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This final report describes the work performed at Ohio University to investigate the feasibility of the use of integrated light detection and ranging (LiDAR) and inertial navigation systems (INS) to support unmanned aerial vehicle (UAV) formation and swarming flight. LiDAR measurements provide an indication of the relative drift errors of the INS on each UAV in the formation. By judicious choice of maneuvers, errors can be isolated to specific vehicles and calibrated.

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FINAL REPORT

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"Unmanned Aerial Vehicle (UAV) Swarming and Formation Flight Navigation Via LiDAR/INS"

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Abstract

This final report describes the work performed at Ohio University to investigate the feasibility of the use of integrated light detection and ranging (LiDAR) and inertial navigation systems (INS) to support unmanned aerial vehicle (UAV) formation and swarming flight. LiDAR measurements provide an indication of the relative drift errors of the INS on each UAV in the formation. By judicious choice of maneuvers, errors can be isolated to specific vehicles and calibrated.

Objective

This study investigated the feasibility of the use of integrated light detection and ranging (LiDAR) and inertial navigation systems (INS) to support unmanned aerial vehicle (UAV) formation and swarming flight. It is envisioned that this architecture will allow operations in non-GPS environments. These operations include relative (intra-fleet) navigation, inter-aircraft communication and geo-referencing of surveillance areas and objects.

Background

UAV research, development, implementation and operation have grown exponentially over the last decade. It is envisioned that future UAV operations will include fleets of coordinated vehicles (formation flight, swarming flight). Advantages of UAV fleets include higher mission reliability (robust against loss of individual vehicles), formation of large synthetic sensor apertures, wide area communication, remote sensing, jamming, target localization and others.

For tight formations, however, very little research has been performed in the area of navigation, especially if one considers a non-GPS environment. What little formation-flight navigation research that has been conducted has assumed a nominal GPS environment. In some threat scenarios, however, GPS will be denied. The next question is what navigation suite can meet the stringent requirements imposed by tight formation (or swarming) flight and possibly also geo-referencing of aerial and/or ground targets?

Approach

The envisioned system would contain a LiDAR (Light detection and ranging) and a tactical grade inertial measurement unit (IMU) in each UAV. The LiDAR is utilized to determine the location of nearby UAVs relative to the 'own' ship and in the future may be able to provide jam-resistant inter-aircraft communication capability. The IMU is utilized to provide guidance and control functions for the UAV as well as feed critical attitude data to the LiDAR. Judicious integration of the LiDAR and IMU data, possibly among multiple UAVs, could be used to limit the IMU error growth and preserve geo-referencing capability.

LiDAR

Light detection and ranging (LiDAR) is essentially just radar based on light energy instead of RF energy. Traditional LiDARs use mechanical scanning of the laser beam to sweep an area and determine the range to each 'pixel' in the viewing of scanning area. More recently, so-called 'flash' LiDARs have been developed. With flash LiDAR, a two dimensional area is illuminated simultaneously and the range to each pixel in the field of view is also determined simultaneously. These sensors currently have limited ranges (i.e., tens of meters) but they are relatively small and cheap and nevertheless provide impressive performance: ranging accuracies on the order of centimeters are possible.

LiDAR-Aiding of the INS

LiDAR can be used to determine the relative separation between the UAVs. For the remainder of this discussion, it will be assumed the formation consists of two UAVs. The IMUs in each UAV will drift as they normally do but the LiDAR will be able to measure this drift:

Z = (INS1_Position – INS2_Position) – LiDAR_vector
    = ([UAV1_true_position + INS1_Pos_err] - [UAV2_true_position + INS2_Pos_err]) –
            (true_vector_from_UAV1_to_UAV2 + LiDAR_err)
    = INS1_Pos_err – INS2_Pos_err – LiDAR_err

Thus this observable takes the classic form of the input to a complementary filter. The inertial errors are low-frequency drifts whereas the LiDAR errors are relatively high-frequency noise. However, it is not possible to use this observable directly in the conventional aided-INS Kalman filter. Since the observable is the difference of the errors in two inertial systems, the conventional integrated Kalman filter has no way to know how the errors are divided between them. Simply dividing the estimated errors 50/50 between the two IMUs ends up causing more harm than good half the time.

Aiding via Multiple Orientations

Conventional aiding is not possible yet the system does measure the relative drift of the IMUs. It would seem there must be a way to exploit this. The approach taken here follows from inertial sensor calibration procedures. When performing IMU sensor calibration, multi-position testing is utilized. For example, the IMU is positioned with its x-axis orthogonal to the gravity field for one test and is positioned in line with the gravity field in another test. The results of these tests can be combined to solve for the bias and scale-factor errors in each sensor.

Following this, it seems reasonable that inertial error isolation in a multi-UAV formation might be achieved by changing the orientation of one UAV relative to another. A simple example will help to illustrate this concept: Assume the IMUs in two UAVs are identical and their only error is a body-y accelerometer bias (recall the positive body-y axis is along the right wing of the aircraft). Assume also that for this example the bias is identical in each IMU. If the two UAVs are flying in formation with identical orientations, the two will drift off in lock-step together (in the body-y direction) and the LiDAR will sense no disparity. That is, the Z observable mentioned earlier will have no inertial errors in it since they have canceled each other. However, if one UAV is subsequently rolled 180 degrees so that it is now flying inverted, then the inertial systems will be observed as drifting towards each other (or apart depending on the sign of the accelerometer bias).

With the two different UAV (and hence, sensor) orientations, the biases in the two UAV/IMUs become observable. Given LiDAR ranging, accelerometer biases can be observed. If relative orientation can also be measured, then gyroscope biases could also be observed.

Mathematical Example

- y1, y2 = relative acceleration error in orientation #1, orientation #2;
- δa_y^1 = UAV #1 accel y bias

$$y_1 = \delta a_y^2 - \delta a_y^1 \qquad y_2 = -\delta a_y^2 - \delta a_y^1$$

- Can solve these equations for the biases:

$$\delta a_y^2 = \tfrac{1}{2}\left(y_1 - y_2\right)$$

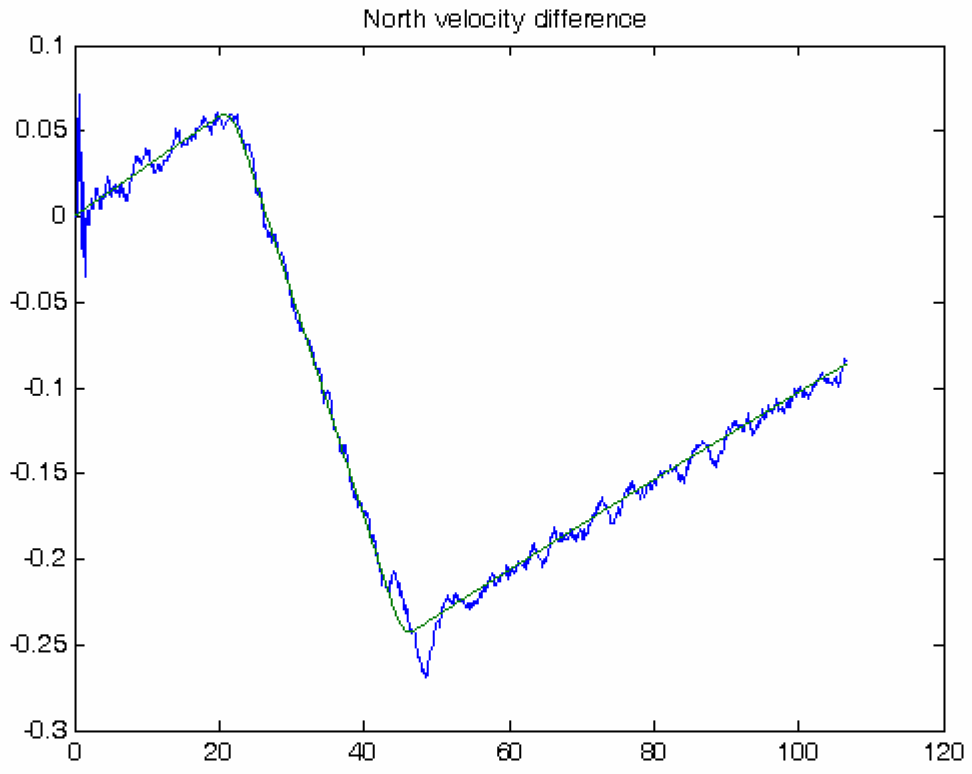
$$\delta a_y^1 = -\delta a_y^2 - y_2$$

Simulation Example

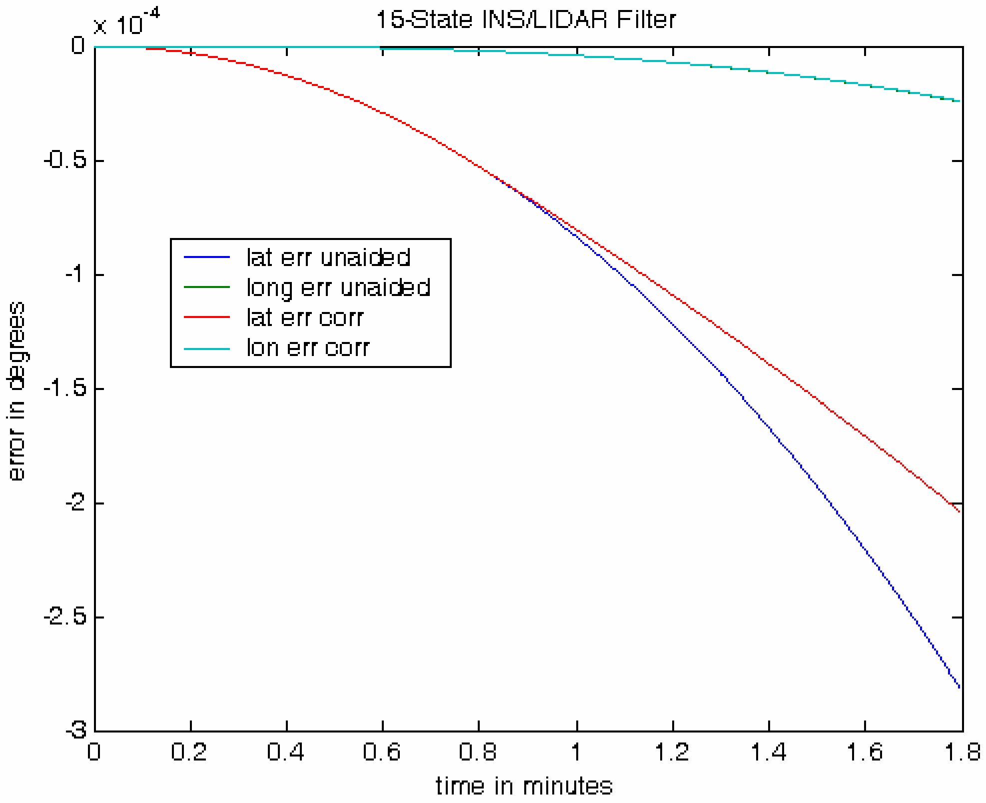
To illustrate how this process could work in a realistic situation, a simulation was developed. The simulation models two UAVs that are 5 meters apart and are flying at a rate of 50 m/s. After 20 seconds, UAV#2 rolls inverted, continues for 20 seconds, then rolls upright and continues. UAV#1 stays straight and level for the entire flight.

- UAV/IMU #1
    - 500 micro-g body-y accel bias
    - Gyro biases of 0.3, 0.2 and 0.1 deg/hr (body x, y, z respectively)
- UAV/IMU #2
    - 800 micro-g body-y accel bias
    - Gyro biases of 0.2, -0.1 and 0.3 deg/hr

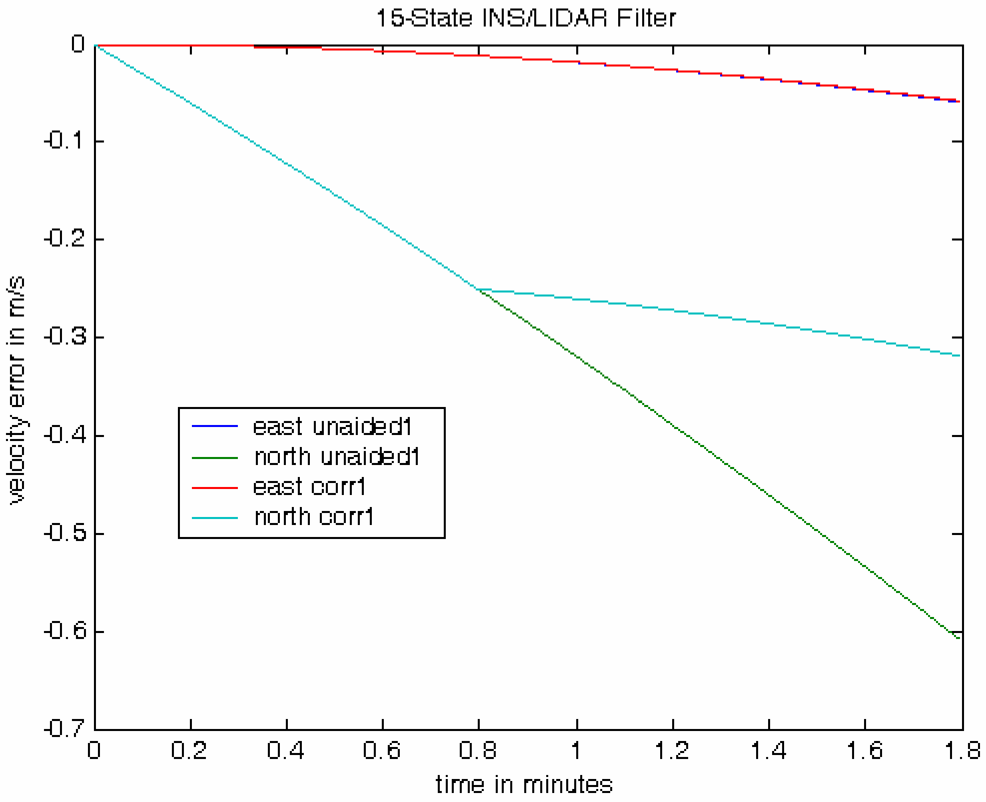
To illustrate the ability of the LiDAR to detect relative inertial errors, the true and estimated relative north velocity error is given in the following figure (note the vertical axis is given in meters per second; the horizontal axis is given in seconds).



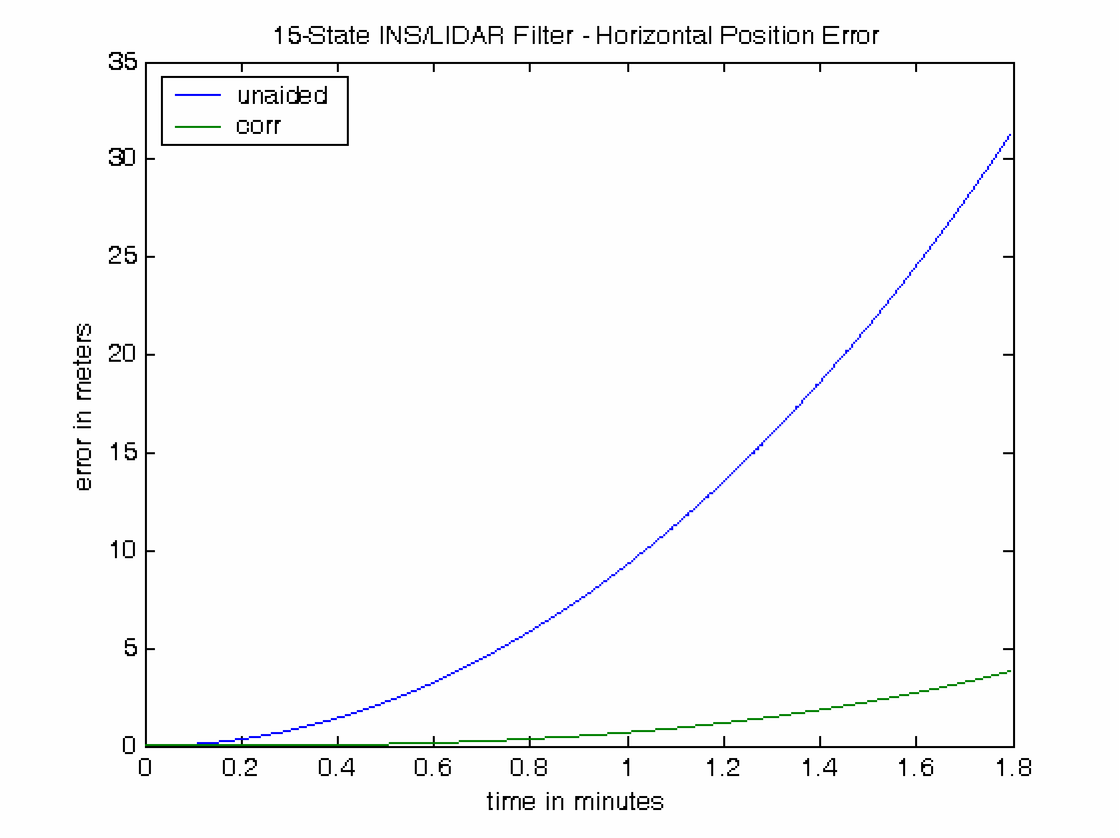
The results of the real-time bias-estimate correction is given in the following figure:



There is no difference between the corrected and unaided solutions up until the bias has been detected (which occurs at approximately the 0.8 minute mark). Although the corrected solution still drifts, its growth is linear rather than quadratic. The velocity results are given in the following:



For non-real-time applications (i.e., where data is being post-processed), the in-flight sensor calibrations can be applied throughout the data set. For the previous example, the post-processed correction errors are dramatically reduced:



Conclusions

Swarming and formation flight of small UAVs requires high accuracy relative positioning (centimeter-level). Flash LiDAR technology makes this possible without the need for GPS (and the requisite carrier-phase processing). This study has shown LiDAR can also be used to measure the relative drift rate between UAV/IMUs. By exploiting multiple relative orientations, sensor biases can be calibrated.