IMPROVING THE ACCURACY OF LOW-COST GNSS BY FUSION WITH INERTIAL AND MAGNETIC SENSORS IN ALPINE SKI RACING

Benedikt Fasel[1], Jörg Spörri[2], and Kamiar Aminian[1]

Laboratory of Movement Analysis and Measurement, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland[1]
Department of Sport Science and Kinesiology, University of Salzburg, Hallein-Rif, Austria[2]

For analysing performance in alpine ski racing, an accurate estimation of the skier's centre of mass trajectory and speed is indispensable. However, the sole use of low-cost GNSS might not be accurate enough to detect meaningful differences. The aim of this study was to introduce a new system that can improve the accuracy of a low-cost GNSS to an acceptable level. To this end, the data obtained by low-cost GNSS was fused with data form inertial sensors and position information of permanent magnets buried into the snow surface along the ski track. This fusion improved the system's accuracy from 2m to 0.5m. Despite the added sensing technologies, the system remained simple and was easy to use. Further improvements are possible and a technical validation of the system could be a major aim for the future.

KEY WORDS: inertial sensors, magnetic sensors, GNSS, sensor fusion, alpine skiing.

INTRODUCTION: For analysing performance in alpine ski racing, the skier's centre of mass (COM) trajectory and COM speed, as well as the energy parameters computed thereof are among the most important parameters (Hébert-Losier, Supej, & Holmberg, 2014). For determining these parameters, an often used approach is the use of global navigation satellite systems (GNSS), either standalone (Gilgien et al., 2015), or combined with inertial sensor suits (Supej, 2010). For skiing applications, differential high-standard GNSS has been demonstrated to provide an accuracy in the order of a few centimetres (Gilgien, Spörri, Limpach, Geiger, & Müller, 2014) but requires the set-up of base stations by trained users. Such an approach provides sufficient accuracy, but lacks in an easy handling that could be performed by coaches during a regular training session. An alternative approach would be the use of a low-cost GNSS, but at the cost of a reduced accuracy of approximately 2 meters (Gilgien et al., 2014). Considering that the range of performance-relevant differences in skiing trajectory is between 0.05m and 1.13m (Spörri, Kröll, Schwameder, & Müller, 2012) low-cost GNSS alone can therefore not be used.
However, from the perspective of information theory, by combining other, GNSS-independent measures (such as inertial sensor data) with the data obtained from the low-cost GNSS system, an increase of the system's accuracy might be feasible (Hall & Llinas, 1997). Accordingly, the present study aimed to improve the accuracy of a low-cost GNSS system by fusing it with inertial sensor data and known locations along the skiing track.

METHODS: One recreational skier was equipped with two inertial sensors (Physilog® IV, GaitUp, Switzerland; 3D accelerometers, 3D gyroscopes, sampling rate 500Hz) attached to the right shank and thigh. An additional inertial sensor with a GNSS module (u-blox M8, u-blox, Switzerland) was integrated in a back protector (P1-Dynamic, Ortema, Switzerland) worn by the skier. The GNSS module was connected to an active GNSS antenna (TW2710, Tallysman, Canada) integrated in the back protector approximately between the shoulder blades (Fig. 1A). GNSS position and velocity was sampled at 10Hz using the GPS and GLONASS signals, while no base stations were used. The shank inertial sensor additionally had a magnetometer (MLX90393, Melexis, Belgium) sampling at 125Hz. All sensors were synchronized wirelessly. Accelerometers and gyroscopes were calibrated using the procedure described in (Ferraris, Grimaldi, & Parvis, 1995), and the magnetometers were

calibrated following the procedure of (Bonnet, Bassompierre, Godin, Lesecq, & Barraud, 2009).
The experiment was performed on a ski slope (350m length and 100m vertical elevation difference between start and finish). Five permanent magnets (Fig. 1B) were buried in the snow with the magnet's South pole painted in orange and located 1cm above the snow surface. Magnet 1 was placed approximately 5m after the start, magnet 5 towards the end of the slope, whereas magnets 2-4 were placed in between (red crosses in Fig. 1C). The slope was surveyed using a drone (Phantom 3 Pro, DJI, China) and Pix4DMapper (Pix4D, Switzerland) was used for automatically reconstructing and geo-localizing the slope in 3D (Fig. 1C). Using the same software, the magnet positions could be visually tracked and extracted with an accuracy of <1.5cm.

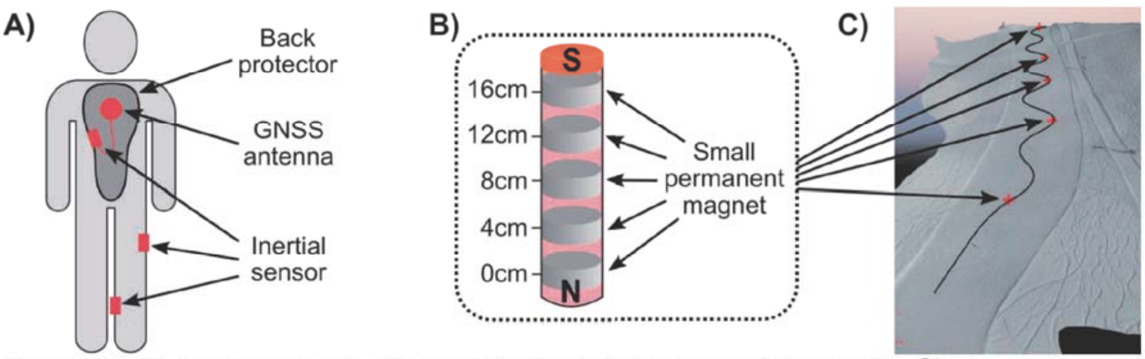

Figure 1: A) sensor setup, B) constitution of permanent magnets, C) reconstructed slope with positions of the magnets marked with crosses and skiing trajectory with the black line.

The skier skied the slope twice, passing in a straight line close to magnet 1 and 5 and taking a sharp right turn around each of the magnets 2-4 (with the ski close to the magnet). Prior to each run, functional calibration movements were performed to reconstruct the body posture in 3D, as described in an earlier study (Ulrich, Fasel, Spörri, Müller, & Aminian, 2015). Moreover, knowing the segments' orientations in a common absolute frame, measured acceleration at each sensor could be matched with the GNSS frame.
Each passing of the magnet caused a peak in the measured magnetic field intensity at the shank sensor and could be automatically detected. Laboratory validation of the setup showed a mean (standard deviation) difference of 4.4ms (11.8ms) between closest sensor to magnet distance measured with Vicon and peak magnetic field intensity. Passages closer than 0.4m to the magnet could always be detected.
In a last step, the 3D position and speed data obtained by the low-cost GNSS was fused with the data from the inertial sensors and the exact magnet positions using the Rauch-Tung-Striebel (RTS) two-pass Kalman smoother (Rauch, Striebel, & Tung, 1965). All data was fused at the position of the GNSS antenna. However, since acceleration data was not measured at the GNSS antenna position directly, it was translated from the corresponding sensor position to the GNSS antenna (Eq. 1). Next, a virtual magnet position (i.e. hypothetical location of the magnet when skier passes the magnet) was computed relative to the GNSS antenna position and based on the previously computed body model. In a second scenario the position of magnet 1 was used to correct for the coordinate system offset between the slope model and the GNSS/IMU system. In a third scenario the position of magnet 5 was additionally used for a further correction of GNSS/IMU fusion error during the RTS smoothing process:

$$\hat{\boldsymbol{a}}(t) = \boldsymbol{a}(t) + \dot{\boldsymbol{\omega}}(t) \times \boldsymbol{r} + \boldsymbol{\omega}(t) \times (\boldsymbol{\omega}(t) \times \boldsymbol{r}) \tag{1}$$

where $\hat{a}(t)$ is the acceleration at the GNSS antenna connected by vector $\boldsymbol{r}$ to the inertial sensor in the back protector where we measured acceleration $\boldsymbol{a}(t)$, angular velocity $\boldsymbol{\omega}(t)$, and angular acceleration $\dot{\boldsymbol{\omega}}(t)$.

The system parameters were tuned using the data from the first run (training-run) solely. The system's performance was then assessed using the second run (testing-run). The system's error was defined as the position difference between the exact magnet position within the slope model and the virtual magnet position at the moment of the detected magnet passing. Errors were reported graphically for all five magnets.

RESULTS: All magnets were detected. Skiing speed at magnets 2-5 was approximately 60km/h while it was 17km/h at magnet 1. Fig. 2 shows the errors at each magnet and dimension whereas Fig. 3 shows the total error distance at each magnet.

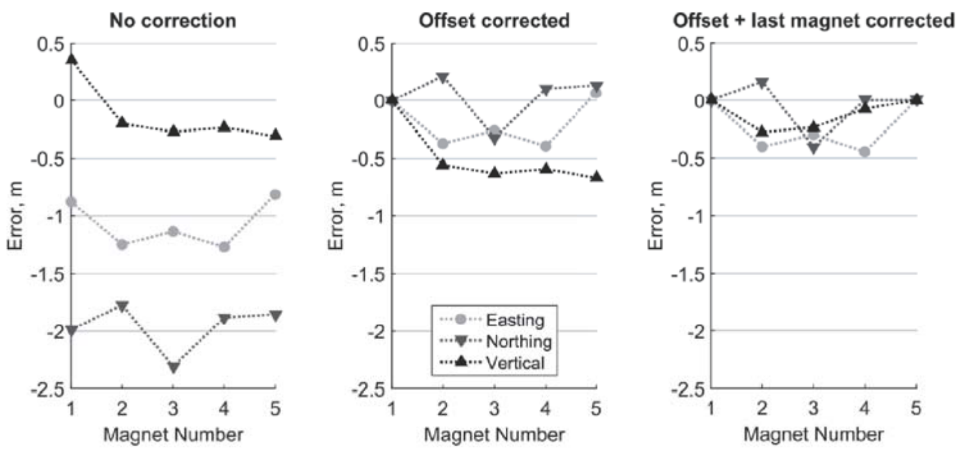

Figure 2: Error between estimated and true magnet position for each scenario.

DISCUSSION: In this study, a new innovative measurement system for alpine skiing has been proposed. By combining low-cost GNSS, inertial sensors, magnetometers, and a terrain model we aimed to provide accurate estimates of the skier's centre of mass trajectory and speed. Instead of using magnetometers for drift correction, they were used to detect the skier's passage of permanent magnets buried in the snow. With this approach, and knowing the exact magnet position from the terrain model, the accuracy of the skiing trajectory was improved from errors in the order of 2.0m to 0.5m. Only the first and last magnets were used. This allowed the remaining magnets to be used as reference points for the purpose of error evaluation. For the skiing trajectory, two main error types were observed: a constant offset and a time-varying offset. The constant offset could be removed using one magnet. The time-varying offset could be reduced using position information from the additional magnet. For a future setup, magnets could be placed at each gate. This might help to better model and remove the time-varying offset.

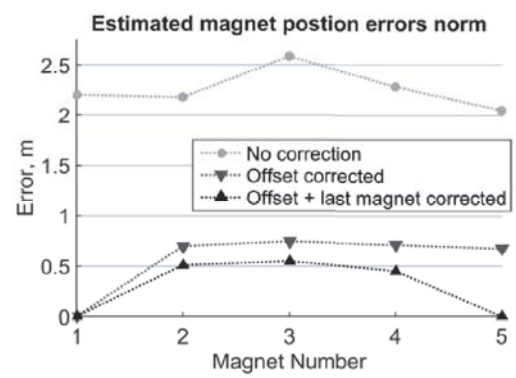

Figure 3: Total distance between estimated and true magnet position.

Modelling the skier's posture was crucial for achieving an acceptable accuracy level. The pendulum body motion during each turn and the high knee and hip flexion of the inside leg led to differences in the total distance between the outside ankle and GNSS antenna (up to

0.5m between two subsequent turns). Thus, neglecting this movement would have added errors in the order of at least 0.5m.

Despite the system's complexity, its setup was fast. The terrain surveying with the drone took approximately one hour but could be fully automatized. Placing the magnets took five minutes and inertial sensor setup another five minutes. In this study, the terrain model was mainly used for the purpose of validation. However, the system could also be used without a terrain model (i.e. without knowledge of the absolute magnet positions). In this case, approximate magnet positions could be obtained by averaging estimated positions from multiple runs and, subsequently, could be used to compute the trajectory relative to the averaged positions.

The main purpose of the present study was a proof of concept. More work is needed for improving the system's performance. Its accuracy could be improved by using more advanced filtering techniques and modelling of the virtual magnet positions. Moreover, a technical validation of the system could be a major aim in for future measurements. For further developments, information about slope inclination from the terrain model should also be considered. This information could be used to obtain more information about the skiers leaning actions or to replay the runs as 3D animations for coaching purposes.

CONCLUSION: A combination of low-cost-GNSS, inertial sensors, magnetometers, and a terrain model allowed achieving significantly higher position accuracy for the estimation of the skier's trajectory than it would be possible by any of these systems alone. The use of low-cost GNSS instead of differential high-standard GNSS simplified the setup considerably, and attaining accuracy close or equivalent to the one of the differential method seems to be possible.

REFERENCES:

Bonnet, S., Bassompierre, C., Godin, C., Lesecq, S., & Barraud, A. (2009). Calibration methods for inertial and magnetic sensors. *Sensors and Actuators A: Physical*, *156*, 302–311.

Ferraris, F., Grimaldi, U., & Parvis, M. (1995). Procedure for effortless in-field calibration of three-axis rate gyros and accelerometers. *Sensors and Materials*, *7*(5), 311–30.

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., & Müller, E. (2015). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *Journal of Sports Sciences*, *33*(9), 960–969.

Gilgien, M., Spörri, J., Limpach, P., Geiger, A., & Müller, E. (2014). The effect of different Global Navigation Satellite System methods on positioning accuracy in elite alpine skiing. *Sensors (Basel, Switzerland)*, *14*(10), 18433–53.

Hall, D., & Llinas, J. (1997). An introduction to multisensor data fusion. *Proceedings of the IEEE*, *85*(1), 6–23.

Hébert-Losier, K., Supej, M., & Holmberg, H.-C. (2014). Biomechanical factors influencing the performance of elite alpine ski racers. *Sports Medicine*, *44*(4), 519–33.

Rauch, H., Striebel, C., & Tung, F. (1965). Maximum likelihood estimates of linear dynamic systems. *AIAA Journal*, *3*(8), 1445–1450.

Spörri, J., Kröll, J., Schwameder, H., & Müller, E. (2012). Turn Characteristics of a Top World Class Athlete in Giant Slalom: A Case Study Assessing Current Performance Prediction Concepts. *International Journal of Sports Science and Coaching*, *7*(4), 647–660.

Supej, M. (2010). 3D measurements of alpine skiing with an inertial sensor motion capture suit and GNSS RTK system. *Journal of Sports Sciences*, *28*(7), 759–69.

Ulrich, B., Fasel, B., Spörri, J., Müller, E., & Aminian, K. (2015). Using inertial sensors to compute an alpine ski racing specific full body kinematic model - an application to track the distance between ankle joint and athlete's center of mass. In *7th yearly congress of SGS Switzerland*.