Sensor Fusion for Robust Urban Navigation: Test Results from the Advanced Position/Navigation and Tracking the Future Force (APNTFF) Program

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ABSTRACT TITLE

Navigation and positioning capabilities have been identified as key enablers for both situational awareness and information superiority when engaged in urban combat. While the Global Positioning System (GPS) has dramatically altered the accuracy and availability of these resources in many domains, this system is inherently limited in urban environments, particularly for dismounted soldiers. To address this need, the US Army created a program titled Advanced Navigation and Tracking the Future Force (APNTFF) whose goal was to provide such a capability through development and integration of a suite of complementary sensors. These sensors – a Micro-Electromechanical System Inertial Measurement Unit (MEMS IMU), dead reckoning system (i.e. a pedometer), Radio Frequency (RF) ranging, and network-assisted GPS – are intended to provide both the accuracy and availability required by dismounted soldiers and to be capable of packaging in a form factor that meets the Army's size, weight, power and cost requirements. This paper documents the results of the final phase of the APNTFF program, in which prime contractor Northrop Grumman combined measurements from these sensors in an integrated navigation system and tested the system in an indoor and urban environment.

1.0 INTRODUCTION

The vision of Army Force Transformation operations are embodied in programs such as Future Combat System (FCS) and Future Force Warrior (FFW) that emphasize a lightweight, highly mobile force with information superiority used as a force multiplier. A key enabler of this vision is a position/navigation and tracking system that is capable of providing own-platform navigation as well as position distribution among the various force elements (warriors, sensors, fires) for virtually all military functions. Dismounted soldiers currently rely on GPS to conduct their mission – whether to identify targets, to move to different locations or to advise their commanders of their location. It is well known that GPS signals are challenged in urban,

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indoor, and wooded environments – precisely the environments in which the current and future engagements will be fought. This need is complicated by the size, weight and power constraints of further equipping the dismounted soldier.

The Army has recognized the importance of developing and demonstrating technologies that complement GPS for its soldiers in an Army Technology Objective-Research (ATO-R) entitled Advanced Positioning/Navigation and Tracking the Future Force. The APNTFF was a jointly funded 6.2 research and development effort and was managed by the Communications-Electronics Research, Development and Engineering Center (CERDEC) and the Simulation and Training Technology Center (STTC). The APNTFF program goal was to provide an affordable, reliable and accurate source of position, orientation and movement information capability to soldiers and other platforms to support operations and training in urban, indoor and other complex environments.

The ATO goals were to demonstrate that emerging technologies could be integrated in a suite having the following parameters, size - 125 cc, weight - 0.2 kg, power - 1.1 watts, costing $1,500, having a robust positioning availability (98% of the time), operational horizontal position accuracy – 1m (CE 95%), and vertical -1m (LE 95%). The program realized that some parts of the soldiers gear could be used to double as navigation functions, for instance the radio could not only be used for voice/data communications but also be a ranging asset, and cameras could be used for correlation or for sensing position displacement/velocity.

2.0 APNTFF PHASE 1

The ATO was conducted in a two phased effort over four years, beginning in 2003. The technical approach was to develop, demonstrate and integrate the following technology solutions: Network Assisted GPS, RF Ranging, Enhanced Dead Reckoning Devices, and MEMS IMU. The expectation is that these sensors, in combination, provide the required accuracy and availability. Strengths and weaknesses of these sensors are described in Table 1, below, which also lists the Phase I companies that participated.

Table 1. APNTFF Sensor Suite

Sensor	Strengths	Weaknesses	Phase I Participants
MEMS IMU	• Facilitates strapdown navigation – position and attitude integration. • 100% availability	• Essentially no "free-inertial" capability at current MEMS performance levels.	• Honeywell, Systron Donner
Network Assisted GPS	• Provides GPS capability when available. • Network assistance facilitates rapid Y-code acquisition. • Improved accuracy through differential corrections.	• Does not mitigate blockage or multipath corruption of GPS.	• Navsys, Center for Remote Sensing

Sensor	Strengths	Weaknesses	Phase I Participants
RF Ranging	• Provide GPS-like range updates with greater urban, indoor penetration than GPS. • Facilitates collaborative navigation between nodes, including other vehicles and dismounted soldiers. • Can be integrated into soldier's comm system.	• Susceptibility to multipath, difficult to model. • Limited coverage in buildings. • Radiates – consumes power, raises detection possibility.	• ITT, Multispectral Solutions, Sarnoff
Dead reckoning (pedometry)	• Does not depend on external signals. • Drifts linearly with soldier motion – superior to IMU. • Possible to calibrate to individual soldier's motion.	• Heavily dependent on fidelity of motion model. • Limited availability during periods of irregular soldier motion.	• Point Research (now Honeywell), Vectronix

In the first phase, which was executed in 2003-2004, technologies were developed and demonstrated at the sensor level. The ATO leveraged a complementary effort entitled Blue Force Awareness Protection Suite (BFAPS) which served to accelerate the demonstration of several technologies, administered by Galaxy Scientific (now SRA). Additionally SBIR activities with Physical Optics and CACI (previously MTL) were conducted to develop and demonstrate optical sensors to limit inertial measurement unit (IMU) position drift.

3.0 APNTFF PHASE II

Phase II of the APNTFF program, which was executed in 2005 and 2006, focused on the selection and integration of sensors into a single navigation system that optimally leverages the strengths of each sensor to provide an overall navigation capability that outperforms each sensor individually. For Phase II of the APNTFF program, CERDEC selected Northrop Grumman as system integrator. This phase was executed by Northrop Grumman's Mission Systems (NGMS) sector, located in Dominguez Hills, CA, together with Northrop Grumman's Navigation Systems Division (NSD), (part of the Electronic Systems sector), located in Woodland Hills, CA. NGMS was responsible for hardware integration and system test, including integration with its FBCB2 situational awareness software, and NSD was responsible for developing and testing the navigation software that integrated data from all four sensors.

4.0 INTEGRATED NAVIGATION SYSTEM

Four sensors were selected for integration in the APNTFF demonstration.

- Systron Donner's MMQ-50. The MMQ-50 incorporates solid-state quartz MEMS inertial rate sensors and silicon MEMS accelerometers.
- A radio developed by ITT under the Defense Advanced Research Projects Activity's (DARPA) SuoSAS program. The SuoSAS radio employs time-of-arrival (TOA) measurements embedded into the communication protocol to extract point-to-point range information within an ad-hoc mobile network [1].

- A dual frequency, 12-channel, P(Y) code Rockwell Collins GB-GRAM GPS receiver that outputs line-of-sight (pseudorange and delta-range) measurements and is capable of direct Y acquisition (though network assistance was not implemented in the final demonstration).
- The Honeywell DRM V, a self-contained system that is worn on the back or hip to detect soldier motion. In addition to MEMS accelerometers for step detection, the DRM V contains a three-axis magnetometer for heading measurement, an altimeter, three-axis gyroscopes for rotation measurement, and a commercial GPS receiver for stride calibration when GPS is in view [2].

Sensor outputs were modified to allow the system to accommodate a common time base and, where applicable, a common position reference. The sensors were mounted on a backpack together with batteries, antennas, and a navigation processor that interfaces directly with the sensors for measurement time-tagging and processing. A tablet PC is employed for system configuration, user interface, data logging, and mark-on-top capabilities. In addition, an FBCB2-based display capability overlays own-position and other blue force positions on a user-supplied map.

The navigation processor implements a strapdown navigation solution with a Kalman Filter aiding via measurement data from the GPS, pedometer and RF ranging systems to estimate navigation and sensor error parameters. In this fashion, 100% availability is not required of any of the three aiding sources. The system is capable of both PVT-aiding and LOS-aiding from the GPS receiver.

The integrated system, as expected, is designed to balance the strengths of each sensor, and in particular, to mitigate the weaknesses of each sensor with respect to the urban environment. As an example, consider the integration of the pedometer with the IMU, which represents the pairing of sensors that do not depend on external inputs. The pedometer has zero drift when the soldier is stationary and approximately linear drift as a function of stride count. The pedometer depends heavily on the magnetometer to project strides in the right direction, and the pedometer is prone to large and generally unmodelable errors in urban environments. The IMU, on the other hand, is not impacted by the urban environment but has very high drift. Figure 1 shows a sample course walked indoors (i.e. GPS denied) with the pedometer-only output and the integrated output. As can be seen, the integrated system uses the pedometer to bound the drift of the IMU and the IMU's performance on short time-scales to provide a smoother output. The performance improvement comes in part from the relative smoothness of navigation heading in comparison to magnetometer heading, as shown in Figure 2. Similar developments to incorporate the GPS and RF ranging sensors in urban environments were also pursued.

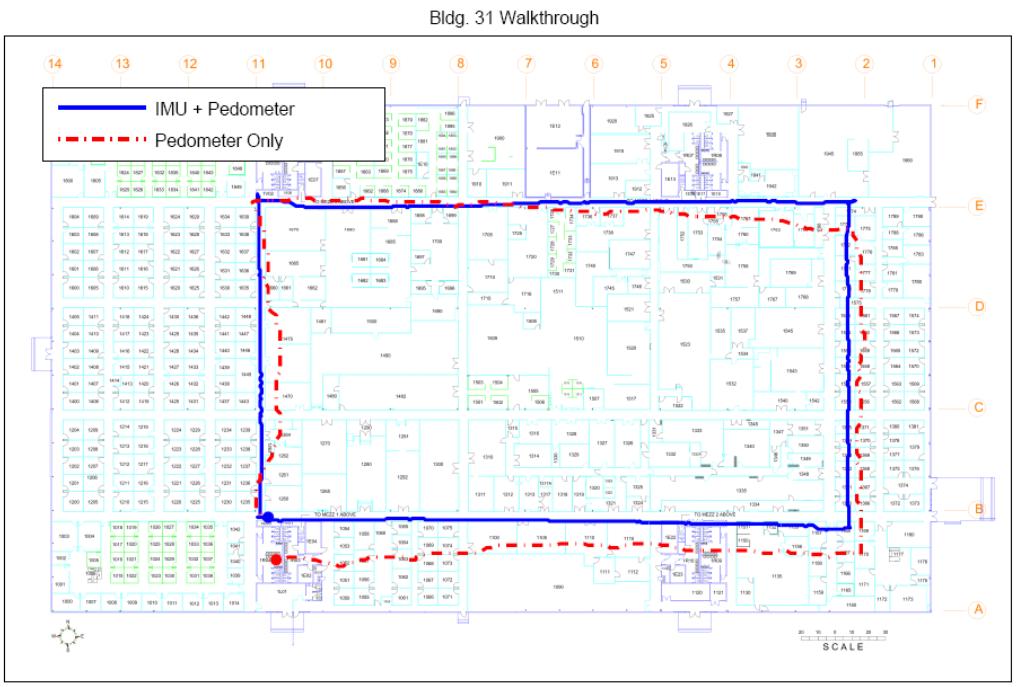

Figure 1: GPS-denied Position Accuracy, DRM-only and Integrated

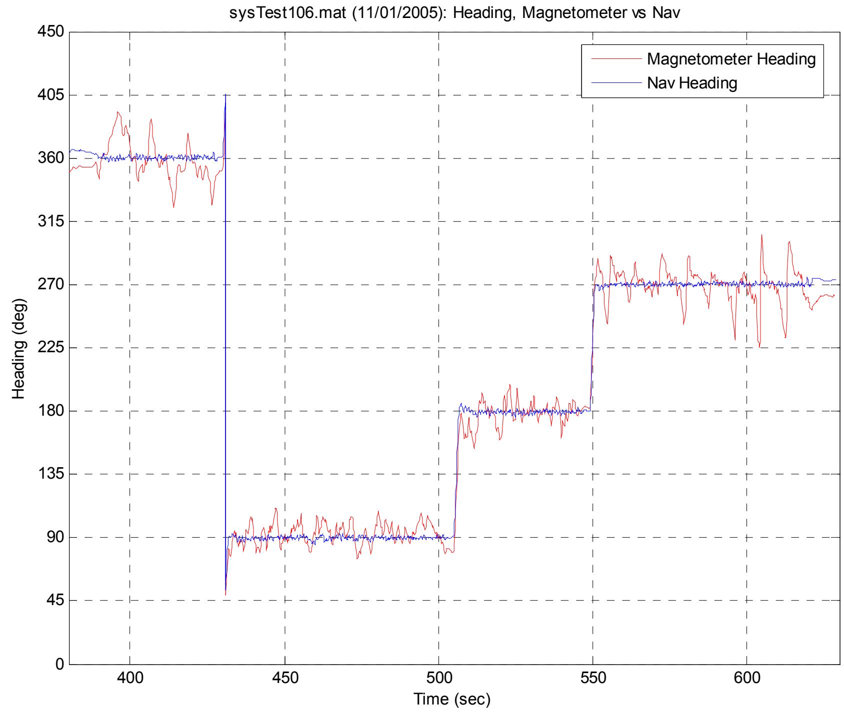

Figure 2: Raw and Integrated Heading Performance

5.0 FINAL EVALUATION

5.1 Test Conditions

The final evaluation of the APNTFF system was conducted at the Northrop Grumman Mission Systems campus in Dominguez Hills, California. The course contains several two story buildings that provide a measure of GPS blockage. The Dominguez Hills campus had been previously surveyed at multiple locations so that a map of the campus could be accurately georegistered. A set of 13 waypoints were selected from the map and georegistered, including indoor and outdoor waypoints, and the courses described below are essentially straight-line paths between these waypoints. The mark-on-top feature in the user interface allowed the tester to mark his location at previously surveyed waypoints, and these marks were also recorded. Assuming approximately constant velocity between any two waypoints, the nav solution can be compared to an interpolated position to yield a reasonable estimate of position error.

Three different course types were created to mimic different operating environments. The three courses were: an outdoor course that skirted the building exteriors; an indoor course that was predominantly in-building and included staircases and elevators; and a mixed course that combined the two. Each course was approximately 1,300 meters in length. The courses were run with different permutations of available sensors. Additionally, the courses were run with either forward walking or a sequence of varied gaits to test the impact of pedometer step detection and characterization on system performance. Over the course of four days, ten test subjects performed a total of 62 test runs, with various parameters changed for each run.

Three SuoSAS radios were used as fixed beacons with their positions pre-loaded into the radio. The radios were positioned to provide reasonable coverage within the test building. Unfortunately, penetration of the radio signal in-building was extremely limited, effectively eliminating this sensor's role in the final evaluation. Separate open-air radio testing was used to validate the Kalman filter's processing of ranging data.

6.2 Test Results

The APNTFF system showed excellent performance across multiple wearers for conditions where either a) the pedometer was enabled and forward walking was used or b) GPS was generally available (i.e. outdoor walks). A typical forward walking condition is shown in Figure 3. These runs include staircase walking and elevator usage. Overall statistics for these cases is shown in Figure 4. Generally, the system maintains accuracies on the order of 6-8m. The "indoor" runs slightly underperform the "mixed" runs, likely due to insufficient time in view of the GPS constellation to calibrate the system errors.

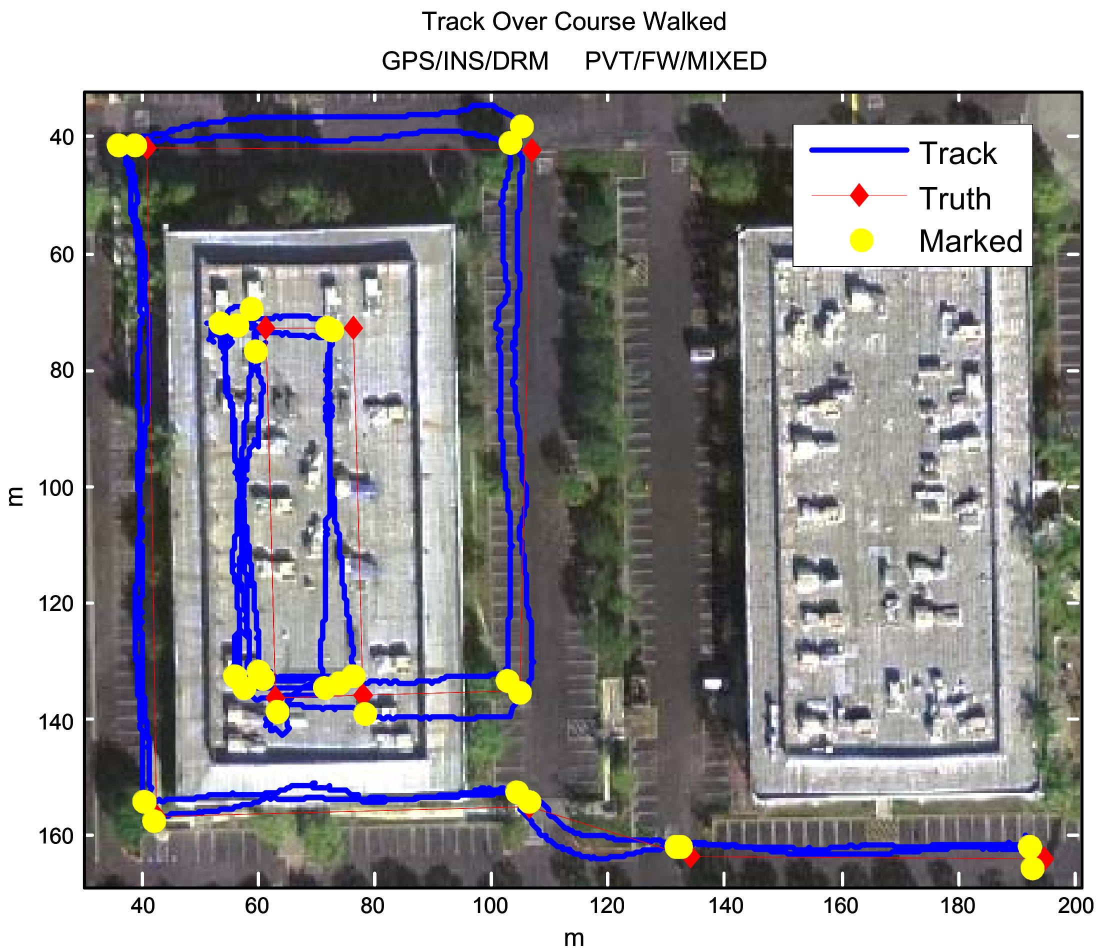

Figure 3: Sample Errors, Mixed Course

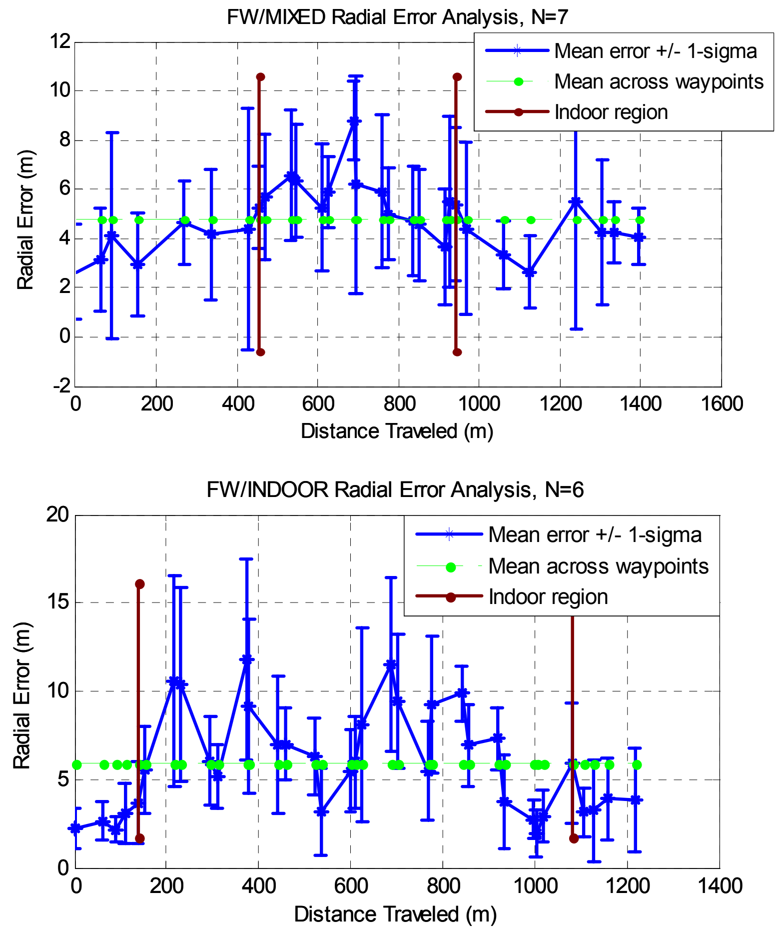

Figure 4. Error Statistics, Mixed and Urban Course

For the varied gait runs, the system performance was limited by the characterization capability of the DRM. When the DRM successfully characterized soldier motion, the integrated system performed reasonably. The APNTFF system also successfully rejects incorrect characterization and does not use that data for updates. However, sustained periods of incorrect characterization degraded the system's capability to maintain an accurate position due to IMU drift. As the position solution degrades, it is forced to rely on the (incorrect) stride updates from the DRM. A typical run with mischaracterized data is shown in Figure 5. In general, the DRM was highly reliable in characterizing forward steps but not sideways or reverse steps. This may be in part to the soldier's added weight from the APNTFF system that shifts his gait away from normal, unburdened human motion. Note that when the GPS constellation is in view, the system correctly relies on GPS and rejects pedometry updates to maintain an accurate solution.

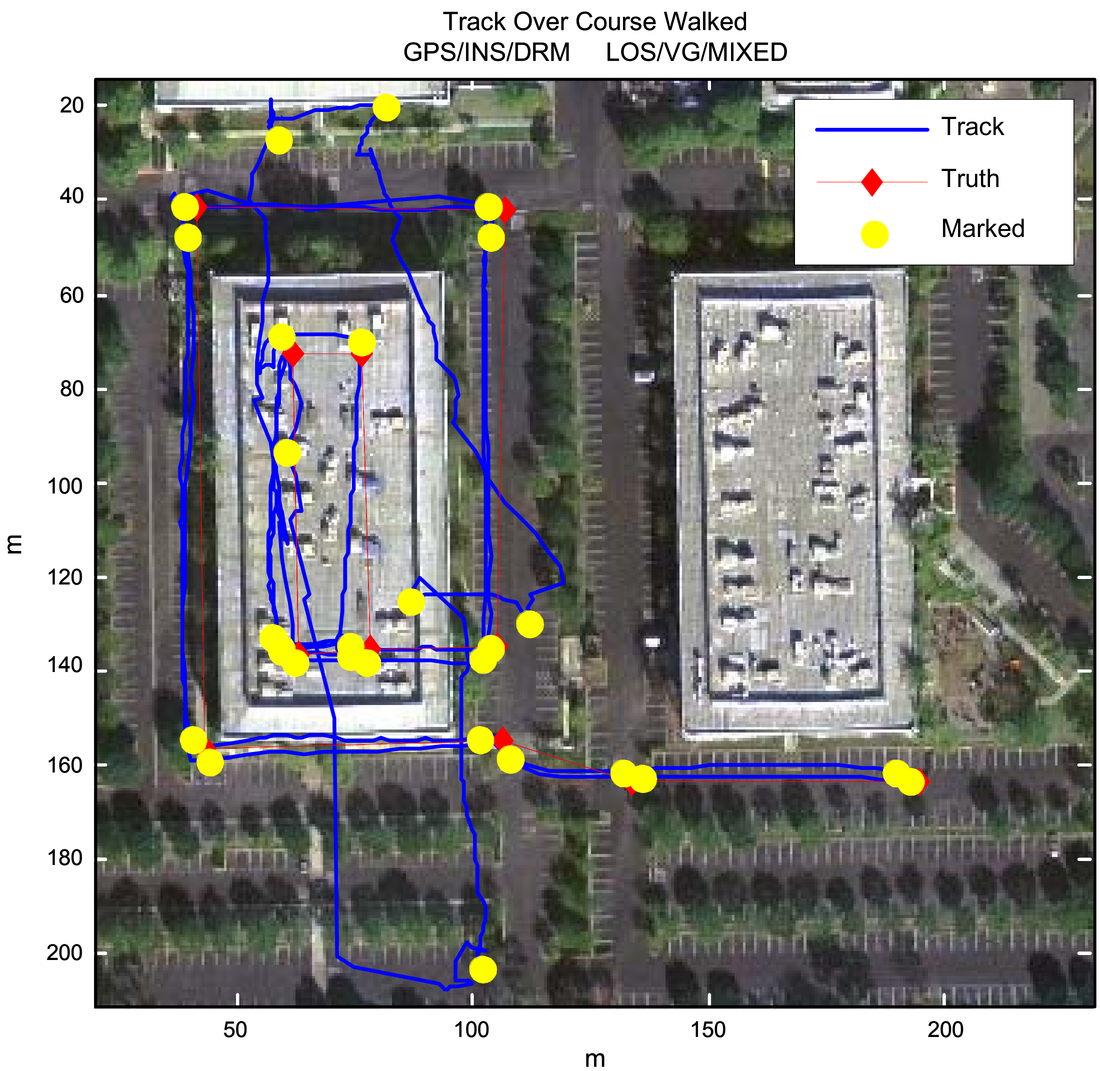

Figure 5: Sample Varied Gait Test, with Mischaracterized Steps

6.0 CONCLUSIONS

The APNTFF program successfully demonstrated integrated operation of the four sensors selected for integration. The APNTFF system demonstrated the ability to selectively use the available and accurate sensors and fuse their inputs into an accurate solution. In particular, the fusion of pedometer and MEMS IMU data to provide a solution that is robust to environmental conditions (e.g. magnetic anomalies) and intermittent stride irregularities yields a solution that remains accurate at the 6-8m level over hundreds of meters traveled, including stairs and elevators. Ultimately, the system remains reliant on the availability of its aiding sensors, and in particular, RF ranging and stride characterization in this regard. Extrapolating these results which were demonstrated in the 6.2 Applied Research realm, it is fully expected through system development that within a 6.3 Advanced Technology Development program an integrated navigation system can be produced that is capable of providing precision performance in a size format found acceptable to the soldier.

7.0 REFERENCES

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