\text{gps}}$. These previously disregarded components will now serve in the synthesis of pseudo-pitch. Incorporating the accelerometer data in the x-axis, we will denote a variable $T$ to represent the longitudinal acceleration along the velocity vector where

$$T = \begin{cases} a^t - g^t, \gamma \geq 0 \\ a^t + g^t, \gamma < 0 \end{cases} \quad (4.3)$$

With the x-direction positive pointing out the aircraft nose, and with $g$ positive pointing down, the effect of $g^t$ depends on the flight path angle of the aircraft. Positive $\gamma$ causes $g^t$ to decelerate the aircraft, while negative $\gamma$ has the opposite effect.

Assuming small angles of $\alpha$ we can also assume that the data from the x-axis accelerometer is roughly parallel to the velocity vector and thus parallel to $T$. We now denote another variable $T_{\text{pseudo}}$ to represent an estimation of the total longitudinal acceleration parallel to the velocity vector

$$T_{\text{pseudo}} = a_x - T \quad (4.4)$$

where $a_x$ represents the acceleration measured by the x-axis accelerometer.

Returning to Figure 4.2 we see that a relationship can be written from known information.

$$\alpha = \tan^{-1}\left(\frac{T_{\text{pseudo}}}{l}\right) \quad (4.5)$$

Finally, combining the various angles using direction cosine matrices, the corrected pseudo-pitch is the following:
\[ \theta = \sin^{-1}(\cos \alpha \sin \gamma + \sin \alpha \cos \phi \cos \gamma) \]  

(4.6)

This approximation is accurate for cases of zero sideslip. Including sideslip angle, the relationship becomes the following:

\[ \theta = \sin^{-1}(\cos \alpha \sin \gamma \cos \beta + \cos \alpha \sin \phi \cos \gamma \sin \beta + \sin \alpha \cos \phi \cos \gamma) \]  

(4.7)

4.4 Corrected Pseudo-Attitude Results from Flight Test Data

4.4.1 Roll Correction

The MATLAB simulations for the corrected roll angle focused on the uncoordinated maneuvers seen in Figure 3.4, as well as stalls and transition from takeoff trim to level flight trim. Modifications were made to the initial simulation scripts so that pseudo-roll and pseudo-pitch angles were calculated as described in the first part of this chapter.

Figure 4.4 shows pseudo-roll and AHRS roll angle data for uncoordinated flight maneuvers utilizing the roll correction MATLAB script. For convenience, Figure 4.4 also repeats the annotated roll angle data seen in Figure 3.4. The effect of the roll correction is obvious. Where before, the uncoordinated maneuvers yielded pseudo-roll angles that disagreed with the AHRS information, the roll angles now agree. RMS error for these maneuvers went from 10.14 degrees using the baseline system to 0.63 degrees using the roll-corrected pseudo-attitude system.
Figure 4.4: Baseline Pseudo-Roll (top) and Corrected Pseudo-Roll (bottom) for Uncoordinated Flight

4.4.2 Pseudo-Pitch

Utilizing pseudo-pitch instead of flight path angle greatly reduces the discrepancy between pseudo-attitude and AHRS attitude about the wing axis. Figure 4.5 depicts
flight path angle compared to AHRS pitch as well as pseudo-pitch compared to AHRS pitch for the same segment of flight test data. The RMS error for the flight path angle is 3.84 degrees, while the RMS error for pseudo-pitch is 0.12 degrees. Note that this was for a case in which roll angle was close to zero; errors would be larger in banked cases.

Figure 4.5: Baseline Flight Path Angle (top) and Corrected Pseudo-Pitch (bottom)
4.4.3 Changing Aircraft Trim
As seen in the previous discussion of pseudo-pitch versus flight path angle, changing aircraft trim results in varying offset between the two indications. Figure 4.6 depicts the period of flight following takeoff. The AHRS data indicates decreasing pitch as the pilot trims the aircraft from takeoff trim to level trim attitude.

Figure 4.6: Flight Path Angle (top) and Pseudo-Pitch (bottom): Changing Aircraft Trim
The RMS error between flight path angle and AHRS pitch calculated for this segment is 6.87 degrees. Comparing pseudo-pitch to the AHRS data, we see a significant reduction in the discrepancy between the pseudo-attitude data and the AHRS data. The RMS error between pseudo-pitch and AHRS pitch for this segment of the flight is 0.86 degrees.

4.4.4 Stalls
Figure 4.7 shows the results for a comparison of flight path angle to pitch attitude for power-on and power-off stalls, as well as a comparison of AHRS pitch and pseudo-pitch for the same segment of flight test data. The RMS error between flight path angle and AHRS pitch is 7.2 degrees for the power-off stall and 9.6 degrees for the power-on stall.
The comparison of AHRS pitch to pseudo-pitch show a significant reduction in the discrepancy. The calculated RMS error is 1.1 degrees for the power-off stall and 0.73 degrees for the power-on stall.
5 Flight Test of Pilot Performance Using Pseudo-Attitude

5.1 Flight Test Protocol

A preliminary flight test was performed comparing the augmented pseudo-attitude system to partial panel flying with a “failed” attitude display. Three pilot subjects flew simple maneuvers under the hood including straight and level flight, and standard rate turns. All pilots had instrument experience. The subject pool and flight test maneuvers were limited due to limited flight test resources for this study, including aircraft availability.

Each pilot flew the specified maneuvers attempting to maintain constant attitude (pitch and roll) within each maneuver. For example, in the straight and level segments, the pilot attempted to maintain zero roll angle and constant pitch. During partial panel flying, the standard attitude display was covered, simulating its failure. Each subject flew all maneuvers with reference to the remaining five standard flight instruments discussed in Chapter 1. During pseudo-attitude flying, a laptop display served as a replacement for the traditional attitude display, which was again covered. The subject flew all maneuvers with reference to the remaining five standard flight instruments, plus the laptop display. All events were compared using AHRS data by calculating RMS error from the instructed flight attitude. GPS altitude data was examined for straight and level flight events. Each subject also completed a Cooper-Harper evaluation of each type of flying.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Subject 1 Flies Partial Panel</td>
</tr>
<tr>
<td>2</td>
<td>Subject 2 Flies Pseudo-Attitude</td>
</tr>
<tr>
<td>3</td>
<td>Subject 3 Flies Partial Panel</td>
</tr>
<tr>
<td>4</td>
<td>Subject 1 Flies Pseudo-Attitude</td>
</tr>
<tr>
<td>5</td>
<td>Subject 2 Flies Partial Panel</td>
</tr>
<tr>
<td>6</td>
<td>Subject 3 Flies Pseudo-Attitude</td>
</tr>
</tbody>
</table>

Table 5.1: Flight Plan Sequencing for Counterbalancing

Since the experiment was conducted during a single flight, the sequencing of subjects was counterbalanced to minimize the effect of fatigue, learning, and other order effects.
Pilots flew from the left seat, changing positions within the cockpit during brief stops on the ground. Table 5.1 shows the flight test sequence.

5.2 Flight Test Setup

A real-time application of the corrected pseudo-attitude system was developed to run from a laptop computer, utilizing acceleration data in two axes from the AHRS system and velocity information from a GPS receiver. The display consisted of a simulated gyro ball displayed on a laptop screen in front of the pilot. Figure 5.1 shows the laptop attitude display.

Figure 5.1: Laptop Attitude Display

Figure 5.2 shows the components of the setup, including the laptop computer, the AHRS system, the GPS receiver with antenna, and the batteries.
The flight was conducted in a Cessna 182 Skylane. The aircraft is pictured in Figure 5.3.
5.3 Flight Test Results

5.3.1 Comparison of Air Data

Figure 5.4 shows GPS position information for a segment of the flight including typical maneuvers. Straight and level segments as well as turns are depicted. This flight segment originated at one airport and terminated at another before pilot subjects changed seats within the aircraft.

![GPS Position Relative to Starting Point](image)

Figure 5.4: Sample Flight Segment: GPS Position Relative to Starting Point

Figure 5.5 shows AHRS roll data for a turn flown by Subject 1 under partial panel conditions, as well as a similar turn flown by the same subject utilizing the pseudo-attitude display. The partial panel data indicates an average RMS error for the three pilots of 3.1 degrees from the reference attitude of 15 degrees. The pseudo-attitude data indicates an average RMS error of 1.12 degrees.
Figure 5.5: Standard Rate Turns: Subject 1 Flight with Reference to Partial Panel (top) and Pseudo-Attitude (bottom)
Figure 5.6 depicts the average RMS errors for each type of flying. Error bars represent one standard error. Using a paired t-test, we find that the pseudo-attitude error is significantly lower than partial panel error (p < 0.025).

![RMS Error Graph]

Figure 5.6: RMS Errors for Standard Rate Turns

Straight and level flight results indicate slightly better performance utilizing pseudo-attitude rather than simple partial panel in the roll axis, but performance results in the pitch axis were less conclusive. Values for pitch and GPS altitude showed no clear benefit for pseudo-attitude over partial panel. One possible explanation for this is given in Section 5.3.3. Figure 5.7 compares roll data for partial panel flying and pseudo-attitude for a segment of straight and level flight by Subject 1.
Figure 5.7: Partial Panel (top) and Pseudo-Attitude (bottom): Roll Angles for Straight and Level Flight
Figure 5.8 shows the RMS roll error results of the various straight and level flight segments. Results show slightly better performance for the pseudo-attitude display. Using a paired t-test gives a result of $p < 0.1$.

![Bar chart showing RMS error comparison between Partial Panel and Pseudo-Attitude](image)

Figure 5.8: Roll Angle RMS Errors for Straight and Level Flight

Figure 5.9 shows a typical GPS altitude profile for a period of straight and level flight with reference to pseudo-attitude by Subject 1. Results for partial panel appear similar when plotted.
Comparing RMS error results in Figure 5.10 for the various segments yields inconclusive results. The RMS error for pseudo-attitude is slightly lower, but the standard error is larger. Results are statistically insignificant. As indicated by the subjects in later sections, this may be the result of lower pilot workload due to an instrument scan that more closely resembles a full panel. Pitch results show similar trends.
Figure 5.10: GPS Altitude RMS Error: Straight and Level Flight

Figure 5.11 depicts a typical pitch profile for a segment of straight and level flight. As with the GPS altitude data, there appears to be no clear performance benefits utilizing pseudo-attitude instead of basic partial panel.

Figure 5.11: Typical Pitch Profile: Straight and Level Flight
The RMS error results appear in Figure 5.12. As with the altitude results, the pitch results are not statistically significant.

![Figure 5.12: RMS Pitch Error: Straight and Level Flight](image)

5.3.2 Subjective Evaluation

Each subject completed a Cooper-Harper evaluation for each type of flying, partial panel flying and flight with reference to pseudo-attitude. The Cooper-Harper scale consists of a series of questions concerning the handling quality of aircraft instrumentation and controls. The flow chart of questions results in a numerical rating between 1 and 10, with lower values corresponding to better quality.

The subjects were reminded that the comparison in this evaluation should be based on a simulated failure of the primary attitude display, where the partial panel scenario would simulate traditional partial panel flying with a failed attitude indicator, and the pseudo-attitude scenario would simulate a failed primary attitude indicator with additional reference from the pseudo-attitude display.

The Cooper-Harper results are displayed in Figure 5.13. Based on the scores, each subject indicated a preference for the pseudo-attitude system. The average partial panel Cooper-Harper score indicates that the pilots rate the system as having minor but annoying deficiencies that warrant improvement, and require moderate to considerable pilot compensation. The pseudo-attitude scores indicate few unpleasant deficiencies.
requiring minimal pilot compensation. Further subjective comments by the pilots are covered in the following section.

![Chart showing Cooper Harper Results]

**Figure 5.13: Cooper Harper Results**

### 5.3.3 Additional Results

Subjective comments made by each subject during the experiment were recorded for further insight about the performance of the pseudo-attitude system. All subjects indicated a need to reduce the level of noise present in the display. All found the noise slightly distracting, but indicated that pseudo-attitude significantly decreased pilot workload during maneuvers due to a more familiar instrument scan (i.e. a scan containing the traditional attitude display).

Subjects indicated less reliance on the attitude display for pitch during the specified flight test maneuvers. Since pitch attitudes remained fairly constant, the subjects favored the information from the vertical speed indicator in their instrument scan to maintain level flight. The subjects indicated the same would be true if they were flying from traditional attitude indication.
6 Product Architecture and Cost

Three basic architectures for a pseudo attitude system are briefly presented in this chapter. Each is intended to serve a specific purpose in the consumer market.

The first proposed architecture is a baseline pseudo-attitude card that could integrate with an existing GPS display system. Numerous versions of moving-map GPS units are currently available in the general aviation market. This architecture would be a stand-alone card that could be integrated to such a system prior to manufacturing, adding additional performance to the moving map GPS unit, in that it could operate in pseudo-attitude mode.

The card would consist of a GPS card and 555 microchip, as well as additional necessary circuitry to allow for the interface between the card and the chip. Estimated manufacturing cost for such a unit is $500.

The second proposed architecture is a sensor augmented pseudo-attitude system. It would serve a similar purpose as the concept above, except that it would contain necessary sensors and algorithms to compute corrected roll as well as pseudo-pitch. Estimated manufacturing cost for this unit is $800, including driver electronics and calibration.

Finally either of the above concepts could operate as a stand-alone unit if it were packaged with its own dedicated display. Incremental manufacturing cost for the display plus packaging is estimated at $1000.

Not included in this estimate is the cost of certification, which is a one-time cost that must be spread across the units produced.
7 Summary and Conclusions

This study identified discrepancies between actual aircraft roll angle and the pseudo-roll angle in uncoordinated flight scenarios calculated by the baseline pseudo-attitude system as previously developed at MIT. The study also identified discrepancies between flight path angle and actual aircraft pitch in all scenarios, especially in stalls. The study identified safety implications associated with these discrepancies in IFR flight conditions.

A method was developed to correct pseudo-roll using a single axis accelerometer mounted in the wing axis. Post-processed flight test data was used to determine the accuracy of the system in different flight scenarios. During severely uncoordinated flight, RMS roll error improved from 10.14 to 0.63 degrees using the sensor augmented system. A method was also developed to create pseudo-pitch information from GPS velocity data and a single axis accelerometer, this time mounted along the longitudinal axis. The discrepancy between flight path angle and aircraft pitch went from 3.8 degrees to 0.12 degrees utilizing pseudo-pitch in place of flight path angle. It should be noted that each method of correction can be used independently or together to correct pseudo-attitude.

A preliminary piloted flight test was performed using three pilot subjects, flying simple maneuvers from reference to a laptop display of pseudo-attitude. For comparison, the same pilots flew a partial panel with a simulated attitude indicator failure. Statistically significant reduction in RMS roll error during standard rate turns was observed using pseudo-attitude instead of partial panel. No significant difference was observed between partial panel and pseudo-attitude in pitch or altitude error during the simple flight maneuvers, indicating that partial panel appears to degrade lateral control more than longitudinal control of the aircraft by the pilot.

Finally from the piloted flight test, Cooper-Harper ratings supported benefits of pseudo-attitude over partial panel.
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