Testing and evaluation of a wearable augmented reality system for natural outdoor environments

David Roberts*[a], Alberico Menozzi[a], James Cook[a], Todd Sherrill[a], Stephen Snarski[a], Pat Russler[a], Brian Clipp[a], Robert Karl[a], Eric Wenger[a], Matthew Bennett[a], Jennifer Mauger[a], William Church[a], Herman Towles[a], Stephen MacCabe[a], Jeff Webb[a], Jasper Lupo[a], Jan-Michael Frahm[b], Enrique Dunn[b], Christoper Leslie[b], and Greg Welch[c]

[a]Applied Research Associates, 8537 Six Forks Rd, Suite 600, Raleigh, NC, USA, 27615
[b]The University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[c]The University of Central Florida, Orlando, FL, USA

ABSTRACT

This paper describes performance evaluation of a wearable augmented reality system for natural outdoor environments. Applied Research Associates (ARA), as prime integrator on the DARPA ULTRA-Vis (Urban Leader Tactical, Response, Awareness, and Visualization) program, is developing a soldier-worn system to provide intuitive 'heads-up' visualization of tactically-relevant geo-registered icons. Our system combines a novel pose estimation capability, a helmet-mounted see-through display, and a wearable processing unit to accurately overlay geo-registered iconography (e.g., navigation waypoints, sensor points of interest, blue forces, aircraft) on the soldier's view of reality. We achieve accurate pose estimation through fusion of inertial, magnetic, GPS, terrain data, and computer-vision inputs. We leverage a helmet-mounted camera and custom computer vision algorithms to provide terrain-based measurements of absolute orientation (i.e., orientation of the helmet with respect to the earth). These orientation measurements, which leverage mountainous terrain horizon geometry and mission planning landmarks, enable our system to operate robustly in the presence of external and body-worn magnetic disturbances. Current field testing activities across a variety of mountainous environments indicate that we can achieve high icon geo-registration accuracy (<10mrad) using these vision-based methods.

Keywords: pose estimation, augmented reality, geo-registered icons, head tracking, soldier-worn, see-through display

1. INTRODUCTION

Applied Research Associates (ARA), as prime integrator on the DARPA ULTRA-Vis program, is developing a lightweight, low-power soldier-worn system to provide enhanced tactical situational awareness for military soldier operations. The system augments the soldier's view of reality with iconic information geo-registered to the real world, enabling the soldier to carry out his mission 'heads-up' with 'finger-on-the-trigger' (Figure 1). This capability offers to improve soldier operational tempo, enhance squad-level command and control, and provide instantaneous situational awareness of user location, friendly locations, and tactical points of interest.

One of the enabling technologies for ULTRA-Vis is accurate and robust estimation of soldier head pose (position and orientation). We estimate pose using lightweight helmet-mounted sensors and a sensor-fusion framework that integrates inertial, magnetic, pressure, GPS, and computer vision data. We have developed this framework with inherent flexibility to accept terrain-based digital elevation data and to leverage opportunistic vision-based azimuth detection methodologies to achieve high geo-registration accuracy even when accelerometer and/or magnetometer measurements are unusable (i.e., during high dynamic conditions or when the Earth's magnetic field is disturbed). Our technology augments the conventional suite of measurements in standard off-the-shelf inertial navigation solutions with vision-based ones. These additional inputs (1) provide orientation measurements when other orientation signals are disturbed or are not available, (2) help to enhance accuracy and robustness even during nominal conditions by enhancing the ability to detect and estimate other sensor errors and disturbances, and (3) provide the opportunity to calibrate magnetometer readings while the system is operating (i.e., even after the initial hard/soft iron calibration). Our system makes use of these vision-based measurements opportunistically, since they may not always be available. We believe that the path to accurate and robust

ULTRA-Vis Tactical Heads-Up Situational Awareness

ULTRA-Vis Wearable
Augmented Reality System

display. The ULTRA-Vis architecture supports ingestion and parsing of CoT (Cursor-on-Target) messages[3] from the soldier's digital radio network. We project that the weight and power for the system components at the conclusion of Phase 3 will be: helmet kit sensor module (0.1 lbs, 1.2 W); helmet kit see-through display and helmet-mounting scheme (0.8 lbs, 8 W); augmented reality processing unit (1.3 lbs, 12 W).

ULTRA-Vis Prototype System

① Helmet kit

② Augmented reality processing (ARP) unit
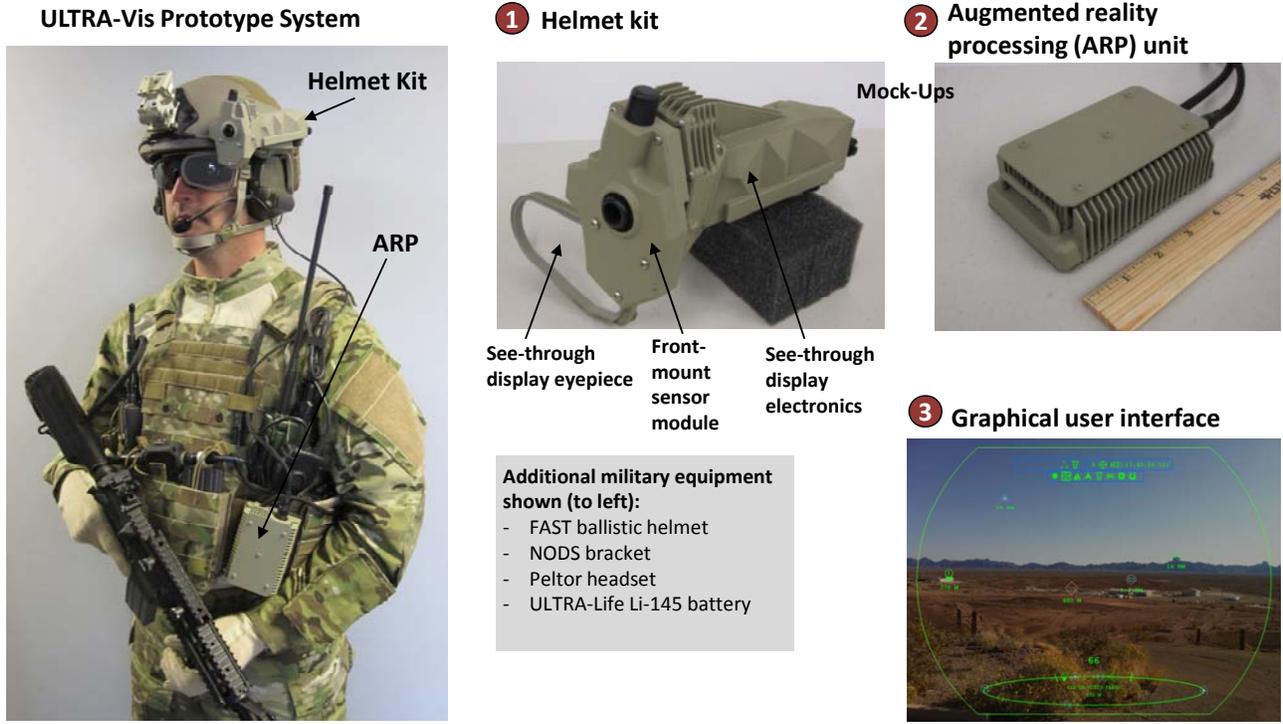
③ Graphical user interface

Figure 2. The ULTRA-Vis prototype system consists of a helmet kit, augmented reality processing unit, and graphical user interface (simulated iconography shown). The helmet kit incorporates a low-SWaP sensor module with a full-color see-through display. The processing unit includes an ARM-based system-on-chip (SOC) used by many Android smartphones and tablets. The ULTRA-Vis system does not interfere with standard military components (night-vision devices, headsets, radios, batteries) and adds minimal weight to the soldier's load. The prototype system processes CoT information from a networked military radio and overlays geo-registered iconic information on the user's view of reality.

2.1 Graphical User Interface

The ULTRA-Vis graphical user interface possesses a high degree of flexibility to meet the needs of different soldier mission CONOPS [4]. We developed the user interface through iterative interactions with the end-user community. The user interface provides operational alerts, system status information, system settings menu access, iconic visualization of geo-registered points of interest, and a situational awareness ring. Operational alerts include, for example, notification that the soldier's radio network is inoperable or that the user is magnetically-disturbed or GPS-denied/degraded. System status information includes the user interface mode ID, system battery level, and operational time (on-the-fly configurable to Local time or Zulu time). The menu is not displayed until activated by the user, via a button/toggle switch located on the helmet kit. With the menu, the user can access and change system configuration settings. Geo-registered icons are rendered within the field-of-view of the display (delineated by the green boundary in Figure 3). We use DOD-standard MIL-STD-2525C symbology, which distinguishes between hostile, friendly, neutral, and unknown symbols based on shape and color. The situational awareness ring is an intuitive tool that offers the user a dynamic real-time 360° understanding of where friendlies, enemies, and other points of interest are located. At the center of the ring is the user's Military Grid Reference (MGR) coordinate. Located above the ring is the user's heading (on-the-fly

---

[3] CoT is a machine-to-machine data exchange language that supports efficient communication of the 'what', 'where', and 'when' of tactical objects in the battlespace [3].

configurable as magnetic or true). On each side of the heading value is a line delimiting the extremes of the see-through display. Icons swing around the ring in response to user rotation. Geo-registered icons and those on the situational awareness ring are displayed with range information from the user, and in some cases elevation (for aircraft icons).
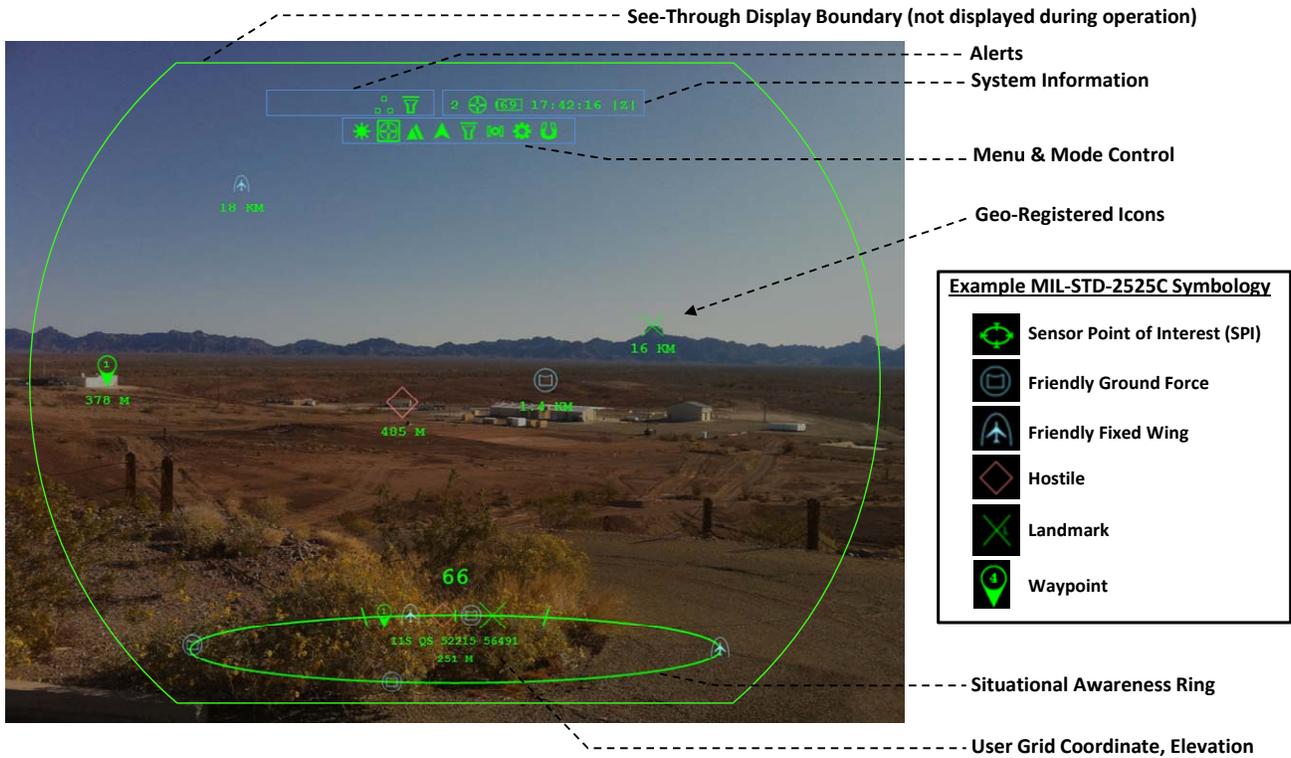

Figure 3. The ULTRA-Vis user interface provides operational alerts, system status information, menu and mode control, visualization of geo-registered icons, and an intuitive situational awareness ring. The image shown above is from our graphical UI design and evaluation tool that we use during end-user interactions and feedback sessions. We have designed the interface to provide mission-relevant information at the proper times during a mission and at the appropriate locations on the display so as not to overwhelm the user. ULTRA-Vis UI simulation tool shown above.

2.2 Operational Benefits

We believe ULTRA-Vis, through its enabling technologies and intuitive user interface, will enhance dismount soldier mission effectiveness. Examples include providing high-accuracy heads-up situational awareness of ground blue forces, terrain landmarks, and sensor points of interest; increasing the tempo of navigation; and providing geo-spatial understanding of aircraft assets and their respective attributes.

Situational Awareness: Accurate estimation of soldier pose enables ULTRA-Vis to augment the soldier's view of the real world with geo-registered virtual cues. This capability has dramatic potential to improve soldier situational awareness. As illustrated in Figure 3, a user can visually track team members (whether visible or occluded), landmarks, and other points of interest (e.g., previous IED locations) while maintaining a posture of 'heads-up' and 'finger-on-the-trigger'. These capabilities can enable greater control of soldiers, reduce fratricide, increase lethality, and increase operational tempo. Accurate visual cues of this nature and the capability to orient all soldiers to graphic control measures (GCMs) can reduce the overhead burden on leaders required to maintain control of units, resources, and movement. Reducing the control burden frees the soldier to focus on the mission and on the enemy.

Navigation: ULTRA-Vis supports increased team operational tempo during dismounted movement and navigation. The image in Figure 4a represents a soldier's arrival at a navigation waypoint during a tactical maneuver. The soldier's next waypoint is automatically projected in his environment (and easily identified on the situational awareness ring), enabling

him to quickly orient himself and initiate movement. He does not need to halt, study his map, or check his compass. The soldier's directional azimuth, current position, and objective are always displayed. If asked to report his location, the soldier can give a status update without stopping or otherwise taking his attention away from his current field of view. If the soldier encounters an obstacle to movement, he can easily detour or bypass the obstacle without losing his orientation to the movement objective. His next waypoint, or other icon of interest, serves as a directional beacon regardless of occlusions to his view or obstacles to his forward progress.

(a)   (b)

Figure 4. The ULTRA-Vis heads-up user interface offers the potential for enhanced dismount soldier mission effectiveness. (a) A soldier can navigate with increased tempo through real-time understanding of his position, heading, and the locations of waypoints and friendly forces. (b) An operator can more effectively manage and direct aircraft movements via heads-up visualization of icons in his real-world view of the airspace. ULTRA-Vis UI simulation tool shown above.

Air Traffic Control: Often, mission success for a soldier depends on his ability to effectively manage airspace for numerous aircraft and to orchestrate aircraft movement in support of ground forces and sensor assets. Some mission profiles mandate unaided visual acquisition of an aircraft. Aircraft that broadcast their location in CoT format can be geo-referenced by ULTRA-Vis, even if the aircraft is out of visual range (Figure 4b). Once in visual range, finding the aircraft can still be very challenging due to occlusions (e.g., clouds, terrain) or other sensory challenges (e.g., acoustic multi-path effects). ULTRA-Vis enables rapid vectoring of a soldier's head to the locations of aircraft assets and immediate user understanding of aircraft attributes (e.g., call sign, altitude).

3. APPROACH TO ACCURATE AND ROBUST POSE ESTIMATION

Pose estimation for our application is equivalent to "head tracking" or "motion capture" as described in other applications [5-9]. The degree of difficulty of this problem depends highly on the context, which includes performance and usability requirements. Head-tracking systems for aircraft pilot applications, for example, resort to instrumenting the cockpit with sensors that can track "markers" rigidly attached to the pilot's helmet. Some motion capture systems used in the entertainment industry consist of large rooms instrumented with multiple cameras that track special markers placed on the body – or body components – of interest. Other systems use cameras mounted on the body to track special markers instrumented throughout the room. These systems achieve high performance by instrumenting and calibrating both the body whose pose is to be estimated and the environment in which it operates.

Our pose estimation problem is challenging on numerous fronts. Our application is optical see-through (as opposed to video see-through). We must achieve high icon geo-registration accuracy and low end-to-end system latency so that icons track well with the observed real-world environment. Additionally, the low-SWAP requirement to be soldier-wearable and the go-anywhere/anytime nature of the intended CONOPS result in our particular pose estimation problem having the highest degree of difficulty. Our system must (1) track the position and orientation of the soldier's head

quickly and precisely; (2) it must do so using relatively low-cost, low-SWAP sensors in a ruggedized package; and (3) it must operate in any arbitrary outdoor environment without requiring specific preparation or instrumentation of the environment. (The system may, however, make use of any instrumentation or information that is already part of the environment or commonly available, such as signals from Global navigation satellite systems (GNSS) and/or known landmark location information.)

A variety of GPS-aided inertial navigation system (INS-GPS) solutions are commercially available that are compatible with the SWAP requirements of our application. However, off-the-shelf solutions do not offer the level of customization needed for our specific application. Our INS-GPS solution is designed to address head tracking of a person walking over arbitrary outdoor environments, so we designed it to take advantage of various assumptions that are valid in this operating condition (e.g., kinematics constraints, the nature of magnetic disturbances, and the nature of dynamic disturbances). In addition, we designed our solution to take advantage of measurements from sources other than the conventional suite of sensors available in an off-the-shelf INS-GPS system. For instance, we take advantage of DTED information to provide a stable measurement of altitude. Most importantly, we leverage a camera and custom computer vision algorithms to provide extra measurements of absolute orientation that allow our system to reach levels of performance that are not possible with off-the-shelf INS-GPS systems.

Our vision algorithms currently estimate absolute azimuth opportunistically in two ways: (1) through horizon matching of distant mountainous terrain and (2) via feature matching to an image frame containing a geo-registered distant landmark. We term this first method *Horizon Matching* and the second method *Landmark Vision*. Horizon matching functions automatically without user involvement. Landmark Vision requires the user to align a crosshair in his see-through display with a distant landmark feature of known coordinates. The system then matches features in the current helmet kit camera frame to features in the landmarked frame to provide an absolute orientation estimate. The user would perform this operation at a point during his mission when he is relatively stationary (i.e., in an overwatch position) and needs to acquire high accuracy geo-spatial situational awareness. We have constructed our sensor-fusion framework with the inherent flexibility to incorporate these vision-based absolute azimuth inputs as well as potential future inputs (e.g., celestial sensing).

We characterize the performance of our system according to visual environment (i.e., which vision-based measurements are available vs. not available) and disturbance conditions (i.e., the presence and absence of magnetic and dynamic disturbances). At this point in our development path, the level of performance of our system when no vision-based information is available is similar to that of off-the-shelf INS-GPS systems, with some improvements in magnetic/dynamic disturbance rejection. When vision-based information is available, however, our current system is able to achieve a significant improvement in accuracy. This level of improvement is consistent across low user dynamics conditions. During high user dynamics conditions (i.e., rapid head turns), the system's ability to obtain vision-based information is degraded, with a corresponding drop in performance. The degree to which high registration accuracy is ultimately required by the user during high motion dynamics is a question we are currently exploring.

As will be discussed in Section 4, we have established metrics and systematic test procedures to quantify performance over a varied space of visual environments and disturbance conditions. We are conducting extensive testing to analyze our current system's performance over this space. We have identified conditions under which our system performs well and conditions where algorithm improvements are necessary. Rigorous testing and evaluation will continue to inform our development efforts as we improve accuracy performance and extend the system's operational envelope.

4. ALGORITHM PERFORMANCE EVALUATION

We have implemented a comprehensive test and evaluation process to assess algorithm performance in the lab and in the field. With each newly developed set of algorithms, we create a system software build executable. We first run the build in a lab test harness capable of processing previously collected raw sensor data sequences. This 'reusable data' process allows us to identify fundamental issues with the new algorithms and gain general insight into system performance prior to physical field testing. Once the build passes this check, we load the build onto the ULTRA-Vis system and proceed to the field to carry out a series of controlled and free-form evaluation sequences. We assess algorithm performance against a set of test metrics that enable us to efficiently identify algorithm deficiencies. Additionally, raw helmet kit sensor data is stored in a reusable data format that supports future in-the-lab software build performance evaluations. This

methodology supports rapid assessment of current algorithm performance using both live and reusable data and allows us to continually track algorithm improvements.

4.1 Metrics

We have developed a set of performance test metrics that support quantitative assessment of our system's ability to render icons on the real-world. The metrics are defined below and presented visually in Figure 5.

> *Jitter*: high-frequency fluctuating motion, evident when staring into the environment
> *Wander*: low-frequency icon motion, observable over minutes to hours
> *Lag*: time lag between real-world motion and icon motion during dynamic movements
> *Bounce:* vertical icon motion with respect to the real-world scene during walking, starting, and stopping
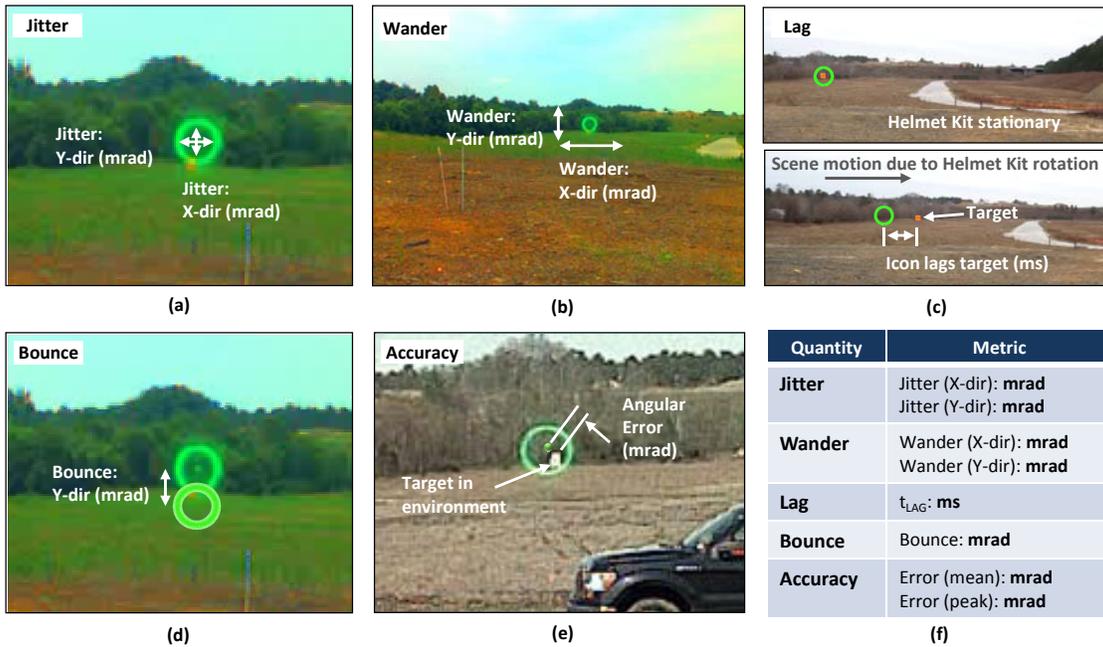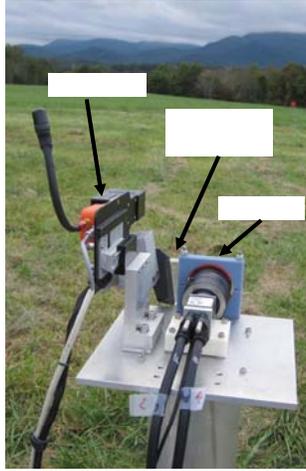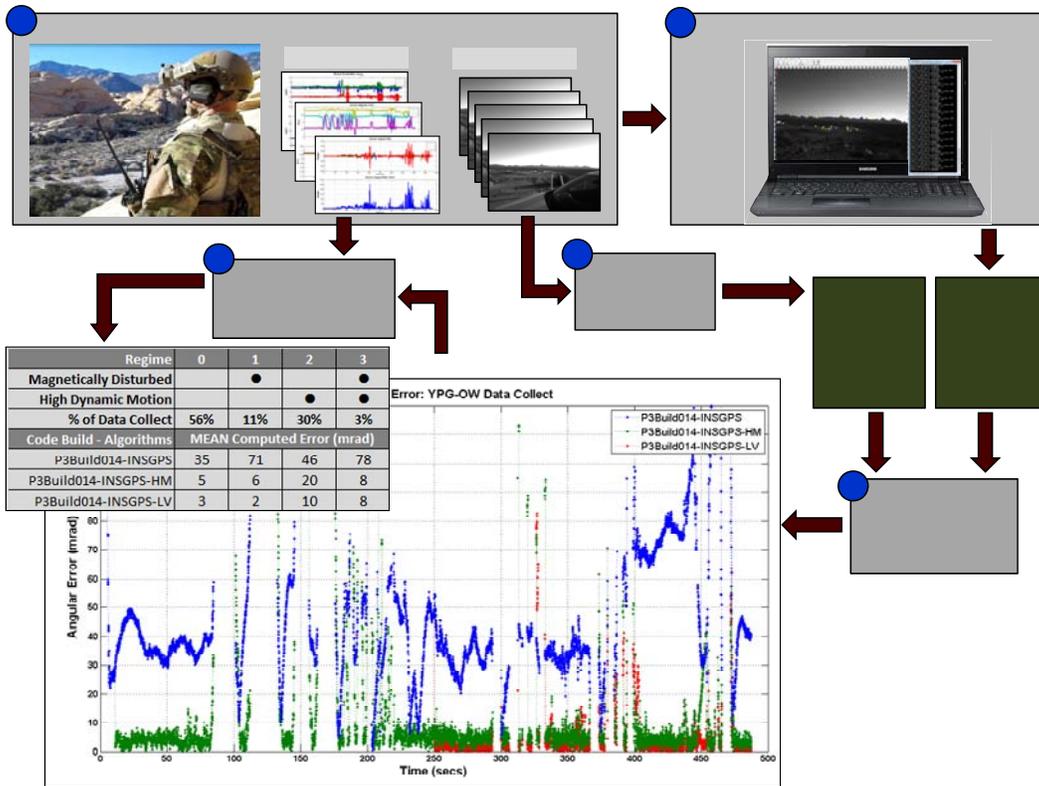> *Accuracy*: angular deviation of icon from real-world feature

Figure 5. We evaluate algorithm performance against five primary test metrics. We test for (a) jitter, (b) wander, (c) lag, and (d) bounce under specific controlled motion sequences imparted by an automated motion system. We assess (e) accuracy performance over the entirety of body-worn data collects, with the user carrying out motions and behaviors representative of dismounted soldier operations. (f) We report metric results as shown.

The ultimate goal is to achieve a high level of performance against all metrics. This goal must be tempered by the fact that high performance against one metric often implies reduced performance against another. As is the case with other classic engineering tradeoff situations (e.g., stability vs. maneuverability, power vs. efficiency, sensitivity vs. specificity), our goal is to identify and achieve the combination of individual performance metrics that is optimal for our particular application. We also recognize that this optimal combination is somewhat subjective. For instance, some users are bothered by any amount of icon jitter in the see-through display and will accept increased response time in exchange for minimal jitter. Others are willing to accept increased icon jitter in exchange for minimal lag and response time. Our goal is to employ test methods that assess algorithm performance against these metrics so that we can expose the most important tunable parameters and use them to implement desired tradeoffs. The focus of this paper is on icon accuracy performance. Although we do not discuss jitter, wander, lag, or bounce metric performance in detail in the paper, we continuously test and track these measures as new algorithms are developed.

4.2 Testing and Data Collection Process

We evaluate jitter, wander, lag, and bounce metrics using an automated motion system (subsequently referred to as the AMS). The AMS is a field-portable computer-controlled platform that can impart azimuthal rotation and forward-

Regime	0	1	2	3
Magnetically Disturbed		●		●
High Dynamic Motion			●	●
% of Data Collect	56%	11%	30%	3%
Code Build - Algorithms	MEAN Computed Error (mrad)			
P3Build014-INSGPS	35	71	46	78
P3Build014-INSGPS-HM	5	6	20	8
P3Build014-INSGPS-LV	3	2	10	8

5. RESULTS

In this section, we present icon geo-registration accuracy results for three data collect sequences in mountainous terrain environments (Table 1). We evaluate icon accuracy performance for three algorithm implementations: INS-GPS only, INS-GPS-HM (which incorporates horizon matching vision-based inputs), and INS-GPS-LV (which incorporates landmark vision-based inputs). The data for all sequences was collected using our Phase 2 testbed system. We will soon be using the Phase 3 prototype system for data collection activities.

Table 1: Representative field data collects

Data Collect	Location	CONOPS	Focus of Analysis	Duration (min:sec)
RedRock-OW	Red Rock Canyon, NV	Overwatch	Horizon Matching	7:01
YPG-Nav	Yuma, AZ	Navigation	Horizon Matching	5:54
YPG-OW	Yuma, AZ	Overwatch	Horizon Matching, Landmark Vision	8:07

For each analysis, we evaluate icon accuracy by computing angular error between the rendered icon position and a distant ground truth feature. We choose ground truth features that are far away (e.g., mountain peaks >5km) so that we can isolate the algorithm's orientation estimate from user positional error. Positional error is dominated by GPS, and since our system relies on GPS for position, near icons will typically exhibit larger angular errors than far ones. In our Phase 3 system, we are implementing methods to minimize positional error by averaging GPS if the user is stationary for a period of time. The user will also have the option to display error rings around the icons, automatically sized to represent the combined position and orientation angular uncertainty.

5.1 Red Rock Canyon, NV: Overwatch Scenario

In data collect RedRock-OW, the user moves within a ten meter square area and performs moderate and rapid head turns, handles and keys his PRC-152 radio, and stands and kneels adjacent to a vehicle (Figure 8a). In Figure 8b, the helmet kit camera image shows a red dot overlaying the ground truth mountain peak. The system's projected icon location for this coordinate is indicated by the green circle, which has radius 10mrad. Figure 8c plots icon angular error for two algorithm implementations: INS-GPS and INS-GPS-HM. Below the icon angular error plot are two timeline graphics. The first timeline captures the behaviors performed by the user during the data collect. The second timeline breaks down the data collect into classified regimes (low user dynamics vs. high user dynamics and magnetically-undisturbed vs. magnetically-disturbed), determined by processing the raw accelerometer, angular rate, and magnetometer data. Regime 0 is the baseline regime defined as low-dynamic user motion and magnetically-undisturbed. Regime 1 is defined as low-dynamic user motion and magnetically-disturbed. Regime 2 is defined as high-dynamic user motion and magnetically-undisturbed. Regime 3 is defined as high-dynamic user motion and magnetically-disturbed. Shown in the table in the upper left quadrant of the icon angular error plot is the percent of time spent in each regime during the data collect. For data collect RedRock-OW, the breakdown is 60% Regime 0, 11% Regime 1, 23% Regime 2, and 5% Regime 3. Also reported in the table is the mean computed icon error for each regime across the different algorithm builds evaluated.

We achieve high icon accuracy over the entire collect for our INS-GPS-HM implementation in the low-dynamics regimes (0 and 1). These are the times when the user takes a moment to assess the environment, before or after head turns, and while not walking at high pace. Under rapid head turns (high-dynamics: regimes 3 and 4), there is larger icon angular error. Figure 9a focuses in on performance during the time period from t=220sec to t=255sec. At t=227sec, the user performs a rapid head turn and body rotation away from the distant mountainous terrain. The gap in data from t=227sec to t=239sec is a result of the icon and ground truth feature not being in the camera field of view. (Note, we plan to incorporate multiple ground truth features and icons that span the full 360° region around the user in upcoming analyses, but have not yet implemented this capability.) The user then turns back at t=239sec. During the head turn at t=227sec, the analysis shows two frames (time duration 100ms) for which the icon error is between 70-80mrad as the icon leaves the field of view of the camera. During the subsequent head turn back at t=239sec, the analysis shows that there are 12 frames (time duration 600ms) before the icon error drops to ~10mrad. This time duration is a result of the searching that the horizon matching algorithms must do achieve a match and is directly impacted by the filter's azimuth estimate (based on the INS-GPS solution) at the instant sufficient terrain geometry is available in the camera field of view. The INS-GPS algorithm exhibits nominal icon error of 20-30mrad during the collect. Following head and body rotations, the icon errors spike to large values, then slowly return to nominal error levels. We are currently working to optimize our INS-GPS filter settings, which will serve to also minimize horizon matching search time following head and body rotations.
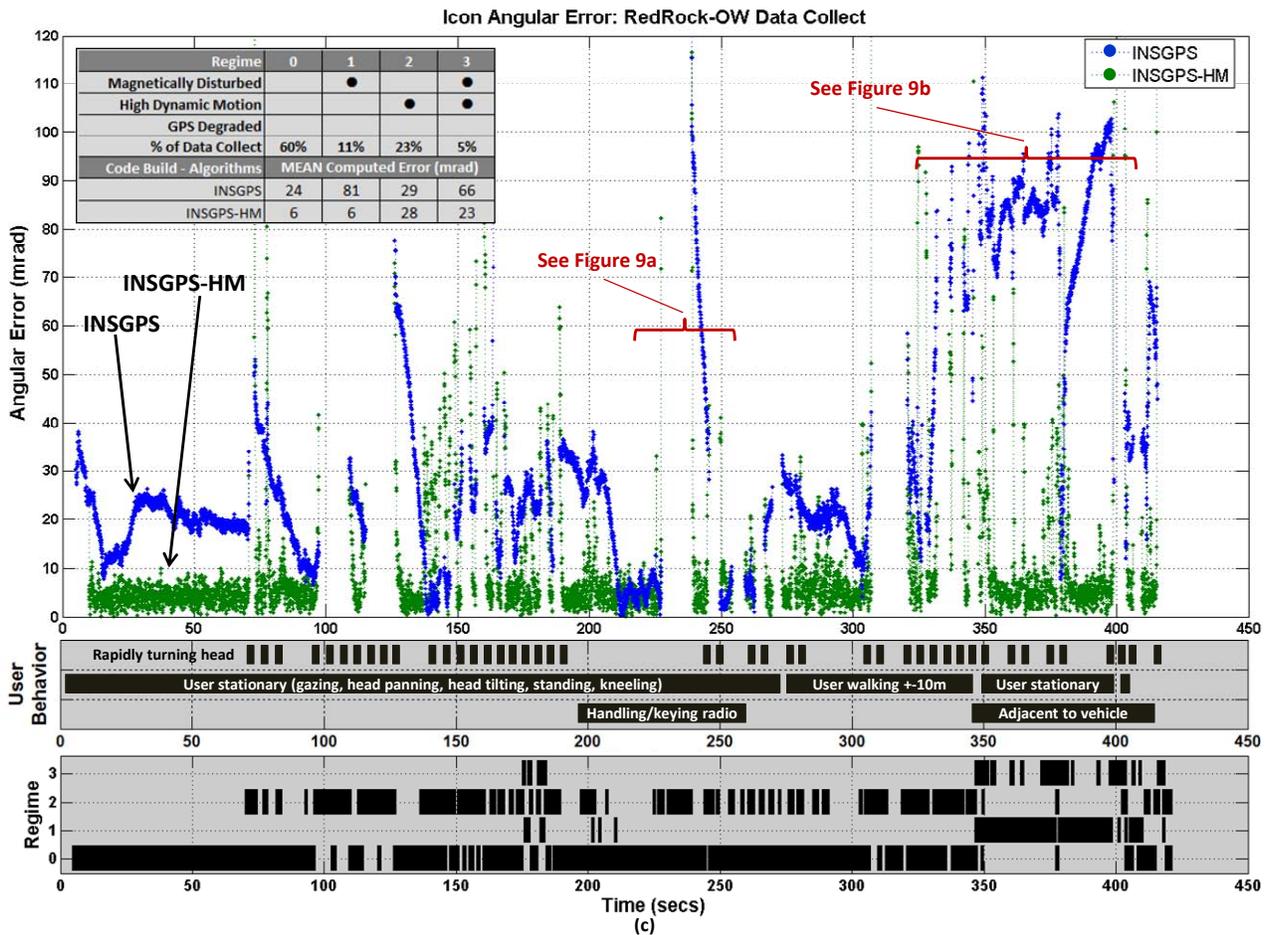
Figure 8. Data collect RedRock-OW using the testbed system: (a) snapshots capturing user behavior during sequence, (b) representative helmet kit camera image with ground truth coordinate (red dot) and rendered icon positions for INSGPS and INSGPS-HM algorithms, and (c) icon angular error plot and reported mean errors for dynamic and magnetic disturbance regimes.

Figure 9b focuses in on the performance during the time period from t=320secs to t=410secs, when the user approaches and assesses his environment in a kneeling position adjacent to the vehicle. During this time, the INS-GPS icon drifts significantly off the ground truth feature (due to its reliance on sensing the earth's magnetic field, which in this case is disturbed) while the INS-GPS-HM icon remains predominantly below 10mrad icon error. Sharp, very short duration spikes in icon error do occur during head turns, as observed throughout the collect. We believe that we will be able to minimize these high-dynamics errors with our current efforts to improve horizon matching algorithm efficiency.
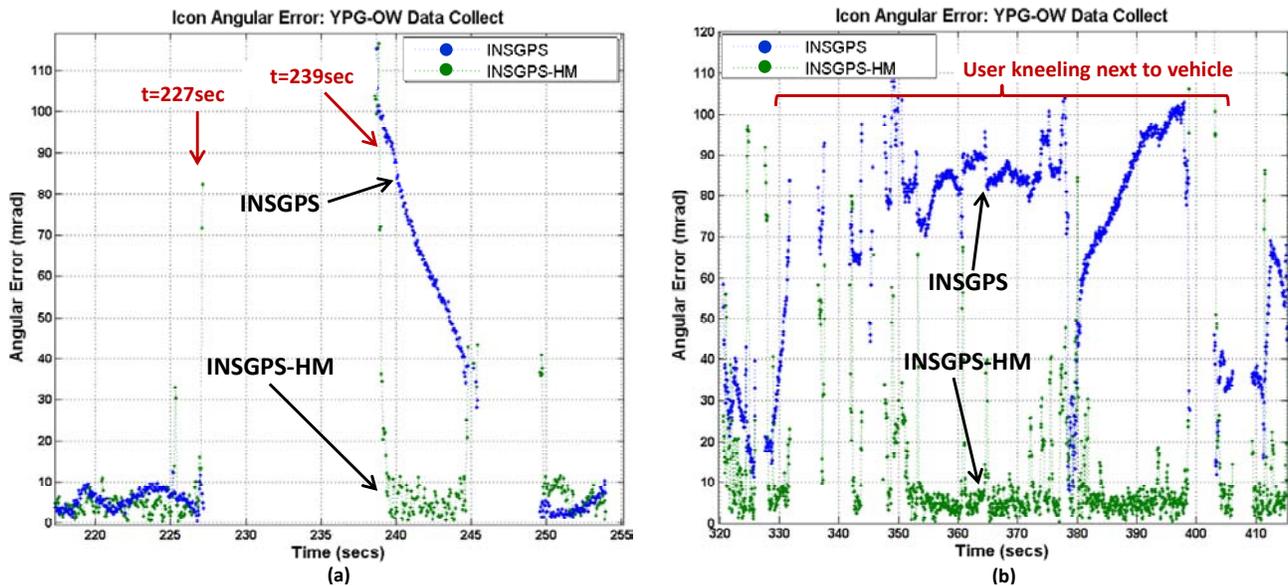
Figure 9. Close-up icon angular behavior for: (a) a head turn/body rotation away from a view of mountainous terrain and (b) user assessment of his environment when kneeling next to his vehicle. Our horizon matching algorithms provide azimuth inputs to the filter that maintain icon angular error below 10mrad for low user dynamics conditions.

5.2 YPG, AZ: Navigation Scenario

In data collect YPG-Nav, the user navigates briskly across 120m to an elevated position on a hill, then back down to the start point. During the sequence, he carries out dismount patrol motions, including rapid head turns and body rotations forward and aft while walking, and stops briefly at numerous points to assess his surroundings (Figure 10a). Figure 10d plots icon angular error over the collect for INS-GPS and INS-GPS-HM algorithm builds. Figure 10b shows the helmet kit camera image at a point in time when the user is walking up the hill. At this time (t=76sec, frame 1530), horizon matching provides an azimuth update to the system, resulting in highly accurate icon geo-registration. Figure 10c shows the subsequent sequence of seven frames (at 20fps). The significant fluctuating icon behavior (errors up to 26mrad) is a result of the high-dynamics encountered during walking. We are working to minimize the magnitude of these dynamic fluctuations by optimizing filter tuning and realizing higher frame rate horizon matching updates. In the low dynamics regimes, the presence of the horizon matching algorithms produces mean icon errors well below 10mrad.

5.3 YPG, AZ: Overwatch Scenario

In data collect YPG-OW, the user is positioned at an overlook point on the hill discussed in Section 5.2. The user spends a period of time assessing his surroundings by rapidly turning his head, gazing into the sky to identify aircraft, and communicating over his PRC-152 radio (Figure 11a). He moves 20m to take cover behind a vehicle (Figure 11b), then returns to his initial start point. Figure 11c plots icon angular error over the collect for INS-GPS, INS-GPS-HM, and INS-GPS-LV algorithm builds. Horizon matching performance is very good over the duration of the collect. The exception is during the short period of time between t=447secs and t=453secs when the user is looking through the windows of the vehicle. In this case, there was insufficient mountainous terrain in the camera field of view for horizon matching to provide an azimuth input to the filter. However, once the user altered his view to look over the vehicle hood, the icon snapped to high accuracy. We are currently working to improve horizon matching performance when only limited mountainous terrain is visible (while not increasing false alarms at other times).
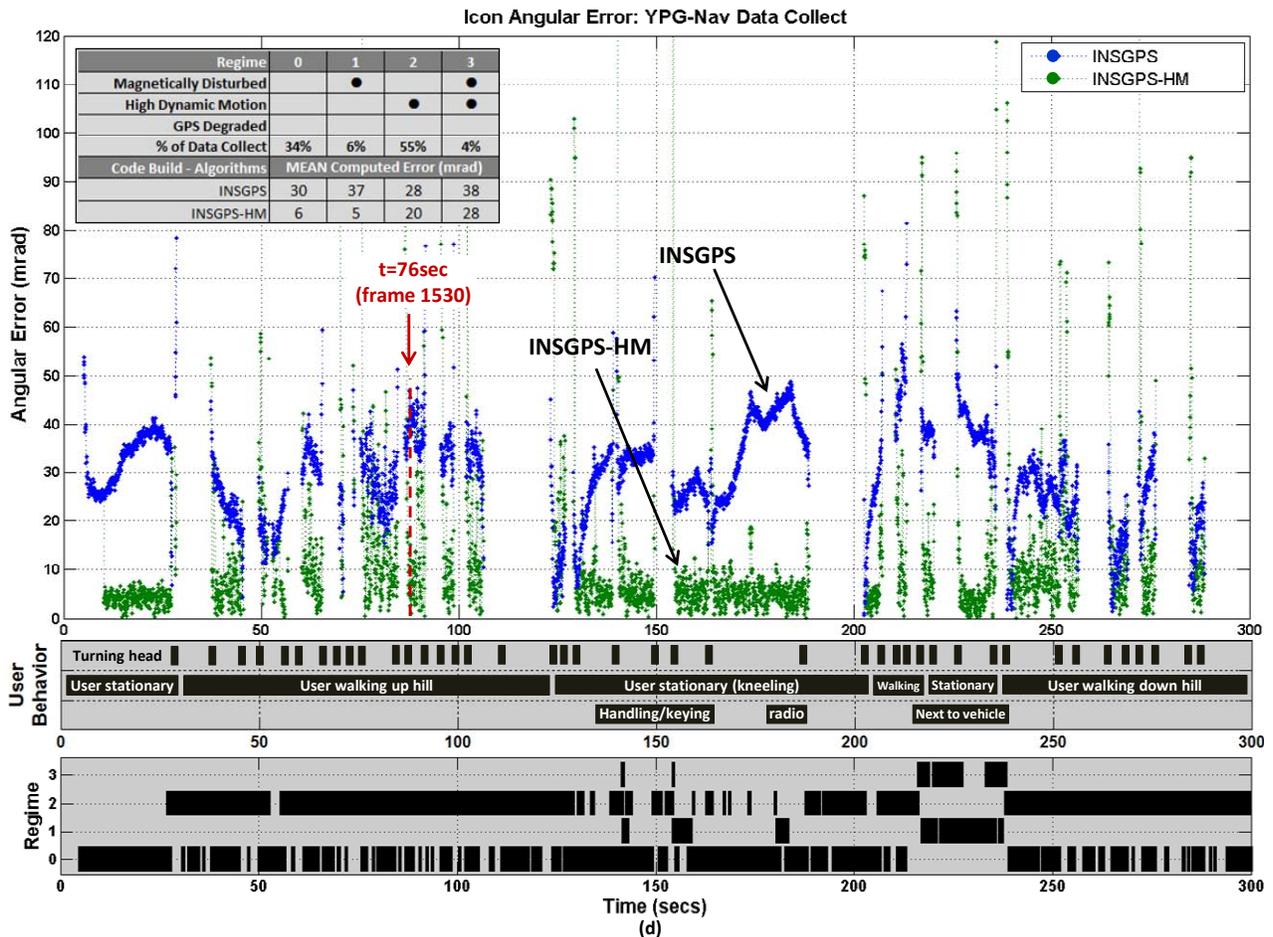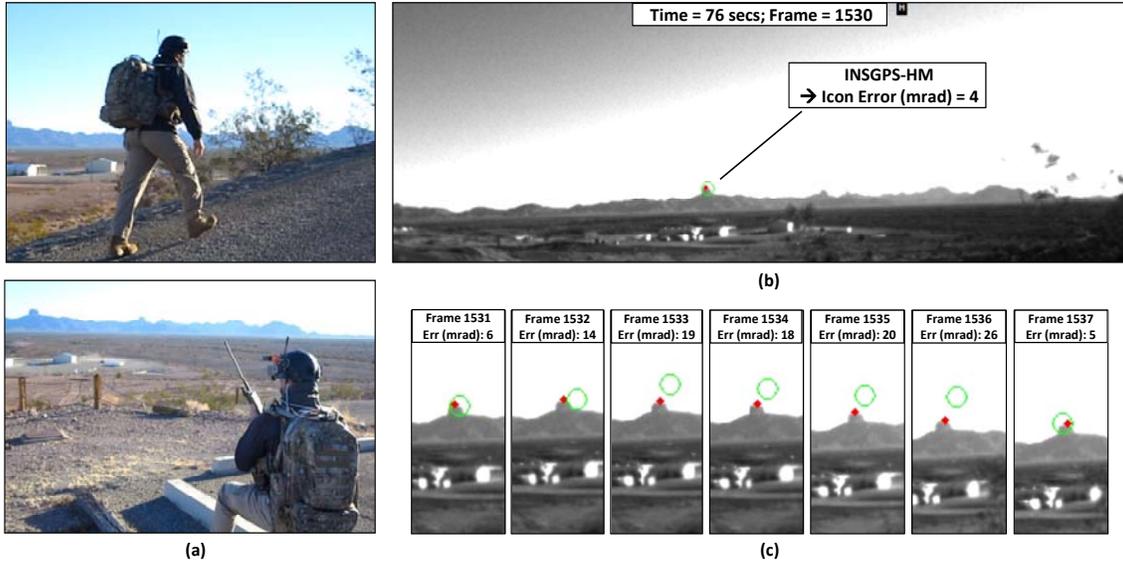
Figure 10. Data collect YPG-Nav using the testbed system: (a) snapshots capturing user behavior during sequence, (b) representative helmet kit camera image with ground truth coordinate (red dot) and rendered icon position for INSGPS-HM algorithms, (c) sequence of consecutive helmet kit camera images (at 20 fps) illustrating degree of icon fluctuation during user walking, and (d) icon angular error plot and reported mean errors for dynamic and magnetic disturbance regimes.
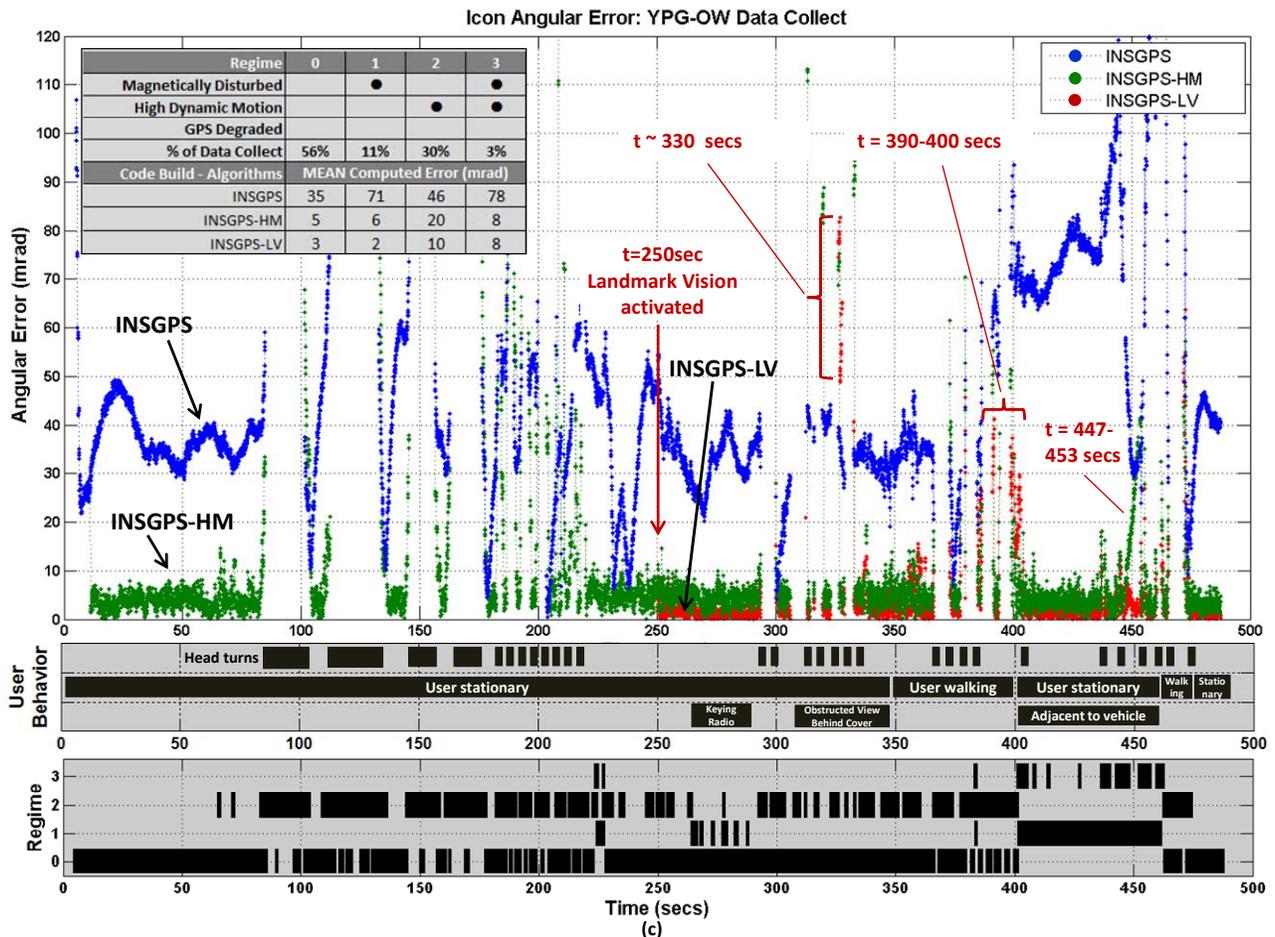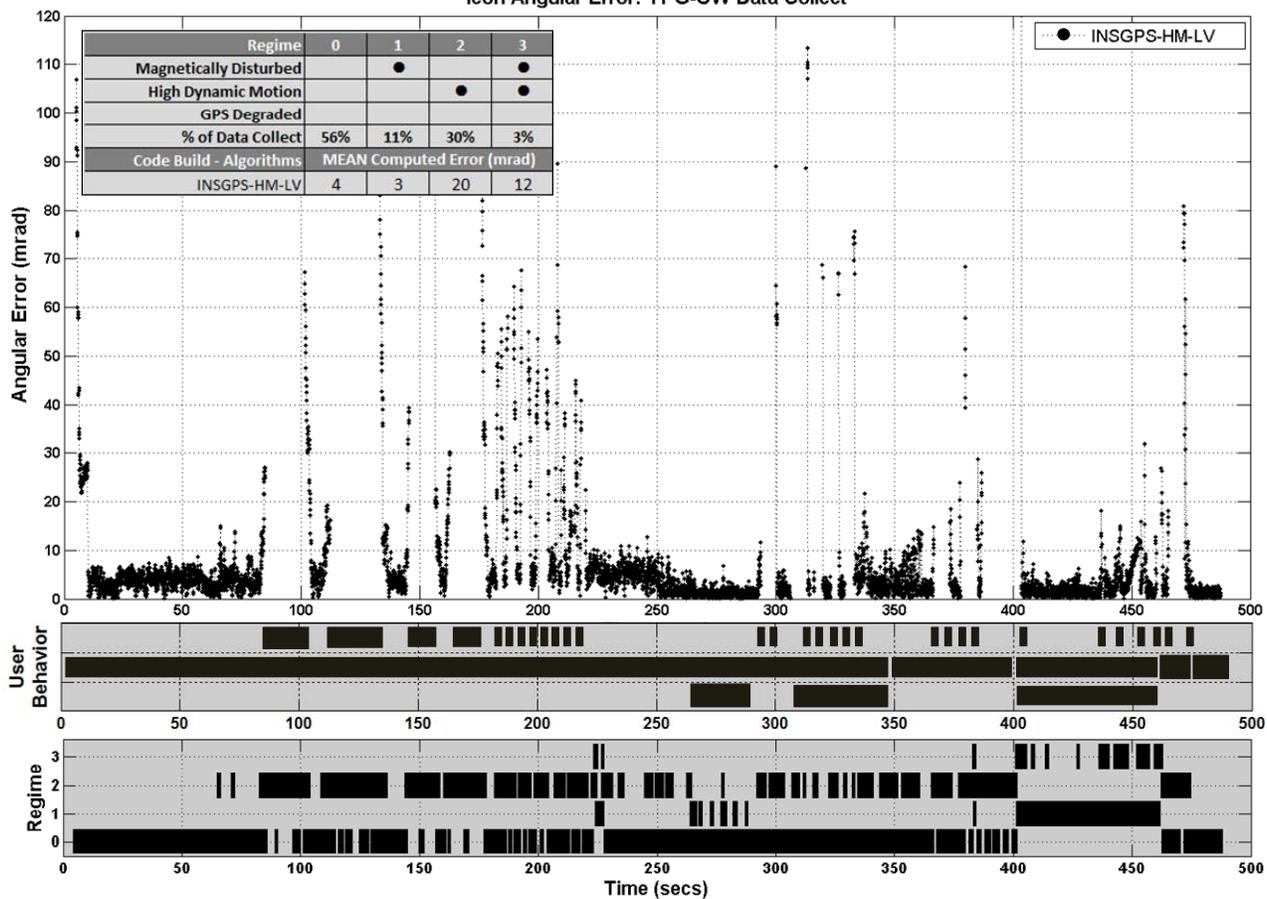
Figure 11. Data collect YPG-OW using the testbed system: (a) snapshots capturing user behavior during sequence, (b) representative helmet kit camera images for user adjacent to vehicle with ground truth coordinate (red dot) and rendered icon position for INSGPS-HM-LV algorithms, and (c) icon angular error plot and reported mean errors for dynamic and magnetic disturbance regimes.

Icon Angular Error: YPG-OW Data Collect

Regime	0	1	2	3
Magnetically Disturbed		●		●
High Dynamic Motion			●	●
GPS Degraded				
% of Data Collect	56%	11%	30%	3%
Code Build - Algorithms	MEAN Computed Error (mrad)			
INSGPS-HM-LV	4	3	20	12

based azimuth detection methodologies to achieve high geo-registration accuracy in the presence of external and body-worn magnetic disturbances. We have demonstrated icon geo-registration errors below 10mrad for testing in varied mountainous terrain and in view of distant landmark features. We continue to explore additional absolute azimuth detection methods (i.e., celestial sensing) as inputs to our framework. We believe that through the inclusion of new and unique opportunistic absolute azimuth detection methods, we will be able to expand the operational envelope for outdoor augmented reality wearable systems.

REFERENCES

[1] Roberts, D. et al, "Soldier-worn augmented reality system for tactical icon visualization," Proceedings of the SPIE, Volume 8383A (2012).

[2] Cameron, A., "The application of holographic optical waveguide technology to the Q-Sight^{TM} family of helmet-mounted displays," Proceedings of the SPIE, Volume 7326, 73260H (2009).

[3] Konstantopoulos, D. and Johnston, J., "Data Schemas for Net-Centric Situational Awareness," CCRTS (2006).

[4] Argenta, C., Murphy, A., Hinton, J., Cook, J., Sherrill, T., and Snarski, S. "Graphical user interface concepts for tactical augmented reality," Proceedings of the SPIE, Volume 7688, 76880I (2010).

[5] You, S., Neumann, U., and Azuma, R., "Hybrid inertial and vision tracking for augmented reality registration." Proceedings of the IEEE Virtual Reality, pp. 260-267. 1999.

[6] Azuma, R., et al. "Recent advances in augmented reality." Computer Graphics and Applications, IEEE 21, no. 6 (2001): pp. 34-47.

[7] Welch, G., and Foxlin, E., "Motion tracking: no silver bullet, but a respectable arsenal." Computer Graphics and Applications, IEEE 22, no. 6 (2002): pp. 24-38.

[8] Foxlin, E., and Naimark, L. "Vis-tracker: A wearable vision-inertial self-tracker." Proceedings of the IEEE Virtual Reality, p. 199. 2003.

[9] Foxlin, E., Altshuler, Y., Naimark, L., and Harrington, M., "FlightTracker: a novel optical/inertial tracker for cockpit enhanced vision." 3rd Int. Symp. on Mixed and Augmented Reality (ISMAR 2004), p.212-221. 2004.

ACKNOWLEDGEMENTS