No GPS? No Problem!
University of Michigan develops award-winning Personal Dead-reckoning (PDR) system for walking users

Works indoors as well as outdoors, without GPS and without any pre-installed beacons or landmarks

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1 INTRODUCTION

The University of Michigan has developed a Personal Dead-reckoning (PDR) system for measuring and tracking the momentary location and trajectory of a walking person, even if GPS is not available. Our PDR system does not require any external references. Rather, it uses data from a six-Degree-of-Freedom (6-DOF) Inertial Measurement Unit (IMU) sensor attached to the user's boot, as shown in Figure 1. From this data the PDR system computes the complete trajectory of the boot during each step.

Figure 1: BAE SiIMU02 Inertial Measurement Unit (IMU) mounted to the foot of a walking subject. Of course, this IMU is too large for most practical uses. Our intention is to implement our PDR system with a much smaller IMU in the near future.

On first glance it appears that this approach is destined to fail, since measuring the linear displacement of slow moving objects with accelerometers is not very feasible. That's because data sampled from accelerometers must be integrated twice to yield linear displacement and this process tends to amplify even the smallest error measurement (e.g. bias drift, noise). However, we use a technique known as "Zero Velocity Update" (ZUPT) that virtually eliminates the ill-effects of drift in the accelerometers – *under certain operational conditions*. We found that such operational conditions exist in legged motion; such as when people walk, run, or even climb. Specifically, our system works very well with different gaits, as well as on stairs, slopes, and generally on 3-dimensional terrain. Conversely, our method does not work at all with wheeled, sea-, or airborne motion.

The PDR system offers two different capabilities, each with its own performance specifications:

1. **Measurement of linear displacement (i.e., odometry):** This is the most important and most basic function of our system – the measurement of distance traveled, without measuring the direction of travel. This capability works like the odometer of a car, which also does not measure the direction of travel. Our PDR system performs this function with an error of less than 2% of distance traveled; *regardless of duration or distance*. The PDR system is also indifferent to the stride length and pace, as well as to the gait, such as walking or running.

There is also no need for calibration, fitting, or adjusting parameters of our system to the walking pattern of a specific user – the PDR system can be used by anyone immediately and without training.

2. **Position estimation (i.e., navigation or dead-reckoning):** This capability includes odometry *as well as the measurement of direction*. Position estimation allows our system to determine the subject's actual location in terms of *x, y*, and *z* coordinates, relative to a known starting location. The measurement of direction is based on the use of gyroscopes, which are known to have drift, just as accelerometers do. However, we have not yet applied to gyros the correction method that we apply to the accelerometers. Therefore, our system is currently susceptible to the accumulation of heading errors over time. Our currently used gyros have a quoted bias drift error of 5.0 deg./hour and, consequently, our PDR system develops heading errors of this magnitude. Therefore, unlike with the odometer function of our system, errors with the full dead-reckoning capability will exceed 2% of distance traveled after some 15 minutes of walking. We have successfully tested our system walking through 3-D environments with staircases several floors high. Our system also measures vertical position, but with errors on the order of 5% of distance traveled.

2 METHODS

It is well known that accelerometers don't produce useful position measurements for walks of more than a few seconds. That's because the accelerometers' drift causes huge position errors after the necessary double-integration. However, the use of a technique known as "Zero Velocity Update" (ZUPT) can assess the drift of the accelerometer with every step of the subject, thereby allowing our system to remove the effect of drift. The application of the ZUPT technique is illustrated in the motion sequence of Figure 2, which shows some of the phases of a stride during normal walking. As is evident from the motion sequence, Point A on the bottom of the sole is in contact with the ground for a short portion of time, Δ*T*. During that time and unless the sole is slipping on the ground, 'A' is not moving relative to the ground and the velocity and acceleration vector of 'A' are both zero.

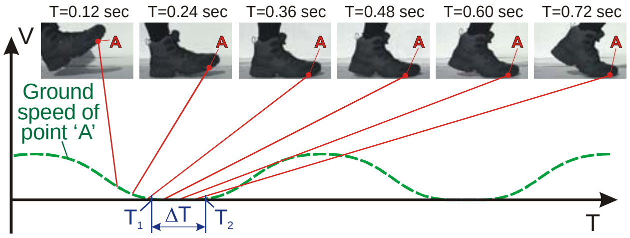

Figure 2: Key phases in a stride. During ΔT, all velocities and accelerations of point A in the sole of the boot are zero.

Therefore, we expect the three accelerometers to show readings of zero during this time. If the reading is not zero, then we assume that the difference between zero and the momentary reading is the result of drift. It is now trivial to record the non-zero value of the accelerometer reading and subtract it from all subsequent readings of the accelerometer. This way we can effectively remove drift from the accelerometer output, at least for a few seconds, until a new step with a moment of zero-velocities allows us to measure and subtract the new drift rate.

After eliminating most drift from the accelerometers with the ZUPT method, we apply a proprietary mathematical algorithm (called "Dedrift-II" in some of our earlier publications) that further improves the accuracy of the accelerometer data by one to two orders of magnitude.

3 RESULTS

Experiment 1 (Complex 3-D Environment)

A typical experiment is shown in Figure 3. In this experiment a subject walked down and up a 4-story spiral staircase. On the way up, the subject left the spiral stair case at each new floor and walked around the square-shaped corridor, before continuing on to the next higher floor on the spiral stair case. After completing this 360-meter trip in 7:42 minutes, the subject stopped at the exact same location where he had started. The error in three runs averaged about 1.7 m, or 0.5% of the total travel distance of 335 meters. This is especially remarkable in light of the excessive vertical travel, and in light of the fact that the subject's gait differed significantly in the three modes of walking during this experiment: horizontal walking, as well as climbing up and down the spiral stair case. The error in vertical direction was larger, averaging 4.2 m or 1.2%.

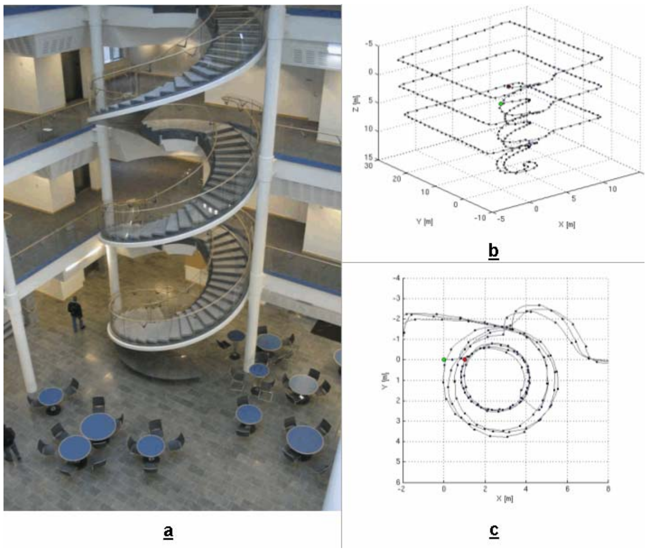

Figure 3: Experimental result in a complex 3-D environment.
(a) Four-story atrium and spiral staircase used for testing.
(b) Trajectory of walking subject as recorded by PDR system
(c) Return position error in the x-y plane (the difference between the start and stop position, i.e., the green and red dot, respectively) is about 1.2 m.

Experiment 2 (Rubble Pile)

In this experiment we tested our system during the traverse of a rubble pile, about 5 meters high and comprising of chunks of broken concrete and soft soil (see Figure 4a and b). Under these conditions, detecting the footfall is more difficult because of foot slippage and because the key assumption in our ZUPT-based method – zero velocities during ΔT – does not always hold on this terrain. The final positioning error for this experiment was X = 2.0 m and Y = -0.6 m for a total traveled distance of 74.14 m. This amounts to an error of about 2.8% of the traveled distance. We believe we can improve upon this result in the future by using a more effective footfall detection algorithm.

Acknowledgements

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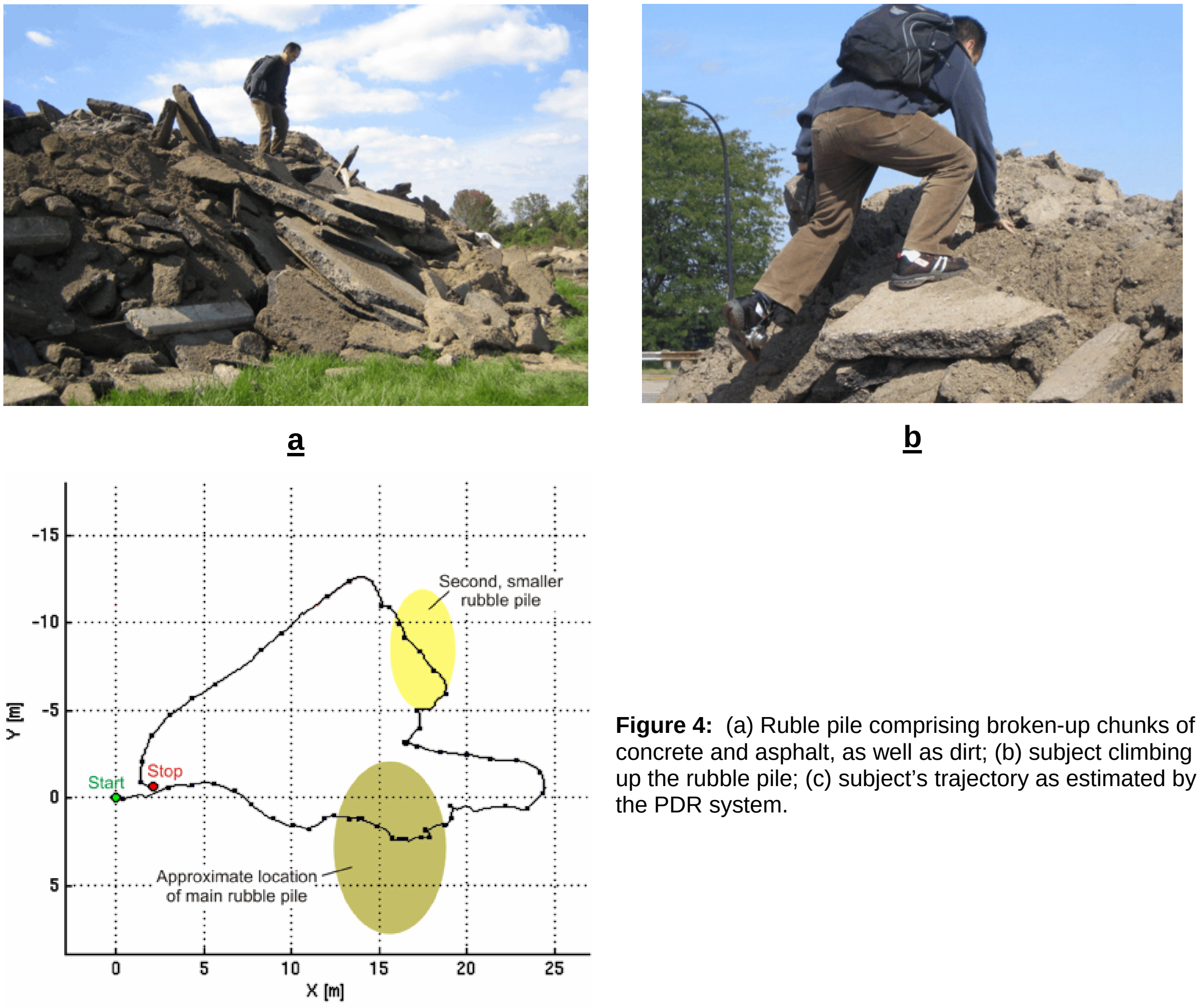

a

b

c

Figure 4: (a) Ruble pile comprising broken-up chunks of concrete and asphalt, as well as dirt; (b) subject climbing up the rubble pile; (c) subject's trajectory as estimated by the PDR system.