Final Report for CCAT Program 1401

For

Personal Dead-Reckoning System

by

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Under UM Project/Grant # F024611

Last Revised: September 28th, 2010

This report focuses exclusively on the demo and testing of the PDR system by the Firefighters of the San Diego Fire Department, the San Miguel Fire Division, and CAL FIRE on September 21-23, 2010.

1 OVERVIEW

Testing of the University of Michigan's (UM's) Personal Dead-reckoning (PDR) system, shown in Figure 1, took place over the course of three days:

Day 1: Tuesday, September 21st, 2010

Testing performed by: San Diego Fire Department.

Location: Vantage Pointe high rise, on 1281 Ninth Ave, in downtown San Diego, California .

Day 2: Wednesday, September 22nd, 2010

Testing performed by: San Miguel Fire District.

Location: La Vida Real retirement complex, 11588 Via Rancho San Diego, El Cajon, California.

Day 3: Thursday, September 23rd, 2010

Testing performed by: CAL FIRE.

Location: Stone Wall Peak trail, Julian, California.

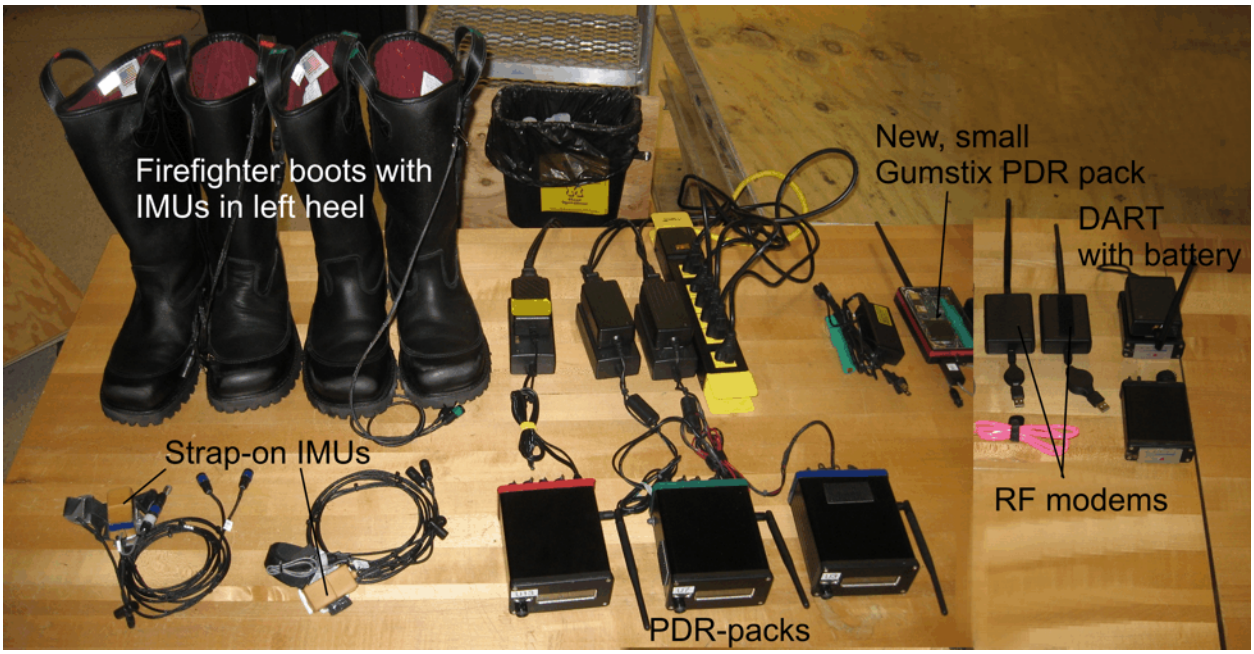


Figure 1: Equipment as tested in San Diego September 21-23, 2010. Each of the PDR packs houses a PC-104 computers, batteries, RF data modems, and support electronics. The much smaller, new Gumstix PDR pack replaces the PC-104 with a Gumstix microcontroller. The small pack was shown at the demo, but not used during testing. The Differential Altimeter Reference Transmitter (DART) was used at the demo to broadcast differential barometric data (thereby correcting the effect of local weather changes on the PDR-packs' altimeter) and it served as a radio repeater. Not shown in this photo are the Altama Desert Boots with in-heel IMUs, which were used by two firefighters during testing by CAL FIRE.

Three PDR systems were available for testing. Because of the colors used for plotting their trajectories on our Operator Console Units (OCUs) we refer to them as the "Red," "Green," and "Blue" system. The Red and Green system had IMUs embedded in the heels of firefighter boots on Day 1 and Day 2. For testing on Day 3 we moved these same IMUs to military-type hiking boots called Altama Desert boots. The Blue system uses a strap-on IMU that was meant as back up, either to replace a defective system or to allow mounting on a subject who cannot wear either of the two boot sizes that we had instrumented.

Figure 2: These Altama Desert Boots were used in outdoor testing on Day 3.

Two PDR systems were used in the tests of Day 1, the Red and the Green system. After the end of testing on Day 1, we found that a mechanical defect had developed in the Green system: the Peltier Effect device (a thin strip of material that must be in physical contact with the IMU to move heat to or from the IMU) used to stabilize the temperature of the IMU had physically separated from the IMU. This defect is not fatal, but it causes erratic behavior that makes it impossible to judge system performance. For this reason we include in the results section for Day 1 only those green trajectories that we believe to have been generated before the defect developed.

Ironically and luckily, in the outdoor tests on Day 3, where the magnetometer was used, we had to intentionally disable temperature stabilization for all PDR systems because switching the Peltier effect device on and off affects the magnetometer. For that reason, the Green PDR system was usable again in the outdoor tests of Day 3.

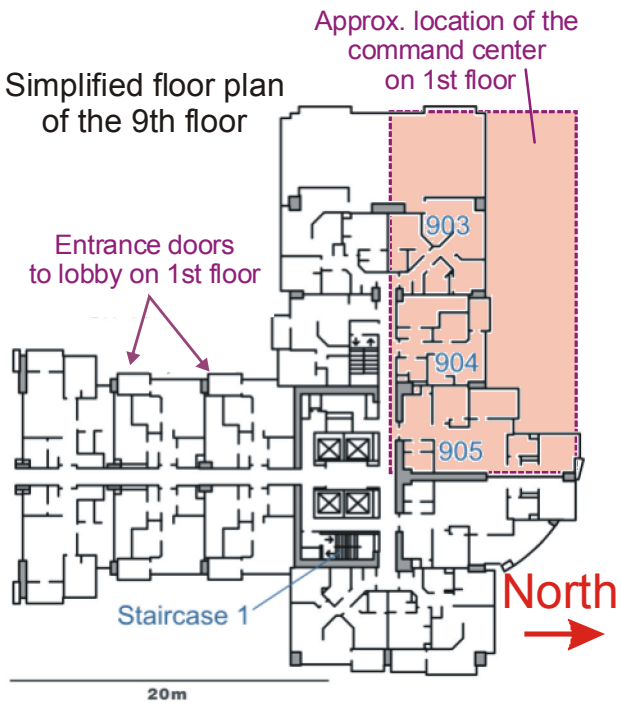
2 TEST RESULTS

2.1 Day 1: Vantage Pointe High Rise

Tests on Day 1 took place in a ~3-year old high rise building, called Vantage Pointe, in downtown San Diego. In these tests the command center was located in an unfinished, store-sized area on the 1st floor (see Figure 3). The firefighting missions were took place in Suites 903-906 on the 9th floor.

The mission scenario called for firefighters to start their mission in or outside of the command center. Firefighters would start their mission by walking down a short section of the steeply inclined Ninth Street to the building lobby. From there, they would take the elevator to the 4th floor, and then Staircase 1 up to the 9th floor. Firefighters would then perform various tasks that involved a fair amount of crawling, mostly in Suites 903-906.

(a)



(b)

Figure 3: Test site.

(a) Photo of the Vantage Pointe high rise in downtown San Diego. The command center was located on the first floor. The marked windows of Suites 905, 904, and 903 are on the north face of the building.

(b) Floor plan of the 9th floor. The approximate relative location and size of the command center on the 1st floor are shown for reference.

2.1.1 Preparations, before entrance to Vantage Pointe was granted

We knew that there was significant spatial separation between the command center on the 1st floor, the mission sites on the 9th floor, and the staircase. We knew and cautioned well before the test that our commercial, off-the-shelf radio modules would not be able to bridge these distances. The staircase presented a particularly difficult scenario because it was surrounded by thick structural concrete walls that substantially attenuated RF signals. We were able to overcome some of the problems by placing an RF responder at a rare strategically advantageous location: The balcony of one of our hotel rooms in the Days Inn on 833 Ash Street. This balcony was less than one city block away from Vantage Pointe and it offered direct line of sight to the command center and to the 9th floor. The repeater used a directional antenna oriented toward the high rise. Indeed, the photo of Figure 3a was taken with a camera held immediately next to, and aligned with, the repeater's antenna, to show the antenna's "view." We also fed the signal from our Differential Altimeter Reference Transmitter (DART) to this directional antenna, and it provided reference elevation data to the command center, the 9th floor and, less robustly, to the staircase. These preparations were done prior to the formal setup that started at 8:30 a.m. As it turned out, the data from the DART was received by all PDR packs at all times, but transmissions from the PDR packs (which use omnidirectional antennas) did not reliably reach the repeater, thus causing the observed RF problems.

2.1.2 Setup

After being admitted into the command center at 8:30 a.m., it took us two hours to set our system up. This unacceptably long setup time can be broken down into several partially avoidable components:

1. 30 minutes normal setup time – unpacking equipment, starting and setting up charging for multiple laptops and PDR systems, outfitting firefighters with boots, system check.
2. 60 minutes RF repeater emplacements and RF testing. We spent a large amount of time trying to work around the range limitations of our RF modules. To do so, we experimented with different locations for additional RF repeaters in the stairwell and on the 9th floor. These experiments were time consuming but could not have been done beforehand because they required access to the building, which was granted only after 8:30 a.m. We also placed a special repeater on the 9th floor that was capable of transmitting data from firefighters via the Internet (using mobile broadband modems). This system is fragile and disconnected several times during the test, but did provide useful data during the last two hours of testing in the afternoon.
3. 30 minutes pinpointing starting point and scale for OCU display. It took us longer than usual to identify a starting point inside the command center and its corresponding X,Y location on the floorplan of the 9th floor. This was due in part to the lack of a floorplan for the command center and an error on our part in pre-calculation the scale factor. The latter caused confusion and prompted several short test walks before we corrected our initial scale factor error. Under normal conditions and without operator errors, it takes about five minutes to preset a scale factor from floorplans or satellite images, and to fine-tune that scale factor on location. Indeed, fine tuning the scale factor can be done while firefighters are already performing their mission.

At the end, we could not establish reliable RF communication and gave up on that. Instead, all subsequent tests were conducted with the incident commander and observers walking in reasonable proximity to the firefighters and carrying laptops with OCUs.

2.1.3 Test results

2.1.3.1 Motion Modes

The first test was aimed at assessing the system's capability to capture typical firefighter modes of motion, other than plain walking. Among the modes were extensive crawling (forward and backward) and others. The test took place in the command center, for which no floorplan was available. Figure 4 shows the resulting trajectories from both the red and the green pack overlaid on a generic metric grid. To minimize clutter, we separated the trajectories in this plot. Ground truth was unavailable but we asked the firefighters to move generally along the perimeter so that the proximity of repeated traverses along the same wall would give some indication of accuracy.

We caution not to interpret the red end position in Figure 4, which differs significantly from the start position, as the return position error. This is because we don't believe that the red firefighter actually stopped tracking while physically standing at the starting position. This assessment is based on the plot, which shows that the firefighter stopped while tracking along the left hand side of the room (likely at the command post table), not at the designated starting point.

Based on our casual observation we believe that both PDR systems performed very well with all tested modes of motion. From the plots we estimate that position errors never exceeded 3-4 meters.

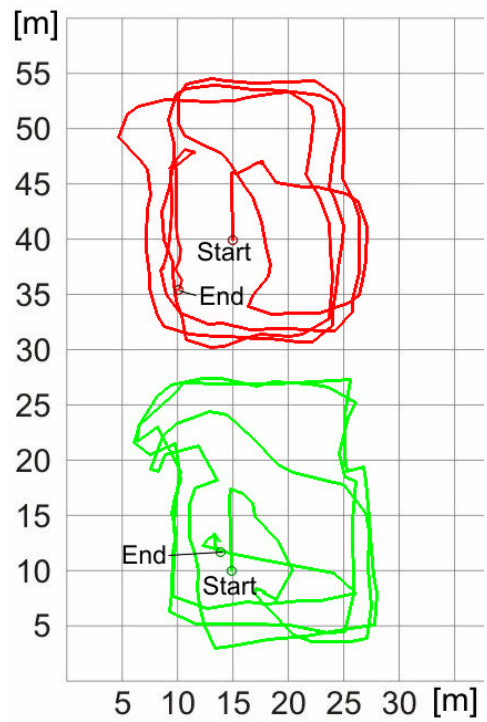


Figure 4: Results of the motion modes test, plotted on a generic 5-meter grid background. To reduce clutter, we separated the red (upper plot) and green (lower plot) trajectories, whereas in reality they overlaid each other.

2.1.3.2 Complex Mission

In the complex mission scenario both the red and green firefighters generally walked together and performed all of the following activities:

1. started in the command center, initialized PDR systems;
2. exited the command center onto Ninth Street, walked to the lobby;
3. rode the elevator up to the 2nd floor;
4. loitered around the corner from the elevator (loitering includes standing around without doing any particular task, walking a few steps here and there, etc.) for several minutes;
5. climbed up the stairs for seven floors to the 9th floor;
6. entered Suite 906, started crawling;
7. while crawling: performed a search or other firefighting tasks;

8. while crawling: exited Suite 906 and entered Suite 905;
9. while crawling: performed a search or other firefighting tasks;
10. exited Suite 905, started walking, walked to stairs;
11. descended stairs. Red firefighter ran down the stairs, for several floors;
12. returned to the command center.

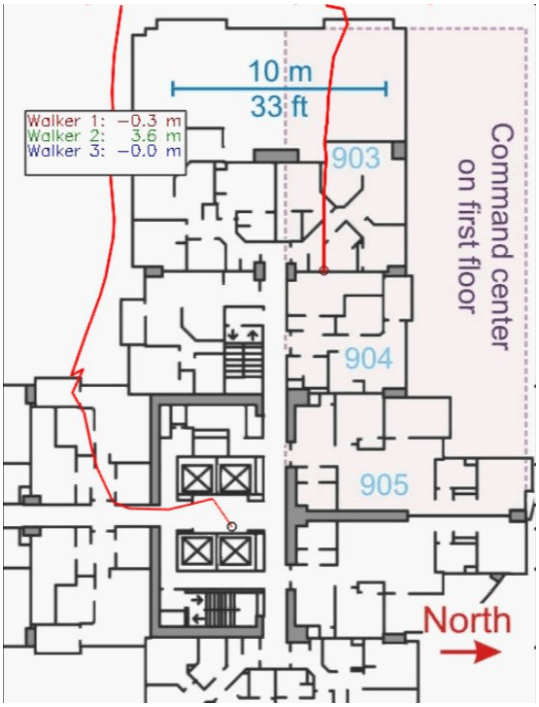
A mechanical problem (temperature control unit detaching from IMU, described in Section 1) caused erratic errors in the green PDR system. During this test we tried twice to correct the sudden, large position errors of the green system manually, but then gave up on that and declared the green system inoperative. Consequently, the snapshots of Figure 5 shows only the red trajectory at several key moments during the test. We removed the trajectory from the defective green PDR unit from these plots to minimize clutter.

Elevation Analysis

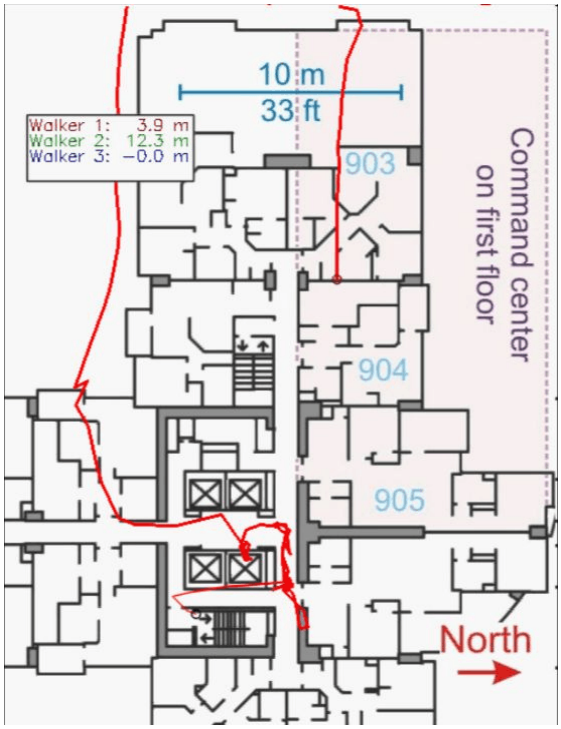
The complex scenario lends itself well to analyzing the accuracy of elevation estimation using the PDR systems' barometric altimeter sensors. We recall that prior to testing we had deployed our differential altimeter reference transmitter (DART) on a balcony of the Days Inn hotel opposite the north side of Vantage Pointe. Table I shows the PDR-measured elevations (displayed in a small window on all plots) and compares them to the actual elevation.

Table I: PDR-estimated elevations during the complex mission scenario, Red PDR system only.

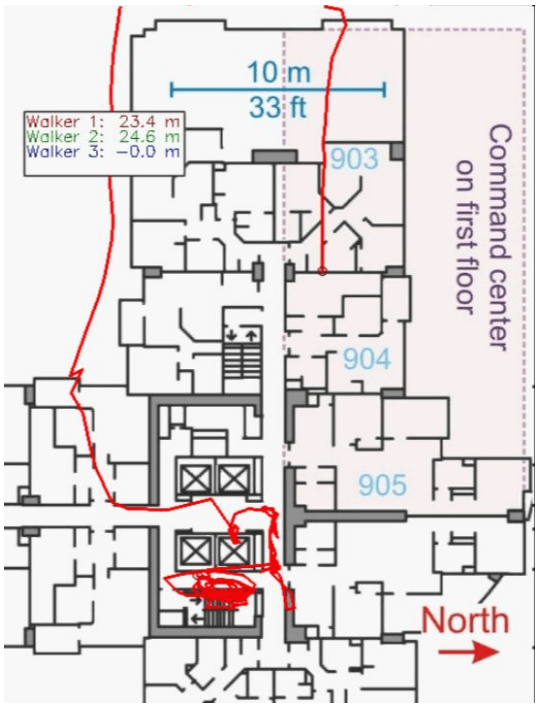
Stage	PDR-measured Elevation	Estimated true elevation	Elevation error
Figure 5a	-0.3 m	-1.2 m	0.9 m
Figure 5b	3.9 m	1.9 m	2.0 m
Figure 5c	23.4 m	22.4 m	1.0 m
Figure 5d	23.8 m	22.4 m	1.4 m
Figure 5e	24.3 m	22.4 m	1.9 m
Figure 5f	-0.3 m	-1.2 m	0.9 m



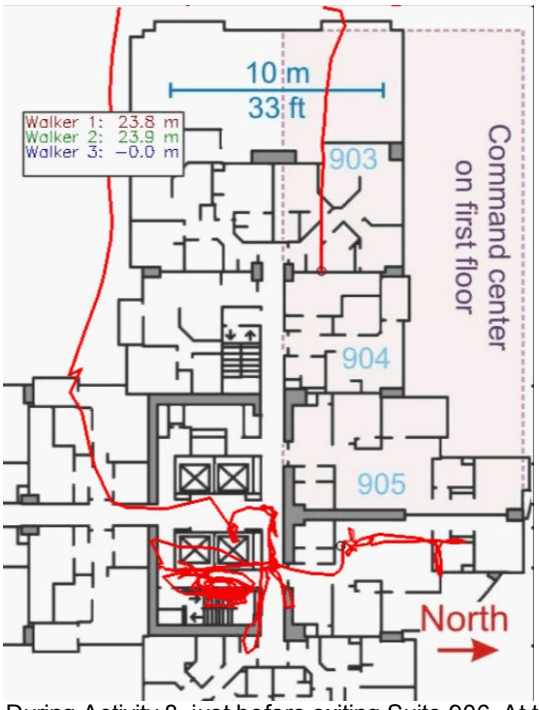
(a) Waiting for elevator in lobby, after Activity 2.



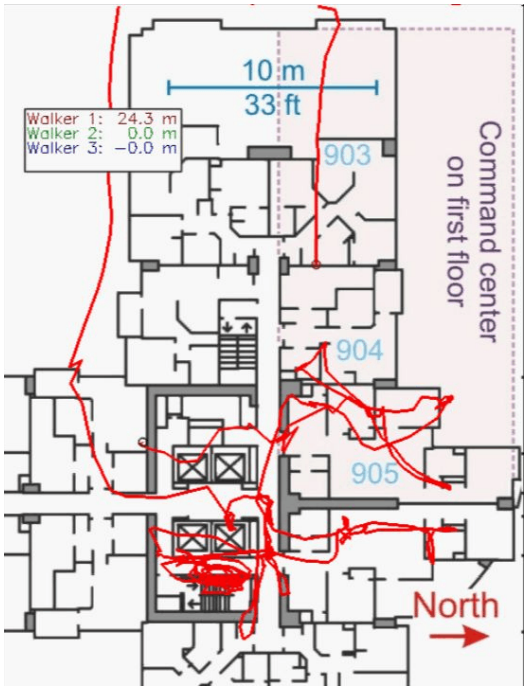
(b) On 2nd floor, after Activity 4.
(Green firefighter is already advancing on the staircase).



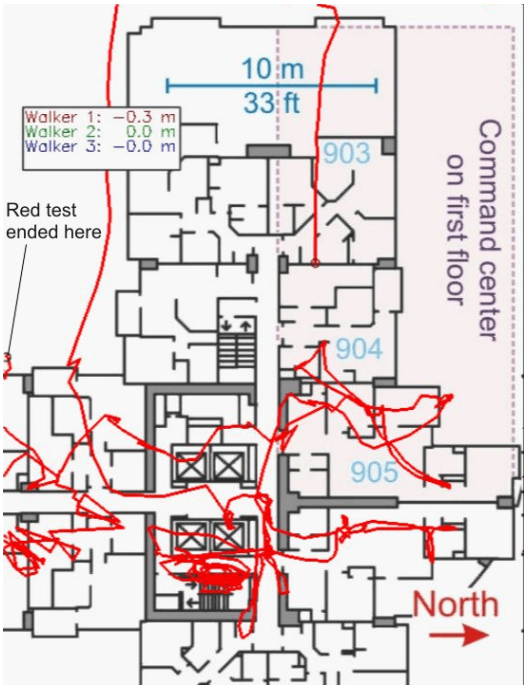
(c) After Activity 5, now on the 9th floor.



(d) During Activity 8, just before exiting Suite 906. At the present location (indicated by the small, dark red circle), our crawling algorithm miscalculated a complex crawling maneuver and introduced a heading error of about 18°.



(e). At the end of Activity 10. Additional heading errors accrued during complex crawling in Suite 905. Present location (small dark red circle) should be between elevators and Staircase 1 at this time.



(f) A different error developed during Activity 11: Fast running down the stairs resulted in impact that exceeded the dynamic range of the accelerometers and caused position errors of 3+ meters per floor, while running.

Figure 5: Snapshots of the Incident Commander's screen during the complex mission scenario. We removed the Green trajectory because the Green system had a mechanical defect.

2.1.3.3 Rescue Scenario

The rescue scenario calls for a first firefighter to perform a task, get into trouble, and call for help. A rescue team is then dispatched to find the downed firefighter. The incident commander sees both the downed firefighter's recorded trajectory and the rescuer's trajectory on the OCU and uses this information to guide him to the victim.

Similar to the complex mission, the first (red) firefighter walked through the lobby, took the elevator up to the 2nd floor, and walked up the staircase to the 9th floor (see Figure 6a). There he entered Suite 906 and performed firefighting tasks prior to becoming incapacitated in the far end of Suite 906. He radioed for help and the (blue) rescuer was dispatched, as shown in Figure 6b).

In this particular walk an error of 2-3 meters (to the left and down) became evident during the rescuer's ascent on the switchback staircase. With the approval of the Incident Commander, we performed a simple manual correction (indeed, just a mouse click on the OCU). This moved the blue starting point 2-3 meters to the right and up. This resulted in a shift of all parts of the blue trajectory 2-3 meters to the right and up, thereby aligning the clearly identifiable staircase ascent with the staircase, as seen in Figure 6b. The rescuer proceeded directly to the far end of Suite 906 and found the downed firefighter immediately. The duration of the rescue walk was 10.8 minutes.

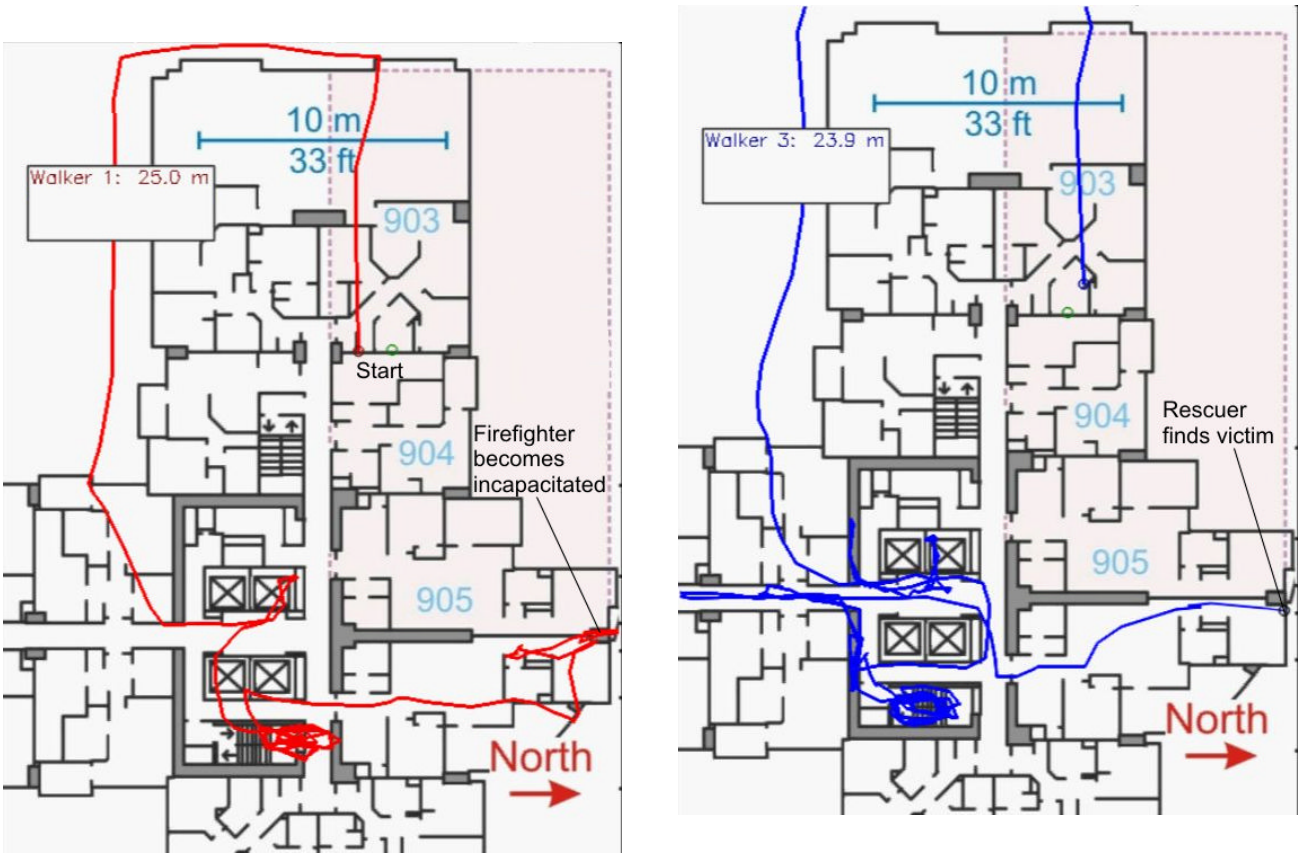
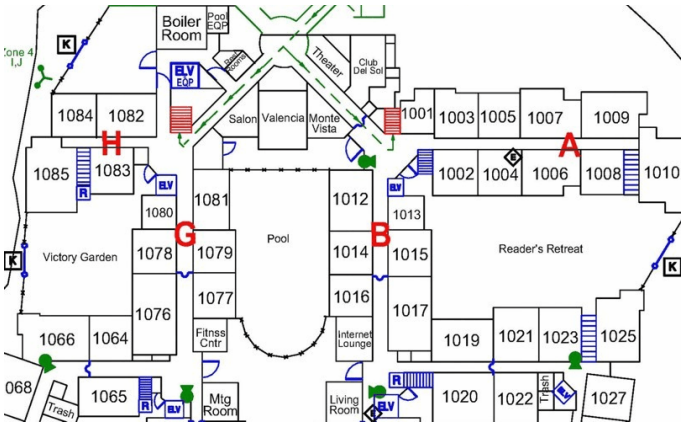


Figure 6: Rescue scenario. We plotted the red trajectory of the eventually downed firefighter and the blue trajectory of the rescuer separately, to minimize clutter. (a) The red firefighter performs a mission on the 9th floor. He becomes incapacitated in the far end of Suite 906 and radios for help. (b) Observing the OCU's display of the red and blue (rescuer's) trajectory, the Incident Commander gives voice directions to the rescuer and guides him toward the downed firefighter.

2.2 Day 2: La Vida Real Retirement Complex

The test site on Day 2 was a large retirement community, La Vida Real in El Cajon, CA, located immediately west of San Diego. The test was conducted by firefighters of the San Miguel Fire District. Figure 7a shows a satellite photo of the entire La Vida Real Complex. All of the testing was confined to the area inside the white rectangular boundaries. Figure 7b shows a floor plan of that exact same area. The complex has three floors, but the layout of the main corridors is almost exactly the same on all floors, and so is the layout of the staircases.

(a)



(b)

Figure 7: Test site: La Vida Real Retirement Community, 11588 Via Rancho San Diego, El Cajon, California.

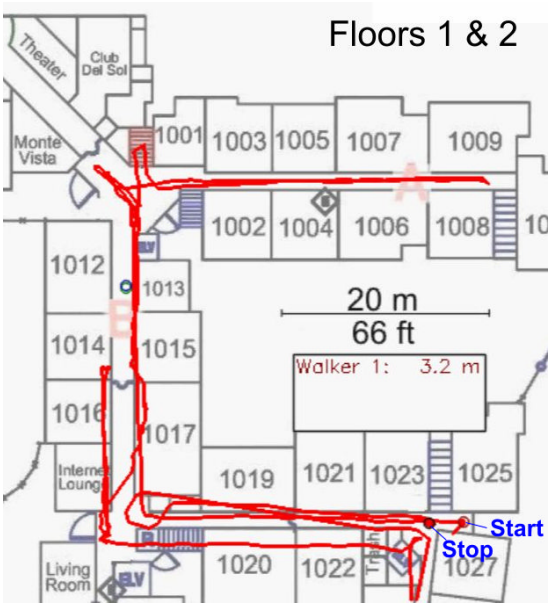
(a) Satellite photo of the entire complex.

(b) Generic floor plan of the area marked by the white rectangle in (a). All testing took place in that area. The layout of all corridors on all three floors is essentially the same.

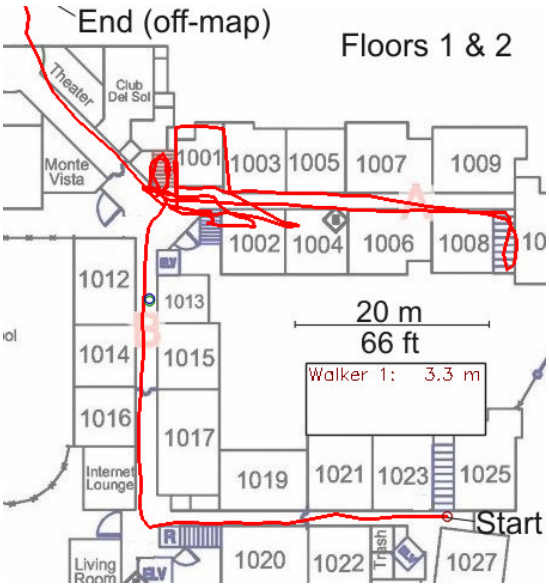
2.2.1.1 *Motion Modes*

We conducted two separate tests that were aimed at assessing the system's capability to capture typical firefighter modes of motion, other than plain walking. In the first test there was extensive crawling (forward and backward), maneuvering around furniture, walking up and down stairs, as well as jogging. Figure 8a shows the resulting trajectory from the red PDR system. The largest position error at any time during the test was about 3 meters. The squiggly part of the trajectory, near Suite 1017, was the result of backward crawling.

The second motion modes test, shown in Figure 8b, included walking up and down stairs, extensive crawling, and *belly crawling*. The system worked very well with crawling on hands and knees. It worked only marginally well with belly crawling, incurring a 30-degree heading error but estimating the distance traveled while belly crawling correctly. The 30-degree heading error (partially overlapping Suite 1002) was corrected by the system itself during subsequent walking. The test ended on the second floor (but off-map) and the PDR system's elevation estimation of 3.3 meters was correct. The largest position error was about 3 meters, immediately after the belly crawl.



(a)



(b)

Figure 8: Results of the motion modes tests.
(a) The first motion modes test included forward and backward crawling.
(b) The second motion modes test included walking up and down stairs, extensive crawling, and even belly crawling. The test ended off-map.

2.2.1.2 *Complex Mission*

The complex mission scenario, shown in Figure 9, started with the initialization at the staircase near Suite 1025. Then the firefighter walked outside to the parked fire truck to take off some gear and walked back into the building and up to the second floor on the staircase by Suite 1001. On the second floor he performed various typical firefighter tasks, presumably while crawling. He then walked back down to the first floor and proceeded into the theater. In the theater he recovered a victim and dragged the victim out into the hallway. The firefighter then returned to the theater and ended the mission. The walk took 15 minutes. The largest position error during this mission was about 3.5 meters.

2.2.1.3 *Rescue Scenario*

The rescue scenario calls for a first firefighter to perform a task, get into some trouble, and call for help. A rescue team is then dispatched to find the down firefighter. The incident commander sees

both the victim's recorded trajectory and the rescuers' trajectory on the OCU and uses this information to guide the rescuers to the victim.

Figure 10a shows the trajectory of the eventually downed firefighter. The walk was about 185 m long, took about 7 minutes, and it included some crawling. The largest position error was about 3.2 m, near the entrance to the theater.

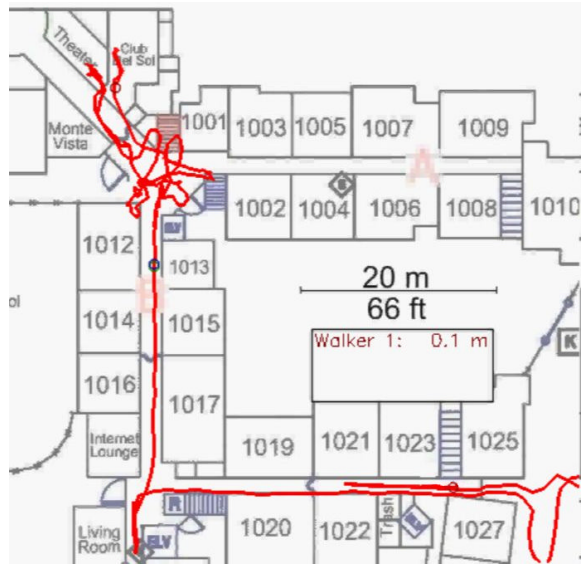
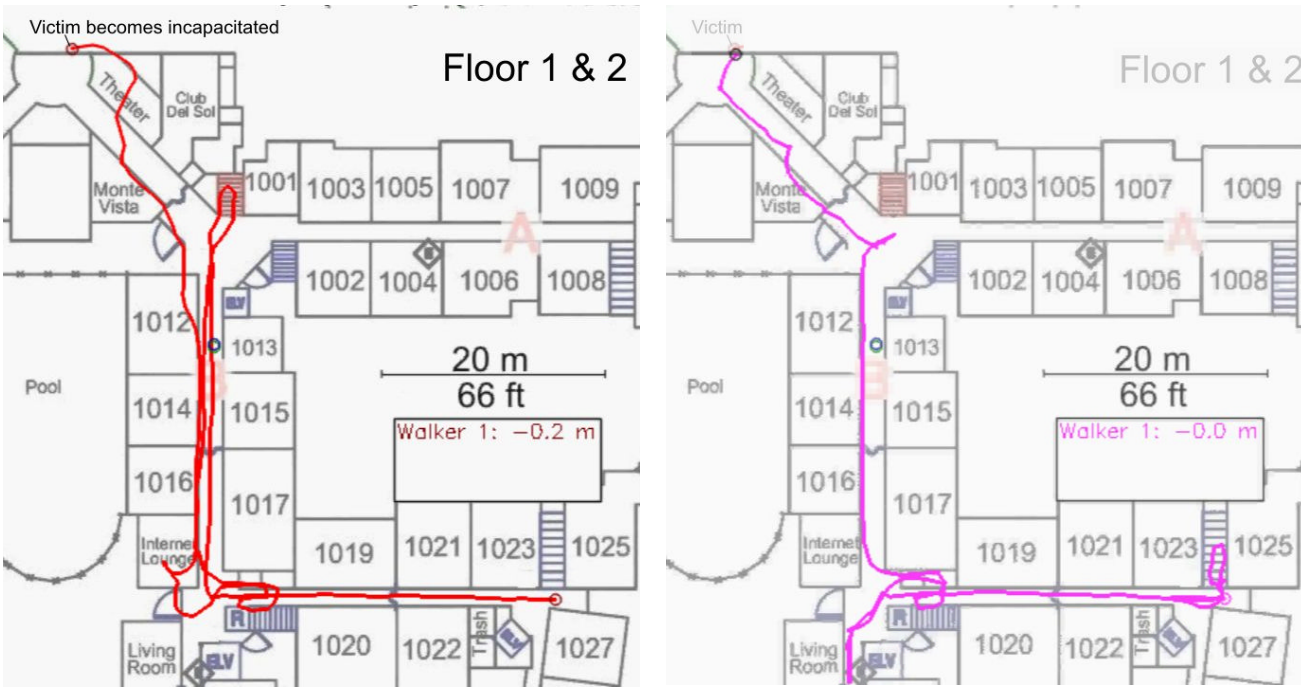


Figure 9: Trajectory at the end of the complex mission.

In our test we had to make a creative modification to this scenario because the green PDR system had technical problems and we prefered not using the blue PDR unit. Instead, it was agreed to have the victim himself turn into the rescuer after simulating becoming incapacitated. To that end, the victim returned to the starting position and then acted as the rescuer, receiving instructions from the Incident Commander. The rescuer's trajectory is shown in Figure 10b. Near the theater, the rescuer was instructed to crawl. He was then directed into the theater and got close enough the location of the victim to declare this test a successful rescue mission. The rescue walk was about 120 m long and took 8.3 minutes. The largest position error was about 3.5 m.



(a) **(b)**

Figure 10: Rescue scenario. (a) Victim's trajectory. Victim becomes incapacitated in the theater. Note that the floorplan is incorrect, we found in an earlier visit at the site that the theater is actually larger than shown. (b) Rescuer's trajectory. Rescuer walked up to the open space between Suits 1001 and 1012 and then crawled for the remainder of the exercise. Despite position errors of about 3 meters, rescuer found the victim (i.e., reached the spot where victim had become incapacitated) right away.

Day 3: Stone Wall Peak Trail

Tests on Day 3 were conducted outdoors, with the help of firefighters from CAL FIRE. The test area was Stone Wall Peak, a mountainous hiking trail about 3.2 km (2.0 miles) long. For this test the PDR system was set to its newly developed outdoor mode that uses magnetometers and IMU. We had intended to have GPS available, as well, but we had trouble with the brand new GPS code, which we had tested for the very first time only two days before leaving for San Diego. Nonetheless, it was agreed that a test of the IMU and magnetometer integration, without any use of GPS, would be of interest. This is because GPS itself is no novelty, whereas firefighter tracking in GPS-denied environments with magnetometer and IMU only is, at least in the firefighter community.

The nominal path, recorded by CAL FIRE firefighters a few weeks ahead of the test (with a handheld GPS unit), is shown as the yellow line overlaid over the Google Earth satellite image of Figure 11. In the actual test we used this Google Earth satellite image as the OCU background for

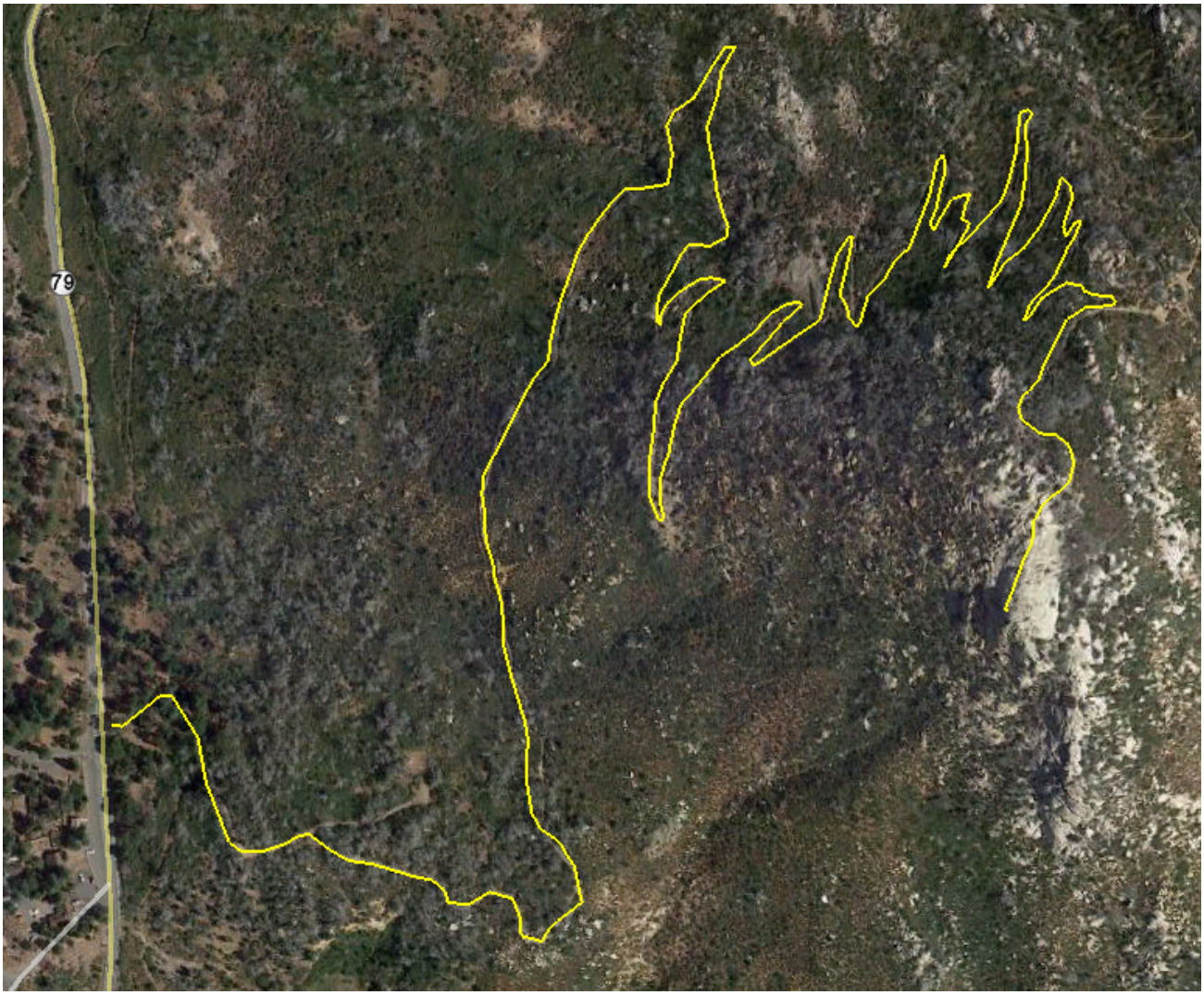


Figure 11: The Stone Wall Peak trail near Julian, California, was the test environment for the outdoor test on Day 3.

plotting the trajectories of the two firefighters (who were using the red and green PDR units). One member of our team also walked the whole trail with our third PDR unit that uses the strap-on IMU and produces blue trajectories.

We found out only at the time of writing this report that all Google Earth satellite images of rolling or mountainous terrain have distortions, due to the perspective of the camera. These distortions make Google Earth images unsuitable as background images for 2-D plots of anything but flat terrain. Distortions become obvious when enabling the View > Grid feature in Google Earth, as shown in Figure 12. Consequently, when our system plotted the firefighters' trajectories over the distorted background picture in real-time, errors appeared larger than what they were in reality.

In contrast to Google *Earth*, Google *Maps* is a 2-D application and satellite images available in 111Google Maps are already corrected for perspective distortions. We realize now that we should

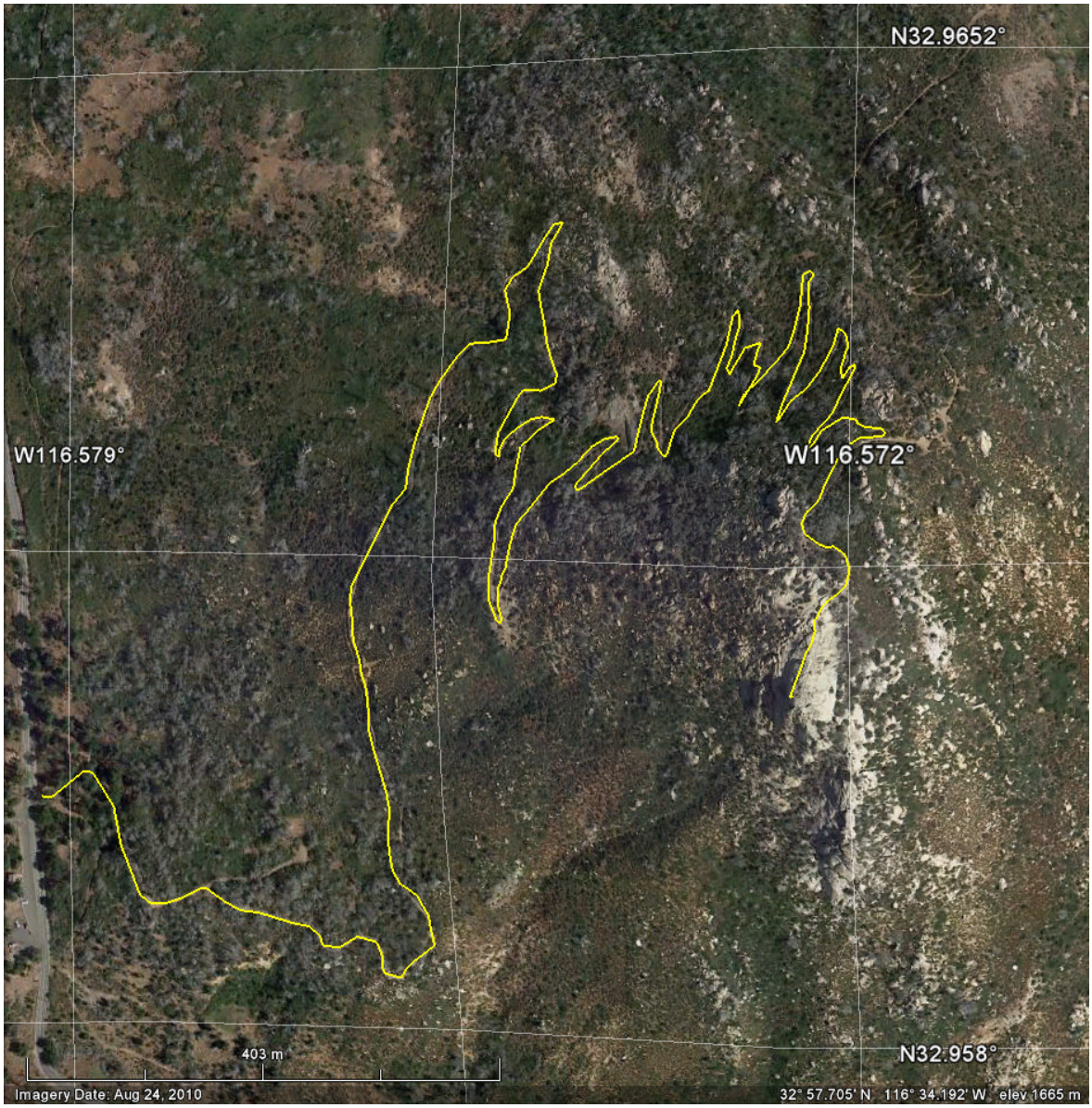


Figure 12: Enabling the display of grid lines in Google Earth illustrates the significant perspective distortions that occur on steeply inclined terrain. On flat terrain, there are no such distortions. We were unaware of this effect at the time of the test.

have used the 2-D images from Google Maps as the background images for our OCU but we were not aware of this issue at the time of the test. To correct this oversight, we downloaded 2-D satellite images from Google Maps and replotted the recorded data from the three PDR units over the distortion-free maps, see Figure 13 and Figure 14.

It is apparent from the plots that at no time a position error exceeded ~40 meters, and most of the time position errors were much smaller, well under 20 meters. These are rather remarkable results, given the length, ruggedness, and partially steep inclination of the terrain, as well as the duration of the hike (about 1 hour in each direction). Indeed, for the most part the performance of all three PDR units rivals that of consumer grade GPS units. The duration of the ascent was 68 minutes.

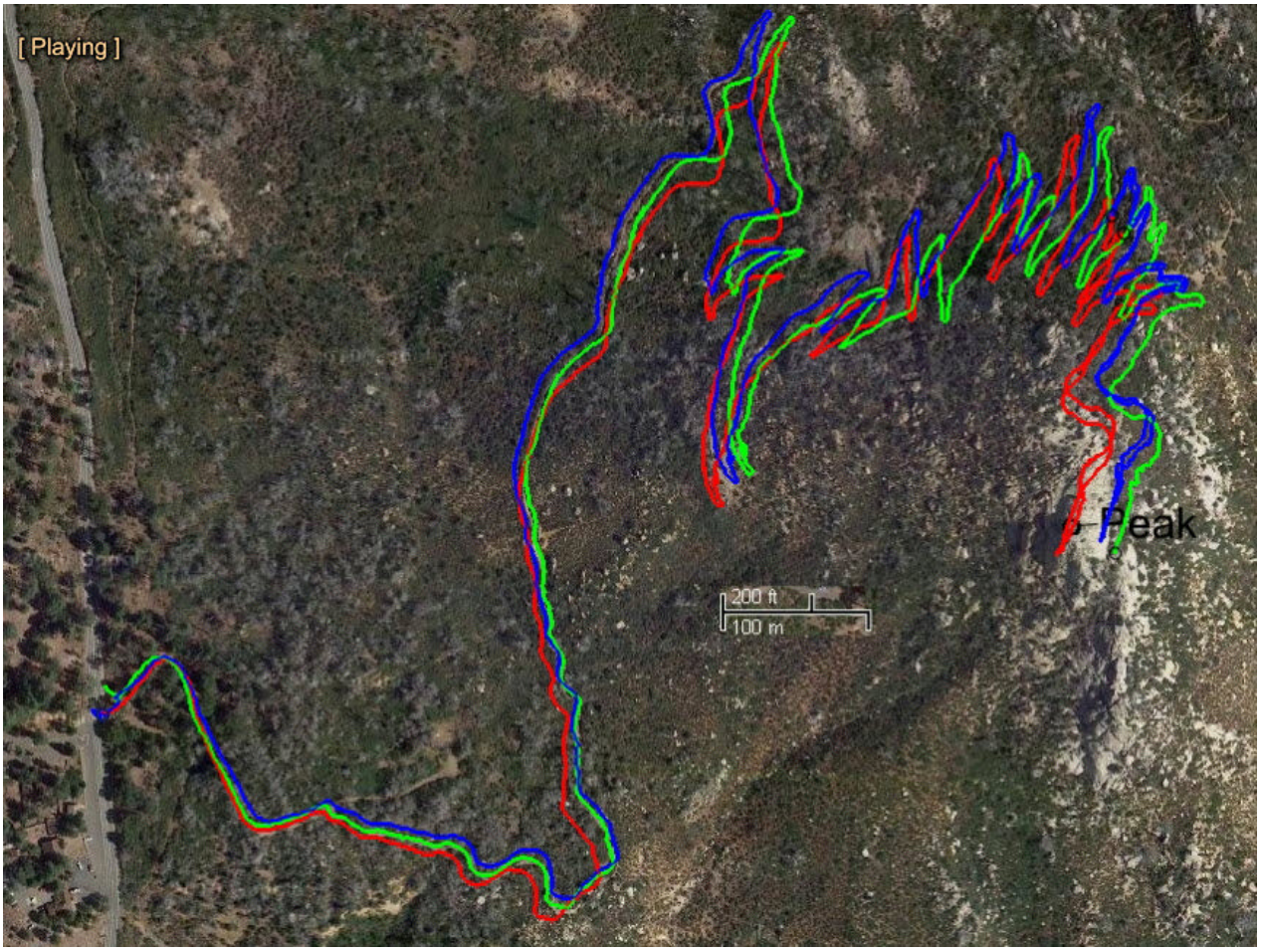
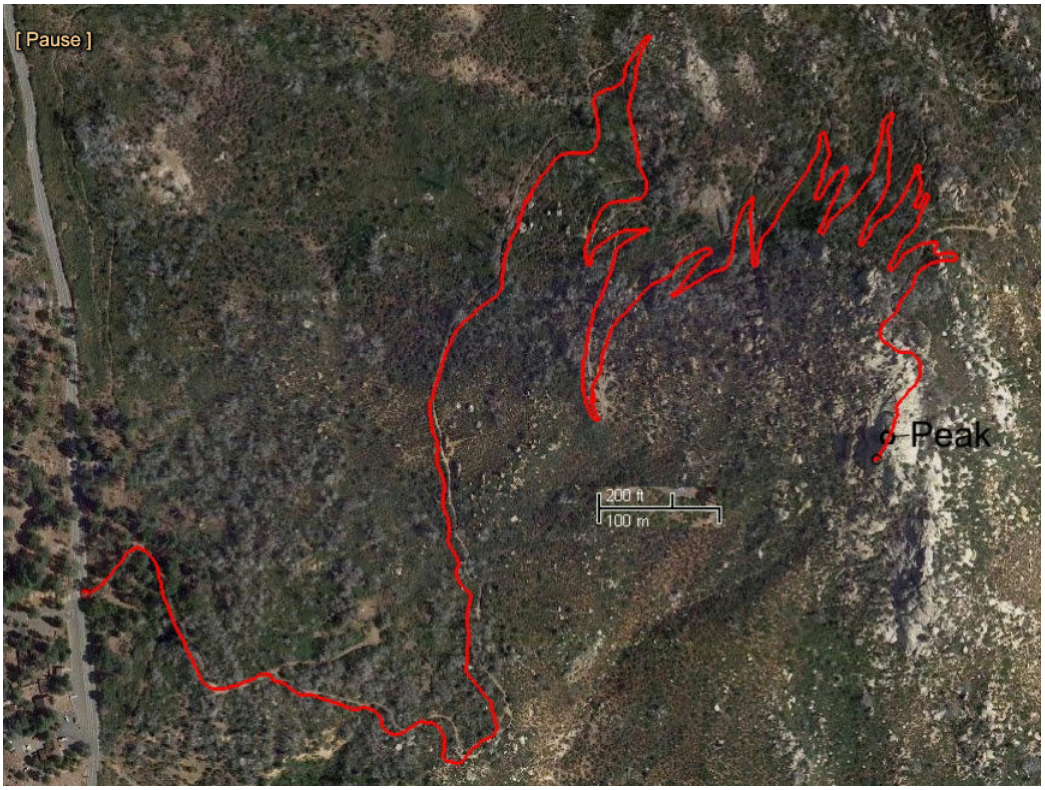
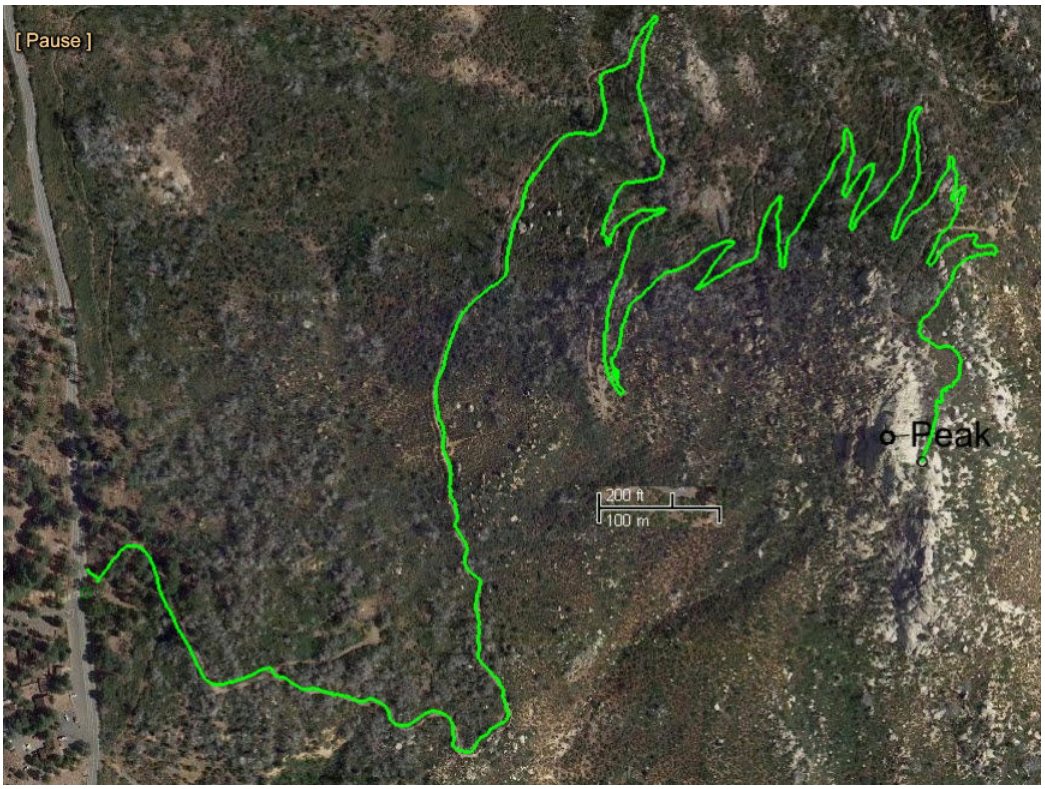


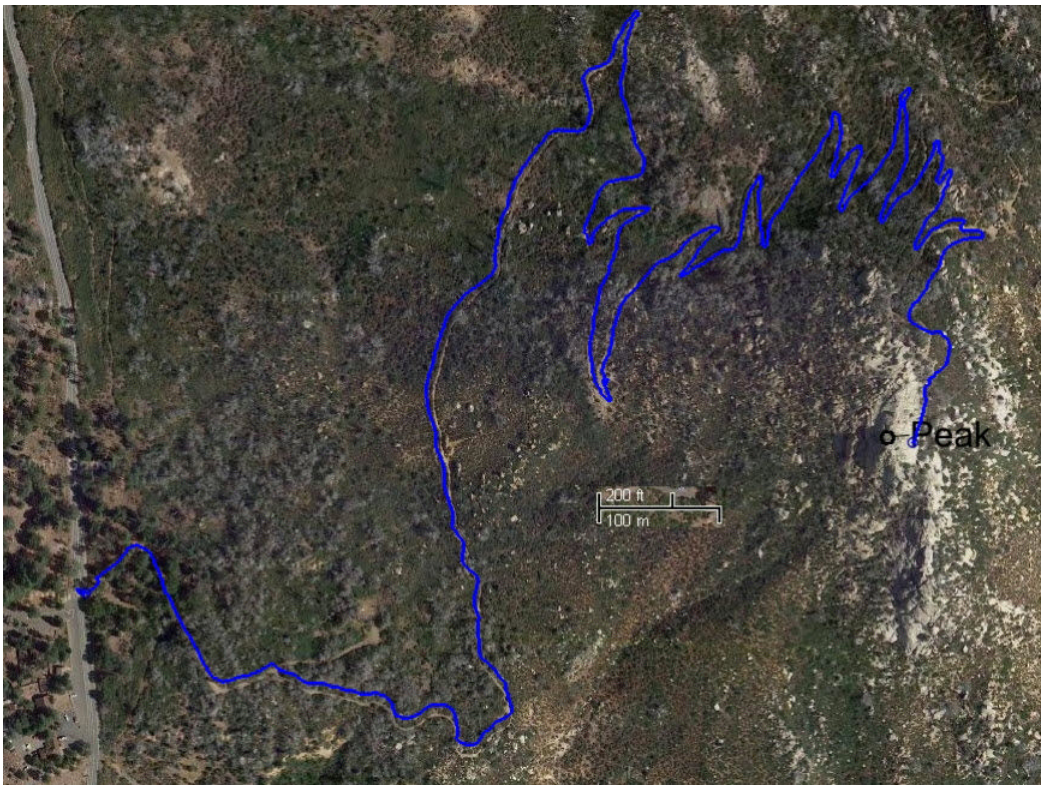
Figure 13: Trajectories as recorded by all three PDR units using IMU and magnetometer only, overlaid over a distortion-free 2-D satellite image from Google Maps. Since the only faintly visible trail is obscured by the three trajectory lines, we provide below three additional plots, one each for each trajectory. An animation of the blue trajectory up and down the trail is available at http://www.engin.umich.edu/research/mrl/video/StoneWall1280x720.wmv



a. Trajectory of the Blue PDR unit



b. Trajectory of the Green PDR unit



c. Trajectory of the Blue PDR unit

Figure 14: In order to avoid occlusion of the only faintly visible hiking trail, we plotted all three trajectories separately.

Figure 15: CAL FIRE firefighters set up for a cover-in-place maneuver during the hike on Stone Wall Peak trail. The two firefighters with the red head gear wear our IMU-instrumented Altama Desert boots. The cover-in-place maneuver had no negative impact whatsoever on the tracking performance of our PDR system.

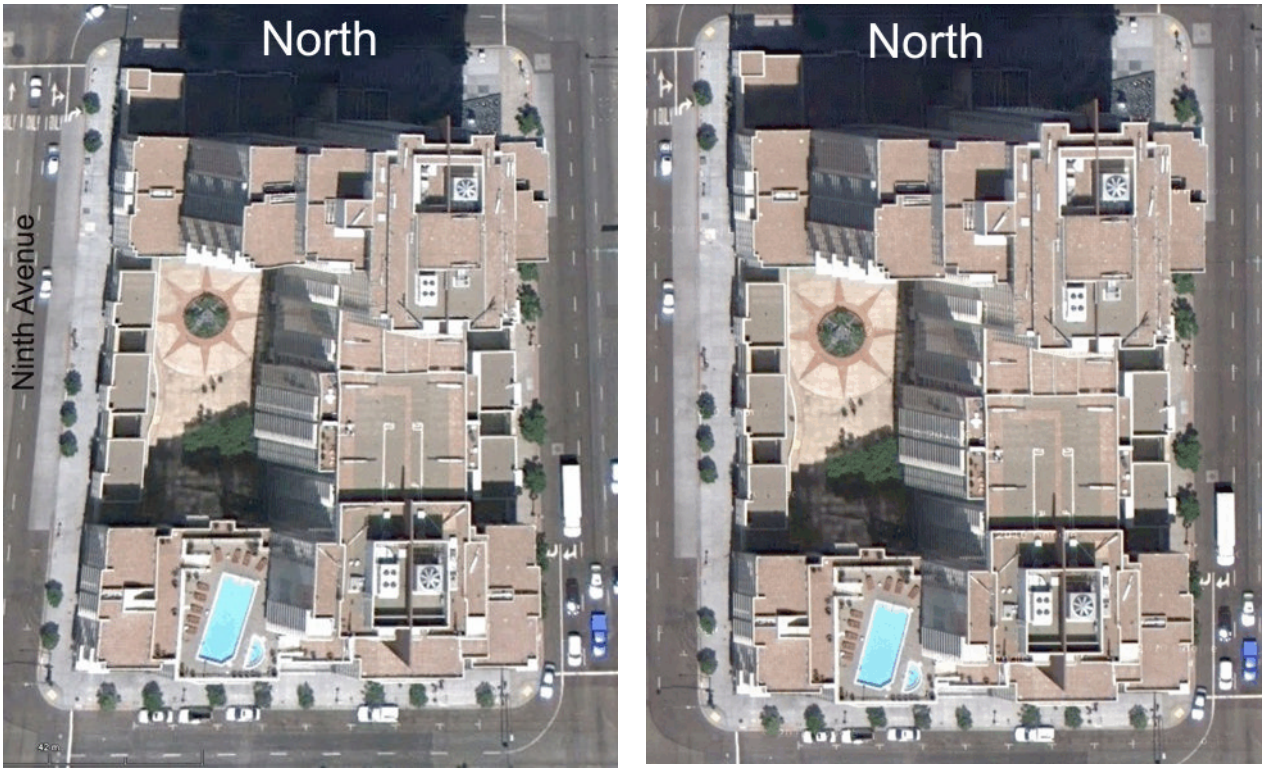
3 CONCLUSIONS

The PDR system works consistently very well with walking in all directions as well as light jogging. It also handles well simple crawling on hands and knees, forward, backward, and sideways.

Modes of motion that the system does not handle well, typically identified by sudden large heading errors on the order of 20°-40° are: very erratic crawling, in all directions, fast running, walking up or down lengthy slopes (typically found only outdoors), and belly crawling.

Performance outdoors with just the magnetometers and the IMU was extraordinarily good. During a 2-mile, more than hour-long hike up a partially steep mountain trail, none of the three PDR system produced position errors greater than 40 meters.

APPENDIX A: MORE ON SATELLITE IMAGES IN GOOGLE EARTH AND GOOGLE MAPS



(a) (b)

Figure A1: Illustration of the distortion of Google Earth 3-D satellite images of rolling or steeply sloped terrain. As an example we chose the city block occupied by the Vantage Pointe high rise building on 1281 Ninth Avenue in San Diego. At that block, Ninth Avenue slopes steeply downward to the south. (a) In Google Earth there is significant distortion, evident in the narrowing of the north portion of the actually rectangular city block. (b) in the 2-D Google Maps application, the exact same satellite image is corrected for perspective distortions and the Vantage Pointe city block appears correctly as a rectangle.