# Aided-inertial for GPS-denied Navigation and Mapping

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## *ABSTRACT*

*This paper describes the use of navigation-grade inertial sensors for in-building navigation and mapping. In particular these sensors are well suited for:*

*1. Long-duration, infrastructure-less, portable in-building navigation*

*2. Generation of high-accuracy, georeferenced in-building photo-maps*

*Photomaps can be converted to CAD diagrams or combined with outdoor land and air imagery of the building for a complete facility map.*

*Facility maps can be used in public safety and military applications to train first responder crews and perform mission planning. In combination with real-time in-building positioning facility maps can provide precise in-building crew locations delivering complete situational awareness.*

## 1.0 AIDED-INERTIAL FOR GPS-DENIED, PORTABLE NAVIGATION

### 1.1 Dead Reckoning

There are a certain missions requiring navigation over extended time periods inside GPS-denied facilities. These missions may extend to many hours without access to GPS or any other infrastructure support. Such missions include navigation and mapping of caves, silos, nuclear facilities and docked or moving ships. The only possible way of navigating in these environments is dead reckoning (Figure 1).

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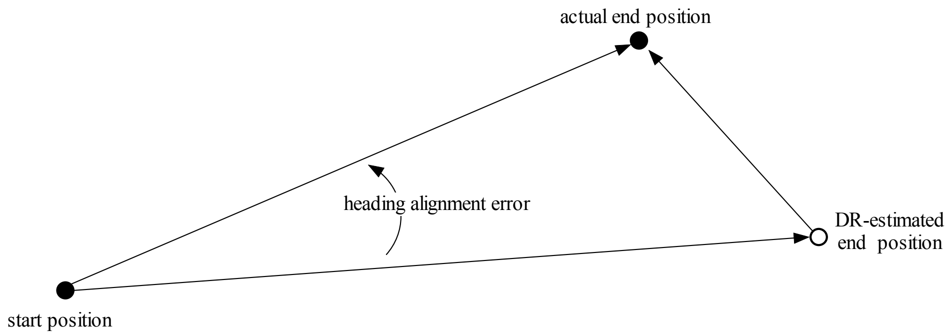



**Figure 1. Dead Reckoning**

In dead reckoning the heading (cross-track) and distance travelled (along-track) must measured accurately and at a high rate to reduce cumulative errors. Cross-track errors are typically the major source of positioning errors and in order to achieve, say, a 1m/km horizontal position error performance heading must be kept to an accuracy of better than 1mrad (0.05deg).

## 1.2 ZUP-aided Inertial Navigation

The only sensors capable of aligning to and maintaining this level of heading accuracy are navigation-grade inertial sensors. Figure 2 shows the diagram for an aided-inertial portable navigator. It's a standard aided-inertial configuration with the nav-grade Inertial Measurement Unit (IMU) as the primary measurement sensor. Its unique feature is that the only aiding is provided by Zero-velocity Updates (ZUPs). GPS signals are used only for the initial alignment and to provide aiding when available.

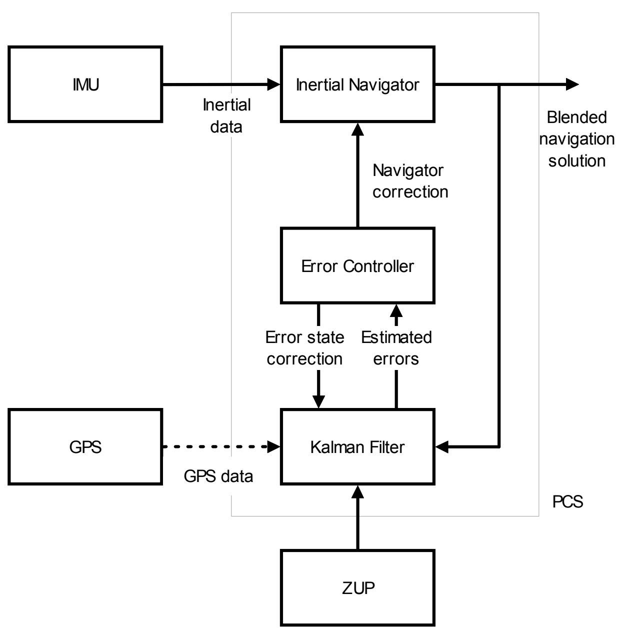



**Figure 2. GPS-denied, ZUP-aided inertial navigation**

## 1.3 Implementation

A ZUP-aided inertial system, the POS LS, was originally developed by Applanix in 2001. The backpack-portable system was developed for land seismic applications and weighed over 40lbs (Figure 3, left). Current implementations of the system are vest-mounted and weigh in at just under 12lbs. The Ring-Laser Gyro (RLG) IMU (Figure 3, middle) provides the incremental velocities and angles to the processor (Figure 3, right with the batteries)

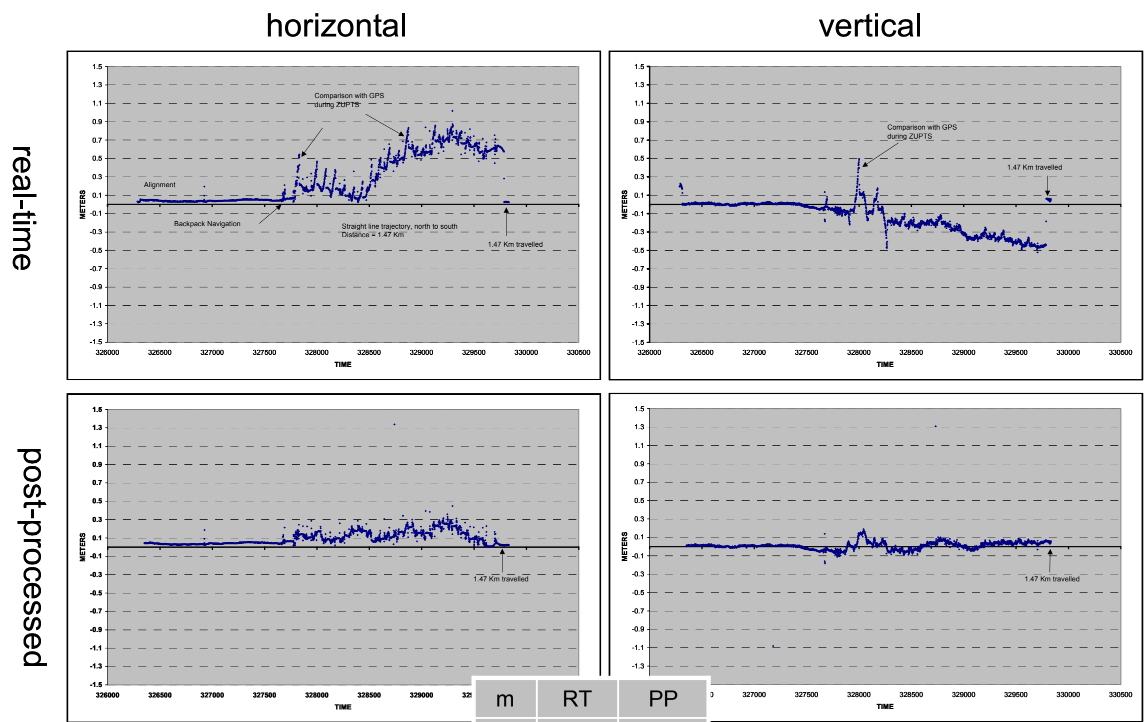

**Figure 3. POS LS (left) and GPS-Denied Navigation and Mapping system (centre and right)**

## 1.4 Operation

System initialization (alignment) takes 10-20min in mid-latitudes depending on the desired accuracy. Following alignment the operator can walk, run, crawl, ride on a vehicle but must perform periodic ZUPs, every 1 to 4 min for 5 to 10sec depending again on the desired accuracy. ZUP start and end notification is provided automatically by the handheld controller (Figure 3). In addition to ZUP notification the controller provides waypoint navigation and other functions depending on the operational scenario.

## 1.5 Performance

System performance was evaluated outdoors along a straight 1.5km North-South path using cm-level accuracy RTK GPS (Figure 4). The maximum real-time horizontal error was less than 1.1m. Vertical errors are about half of horizontal (0.5m) and post-processed is again half of real-time. This exceptional level of performance is necessary in order to maintain positioning accuracy during missions extending over several hours.




| m | RT | PP |
|---|---|---|
| H | 1.1 | 0.5 |
| V | 0.5 | 0.15 |

•

**Figure 4. Real-time and post-processed horizontal and vertical performance**

### 1.6 Inertial Navigation Applications

The ZUP-aided system described in Figure 2 provides full six-degree position and orientation measurements derived solely from motion dynamics. As a result, the system operates without any infrastructure support: No GPS, RF, magnetic, barometric or map aiding is required. It can be operated in virtually every environment accessible by humans or robots and under virtually all dynamics experienced on these platforms. By virtue of the navigation grade sensors used, orientation accuracy is maintained over extended periods and the system can navigate accurately over several hours. The high cost of these sensors presently limits the use of these systems to navigation applications where no other sensors are capable of meeting the stringent requirements for extended, high-accuracy missions in infrastructure-less and potentially hostile environments. These environments include silos, caves, nuclear facilities and moving or docked ships.

## 2.0 GPS-DENIED MAPPING USING AIDED INERTIAL

As opposed to the specialized missions described in the previous section, the vast majority of in-building operations are carried out in known and established facilities. An in-building positioning system provides limited information regarding the location of the operator within these facilities unless accompanied by an accurate and up-to-date building map. Existing as-builts and blueprints are often inaccurate and out of date. The GPS-denied navigation system described in the previous section can be augmented with an imaging sensor to provide accurate, low-cost in-building photomaps of virtually any facility.

The diagram in Figure 5 is the ZUP-aided system of Figure 1 augmented with the addition of an active or passive, imaging sensor and a suite of post-mission software modules for georeferencing, visualization and CAD conversion. Accurate georeferencing of the images is possible by using the accurate position/orientation measurements and by extracting depth from consecutive image sequences. The GeoImage software selects image features and extracts depth from a sequence of frames containing this feature. The result is a fully georeferenced video of the building's insides.

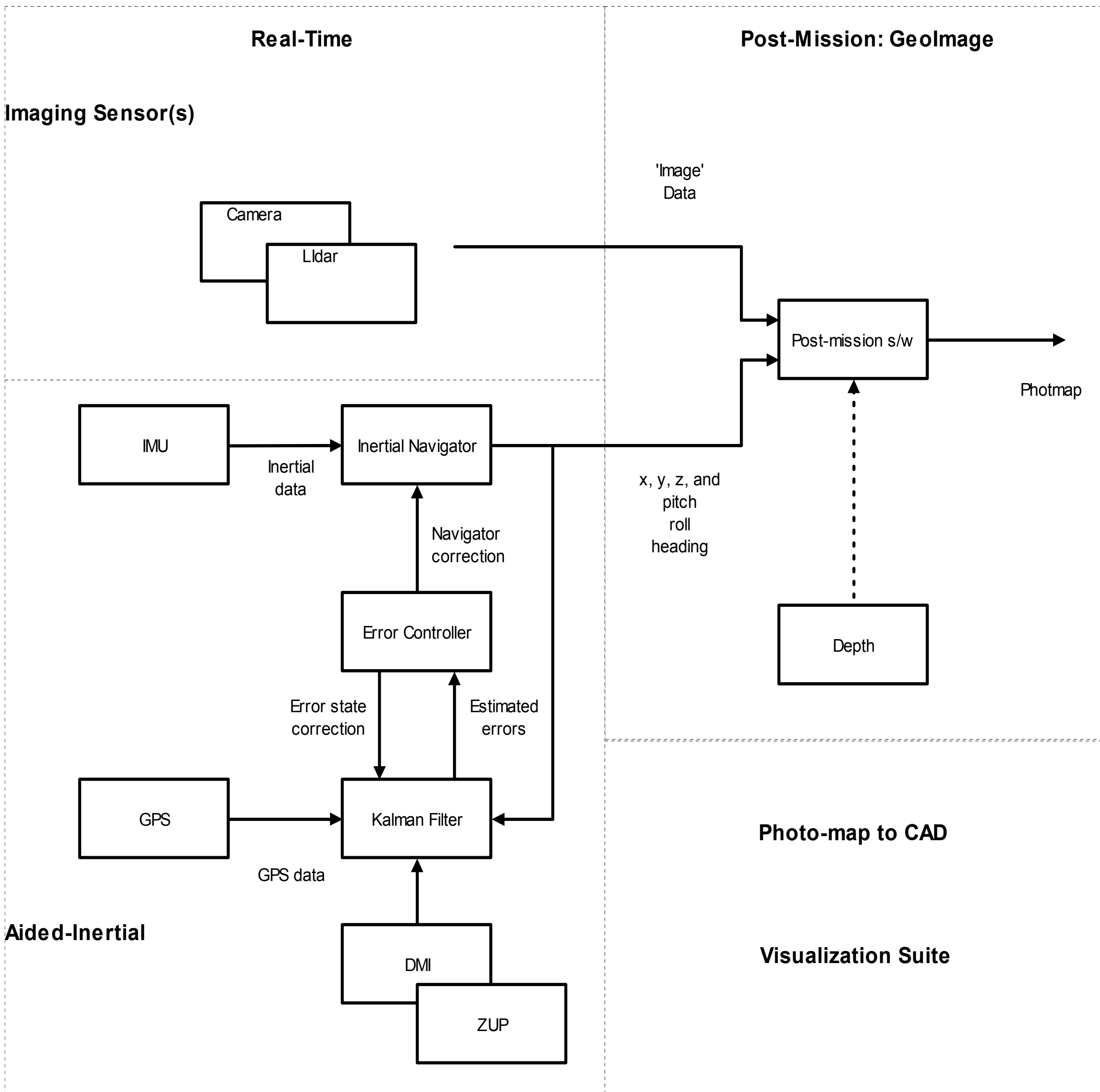



**Figure 5. Aided-inertial in-building mapping system**

## 2.2 Portable, in-building Mapping

A portable in-building mapping system is shown in Figure 6.

Figure 6. In-building mapping prototype: Backpack, camera and vehicle version.

It consists of the aided-inertial components (IMU, processor and batteries) and an eleven-sensor camera (the "dodecahedron") mounted on a backpack for a near $360^0$ view. The location of the camera provides a "natural" view of the traversed surroundings. The system is operated in the same simple manner as the navigation system: Align, walk and ZUP. By virtue of the fact that once aligned the system can provide indoor position/orientation measurements for several hours without the need for alignment, GPS or any infrastructure translates into a high production rate and significant cost benefit. The high-accuracy of the geo-referenced interior data permits their seamless integration with air/land photomaps of the building's exterior to produce complete facility maps. Applications of such facility maps include support for public safety operations and indoor asset management.

## 2.3 Facility Maps

High risk public safety operations are often in large, established facilities. These include government, financial, nuclear and educational facilities. Photomaps of these facilities can be used for first responder training, mission planning and in combination with a low-cost in-building positioning system to provide precise in-building location and full situational awareness. A facility map video combining indoor and outdoor photomaps of Canadian Forces Based (CFB) Gagetown (Figure 7) will be shown during the presentation.

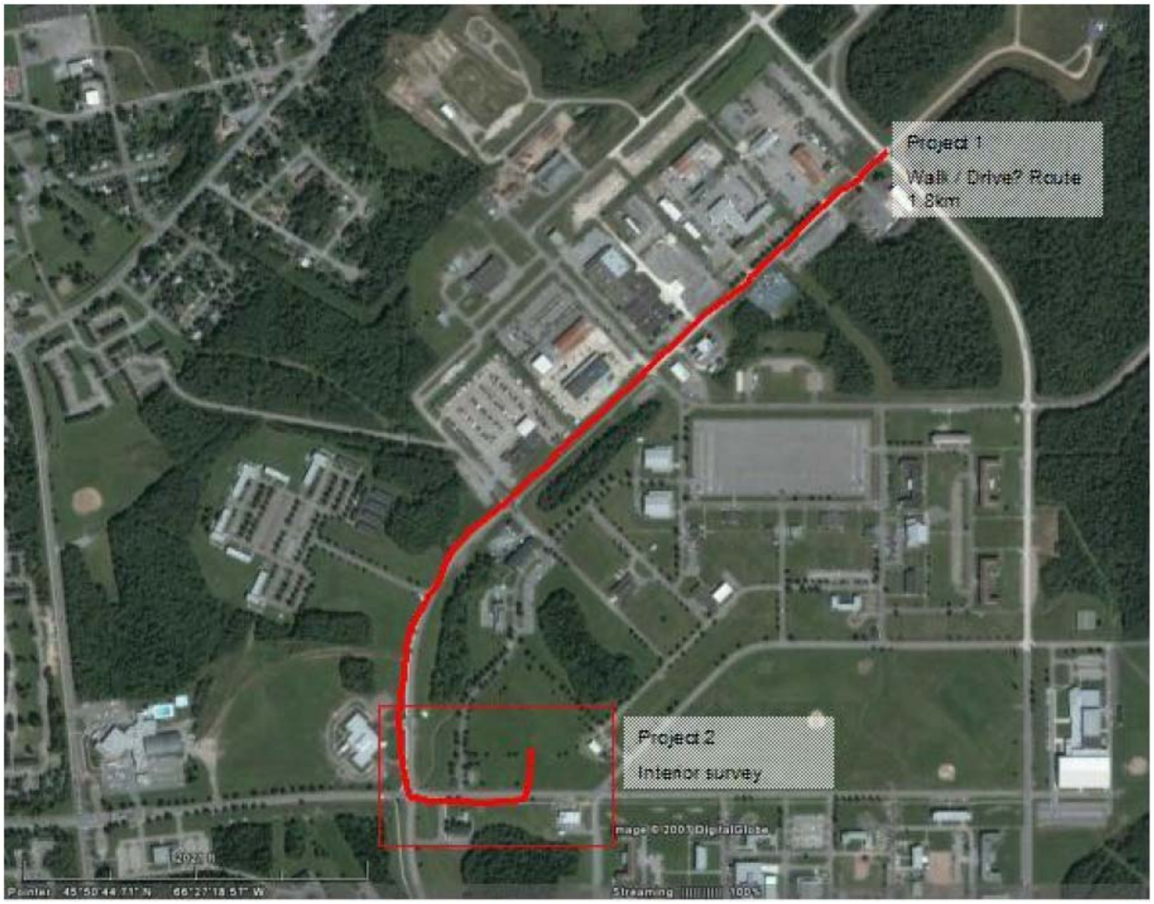



Figure 7.CFB Gagetown.

## 3.0 CONCLUSIONS

Portable, aided-inertial systems using navigation grade IMU are capable of navigating without any infrastructure support. Unaffected by motion dynamics and operating environment they are capable of precision navigation over several hours in virtually any area accessible by humans. Uniquely suited to special operations missions they are used to map and navigate in caves, silos, nuclear facilities and ships. The range of their application is presently limited, however, by the high cost of the IMU.

Portable aided-inertial systems augmented with an imaging sensor can be used to accurately and efficiently map building interiors. Interior photomaps can be combined with georeferenced images of the building's exteriors to generate complete facility maps. Due to the efficiency of the data collection process the cost of facility map data can be relatively low. Facility maps can be used by public safety crews and military for first responder training, mission planning and in conjunction with in-building positioning systems to translate real-time operator positions to precise in-building locations.