In Step with INS

Navigation for the Blind, Tracking Emergency Crews

by Quentin Ladetto and Bertrand Merminod

Integrating a GPS receiver with an inertial measurement unit, a barometer, and step-length algorithms, Swiss researchers have extended pedestrian navigation to urban canyons and indoors. The module applies pattern recognition to accelerometer signals, determining a user's step "signature." This can aid blind people in reaching unfamiliar locations and enable emergency coordinators to track rescue workers through chaotic conditions.

As demand increases for positioning rescue crews, military users, and individuals with special needs, miniaturized low-power inertial measurement units (IMUs) coupled with GPS receivers and other sensors can provide accurate position in both indoor and outdoor situations. However, the classic GPS/IMU approach used for vehicle navigation does not adapt well to pedestrian navigation. Limitations on weight, size, and ergonomy of the device, and the need to determine position both with and without a GPS signal (for example, indoors or on sidewalks obscured by tall buildings) require a new approach.

Over four years of testing in a broad range of applications and environments, the Geodetics Laboratory of the Swiss Federal Institute of Technology has developed a Pedestrian Navigation Module (PNM) fulfilling these requirements. The PNM consists of a high-performance, commercial-grade GPS receiver, a digital magnetic compass with embedded dead-reckoning algorithms, and a barometer . The latest version of the module, currently in testing, also integrates a gyroscope for indoor positioning and for improved reliability in magnetically disturbed areas.

Under dense canopy or in urban canyons with poor GPS signal reception, the PNM changes positioning strategy and uses step-length models and algorithms to determine user position.

The nature of human walking varies greatly, making prediction difficult and requiring on-line calibration and the use of physiological models. To overcome the limitation of models derived from "standard" walking conditions, we have researched and developed models to automatically detect forward/backward and sideways displacements. Differentiating and filtering positions epoch-by-epoch to deduce the speed and azimuth can then calibrate the parameters used in this dead-reckoning (DR) mode.

Navigation for the Blind. When walking alone, blind people tend to follow a path they know and have travelled frequently, because of the evident difficulties they face in unfamiliar surroundings. The PNM does not intend to replace the white cane or the seeing-eye dog, but to augment these devices by indicating the user's position and providing directions. Connected to a Braille module receiving the positioning data, the system refers to a geo-referenced database and outputs an address. If the person wants to reach a precise destination, the system will compute and continuously indicate the best trajectory to this location. As the Braille–GPS software allows registering waypoints, the system can map places of interest such as bus stops, shops, and so on. Its principal advantage is not relying purely on GPS visibility, so it can be extended for indoor applications and is much more reliable in downtown environments.

Positioning Rescuers. In an emergency, coordinating rescue groups or individuals in a very rapid timeframe is always crucial. Knowing each crew member's position, both once an alarm sounds — before response has begun — and during the actual rescue work, can contribute greatly to safety and lifesaving. This is particularly true when crew members have entered buildings.

Module Components

The adjacent photos depict stages of PNM development, and **Figure 1** presents the integrated data flow.

Accuracy. The current PNM prototype uses the GPS receiver in navigation mode only, with no differential correction, delivering precision of absolute positions of ±10 meters. The relative positions between epochs are used to calibrate different models, and these have a much better relative precision, less than 1 meter.

The digital magnetic compass (DMC) consists of three micro-electromechanical (MEM) accelerometers and three magnetometers, producing an azimuth accuracy of 0.5°; at elevation range of 30° an accuracy of 0.15°; at elevation range ±45°, accuracy 0.20° (2 sigma in each case); 3D-accelerometer range of 2g; 3D-magnetometer range ±100 micro Tesla, typical resolution 0.01 micro. The DMC weighs less than 28 grams, and measures 31 × 33 × 13.5 millimeters.

The barometer has a resolution of 0.1 mbar and a relative pressure accuracy of ±0.5 mbar.

Outputs. The GPS receiver outputs NMEA messages. 3D positions are used to get the absolute position as well as to calibrate different physiological models.

The DMC outputs accelerations and magnetic field in three directions, to compute the azimuth, bank and elevation. The accelerations are also used to detect step events.

The barometer outputs temperature and pressure values used to compute altitude.

Updates. The DMC has a 60-Hz update capability, and the GPS receiver a 5-Hz capability. Depending on the requirements and type of pat-

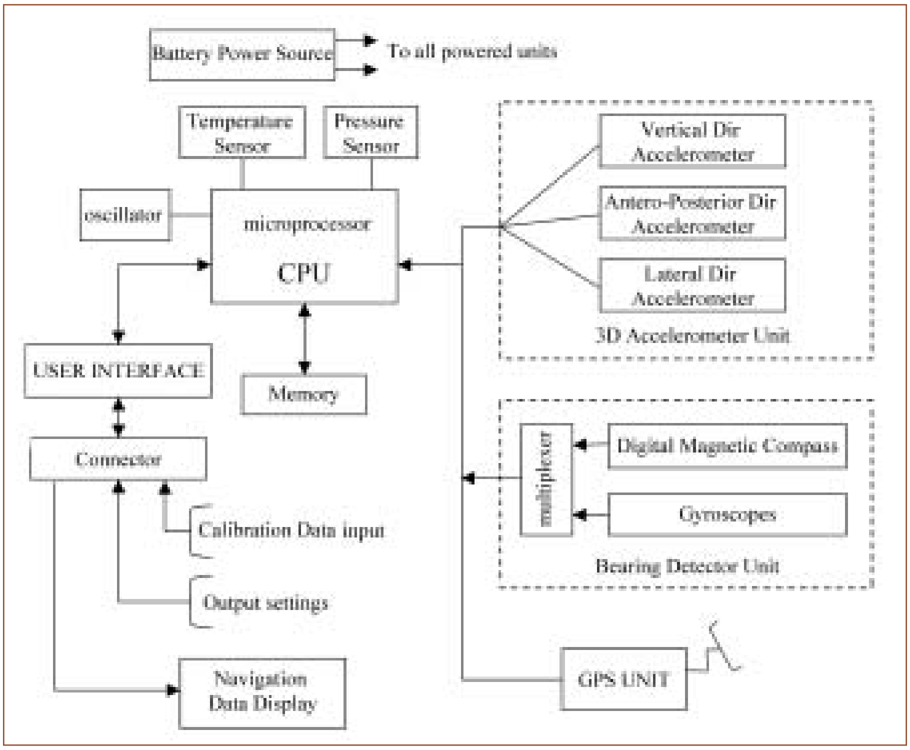


FIGURE 1 Schematic representation of the Pedestrian Navigation Module (PNM).

(A) The functional core of the (PNM), measuring 73.7 × 48.3 × 18 millimeters and weighing less than 50 grams

(B) The first prototype, with packaging and connector

(C) Second prototype, reduced in size for better ergonomy. It includes a white plastic box with belt clip, an active GPS antenna, serial interface cable, and 9V Lithium battery. It weighs ≈150 grams, not including battery or antenna, and measures 103 × 62 × 23 mm (without belt clip).

(D) The latest prototype, currently in testing, also integrates a gyroscope, necessary for indoor navigation as well as navigating in magnetically disturbed areas.

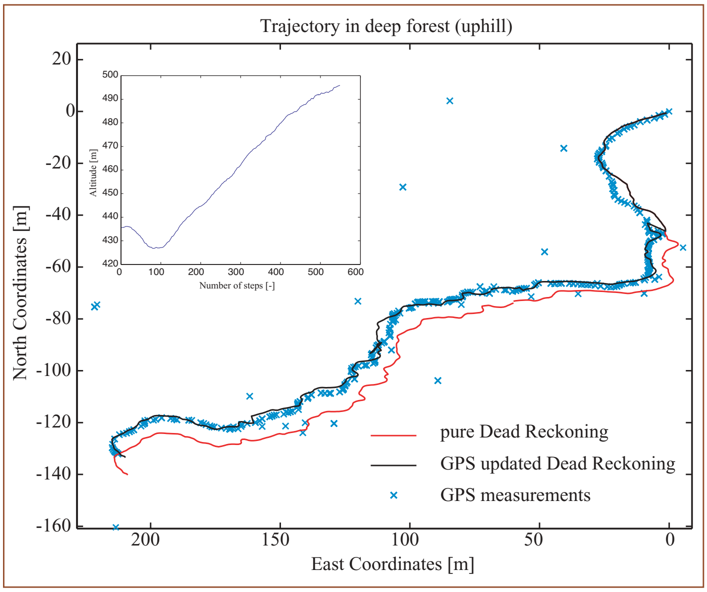


FIGURE 2 Path recorded under dense canopy. A high-sensibility antenna enabled GPS fixes. Results in pure dead-reckoning mode show that even when walking through foliage, with a significant change in altitude, the physiological models in use can track these special circumstances and bring the DR estimate trajectory close to the true one.

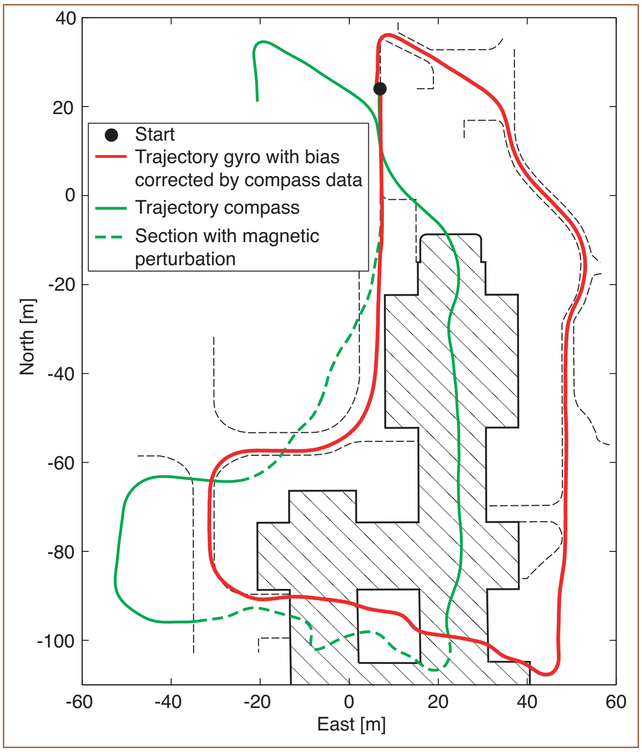


FIGURE 3 Superimposed trajectories, one obtained using the compass output only (green) and the other one using both the gyroscope and the compass data (red). Even if the compass trajectory is out, the use of the azimuth still improves the gyroscope trajectory.

tern we would like to detect, we can increase or decrease the DMC frequency. Before giving the module to the user, we set all sensors to work in parallel at a fixed frequency. The user can access the raw data at varying frequency, but the navigation software runs only at the determined raw-data frequency.

The output frequency of the NMEA message is one message per step. This means that if the person is standing still, no message is output. The PNM updates information to the user only when a change in position occurs. The NMEA output format makes the system fully compatible with common GIS and navigation software.

Power. The DMC function on 5 volts, the GPS receiver on 3.3 volts, V, and the barometer on 3 volts. The devices' operating period depends on sensor use, power-saving mode, and so on. At present the PNM works with a Lithium 9-volt battery for about eight hours continuously.

Ergonomics. Pedestrian use requires a small, lightweight device that can be worn without discomfort. The PNM weighs about 150 grams, and works optimally if worn (clipped) at the belt level. However it also works well when worn anywhere on the trunk, as all misalignment and parameters are calibrated once it obtains the first GPS fixes.

Navigation Calculation

The DMC accelerometers detect step occurrences and the direction of displacement (forwards, backwards, left, and right). To be considered as corresponding to a displacement, each vertical impact (detected when the foot hits the ground) must be followed by an anterior–posterior (AP) or lateral acceleration. The pattern of the signal and its numerical value provide information on the type of movement (going up or down stairs, crawling, and so on), and on the type of ground over which the person walks (hard or soft surface, sand). The model also factors in different dynamics that can occur in different applications, that is, in navigation for blind or elderly persons, military personnel, and so on.

The step length model is calibrated using either speed measurements or a known distance. As the model uses 3-dimensional speed, the velocity is computed in two different ways, according to the kind of data available and the type of application (see **Figure 2**).

If no differential corrections are available to improve satellite positioning, the module computes only the horizontal speed with GPS data while deducing the vertical component from the pressure sensor output. With available differential corrections, the PNM computes three-dimensional speed.

The DMC and/or the gyroscope provide azimuth of displacement, initially aligned with DMC output. In case of magnetic disturbances, the compass will react while the gyroscope remains unaffected; continuous comparison of both outputs allows dead-reckoning correction of the azimuth. If GPS data are available, the DMC's magnetometer azimuth bias is corrected, as well as the bias and drifts of the gyroscope, considering the heading computed from GPS as the true value.

Bearing Data from the Gyroscope

When both gyroscope and magnetic compass data are available, the DMC will determine the gyroscope's absolute orientation (see **Figure 3**). It will then check the presence of magnetic disturbances; in case of a disturbance and no turn, the gyroscope remains still while the compass indicates a turn. If both sensors, comparing the respective azimuth rate of change, do not indicate a turn at the same time, then no turn is considered, and a magnetic perturbation is detected. At this stage, the PNM considers only the gyroscope output to compute the azimuth of displacement. If both data are coherent, they are merged through a Kalman filter. Computed GPS azimuth also models the bias of the magnetic compass and the bias and drift of the gyroscope.

GPS positions and speed are required to recalibrate the different models and provide the user's absolute location. With minimal change, any type of position provided by another system (GSM, Loran, and so on) can be implemented in the filter. Thus, the developed algorithms can include other positioning systems.

Position Computation Procedure

The procedure starts with the initialization of the different models used with physiological inputs such as body height, leg length, and weight. Next, the PNM determines whether the displacement is in the AP direction or not, to select which model to use (see **Figure 4**).

If the displacement is lateral, the stride is determined as a percentage of a stride in the AP direction. If the movement is in the AP direction, the procedure determines the variance and the frequency of the AP displacements. Specifically, this step involves determining the elapsed time between two successive AP displacements and the variance on the AP signal value.

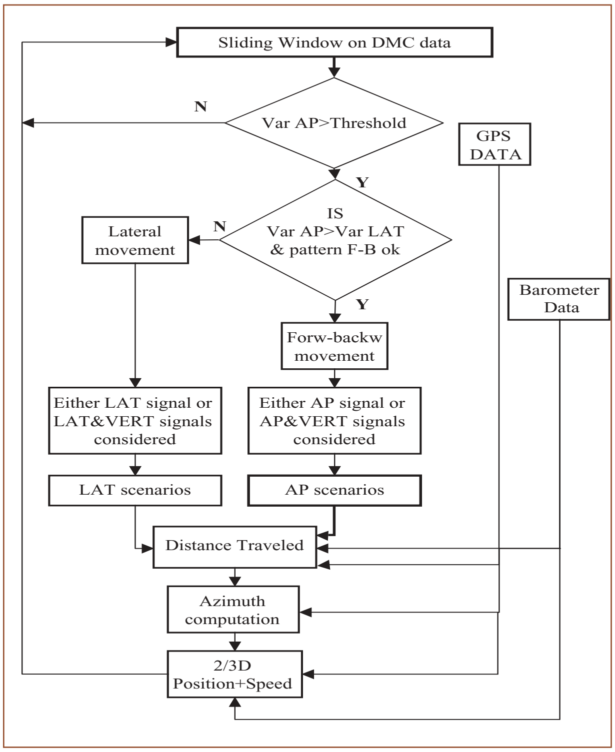


FIGURE 4 Pedestrian navigation algorithm

The PNM then uses these parameters to determine the pedestrian's 2-dimensional speed. With barometer data, it can determine 3-dimensional speed.

Next, the PNM calculates distance traveled using the time between the AP displacements (traveled distance is the product of walking speed and time between the AP displacements).With known speed, different physiological models are called to determine step length. Three-dimensional speed provides slightly better results than 2-dimensional speed. These models provide respective indicators of distance traveled that can be integrated or used separately relative to the previously calculated distance.

The PNM periodically checks to determine whether GPS data are available. If so, it calibrates the different models for speed and step-length determination. The PNM checks to see if enough GPS data has been acquired to provide a good calibration. If not, it initiates a wait period, recording additional absolute and relative information.

Once sufficient GPS data is acquired, the models are re-calibrated, whereupon the new values replace the ones determined from the physiological inputs.

PNM Position. As the PNM, optimally belt-attached, provides the azimuth of the front part of the body — not necessarily the direction of walk — it is therefore necessary, depending on circumstances, to correct its signal according to the type of movement detected.

This procedure starts with acquisition of azimuth data from the DMC and/or gyroscope. The PNM adds declination of the azimuth to the computed value, and smoothes the raw signal of the azimuth with a cascade of low-pass filters to eliminate environmental and walking-derived noise. The displacement (forward/back or left/right) will then modify the angle to be added to the given azimuth to find the azimuth of displacement.

If the displacement is lateral, the left or right direction is identified from the results obtained in these scenarios. The azimuth signal AZ is adapted accordingly by subtracting 90° therefrom in the case of a left displacement, yielding AZ−90°, or adding 90° thereto in the case of a right displacement, yielding AZ+90°.

During lateral displacements, a rotation of the body can be observed. This additional angle has to be removed to compute the real azimuth of displacement.

The PNM performs a similar adaptation of the azimuth signal for AP displacements. In this case, the procedure determines if the displacement is forward or backward, adding 180° in the case of backward displacement, yielding AZ+180°, and leaving the azimuth signal unchanged in the case of forward displacement, this being the reference direction.

The PNM then checks whether GPS data are available. If so, it corrects possible misalignment of the module, bias and drift of the different sensors, thus calculating the azimuth for each step and providing cumulative displacement data.

From this, it obtains the two-dimen-

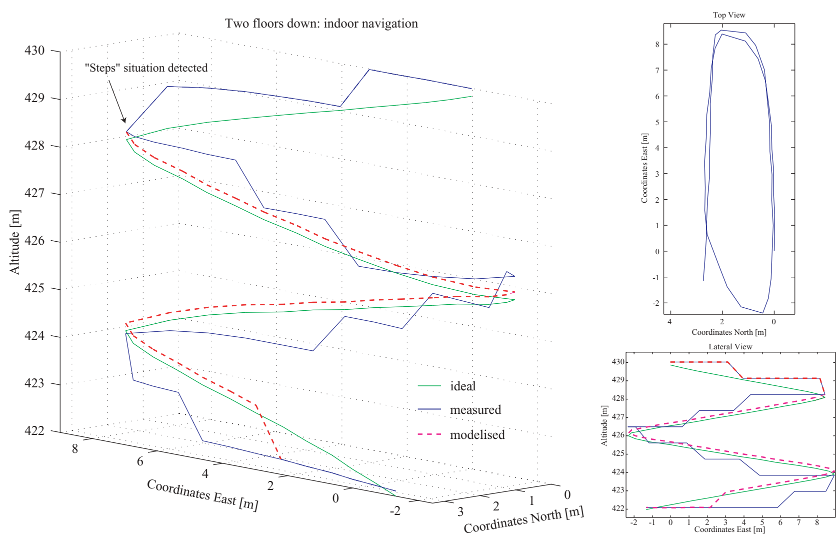


FIGURE 5 3-D representation of downward walking for a stair scenario inside a building. The altitude change of 7.8 m is modeled here after filtering the pressure by 7.28 m. The improvement of the sensor resolution is possible here thanks to the detection of the situation and an appropriate pressure treatment.

The PNM directly outputs NMEA messages that will be read by the BrailleNote GPS module. BrailleNote GPS is a fully accessible Braille or talking GPS for people who are blind or visually impaired.

sional position and speed by navigation in DR mode. The PNM then pursues the procedure to obtain a three-dimensional position, that is, one taking altitude into account.

To this end, it first determines whether barometer data is available. If not, DR navigation is limited to 2-D position and speed. However, altitude can still be obtained from GPS data. The PNM therefore checks availability of GPS data; if no such data is available, it provides only 2-D position and speed in DR mode.

Learning Phase

The PNM applies pattern recognition to accelerometer signals to determine a "signature" specific to the user's type of step motion: forward, backward, left or right sidestep, using a model to identify a pedestrian's signature acceleration patterns and recognize the corresponding steps.

In the learning mode, the pedestrian performs a program of step motions corresponding to walking and/or running situations, including positive and negative gradients, turning at different rates, and so on. The PNM thus establishes a library of acceleration data for these conditions. Though optional, this phase increases reliability in the detection of specific movements.

Differential Barometry

The PNM integrates a hybrid barometer device with a pressure sensor and an analog-digital convertor interface, providing pressure- and temperature-dependent voltage. The module also contains readable coefficients for accurate sensor calibration. This low-power, low-voltage device with automatic power-down switching applies several filtering processes to reduce the noise on the pressure, giving an accurate value in steps of 0.01 mbar and a temperature value in steps of 0.1 C. To correctly fit the approximate curve with the local meteorological conditions, GPS updates are done. If a barometric reference station is available, differential barometry is possible. Several tests have shown that precision better than 50 centimeters in absolute altitude can be maintained up to several kilometers from the reference station, even in changing weather conditions.

Antenna

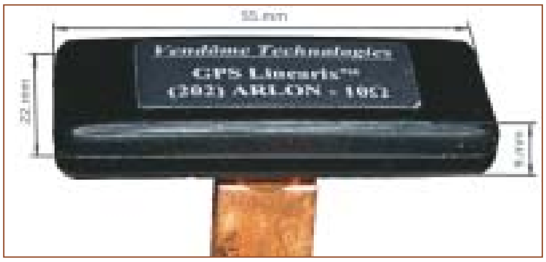
If the GPS receiver needs to be tuned to fit the specific dynamic of pedestrian navigation, the antenna plays a major rule. As most market-available antennas are designed for car navigation, they take advantage of the car's metal structure to improve the GPS signal reception. Pedestrian use reduces this efficiency. Therefore the PNM uses an antenna specifically designed for pedestrian navigation. **Figure 7** depicts GPS availability in a downtown environment and the necessity of DR capabilities for continuous reliable positioning. As shown in **Figure 6**, pedestrians walk on sidewalks, where more than 50 percent of the sky is totally obstructed by buildings, requiring the use of every available GPS signal, even the weakest ones.

FIGURE 6 Continuous and unique representation of the Figure 7 (page 38) trajectory output by the PNM. Only five GPS positions were used to calibrate the different models and bound the statistical error over this 4-kilometer route.

Conclusion

"In 15 meters, turn right on St-Guérin Street, then your destination lies 200 meters ahead." While this kind of information has become quite common for car navigation, it now becomes possible for pedestrian navigation as well.

The PNM provides autonomous position, even without GPS signal availability. Operational at less than 150 grams, and at the size of a portable phone, this ergonomic system can supply positioning data to a GIS or navigation software running on a palm digital assistant (PDA) or wearable



This GPS antenna for pedestrian navigation is a miniaturized plate antenna with controlled impedance. Its characteristics allow remaining in the frequency workspace even when the center frequency varies because of the presence of the human body. For testing purposes, the antenna was adapted and coupled with a modified 20dB enhancer.

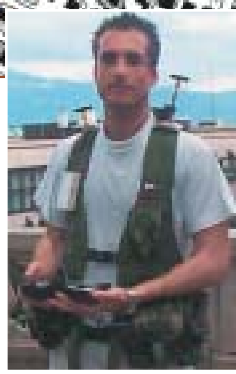


FIGURE 7 Trajectory in downtown Lausanne with three GPS receivers, using three different antennas: a commercial antenna patch (blue), a special helicoidal antenna (red), and a specific linear antenna (green).

(inset) The author wearing two PNMs and two GPS receivers.

Step Modeling

Like fingerprints, the walking profile uniquely characterizes a person. As the frequency content varies widely, a general model requires a normalization procedure followed by individual adaptation. This concept of standardization comes from the observation that the step frequency of unconstrained displacement is more or less equal for everybody. Speed differences therefore result from stride length. A hypothesis that step length is proportional to height, or to leg length, seems reasonable.

Standardizing displacement speed by these parameters, it is theoretically possible to go from individual to more universal models. Each stride is however, and fortunately, not equal to a fixed value. Internal step variability, by the same person and at a given frequency, is simply impossible to predict. Our goal is therefore not the precise step modeling but reliable reproduction of a travelled distance composed of a sample of steps. This can be expressed as: For a given frequency, the step length of an individual can be considered as constant. Natural stride variation follows a normal distribution centered at zero, where the variance is inversely proportional to step frequency. This means that to a longer step will correspond a shorter one, assuming a constant distance for a given number of step at a defined frequency.

On the other hand, we must stress the almost total freedom of movement of pedestrians as well as the direct influence of the type of walking surface. Fatigue, poor physical condition, snow or other inhibitors can make well-calibrated parameters irrelevant in different environments. We adapt different models to each situation with the use of external information, mainly GPS data.

To verify if this theory could also apply to the blind, we conducted several tests, in which blind subjects moved freely, without any personal or seeing-eye dog guide, aided only by their walking stick (**Figure 8**).

Results show that the walking frequency is strongly correlated to the knowledge of the path as well as to the congestion of the sidewalk. The step-length changes are in harmony with the theory, and physiological models, once calibrated, can be used as for sighted subjects. Obstacles (advertising placards, display rack)s caused lateral movements detected by directly analyzing the pattern of the tri-dimensional acceleration signals. Several movements of interest were discretized to get a dictionary of patterns for matching.

This physiological approach limited position error to less than 5 percent of distance travelled. In good conditions, we obtained errors between 1 and 2 percent.

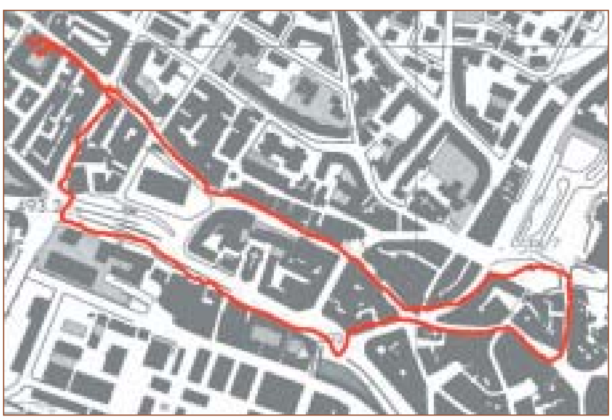


FIGURE 8 Pure DR navigation by a blind person in downtown Lausanne. The 1.9-kilometer path shows small discrepancies but reliably determines the real path followed. Bus power lines and parked cars negligibly influenced the computed trajectory.

computer. For data collection, blind navigation, emergency crew tracking, or military application, it can bring people to their destinations. ⊕

Quentin Ladetto *is a Ph.D. candidate in the Geodetic Engineering Laboratory at the Swiss Federal Institute of Technology in Lausanne. He holds a M.Sc. in Surveying Engineering from the same university. His present research focuses on augmented GPS algorithms for human positioning. He leads the scientific development for the FitNav project, a combined sensor system for integrated personal navigation, a collaboration scheme financed by the Swiss Government and Leica Vectronix AG. Email <quentin.ladetto@a3.epfl.ch>.*

Bertrand Merminod'*s areas of expertise are surveying and geodesy with special emphasis on satellite positioning. His main research fields are the algorithm development for surveying, kinematic GPS positioning, and Kalman filtering. From 1989 to 1993, he directed a project for mapping revision in Lesotho (Southern Africa). After an involvement in GPS navigation for aerial photography with Leica, he was named professor at the Swiss Federal Institute of Technology in Lausanne in 1995.*

Manufacturers

The Pedestrian Navigation Module results from a close collaboration between the Swiss Federal Institute of Technology (EPFL) and **Leica Vectronix AG** (Heerbrugg, St. Gallen, Switzerland), incorporating the Leica Vectronix *DMC-SX* compass.

Geodetic Engineering Laboratory
Swiss Federal Institute of Technology
CH - 1015 Lausanne
Tel. +41 (0) 21 693 27 55
Fax. +41 (0) 21 693 57 40

Email: quentin.ladetto@a3.epfl.ch