Kinematic correction for a spatial offset between sensor and position data in on-the-go sensor applications

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Abstract: On-the-go data collection yields spatially referenced information at a sub-field scale that is needed for many applications like precision farming. A spatial offset occurs between sensor and position measurements if the GPS-antenna is not placed on top of the sensor. To correct for such an offset, we present a kinematic model that accounts for the mechanisms underlying the offset. The model was applied to a soil electrical conductivity survey on a 135 ha site with over 100 000 data points. Application of the model improved the accuracy in geostatistical analysis by 30 %.

1. Introduction

Detailed knowledge about site patterns at fine resolution is needed for decisions on a wide range of farm management problems [Ad04, Au01]. Accordingly, sensor-based soil testing has become a widely used approach in soil science and precision farming [Ad04, Au01, CP05]. In ground-based surveys, this is usually accomplished by “on-the-go” sensor applications with vehicle-mounted sensors and a global navigation satellite system (GNSS, such as the Global Positioning System, GPS) receiver connected to a computer, which synchronously collects the measurements of both instruments [Ad04]. A possible complication in such a configuration is that a spatial offset occurs where the GNSS antenna is not placed directly on top of the sensor [Sp00]. As this adds uncertainty to inferences from the measured variable [CK03, GB10], the measured GNSS antenna positions have to be corrected. Generally the offset depends on movement parameters such as velocity of the vehicle, travel direction or curve radius. In such cases the kinematic concept of the tractrix [GKM93] seems promising for the prediction of the positions of a sensor towed by a GNSS-equipped vehicle. We examine the applicability of a tractrix-based model to measurements with a ground conductivity meter and demonstrate the model’s benefits regarding the accuracy of the resulting map.

2. Kinematic Model

Our model describes the movement of a towed sensor as the tractrix of the hitch point of the drawing vehicle. While the vehicle moves, GNSS antenna positions are measured at discrete times synchronously with sensor measurements. We derive the hitch point positions by rotating the vector between antenna and hitch point from vehicle coordinates into field coordinates (Fig. 1 a), [SH09]). Therefore, the heading of the vehicle is estimated as denoted in Fig. 1 b). We assume that the hitch point moves on a straight line between two successive positions and derive the heading of the hitch point as denoted in Fig. 1 c). Consequently, we derived an equation for the tractrix of a linear steering curve in field coordinates, which allowed the calculation of any position of the sensor from its previous position and the movement of the hitch point. (An implementation of the model in R [Rd11] can be obtained from the author.)

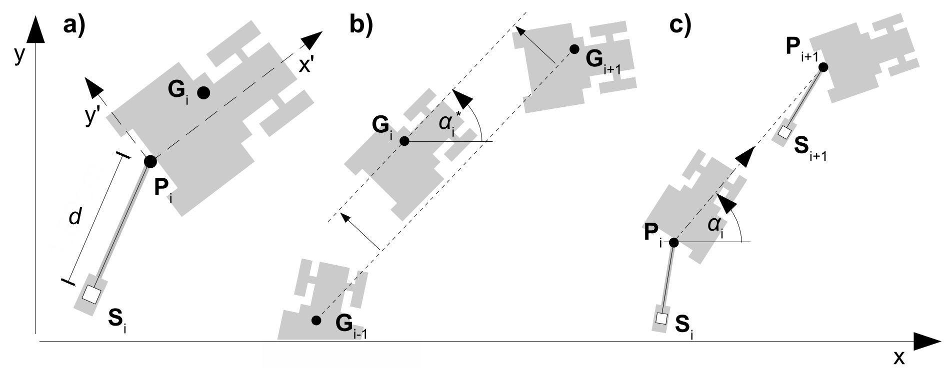

Fig. 1: a) Drawing vehicle equipped with a GNSS antenna at $\mathbf{G}_i$ and a sensor at $\mathbf{S}_i$ attached to the hitch point at $\mathbf{P}_i$ with fixed spacing d. The index specifies a point in time. x and y denote the earth-fixed field coordinate system, x' and y' the vehicle-fixed vehicular coordinate system. b) The heading of the drawing vehicle at $\mathbf{G}_i$, α_i^*, is approximated by the direction of the vector ($\mathbf{G}_{i+1}$-$\mathbf{G}_{i-1}$). c) The hitch point moves with direction α_i between $\mathbf{P}_i$ and $\mathbf{P}_{i+1}$.

3. Model Evaluation

We applied the model to a survey of apparent soil electrical conductivity (EC_a) with an EM38 ground conductivity meter (Geonics Ltd., Mississauga, Canada) at a 135 ha site. The site exhibited spatial patterns in EC_a on a sub-field scale, and was thus adequate to test the improvement on the assessment of spatial structures by modelling sensor positions. GNSS antenna positions and sensor data were collected synchronously at 1 Hz. The offset between antenna and hitch point was 2.25 m, that between hitch point and sensor was 3.25 m. In total, 103 867 measurements were taken. Driving at 7 km h^{-1} to 17 km h^{-1}, the distance between successively recorded positions ranged between 2 m and 5 m. The spacing between adjacent passes was 3 m to 5 m and curve radii were 2 m to 6 m.

We calculated anisotropic semivariograms in driving direction and perpendicular to it with measured and modelled positions respectively. They illustrate the direction dependent artefacts introduced by the offset between GNSS antenna and sensor when recording data in opposing direction on adjacent passes. Kriging-based cross validation was applied to assess the improvement of the prediction of individual EC_a measurements by the modelling. To assess curved pathways in particular, cross validation was also exclusively performed in areas where turning of the vehicle occurred ('headland area').

4. Results

The semivariance for lags <6 m calculated from positions of the GNSS antenna was considerably higher perpendicular to the driving direction (cross-pass) than along the path (Fig. 2, circles) while it was similar in along-path and cross-path directions (Fig. 2, squares) when derived from modelled sensor positions. This indicates that an apparent anisotropic spatial process (i.e. the offset) was superposed to the real spatial pattern of the measured variable [Zi93]. The RMSEs of cross validation with GNSS positions (1.52 mS m^{-1}, 1.83 mS m^{-1} for total and headland area, respectively) were similar to the accuracy of the sensor (±1.5 mS m^{-1} according to manufacturer). Still, the improvement by using modelled sensor positions was significant ($p<0.01$) and more pronounced on the headland area (RMSE 33 % lower) than in the total area (RMSE 25 % lower).

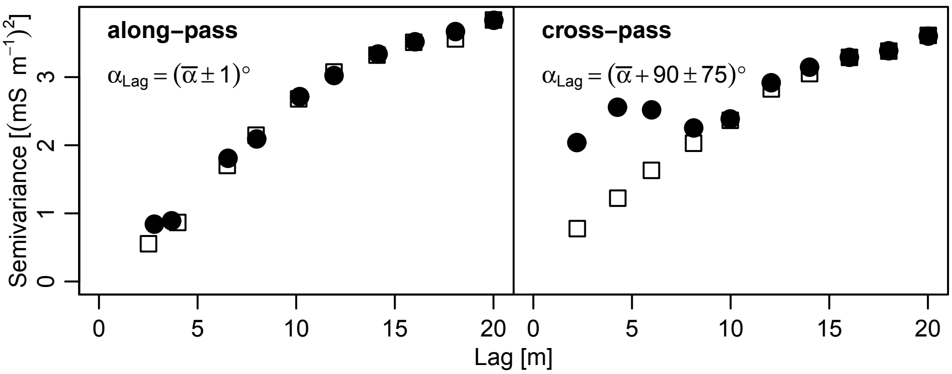

Fig. 2: Anisotropic semivariograms derived from GNSS antenna (circles) and modelled sensor positions (squares). Left panel: semivariogram in mean driving direction ($\overline{\alpha}$) with a small tolerance to include only pairs of positions lying on the same pass (6 % of total 485 000 pairs of positions). Right panel: anisotropic semivariogram perpendicular to $\overline{\alpha}$.

5. Discussion

Though the concept of tractrix has been used for the prediction of vehicle offtracking [GKM93, TMT92], to our knowledge, the benefits of this concept for on-the-go sensor applications and mapping have not yet been investigated.

Our model substantially decreased the effects of an offset between a GNSS antenna and a towed sensor, as shown by the reduction of directional dependence of the nugget (Fig. 2) and interpolation error. The pronounced improvement on headland area reveals the particular benefit for curved pathways. Our model relies on negligibility of centrifugal forces in curves, which can be easily controlled by driving sufficiently slow [GKM93]. Further improvements might be due to consideration of temporal offsets [SDK01], tilting of the vehicle [Sp00] and usage of more elaborate positioning technology [BGK98, HMT00, SH09]. An implementation for mapping or real-time applications [AHM04, Au01] and integration with other technologies [Sp00] is conceivable. Application of the model only requires knowledge of GNSS antenna positions and geometric configuration of GNSS antenna and sensor.

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