Design of a Low-Cost GPS/Magnetometer System for Land-Based Navigation: Integration and Autocalibration Algorithms

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Key words: land-based navigation, low-cost guidance system, GPS/magnetometer integration, autocalibration algorithm.

SUMMARY

The land-based navigation, paying attention to precision farming, is the research topic: the final purpose is the design and development of a guidance-aided system focusing on a low-cost GPS receiver able to provide a pseudorange-based solution only. Specific tests have been carried out to reproduce the trajectories followed by the vehicle in agricultural applications, whose accuracy target is typically 1 m. Results show that the investigated low-cost receiver is affected by a drift in time which is mainly detected while turning and causing a deviation from the optimal reference solution. Thus, the goal is to correct this behavior because the deviation accumulates during time and causes a not optimal treatment of the field (waste of material and money).

Paying attention to the cost of the system, a new idea is proposed: the integration between the low-cost GPS with a magnetometer/digital compass. A dedicated algorithm has been also implemented, taking the heading provided by the magnetometer and using it to correct the deviation in turns. Unluckily a magnetometer is deeply influenced by ferrous materials and the sensor is supposed to be installed on the vehicle, which is mainly made by metal. As a consequence, the sensed measurements are affected by a deviation from the actual magnetic field. Those disturbances need to be properly reduced by an autocalibration procedure. A new approach for the autocalibration problem has been developed and implemented; then the comparison with respect to the traditional method has been also performed in order to test and validate the new idea. A comprehensive and detailed description of all the algorithms will be produced concerning both the sensors integration (GPS and magnetometer) along with the magnetometer autocalibration. Particular attention will be focused on results and performances of the autocalibration procedure, which appears to provide very interesting results. The new approach, which is simply based on the covariance matrix, appears to be more successful than the traditional one. Several tests have been analyzed: the stand-alone low-cost GPS provides solutions which are not acceptable for precision farming applications, while the integration with a magnetometer slightly increases the accuracy. Furthermore, the innovation of the research is connected to the autocalibration algorithm itself. The final goal was the design of a low-cost system for supporting the guidance in land-based navigation; improvements are still required but the goal is close to be achieved.

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1. INTRODUCTION

This paper mainly focuses on the problem of land-based navigation by means of satellite positioning techniques. First of all, it should be highlighted how this topic is still an open worldwide research. Indeed, a great effort has been done concerning the airborne navigation within the general field of Mobile Mapping Technology (MMT) applications (Grejner-Brzezinska 2005). Referring specifically to land-based navigation, several aspects still need to find a solution in terms of accuracy and acceptability from an economic point of view. All those reasons encouraged to follow this challenging research. Recently, MMT potentialities became evident for a large number of applications; this forced a quick progress concerning the involved technology. As a consequence, such kind of research is strongly connected to the industrial community along with the scientific one. The main topic of this research is the use of low-cost GPS (Global Positioning System) for land-based navigation with particular attention to precision farming applications. Precision farming, sometimes called site-specific agriculture, is a strategic task for agriculture involving the use of different technologies such as GPS, GIS (Geographic Information System), remote sensing and so on. The minimal accuracy target for those applications is 1 m. It is worth to underline that an absolute accuracy would be the best solution but a sub-meter level of accuracy is impossible to achieve just by a single point positioning based on code signal only. Concerning those kinds of applications, a relative accuracy is even more important and can be very useful: it means that the sub-meter level of accuracy needs to be achieved with respect to the starting point of the vehicle. It does not matter if in an absolute point of view the starting point is not that accurate, what really matters is the optimized covering of the field while the vehicle is moving in relation to the initial position. Thus, the goal of this research is a sub-meter accuracy in relative terms and this may be achievable by means of low-cost sensors.

Low-cost GPS are able to provide a pseudorange-based solution only which, unfortunately, is affected by several meters of uncertainty (Leick, 2004) due to the single point positioning based on code signal only. Improvements are achieved by phase smoothing and additional filtering but still the accuracy is worst than 1 m and the challenge goes on. A solution to this problem still exists: it is obvious how such system could be improved by using a differential (DGPS or RTK) approach (Rizos, 2007; Wubbena et al., 2005). Allowing to receive corrections, it would provide a decimeters or centimeters level of accuracy, respectively. The point is that it would not be anymore a low-cost system: the problem of achieving a sub-meter accuracy can be solved despite of a higher cost. The challenge is to find a cheaper solution and improve pseudorange-based GPS operating in a stand-alone mode. A low-cost system, able to provide sub-meter accuracy, is the most important feature to make the GPS attractive for farmers. The system supports the human guide by means of a display, mapping the direction produced by the GPS put on top of the vehicle: the driver follows the single point

positioning solution visualized in order to cover the full field in an optimal way. In order to improve GPS solutions, the integration with additional sensors, such as magnetometers and IMU (Inertial Measurement Unit), has been investigated.
Concerning the land-based navigation, some essential aspects still appear to be critical: just an example, a lot of unsolved inconveniences occur because of frequent GPS losses of lock in urban canyons (Grejner-Brzezinska 2005). Indeed, the problem of GPS/IMU integration with all the related critical aspects was also deeply studied (Jekeli, 2001; Grejner-Brzezinska 2005). As a consequence, a better awareness of the potentialities and performances of the integration allowed the Authors to be able to design a low-cost system based on GPS and integrated sensors for supporting the human guidance in agricultural activities. Looking at the research, a high innovation content appears both from a scientific and a commercial point of view. Either manufacturers of high-tech systems and factories or companies offering services in the mentioned applications are concerned. After mentioning the implications, let start with the description of the research. The starting point of this research was the use of a particular kind of low-cost GPS receivers able to receive the code signal only, therefore providing a single point positioning without any carrier phase smoothing. They were originally developed for marine applications, but the manufacturer aimed to test their suitability for agriculture applications too. Tests and results are below described in order to highlight performances and problems. Following, a solution is proposed and investigated. The paper follows this workflow: the pseudorange-based GPS, working in a stand-alone mode, has been analyzed for precision farming navigation; the design of a low-cost system based on GPS/magnetometer integration has been investigated along with a proper algorithm; description of the implemented procedure with details on the integration algorithm are given; list of encountered problems and proposal of an innovative solution: a new autocalibration approach.

2. NAVIGATION BASED ON LOW-COST GPS

2.1 Test description

Specific tests have been carried out to simulate the particular trajectories followed by the vehicle in agricultural applications: both static and kinematic steps allowed to collect data along straight and parallel trajectories with reduced velocity, such as 20÷40 km/h (the motion of tractors when involved in field treatment). Three static stops of 20 minutes were performed, spaced with two kinematic steps of about 30 minutes: repetitions of the same trajectory were done. The vehicle was equipped with a double-frequency geodetic receiver (GX1230 with AX1202 antenna by Leica Geosystems) to provide reference solution and a low-cost receiver (TruRover by Leica Geosystems), both installed on the top of the vehicle. A reference station was tracking in the area in order to obtain a reliable reference solution for the geodetic trajectory by computing a relative positioning of the moving receiver with respect to the static one (geodetic post-processing at 1 Hz sampling rate). The low-cost receiver is not able to store any raw data; it just provides a NMEA format data stream containing coordinates (logging rate is 5 Hz). They were obtained by a single point positioning based on code signal only. The system was connected to an on-board laptop in order to store all dataset required for processing. Those tests were carried out in a parking lot nearby the Engineering Faculty of the University of Modena (Italy): the area dimension is about 200x200 m^2 that allowed to perform long straights sections separated by curves and repeat them several times. For test configuration and investigated area see Figure 1.

Figure 1. Test configuration: the vehicle equipment with both GPS on the top (left side), the master station for the reference solution processing (middle) and the trajectories (right side).

2.2 Results

Concerning the low-cost receiver, results are ready to be analyzed because coordinates are included in NMEA format output files. The reference solution was obtained by processing the raw data with respect to the master station, whose position was previously computed thanks to permanent stations located in the area. Performances of the low-cost instrument were evaluated by comparing NMEA format coordinates with the carrier-phase reference solutions. Results show that the low-cost receiver is affected by a drift in time causing a deviation with respect to the reference solution (see Figure 2 and Table 3). In the straight portions of trajectory, the difference between the two paths is well within 1m; a bias, often larger than 1m, is mainly detected in turns (Castagnetti, 2010a and 2010b; Biagi, 2007); thus, the goal is to correct this behavior because, as a consequence, straight portions are influenced too. The drift, indeed, accumulates during time and causes a bad and not optimal treatment of the field due to the fact that parallel and subsequent straights are spaced by a slightly increasing value. This has also economic consequences because not covering the field in an optimal way reduces the productivity and causes waste of resources and money. See Figure 1 for any details about test configuration and Figure 2 along with Table 3 for results.

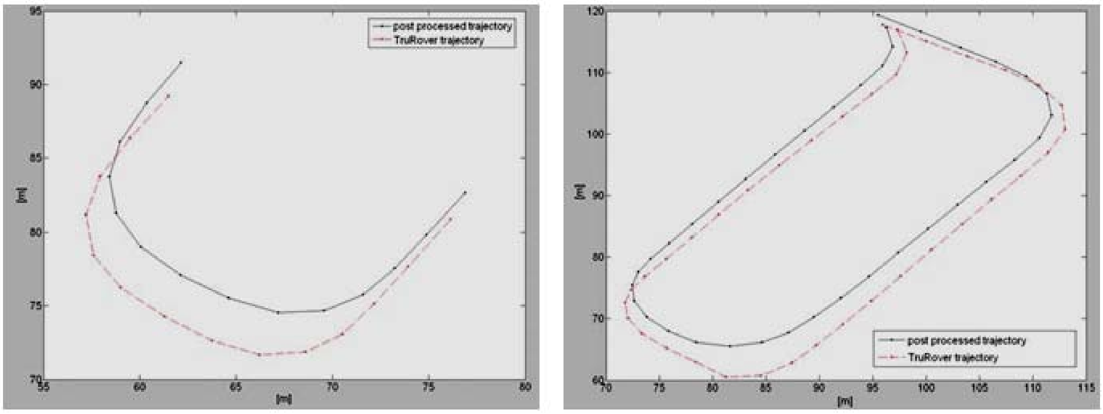


Figure 2. Example of the error in turns and trajectory estimation. Coordinates in meters, with respect to a mean position.

	1st kinematic section						**2nd kinematic section**				
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R1**	**R2**	**R3**	**R4**	**R5**
Pop	136	118	123	128	127	119	106	101	101	92	85
ΔE	0.3	0.3	0.4	0.3	0.3	0.4	0.2	0.1	-0.10	0.10	-0.2
$Max_{\Delta E}$	1.5	1.8	1.7	1.3	1.3	1.5	1.2	1.5	1.3	1.2	1.3
$Min_{\Delta E}$	-1.1	-1.3	-1.0	-1.0	-1.3	-0.8	-1.0	-1.2	-1.3	-1.4	-1.9
$\sigma_{\Delta E}$	0.6	0.7	0.6	0.6	0.7	0.5	0.5	0.6	0.6	0.5	0.7
ΔN	1.6	1.7	1.9	2.1	2.2	2.6	2.1	2.1	1.2	1.4	1.2
$Max_{\Delta N}$	3.3	3.5	4.0	4.6	4.0	4.6	5.3	7.6	4.9	6.8	2.9
$Min_{\Delta N}$	0.3	-0.3	0.0	0.1	0.2	0.3	-0.5	-0.2	-2.0	-0.9	-1.2
$\sigma_{\Delta N}$	0.6	0.8	1.0	1.0	0.8	1.0	1.0	1.4	1.4	1.3	0.8

Table 3. Statistics of the errors of the low-cost receiver. Results about the straight tracks of 1st and 2nd kinematic step (6 and 5 repetitions respectively). Rn: n repetition of the trajectory. Pop: number of results. ΔE, ΔN: mean errors in East and North; $\sigma_{\Delta E, \Delta N}$: standard deviations; $Max_{\Delta E, \Delta N}$, $Min_{\Delta E, \Delta N}$: maximum and minimum. All values in m.

Tests highlighted limitations and problems of pseudorange solutions provided by the investigated low-cost receivers. Those GPS were developed neither for land-based navigation nor specifically precision farming, but for maritime navigation. This is the reason why weird and not proper performances occurred during the first experimentation: the detected time drift causes a deviation of the vehicle trajectory with respect to the optimized coverage of the field. The reason for the radii overestimates in the curves is probably due to the presence of a filter not especially studied for farming applications and implemented inside the receiver firmware. This unknown filter provides not proper estimates in turns and worse resulting coordinates by predicting a larger curve radius. Thus, it produces an offset at the end of turns which does not allow to correctly position the vehicle in the following straight line.

This was the goal for first efforts: trying to reduce turns drift by removing the effects of the inside filtering. Firstly, a great effort was addressed to provide such improvement mainly in turns reconstruction by means of GPS positions filtering based on the Kalman technique (Kalman, 1960). For this reason, an algorithm based on the predictive properties of Kalman filter was implemented in Matlab language with the purpose of describing the process by means of two different models. The choice between them is done depending on the position of the vehicle moving on the field: a constant velocity model for straight paths and a constant acceleration model for turns.

In order to test the proper operation and quality of the algorithm, some simulations were carried out in order to obtain data scattered around a straight line. Verified the filter working on simulated data, the algorithm was tested on the real dataset. No significant improvements resulted, a slight correction can be noticed but errors are still greater than 1 m. The failure of this simple approach suggests the need of a new approach. The low-cost GPS in a stand-alone mode is not able to provide a sub-meter accuracy; thus, additional information provided by external devices may be investigated for better performances of the system.

3. GPS/MAGNETOMETER INTEGRATION AND NAVIGATION

Clearly appearing how a pseudorange-based GPS working in a stand-alone mode was unable to provide a sub-meter accuracy not even by a proper filtering, a new idea was required for the next step of the research. The sub-meter relative accuracy needs to be achieved by a low-cost system: this is the unavoidable requirement for precision faming applications. Hence, the development of an attractive system which is at the same time capable of accurate positioning of the moving vehicle but accessible to most users. As already described, an algorithm for low-cost receivers has been implemented to perform absolute positioning based on code pseudoranges only in a stand-alone configuration and without exploiting any further information due to the presence of additional devices such as, for instance, an odometer or steering monitoring and detecting system.

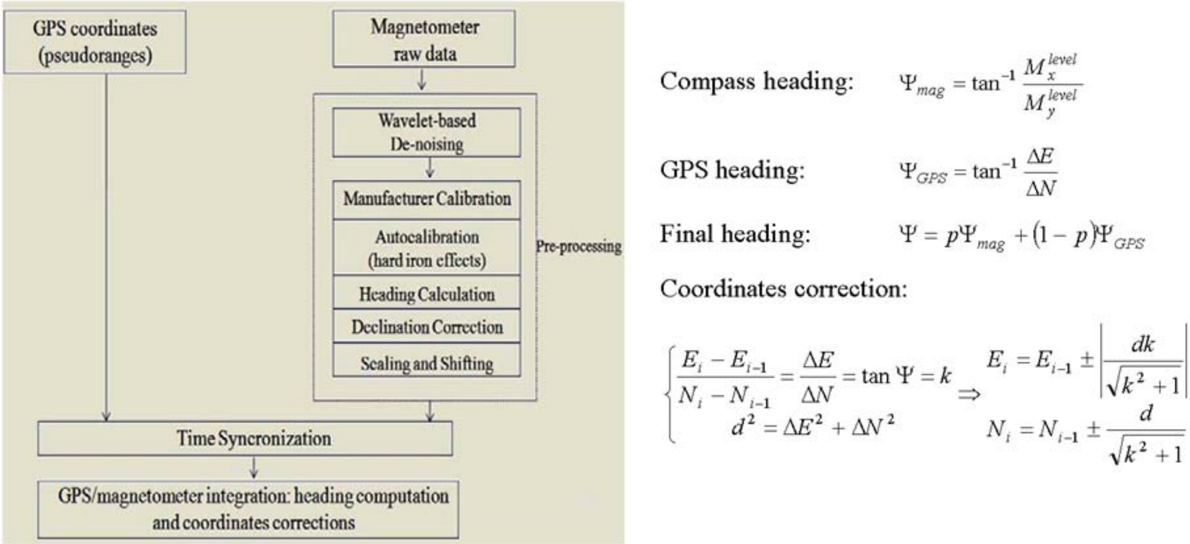
A solution to problems shown in the previous section could be found thank to the integration with external devices. For the particular application, a magnetometer has been taken into account. The integration problem was firstly studied; the comprehension of GPS/IMU integration (Jekeli, 2001) together with the knowledge of critical aspects in general land-based navigation, allowed to design an integrated system able to be successfully used in precision farming. Great attention has been paid to the cost of such system and to the problems detected by using pseudorange-based receivers. The goal is to provide the trajectory reconstruction in turns section: a reference angle to be used to correct the GPS curve radius is required. A new idea is proposed and investigated in order to focus on the specific problem highlighted in curves. The idea is the integration between the low-cost GPS with a magnetometer/digital compass (this is the chosen external device able to provide the reference heading angle): a dedicated algorithm has been implemented taking into account the heading solution by the magnetometer and using it to correct the deviation during turns.

The magnetometer has been chosen because the information which needs to be corrected is an horizontal angle. The problem, indeed, is the curves radius of the vehicle and the sub-meter accuracy is required in order to provide a subsequent straight track which is regularly spaced by the previous one. The magnetometer is a sensor giving an heading angle and, furthermore, its cost (about 100$ per axis for the cheapest one) is very low if compared with some other devices (see Castagnetti, 2010b for cost analysis). Indeed, inertial systems have been also considered, but they costs too much for the aimed design. The new cheaper MEMS IMU can be handled but they have a strong drift, quickly rising with time.

3.1 Integration Algorithm

The proposal for the design of a low-cost guidance system for precision farming purposes, is based on the integration between a low-cost GPS receiver, able to receive the code signal only, and a magnetometer/digital compass able to provide the heading angle of the moving vehicle. This might be used to reconstruct the curve radius and correct the GPS drift in turns.

As a consequence an algorithm has been implemented in Matlab language in order to test the integration. The general workflow of the procedure is depicted in left Figure 4. The concept of the procedure is described below along with details on implementations. Equations of the integration algorithm are specified in right Figure 4.



Compass heading: $\Psi_{mag} = \tan^{-1} \frac{M_x^{level}}{M_y^{level}}$

GPS heading: $\Psi_{GPS} = \tan^{-1} \frac{\Delta E}{\Delta N}$

Final heading: $\Psi = p\Psi_{mag} + (1-p)\Psi_{GPS}$

Coordinates correction:

$$\begin{cases} \frac{E_i - E_{i-1}}{N_i - N_{i-1}} = \frac{\Delta E}{\Delta N} = \tan\Psi = k \\ d^2 = \Delta E^2 + \Delta N^2 \end{cases} \Rightarrow \begin{matrix} E_i = E_{i-1} \pm \left| \frac{dk}{\sqrt{k^2+1}} \right| \\ N_i = N_{i-1} \pm \frac{d}{\sqrt{k^2+1}} \end{matrix}$$

Figure 4. Design of a low-cost system for supporting guidance in precision farming: workflow of the implemented algorithm for GPS/magnetometer integration (left side); basic equations for heading angle computation for curves reconstruction (right side).

As implemented by means of equations read in right Figure 4, the curve radius correction is based on a final heading angle depending on both the GPS solution and the magnetometer measurements. The magnetometer heading angle is computed by means of the sensed Earth magnetic field components (see section 3.2). In the following section, details on the procedure implemented by the Authors in order to have a reliable heading angle by magnetometer data. An heading angle can be also computed starting from GPS solutions only and it is independent, no relations are with the heading angle from the compass. Taking into account that the GPS solutions along straight portions of trajectory are not bad and its accuracy is acceptable, the final heading angle, which is going to be used to compute the proper correction for curve radius reconstruction, results from a weighted average of GPS-based heading and compass-based angle. Two different weights have to be used depending on the position of the vehicle: if it is moving along straight directions more importance is left to the GPS-based heading angle because GPS solutions were reliable; whereas in turns a higher weight is given to the compass angle because it might correct the GPS drift. A new set of corrected coordinates can be calculated thanks to the correction factor which is also based on the distance between subsequent points; concerning about distances it is reasonable to trust in GPS because it has to be improved only in turns, that is angular property. Therefore, the implemented algorithm for curve radius reconstruction is concerned with the following steps:

− compass heading, available by the magnetometer (M_x and M_y are components of the sensed magnetic field in the local horizontal plane);
− GPS heading calculated by GPS coordinates (East and North);
− final heading, calculated by means of a weighted average of the compass heading and the GPS one, depending on the vehicle position;
− distances computation starting from GPS coordinates;
− correction factors to be applied to the previous coordinates can be calculated in order to determine the new position because all elements are available (d and k);

– sign definition depending on the direction of the vehicle (the decision is based on the final heading angle value)

– coordinates update and plot generation.

The time synchronization is a key role step; it consists on joining magnetometer data (100 Hz) at the same sampling rate as GPS solutions (1 Hz). Several interpolating strategies were taken into account; finally the moving average was chosen and implemented. Let just mention that raw magnetometer measurements are firstly subjected to de-noising (wavelet-based strategy has been chosen).

3.2 Autocalibration Procedure

The external and cheap device chosen in this proposal of design for a low-cost guidance system is a magnetometer. The great problem with a magnetometer is that it is deeply influenced by ferrous materials (Caruso, 2000) and the sensor is supposed to be installed on the vehicle, which is mainly made by metal. This causes a deviation from the actual magnetic field and the sensed measurements are affected by those disturbances, which must be taken into account and properly reduced. This is done by an autocalibration procedure implemented in Matlab language whose results are discussed and shown in Figure 5.

The magnetometers are used for absolute heading determination with reference to the local magnetic North, where the heading is derived from the horizontal force of the magnetic field.

The magnetometer chosen for this research (MTi by XSENS Technologies) measures absolute orientation through a combination of three-axes magnetic sensors and two-axes tilt sensors (inclinometer). The magnetic compass senses the Earth's magnetic field intensity and the inclinometer measures the angle between the direction of the gravity and the sensing system. If the magnetometer was aligned with the local horizontal plane (during tests attention should be paid to its placement which must be as horizontal as possible), the heading, ψ, would be calculated as (Moafipoor, 2009):

$$\psi = \tan^{-1} \frac{M_x^{level}}{M_y^{level}}$$

where *M* represents the Earth magnetic field along *x* and *y* axes, aligned with the horizontal plane. The measured magnetic azimuth is also subject to magnetic disturbances, superimposed into the Earth's magnetic field (Caruso, 2000): the quality of the magnetometer heading strongly depends on tilt compensation (if not horizontally located) and the calibration procedure, including identifying possible error sources and removing them from the measurements.

A comprehensive study on possible magnetometer error sources shows five significant factors which can impact the compass accuracy (see Caruso, 2000; Moafipoor, 2007): magnetic sensor sensitivity, nearby ferrous materials, sensor tilt, declination angle and temperature.

In this research great attention was paid to nearby ferrous materials: when the magnetometer is close to ferrous materials, its measurements are corrupted by the local magnetic field coming from these materials. The ferrous materials are usually classified into two groups: hard iron and soft iron. The magnetic field of the hard iron varies very slightly in space and causes a quasi constant bias in heading observations (Caruso, 1997): as a result, it adds a constant magnetic field component to the Earth magnetic field. As a consequence, the sensor needs to be calibrated to compensate the local variation of the Earth's magnetic field. In the present research, no external aid has been taken into account so an autocalibration procedure has been implemented and applied (no additional devices are available and the purpose is to investigate whether GPS may be improved by the magnetometer itself). The traditional autocalibration method (inspired by Caruso,1997), is based on the fact that the locus of error-free magnetometer measurements is a circle if the sensor moves around a circle. The impact of various magnetometer errors would distort the shape of this circle; however, the circular constraint eventually can be used to partially estimate local variations of the Earth's magnetic field.

Practical implementation of the autocalibration does not require any reference headings, but this method strongly depends on the position and the effect of ferromagnetic materials in the proximity of the sensor. If the sensor's location is changed and it is exposed to a new environment, a new calibration is necessary for identifying and removing effects of the new magnetic environment.

$$\begin{aligned} M_x &= S_x M_x^{Level} + B_x \\ M_y &= S_y M_y^{Level} + B_y \end{aligned} \quad \rightarrow \quad \begin{aligned} & S_x = Max\left(1, \frac{M_y^{Max} - M_y^{Min}}{M_x^{Max} - M_x^{Min}}\right), S_y = Max\left(1, \frac{M_x^{Max} - M_x^{Min}}{H_y^{Max} - H_y^{Min}}\right) \\ & B_x = \left(\frac{M_x^{Max} - M_x^{Min}}{2} - M_x^{Max}\right) S_x, B_y = \left(\frac{M_y^{Max} - M_y^{Min}}{2} - M_y^{Max}\right) S_y \end{aligned}$$

S_x , S_y are two scale factors, B_x, B_y are two biases along the horizontal axes of the magnetic field, M appears several times meaning the maximum and minimum of the measured magnetic field along x and y axes. To calibrate the magnetometer using the above equation (Moafipoor, 2009), a simple method is to perform a loop maneuver and to determine scale factors as the ratio of the major and minor axes, changing the circle to an ellipse, and bias parameters as the offset center of the ellipse.

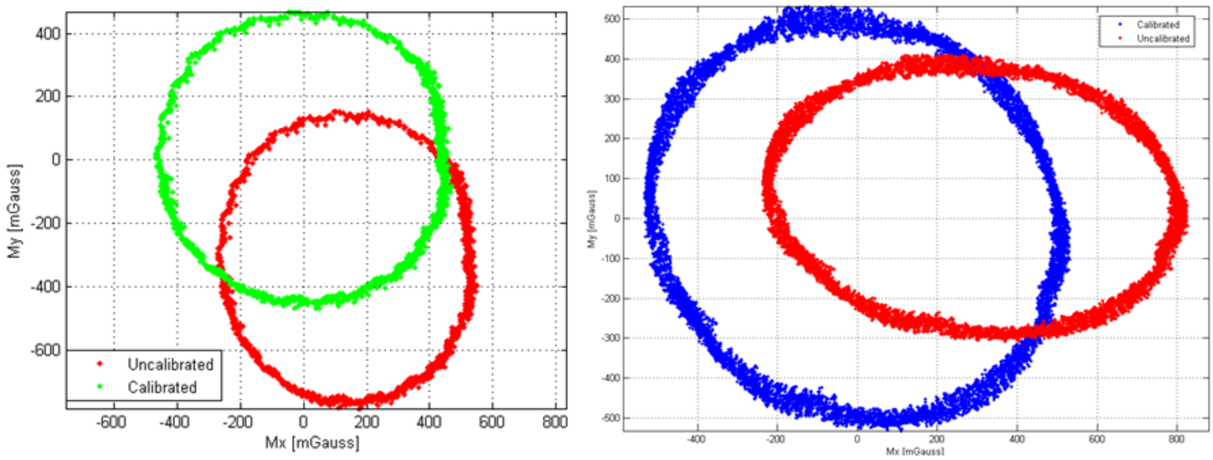


Figure 5. Performances of the implemented autocalibration procedure for iron effects correction. Computation on simulated data (left side) and on real data (right side).

First of all the above mentioned autocalibration approach has been implemented and applied to a simulated dataset in order to test the successfull implementation. Results are shown in left Figure 5 where the red line represents the uncalibrated data while the green one the corrected data. The scale factor and the deviation from the round shape are properly corrected. The second step is the computation on real data: results are shown in right Figure 5 where a strong correction can be appreciated along with a slightly residual oval shape.

3.3 Tests and results

New dataset were collected: the magnetometer was put on the vehicle together with two GPS receivers (the low-cost one and a double frequency one for the reference trajectory). The magnetometer was added to the on-board equipment and connected to a laptop for data storage. New tests were performed in a parking lot and, again, simulating tractors trajectories (Figure 6). Circular maneuvering were also performed for the autocalibration process.
Data were processed and heading angles, resulting from the magnetometer, were integrated with pseudorange GPS solutions by means of the implemented algorithm. The algorithm estimates the final coordinates by properly weighting the heading angles obtained by the original GPS coordinates and the heading observations provided by the low-cost magnetometer. Particular attention has to be paid to weights: higher weight to magnetometer measurements in turns and more importance to the GPS-based one in straights because the problem is mainly evidenced while the vehicle bends. Thus, after the data pre-analysis (autocalibration and synchronization), the heading angle is ready to be used and integrated with GPS data: the magnetometer heading angle should have a higher weight when the vehicle is in curves because it is exactly where the GPS does not provide a reliable solution and it has to be corrected. The right curve radius can be reconstructed by the aid of the compass and the sub-meter accuracy can be maintained both in turns and straight portions.

Figure 6. Test configuration: vehicle equipment with both GPS on the top and the magnetometer inside (left side); comprehensive view of the area with trajectories (right side).

Both the autocalibration and the integration algorithm were run on collected data. Results are shown in Figure 7. The upper left plot represents a single repetition of the trajectory in the parking lot; it can be easily noted from the yellow line that the implemented integration works properly but it does not improved results with the going of time: turns reconstruction by magnetometer measurements seems to be a good idea but more analysis must be done.

Indeed, a deeper study about the influence of the weights may help to improve results. In addition, magnetometer data have to be carefully analyzed because an unexpected drift with time occurs causing errors in positioning with respect to the reference solution: at the beginning the compass heading works properly and solutions are reliable but in the following a slow drift is clear.

The upper right plot in Figure 7 shows the heading angle comparison among the magnetometer one, the low-cost GPS one and the reference one and also provides the pattern of the computed final heading. The plot confirms that the heading computation works properly and that compass measurements provide reasonable solutions. The yellow line, showing the final heading, actually yields to the coordinates correction factor, that strongly depends on the chosen weight. The GPS reference heading angle is given just to provide a comparison and see if some improvements has been achieved.

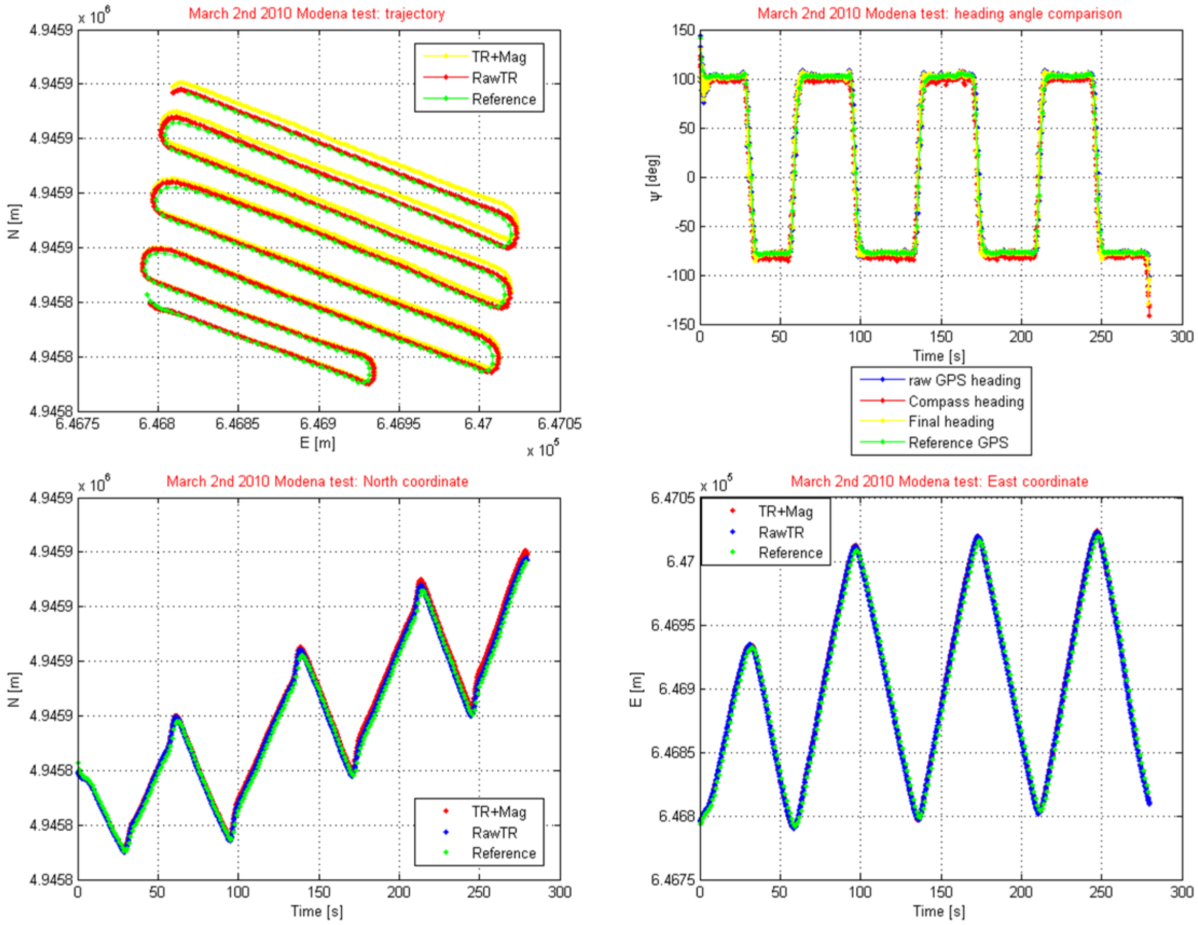


Figure 7. GPS/magnetometer integration: trajectory (upper left side); heading angle (upper right side); North component (lower left side); East component (lower right side).

The lowest two plots of Figure 7 show the East and North components comparison in order to clarify that more analyses should be done in order to investigate the late drift caused, maybe, by magnetometer measurements. Note that the East component is more accurate; the error grows with time and mainly influences the North component where a separation between the blue (stand-alone GPS) and the red (GPS/magnetometer integration) lines is more evident in the second half of the trajectory.

This might be due to a wrong or not completely controlled correction of the deviation angle when the Geographic and the Magnetic North have to be aligned. A deep check was done on this section of the procedure and no errors were detected concerning the North alignment. A more specific study should be performed in order to figure out whether this is a problem of the implemented algorithm or maybe due to a time drift relevant to the magnetometer itself.

As previously noticed in right Figure 5, the implemented approach does not provide a perfect and optimal calibration for ferrous materials. A slight deviation from the circular shape still occurs and this might be the reason for a rising deviation in final trajectory. Efforts, now, are addressed to a new autocalibration approach, an innovative strategy implemented by the Authors. This new idea for the autocalibration aims to improve the final heading angle in order to provide an optimized integration between a pseudorange-based GPS and a magnetometer for the design of a low-cost guidance system for farming applications. Once a good calibration is gained for magnetometer data, any further problems highlighted in results should not be due to magnetometer data. This possible error source would be removed, thus new hypothesis for solutions could to be considered.

3.4 New magnetometer autocalibration

Although the integration algorithm runs properly, the final trajectory is not yet properly corrected and the accuracy target is not yet gained. The identified problem mainly concerns the North direction where a weird deviation occurs and increases with time. As a consequence the final solution is not optimal. This problem might be due to raw magnetometer data which are affected by high level of measurements noise or the declination correction is not good enough: both these hypotheses have been deeply analyzed but are not the source of inconveniences. Another option is that the standard autocalibration is not optimized. As above mentioned, right Figure 5 shows some residuals in the implemented autocalibration so that a new idea has been developed about the autocalibration strategy. The basic idea is simple: the distorted magnetic field displays as an ellipse while it should be a perfect circle as soon as the sensor is moving in circles. Running the vehicle in circles while performing tests allows to have data for the autocalibration for hard irons effects. So that the final purpose of the autocalibration is still to correct data by computing parameters in order to change the original shape in a perfect ring. The new approach is based on a well-known statistic method to transform a variable in order to normalize (e.g. to transform in an identity matrix) its covariance matrix. Applying this strategy to the magnetic field components x and y, their values are corrected and the shape changes into a perfect ring. Detailed equations of the new autocalibration algorithm are described in left Figure 8, while results are shown in right Figure 8, where the results provided by the standard and the new autocalibration approaches are compared with the uncalibrated data.

In right Figure 8 the same data of right Figure 5 are displayed together with a new dataset resulting from the new autocalibration approach (green line). The scale factor is almost the same because the old method was good concerning this parameter. A real improvement can be appreciated in the distortions affecting the shape. The new implemented autocalibration seems to improve significantly the magnetometer data pre-processing with respect to the traditional approach.

$$M = \begin{bmatrix} M_x \\ M_y \end{bmatrix}$$

$$\mu = \frac{1}{n}\sum M_i ; C = \begin{bmatrix} \sigma_{M_x}^2 & \sigma_{M_x M_y} \\ \sigma_{M_x M_y} & \sigma_{M_y}^2 \end{bmatrix}$$

$$\varepsilon = M - \mu$$

$$\mu_\varepsilon = 0; C_{\varepsilon\varepsilon} = C = TT^T$$

$$\vartheta = T^{-1}\varepsilon = T^{-1}(M - \mu)$$

$$C_{\vartheta\vartheta} = T^{-1}CT^{-1T} = I$$

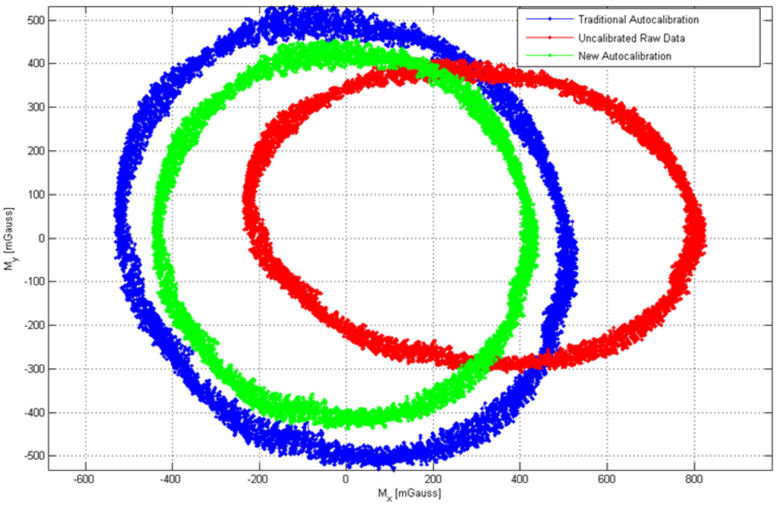


Figure 8. Performances of magnetometer autocalibration algorithms: basic equations of the new approach (left side); results comparison (right side: green line for the new approach, red line for uncalibrated data and blue line for the traditional approach).

4. CONCLUSIONS

A land-based navigation based on low-cost GPS receivers, providing pseudorange solutions only, has been deeply analyzed for precision farming applications. The minimal relative accuracy for those activities is 1 m. A problem while the vehicle is turning was detected: a deviation often greater than 1 m caused a not optimal treatment of the field. As a consequence, a big waste of materials and money is unavoidable when large fields have to be managed.

The first effort to figure out the problem consisted in the implementation of a Kalman-based filtering. No improvements were provided. The second effort aimed to find a solution by means of the integration with external devices. Thinking about the specific problem, a reference heading angle is required to improve the reconstruction of the curves. Thus, the idea is the use of a low-cost system based on the integration between a GPS and a magnetometer/digital compass. A dedicated algorithm has been also implemented in order to get the heading angle ready to be integrated with GPS solutions and provide the corrected trajectory. Some inconveniences still occur when running the algorithm because a deviation mainly detected in the North direction appears to rise with time. Some analyses concerning the Magnetic and Geographic North alignment (declination correction) confirmed that no errors have been made in that section. Concerning the magnetometer data, attention should be paid because of deviations due to nearby ferrous materials. A traditional autocalibration approach was adopted but results are not optimal. A new strategy has been investigated and present results are encouraging. More data and more analyses are required in order to optimize the algorithm both in the autocalibration and in the integration procedure. New tests will help to better understand the behavior of magnetometer heading angles. This will also help both in choosing the proper weighting strategy and improving integration with GPS data.

The weighting strategy has a great influence on solutions when turns are of concern, while straight portions are less affected.

The goal of future developments is an optimized design for a low-cost system to be successfully used in precision farming applications for supporting the human guidance. Further analyses could be performed by connecting the system with external devices and sensors which already are in the vehicle such as odometers, steering system and so on. Additional data from on-board sensors could improve the solution without asking any additional cost.

The effective usefulness and the suitability of such system would require all the computations to be performed in real-time, while the operators is moving. During the design of the system and algorithms implementation, the potentiality to work in real-time mode has been taken into account. Future efforts should be addressed towards this purpose in order to make the system attractive for manufacturers and then for users too.

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BIOGRAPHICAL NOTES

Cristina Castagnetti successfully completed her PhD in March 2010 at the University of Modena and Reggio Emilia. She took her degree in Environmental Engineering studying kinematic positioning by means of GNSS. Her PhD dissertation focused on land-based navigation with particular attention to the design of a low-cost system for precision farming application (guidance aided by GPS and external sensors). She is also involved in GNSS permanent networks and reference frames.

Ludovico Biagi is a full time researcher, interested in GNSS permanent networks: particularly, he is involved in the implementation of real time positioning services and of a zero order permanent network in Italy; he is studying and implementing new algorithms for geodynamical deformations analysis from coordinates time series. He is professor of Geodetic and Deformation Monitoring and Remote Sensing at Politecnico of Milan (Polo of Como).

Alessandro Capra took his degree in Mining Engineering at the University of Bologna (Italy). He is Full Professor of Geodetic Sciences, Surveying and Mapping at the Engineering Faculty of University of Modena and Reggio Emilia. He also is Chief officer of Geosciences group of SCAR (Scientific Committee on Antarctic Research), President of SIFET (Italian Society of Photogrammetry and Surveying) scientific committee and Editor-in-chief of *Applied Geomatics* journal.

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