Antenna Aimpoint Integration for Staring-Mode Surveillance (AIMS)

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Abstract—Current persistent surveillance approaches require robust designs to maintain a fixed operational picture. In this paper, we design, develop, and demonstrate a feasible aimpoint solution. In the design, we derive the mathematical transformation requirements to show a system-level design. Using the transformations, we develop an operational methodology for real-time and robust aimpoint solution that includes a ground antenna, and an aircraft with a gimbal mounted camera and data link. Finally, we demonstrate a workable prototype with real-world results. The AIMS methodology supports communication timing constraints, a closed-loop feedback for error correction, and a succinct, efficient, and effective method for maintaining persistent surveillance. (Abstract)

I. INTRODUCTION

Current sensor exploitation designs include persistent surveillance of a designated area of regard (AOR). To maintain a staring-mode fixed location requires accurate locations of the aircraft, camera angles, and directional ground antennas. The errors that propagate from the uncertainties result in an open-loop design could severely alter the operational picture locations. To correct for these results, we designed a closed loop feedback system to maintain a consistent approach to observations.

**Figure 1. Staring Mode Sensing**

Persistent surveillance [1, 2] is an operational approach that affords continuous updating of an AOR. To design a method, requires communications and algorithmic efficiency as well as effective use of hardware constraints to maintain a fixed aimpoint. The Aimpoint method has been researched for many years but as new hardware is available, or scenarios change; there are continual interests in exploiting technology for robust solutions.

This paper develops an aimpoint solution for staring-mode surveillance and air to ground data links. Section 2 overviews transformations from earth-to-body-to-camera-to-line of sight for aimpoint determination. Section 3 describes a real world experiment and results. Finally Section 4 draws conclusions.

II. AIMPOINT DERIVATION

Aimpoint detection for staring mode operation requires direction coordination between a Global Positioning System (GPS) and Inertial Navigational System (INS) localized platform, camera angles, and directional ground antenna. Using the position of the aircraft and a designated point on the ground, the objective is to provide correction feedback to the aircraft’s gimbal so a point on the ground is constantly pointed to as the aircraft’s position is changed by flight conditions.

**Figure 2. Axes defined relative to inertial axes by Euler’s angles \( \phi \) = roll, \( \theta \) = pitch, and \( \psi \) = yaw or heading angle.**

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A. Inertial Navigation System

The INS system includes the position vector

\[
\begin{pmatrix}
\psi \\
\phi \\
\theta \\
\lambda \\
h \\
t_1 \\
t_2
\end{pmatrix} = \begin{pmatrix}
\text{heading} \\
\text{roll} \\
\text{pitch} \\
\text{latitude} \\
\text{longitude} \\
\text{altitude} \\
\text{TimeStart} \\
\text{TimeEnd}
\end{pmatrix}
\] (1)

The X (pitch), Y (roll), and Z (azimuth) directions of the inertial frame are marked on the IMU shown in Figure 3. The IMU is mounted to the aircraft’s body so that the right wing follows X and the nose of the aircraft follows Y.

![Figure 3. Novatel DL4+ SPAN IMU with its default orientation.](image)

B. East, North, Up Coordinate System

In many targeting and tracking applications the local East, North, Up (ENU) Cartesian coordinate system is far more intuitive and practical than Earth Centered Earth Fixed (ECEF) or Geodetic coordinates. Since our orbits are small in the range of 2 – 10 miles in diameter and we won’t fly at the poles the earth does not have a large curvature thus we use a local ENU coordinate system.

![Figure 4. Earth Tangential Plane. ENU coordinate system compared with ECEF [17].](image)

A degree of latitude remains constant from the equator to the poles and can be estimated as 1 nautical mile or 362,057 feet [16]. At any latitude, the length of 1 degree of longitude can be estimated by multiplying the length of 1 degree of longitude at the equator times the cosine of the latitude [16]. The platform or target position is defined as

\[
\begin{pmatrix}
L \\
\lambda \\
h
\end{pmatrix} = \begin{pmatrix}
\text{latitude} \\
\text{longitude} \\
\text{altitude}
\end{pmatrix}
\] (2)

Given the position of the platform (p) and target (t), a vector can be computed as

\[
\text{deg to feet} = 362057
\]

\[
\text{LLA Diff}(p, t) = \text{deg to feet} \left( \frac{p_0 - \text{deg to rad}}{t_1 - t_0} \right)
\] (3)

The LLA_Diff function result is a vector in ENU form and represents how many feet east the platform is from the target, how many feet north the platform is from the target, and the altitude difference between the platform and target.

C. Earth to Body Transformations

A transformation must be applied to account for the vehicle’s attitude; this transformation is often referred to as the earth to body transformation which is described below:

\[
M_{\psi}(\psi) = \begin{pmatrix}
\cos(\psi) & -\sin(\psi) & 0 \\
\sin(\psi) & \cos(\psi) & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[
M_{\phi}(\phi) = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos(\phi) & -\sin(\phi) \\
0 & \sin(\phi) & \cos(\phi)
\end{pmatrix}
\]

\[
M_{\theta}(\theta) = \begin{pmatrix}
\cos(\theta) & 0 & -\sin(\theta) \\
0 & 1 & 0 \\
\sin(\theta) & 0 & \cos(\theta)
\end{pmatrix}
\]

\[
M_{\text{attitude}}(\theta, \phi, \psi) = M_{\psi}(\psi) \cdot M_{\phi}(\phi) \cdot M_{\theta}(\theta)
\]

\[
\text{PointVect} = M_{\text{attitude}}(\theta, \phi, \psi) \cdot \text{LLA}_\text{Diff}(p, t)
\]

This transformation is very important in strap down (mounted directly onto the host vehicle’s frame) inertial navigation systems. A gyro stabilized platform of the inertial system is intended to maintain a “reference” coordinate system, which is fixed relative to the stars. If the gyroscope has a low drift...
rate, the angular deflection of the platform from the inertial coordinate system will remain small after a long time interval. That is, in the presence of disturbance torques about the gyroscope precession axes, the gyro stabilized platform will exhibit a small drift rate.

D. Antenna or Camera to Body Transformation

The aircraft has a two axis gimbal that attempts to keep the antenna or camera pointed at a target on the ground. Typical installation is depicted below in Figure 5.

\[ \text{pan}(E, N, U) = \arctan(-E, N) \]

\[ \text{tilt}(E, N, U) = \arcsin(U) \]

III. AIMPOINT EXPERIMENTATIONS

Consider an environment in which a staring mode sensor is monitoring an AOR centered at an aimpoint. The aimpoint location has a ground station that performs a near real time data link from the aircraft sensor to ground based networks. In this scenario the data link can sustain a maximum pointing error of 20°. The sensor and data link are mounted in the aircraft as depicted in Figure 6.

Real-world analysis is complicated by the scenario (i.e. aircraft, sensor), hardware of choice (i.e. communications protocols), and the algorithms (i.e. latencies and processing speed). The transformation equations would afford a line of sight (LOS) vector to the aimpoint; however the stochastic uncertainty from the aircraft position due to wind gusts and the gimbal slew will cause an offset in the camera images. The goal is to determine the camera/antenna pointing angles and the corrections needed to control the gimbal to maintain persistent surveillance of the AOR. We show the instantiation of the derived quantities in an experimental environment. The results presented here were then transferred to an embedded system design for operation use. The camera and antenna are mounted on an aircraft from which an aimpoint is selected on the ground. To measure pointing error an IMU was placed on the rear of the sensor head. The aircraft is to circle above at a fixed altitude, maintaining persistent surveillance on the aimpoint. If the system is able to maintain the aimpoint, then the collected imagery will be a continuous observation of the area around the target and the data link between the aircraft and the ground will be maintained.

IV. RESULTS

The operational results included an aircraft, the design hardware and the embedded algorithm solution. Figure 7 presents the graph offset versus time and compares the commands given.

Figure 5. Installation of the two axis gimbal mounted on a Twin Otter aircraft.

Figure 6. Sensor and Antenna configuration as installed in the Twin Otter aircraft. On the rear of the sensor is an IMU to measure pointing error.

Figure 7. Pan/Tilt versus time. The commands are divided by ten.
Figure 8 presents the results from the pan-tilt offset relative to each other in coordination, ideally this would be a tight “shotgun” pattern. Note that the plots from Figure 7 show that the vertical excursions are happening when the sensor head is hitting the lower stop of the gimbal at -40°.

In order to determine the cyclic nature of gimbal point, we did an FFT on the data. Figure 10 shows the results of the FFT error.

![Figure 8. Pan-tilt offsets](image)

The goal was to provide tracking accuracy for an aimpoint in 3D over the aircraft flight. Figure 11 shows the aircraft position looking down the camera head as calculated by the IMU mounted on the rear of the sensor. The state position vector is sized to be the distance from the aircraft to the target. An ideal situation is when all the vectors align to a single point on the ground (lat, long, alt) with altitude = 0.

![Figure 9. Pan-tilt error versus time in 3D.](image)

![Figure 10. FFT error over time.](image)

![Figure 11. Plot of LOS vector from the sensor head to the aimpoint as measured by the IMU on the rear of the sensor head.](image)
V. DISCUSSION & CONCLUSIONS

We derived, developed, and demonstrated an Antenna Aimpoint Integration for staring-Mode Surveillance (AIMS). Through simulations and operational verification and validation, the solution showed remarkable accuracy. The data link was maintained for the duration of this flight and the imagery covers the AOR. AIMS could be improved with a control based algorithm and faster gimbal.

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REFERENCES