On Foot Navigation: When GPS Alone is Not Enough

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Integration of GPS/INS navigation systems is a common topic for aeronautical and road applications. The use of these technologies for personal localisation requires more than just portable sensors and a change of ergonomics; it requires a totally different approach for dead reckoning algorithms. This paper will focus on different human applications and reveals the particular problem encountered.

KEY WORDS

1. Human Factors. 2. GNSS. 3. Integration.

1. INTRODUCTION. Contrary to a widespread belief, satellite signals from GPS and GLONASS are not continuously available everywhere on Earth, and in all weather conditions. Electro-magnetic waves may be interrupted or affected by multipath in urban canyons, or under dense vegetation. Furthermore, optimal antenna positioning is not always possible to ensure good reception. To remedy these limitations, dead reckoning systems are necessary. Although inertial systems (INS) such as gyroscopes and accelerometers have been used frequently in aviation and car navigation, the application of these technologies to the positioning of individual persons is still in its infancy. The integration of GPS measurements with data from other portable sensors is one of the strongest research domains at the Geodetic Engineering Laboratory of the Swiss Federal Institute of Technology, in Lausanne (EPFL).

2. COUPLING SATELLITE DATA WITH DIFFERENTIAL BAROMETRY. As a direct consequence of the geometry of a satellite system, altimetry is the weakest component of the 3-D position. In fact, the majority of the errors disturbing the GPS signal are in the vertical direction. With the aim of improving this component, the combination of GPS code with barometric altitude, measured by a high precision portable meteo station (HM30 Thommen), appears to be a good solution. Different studies (Sudau 1994, Perrin 1999) have shown that altitude values are strongly influenced by atmospheric conditions. The precision of the measurements provided by only one barometer presents an important drift, which is directly correlated with the displacement of the air masses through time. An initial precision of 1 m deteriorates rapidly to reach 10 m after 1 hour.

By analogy with DGPS, the use of a barometric base station situated at a known altitude improves the results considerably, as well as their temporal stability. A test conducted on the levelling network of the city of Lausanne, with more than 300 m height difference, showed a sub-metric precision of the computed relative altitudes. The relationship between the mean error of the altitude, and the distance from the base station is: $\sigma_H = 46[cm] + 42$ ppm. It has emerged from different tests that precise modelling of the temperature is an important part of this method. Using the Laplace equation rather than the Jordan equation (Kahmen and Faig 1988) for a 300 metre difference in height, an uncertainty of 5 °C induces an error of 5·5 m in altitude. Dynamic trials at more than 60 km/h with skiers and cars have brought to the fore perturbations linked with air displacement (high/low pressure).

Differential barometry improves the determination of the vertical component significantly, from ± 100 m for GPS alone to ± 0·6 m with differential barometry (Figure 1). Moreover, this additional data brings further advantages. A single fix

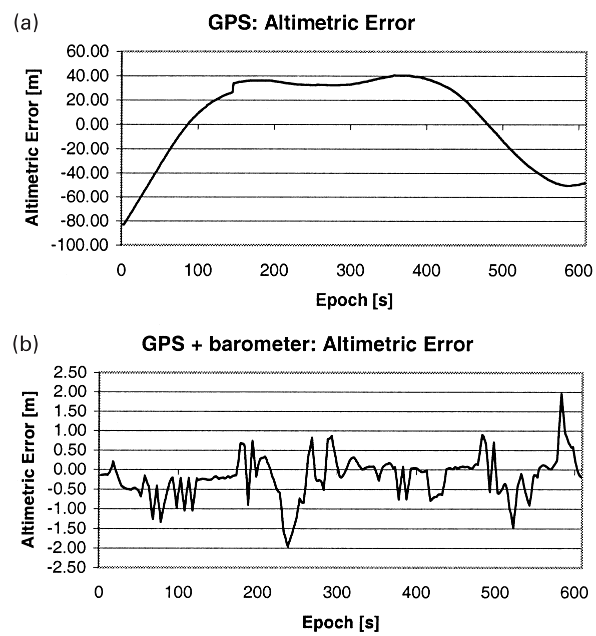

Figure 1. (a) Precision in altimetry using GPS alone has an uncertainty of ± 100 m.
(b) Integration of barometric measurements and GPS improves altimetric precision to 0·6 m.

requires the simultaneous availability of at least 4 satellites; 3 are sufficient when the vertical component is determined by means other than GPS. Compared with a GPS-only solution, the added redundancy improves the capability to detect errors in the measurements.

3. GPS AND ACCELEROMETRY: AN EVENTFUL LOVE STORY.

The high sampling frequency (5–20 Hz) of the latest receivers has opened expectations for

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new applications. In alpine skiing, the analysis of speed and acceleration profiles permits the identification of parameters that can enable improvements in athletic performance. The precise position of skiers is determined by DGPS, using smoothed code algorithms, while Doppler measurements provide accurate speed (Figures 2 and 4).

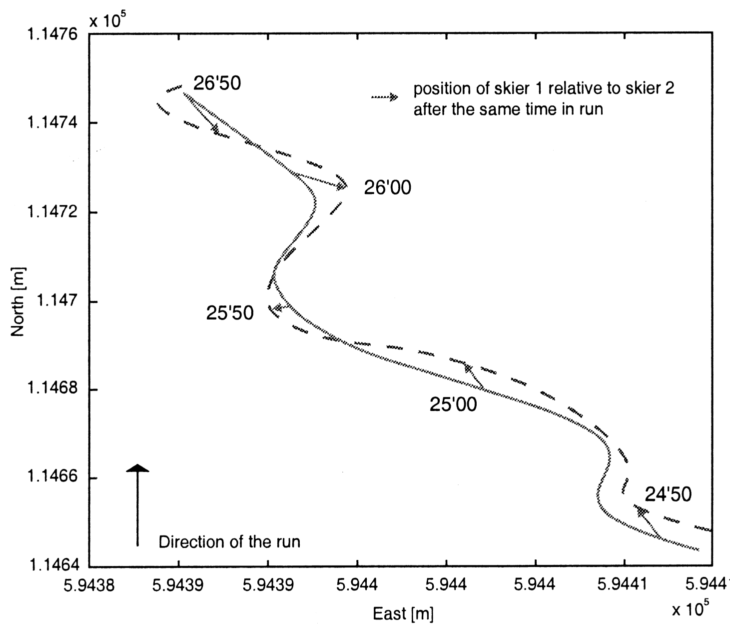

Figure 2. The superimposition of two runs shows where skier 1 made up time previously lost on skier 2. We can appreciate the tighter trajectory of skier 1 passing closer to the gates and so gaining time.

Accelerometers give complementary information for a-posteriori analysis, such as the propulsion force at the start of the run, the aerial phase proportion (jumps) during the whole run and the centripetal acceleration in curves. Filtering lateral accelerations determines the individual signature of each gate passage (Figure 3). By coupling all this information with video shots, every movement of the skiers can be directly related to its effect.

4. REPLACING GPS. As satellite signals are not always available (for example in urban canyons, during indoor activities, etc.), there is a major interest in finding sensors capable of replacing satellites during all blind periods. Again, accelerometers and dead reckoning navigation appears to be the promising solution. In collaboration with the Institute of Physiology, algorithms are being developed within the scope of a project that aims to relate the energy expended by people with their physical daily activity. Previous studies have demonstrated the great impact of an incline on walking energy expenditure (Bobbert 1960, Minetti 1995), which is poorly estimated by accelerometry alone in uphill and downhill conditions (Melanson and Freedson 1995, Terrier, Aminian and Schutz 1999). In open areas, DGPS phase positioning presents the most suitable and accurate solution for defining the speed

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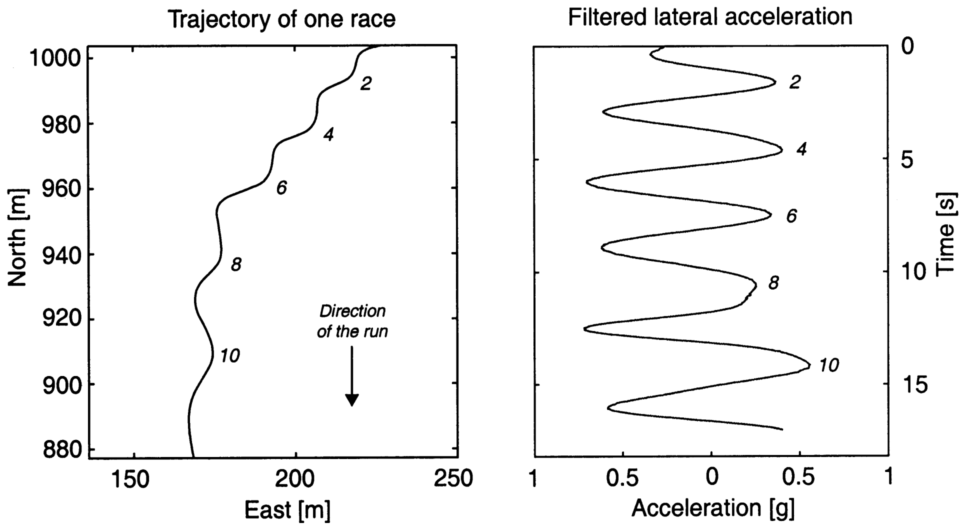

Figure 3. During a Super G skiing run, each gate passage can be clearly identified through the variations of the filtered lateral acceleration.

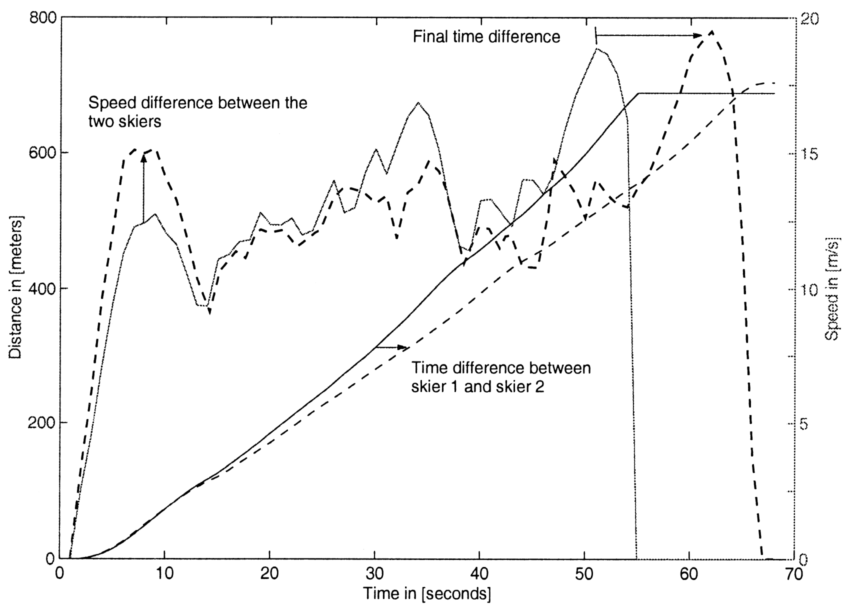

Figure 4. Speed and cumulated distance profiles for two skiers on the same run.

and slope travelled by a person. Several tests have shown that combining both antero-posterior accelerometry and differential barometry can approximate the DGPS speed very well, the mean correlation coefficient value being around 0·9 (Figure 5).

However, what about dead reckoning for people localisation? The total loss of satellite data has been almost completely solved for vehicles using odometer and map-matching, but because of the complexity of the human walking pattern, the optimal solution for 'on foot' navigation is still to be improved. Dead reckoning for people

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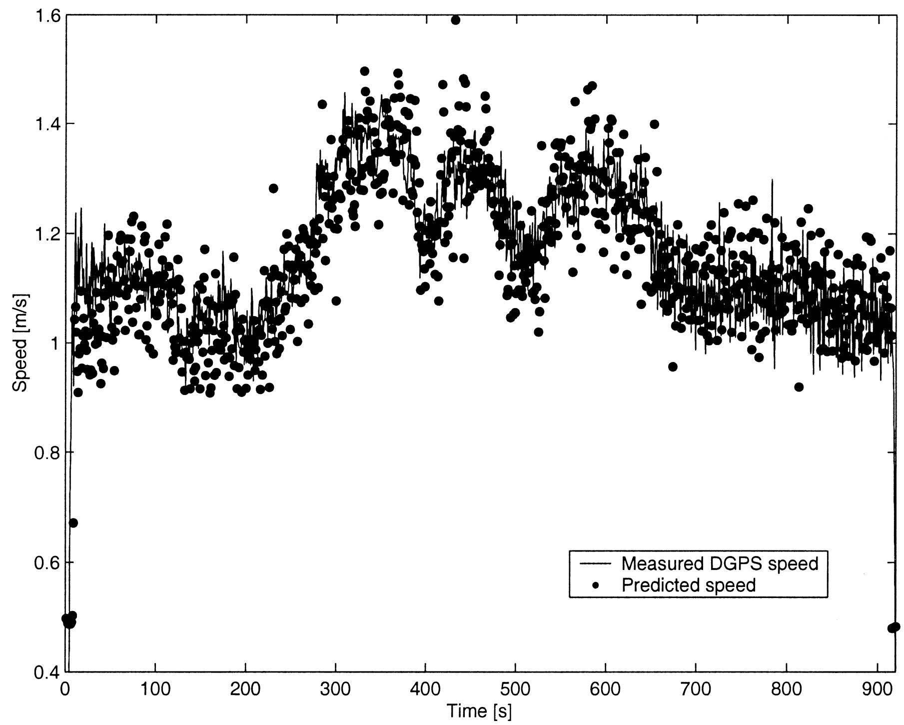

Figure 5. Speed prediction with coupled accelerometer and altimeter versus DGPS phase measurements taken as 'ground truth'. Correlation between measured and predicted speed is $r = 0{\cdot}92$.

is principally based on step count and azimuth of displacement. The number of steps is calculated by accelerometry, and the azimuth is obtained through means of an electronic compass (fluxgate). Two main difficulties appear very quickly. The first comes from the length of strides that permanently varies with the slope and with the walking attitude of a person. The second is the presence of biases in sensor data caused by magnetic perturbations such as high voltage lines or metallic objects. Preliminary tests (Jud 1997, Anken 1999) were conducted using the commercial Dead Reckoning Module™ from Point Research Coorporation (USA). These tests brought to the fore the necessity for periodical re-calibration of the sensors. Again, DGPS, when available, presents a convenient solution. Most of the time, the shape of the route is preserved by original measurements, while absolute position mainly suffers from biases. If applications allow post-processing treatments, 1–2 metre precision results can be reached after an affine transformation (Figure 6). The main constraint of this method is that the person has to stop on points with known coordinates during the run. This aspect is far too constraining for common use but could be very interesting for surveying tasks. Research is actually focusing on the integration of a GPS receiver to a high accuracy positioning module manufacturer by Leica AG. This device (Leica DMC-SX) includes three magnetic field sensors, three acceleromoters that are also used as tilt sensors, and a thermometer. All sensors are connected to an integrated data logger.

It must be stressed that simple or double integration of 3-D accelerations to deduce

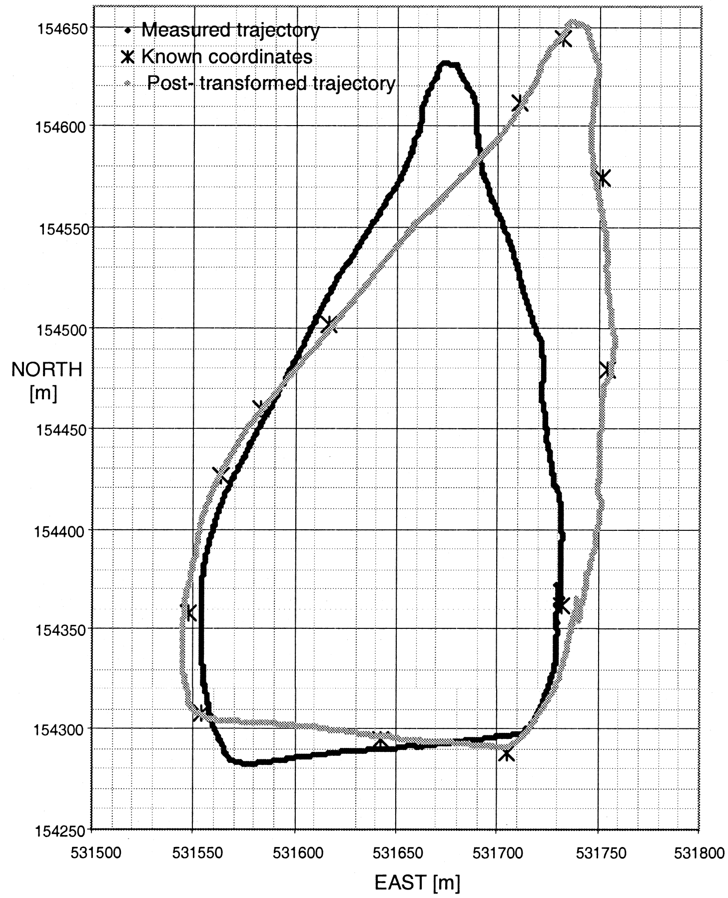

Figure 6. Measured and transformed trajectory after an affine 4 parameters transformation. The standard deviation on the known points is 1·25 m.

speed and position is not possible because of the lack of orientation and precision of the sensors. This method is applicable in aeronautical navigation where a speed error of 1 m/s after a small period of integration, represents only 035 % of the speed. This proportion totally changes for normal human walking speed of about 1·5 m/s.

5. CONCLUSION. Even if it appears that satellite positioning has revolutionised the worlds of both surveying and navigation, we have to beware of considering GPS as the global solution to all problems of localisation. Used alone, it does not cover all navigation needs, but reveals itself as an excellent component of a more complex system, in which each element improves the efficiency of the whole. As human walking parameters are strongly correlated with time, laboratory research is directed to the use of wavelet transformation analysis, together with Kalman filtering. Different methods to extract the occurrence and the frequency of steps are being developed. Dynamic calibration of the stride using GPS measurements is another primary research topic. Whether with accelerometers, gyroscopes, barometers or inclinometers, the optimisation of data coming from space will depend strongly on its

terrestrial homologue. Adapting the famous military proverb about strategy, we can affirm that:

'In GPS sensor integration there is strength!'

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