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

Cristina Castagnetti[(a)], Ludovico Biagi[(b)], Alessandro Capra[(a)]

(a) University of Modena and Reggio Emilia – DIMeC
(b) Politecnico of Milan - DIIAR c/o Polo di Como

Outline

- Motivation and purpose
- Application field
- Research steps:
  1. GPS-based navigation and limitations
  2. GPS/magnetometer integration
- Integration and autocalibration algorithms
- Conclusions and future developments

Motivation and Purpose

- Land-based navigation
- Precision farming applications (accuracy < 1m)
- Low-cost guidance system
- Pseudorange-based GPS analysis
- Multi-Sensors Integration (GPS/magnetometer)
- Proposal for a low-cost integrated guidance system:
  - Sensors configuration
  - Algorithms implementation

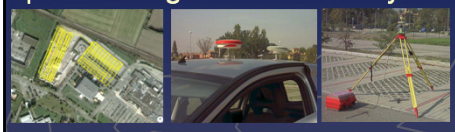
Application field

Precision farming
or site-specific agriculture

strategic task for agriculture involving the use of different technologies such as GPS, GIS, remote sensing, etc.

GPS-based Navigation

Low-cost GPS performances: pseudorange solutions analysis



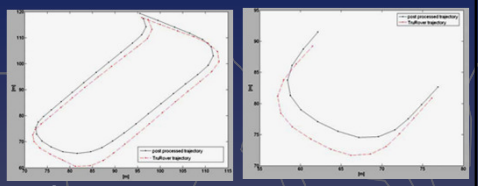
	1st R	2nd R	3rd R	4th R	5th R	6th R
Pop	136	118	123	128	127	119
ΔE	0.3	0.3	0.4	0.3	0.3	0.4
$Max_{\Delta E}$	1.5	1.8	1.7	1.3	1.3	1.5
$Min_{\Delta E}$	-1.1	-1.3	-1.0	-1.0	-1.3	-0.8
$\sigma_{\Delta E}$	0.6	0.7	0.6	0.6	0.7	0.5
ΔN	1.6	1.7	1.9	2.1	2.2	2.6
$Max_{\Delta N}$	**3.3**	**3.5**	**4.0**	**4.6**	**4.0**	**4.6**
$Min_{\Delta N}$	0.3	-0.3	0.0	0.1	0.2	0.3
$\sigma_{\Delta N}$	0.6	0.8	1.0	1.0	0.8	1.0

	1st R	2nd R	3rd R	4th R	5th R
Pop	106	101	101	92	85
ΔE	0.2	0.1	-0.10	0.10	-0.2
$Max_{\Delta E}$	1.2	1.5	1.3	1.2	1.3
$Min_{\Delta E}$	-1.0	-1.2	-1.3	-1.4	-1.9
$\sigma_{\Delta E}$	0.5	0.6	0.6	0.5	0.7
ΔN	2.1	2.1	1.2	1.4	1.2
$Max_{\Delta N}$	**5.3**	**7.6**	**4.9**	**6.8**	**2.9**
$Min_{\Delta N}$	-0.5	-0.2	-2.0	-0.9	-1.2
$\sigma_{\Delta N}$	1.0	1.4	1.4	1.3	0.8

Statistic of the errors of the low-cost receiver results in straight tracks (1st and 2nd trajectory) with respect to the reference carrier phase-based solution.

– Biagi, L., Capra, A., Castagnetti, C., Dubbini, M. and Unguendoli, F., 2007. "GPS navigation for precision farming". *Proceedings of the 5th Symposium on Mobile Mapping Technology*, Padua 2007, ISPRS volume XXXVI, part 5/C55 pp: 46-53.
– Castagnetti, C., 2010. "*GPS-aided land-based navigation and precision farming applications: improving GPS solutions by means of MEMS IMU and low-cost sensors*". Dissertation presented in partial fulfillment of the requirements for the Degree Doctor of Philosophy. 1

Low-cost GPS limitations

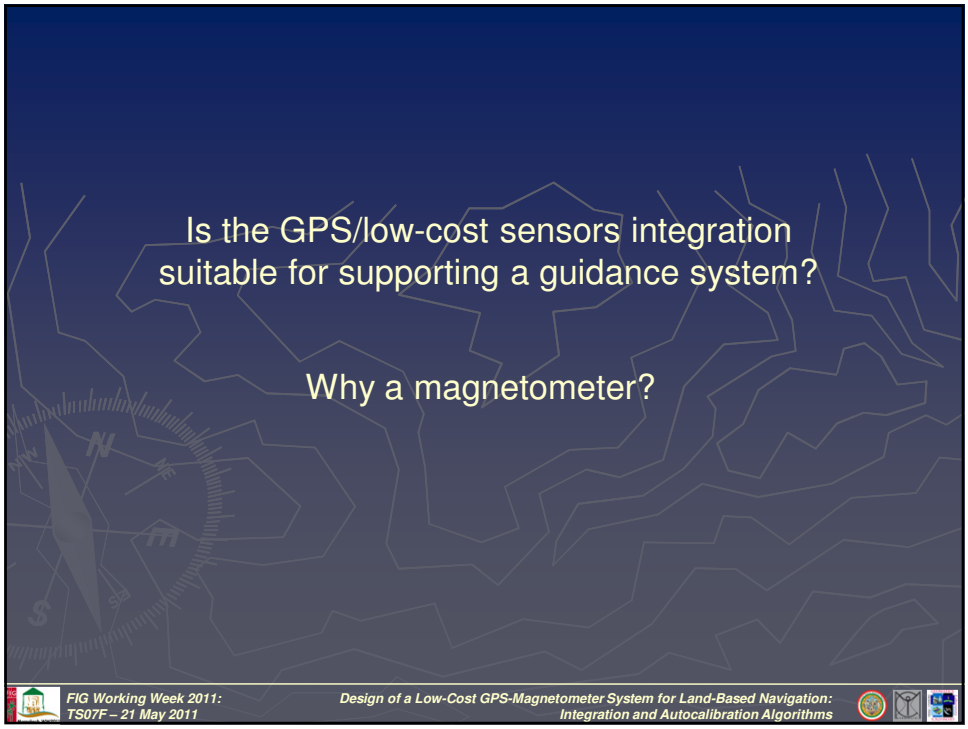


- Highlighted problems:
  - Shift mainly in turns
  - Drift with time
  - Deviation from optimal trajectory
  - Waste of resources
- Improvement efforts:
  - Kalman filtering with two different models
- Failure

– Biagi, L., Capra, A., Castagnetti, C., Dubbini, M. and Unguendoli, F., 2007. "GPS navigation for precision farming". *Proceedings of the 5th Symposium on Mobile Mapping Technology*, Padua 2007, ISPRS volume XXXVI, part 5/C55 pp: 46-53.
– Castagnetti, C., 2010. "*GPS-aided land-based navigation and precision farming applications: improving GPS solutions by means of MEMS IMU and low-cost sensors*". Dissertation presented in partial fulfillment of the requirements for the Degree Doctor of Philosophy. 1

FIG Working Week 2011: TS07F – 21 May 2011
Design of a Low-Cost GPS-Magnetometer System for Land-Based Navigation: Integration and Autocalibration Algorithms


Available Solutions:
Double frequency GPS
RTK GPS positioning
Integration with external sensors
FIG Working Week 2011:
TS07F – 21 May 2011
Design of a Low-Cost GPS-Magnetometer System for Land-Based Navigation:
Integration and Autocalibration Algorithms


Is the GPS/low-cost sensors integration
suitable for supporting a guidance system?
Why a magnetometer?
FIG Working Week 2011:
TS07F – 21 May 2011
Design of a Low-Cost GPS-Magnetometer System for Land-Based Navigation:
Integration and Autocalibration Algorithms

Low-cost Guidance System

+

+ Pre-processing and Integration Algorithm (implemented in Matlab v.7.0)

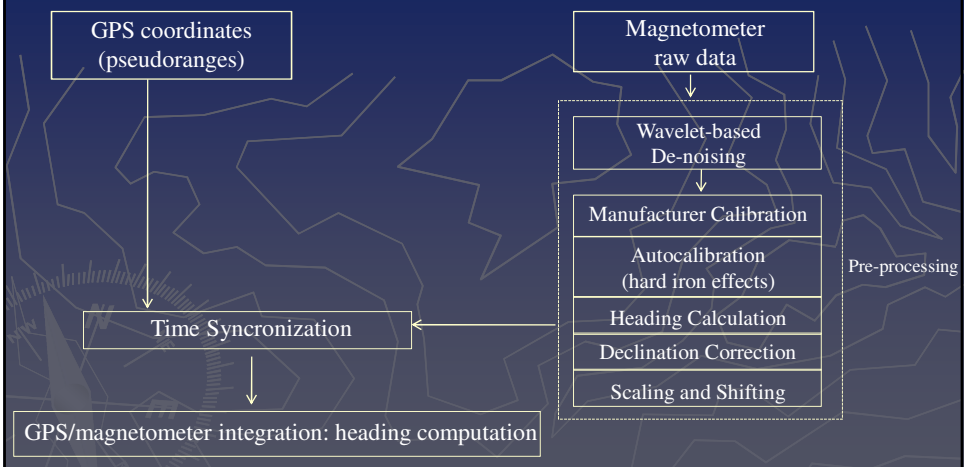
GPS low-cost receiver (*TruRover Leica*)

- code signal only;
- single point positioning;
- 5Hz;
- NMEA output format;
- no raw data storage

Low-cost MEMS IMU (*MTi XSENS*)

- MEMS IMU (3gyros+3accelerometers);
- 3 axes magnetometer;
- 100Hz;
- ASCII output format;

Implemented Algorithm



Algorithm Workflow: implementation in Matlab language.

Autocalibration Algorithm

GPS coordinates (pseudoranges)

Magnetometer raw data

Wavelet-based De-noising

Manufacturer Calibration

Autocalibration (hard iron effects)

Heading Calculation

Declination Correction

Scaling and Shifting

Pre-processing

Magnetic field corrections:

$$M_x = S_x M_x^{Level} + B_x$$
$$M_y = S_y M_y^{Level} + B_y$$

$$S_x = Max\left(1, \frac{M_y^{Max} - M_y^{Min}}{M_x^{Max} - M_x^{Min}}\right), S_y = Max\left(1, \frac{M_x^{Max} - M_x^{Min}}{H_y^{Max} - H_y^{Min}}\right)$$

$$B_x = \left(\frac{M_x^{Max} - M_x^{Min}}{2} - M_x^{Max}\right) S_x, B_y = \left(\frac{M_y^{Max} - M_y^{Min}}{2} - M_y^{Max}\right) S_y$$

Traditional autocalibration method (Caruso, 1997 and 2000; Moafipoor, 2007 and 2009): the locus of error-free magnetometer measurements is a circle if the sensor moves around a circle

Autocalibration Algorithm

GPS coordinates (pseudoranges)

Magnetometer raw data

Wavelet-based De-noising

Manufacturer Calibration

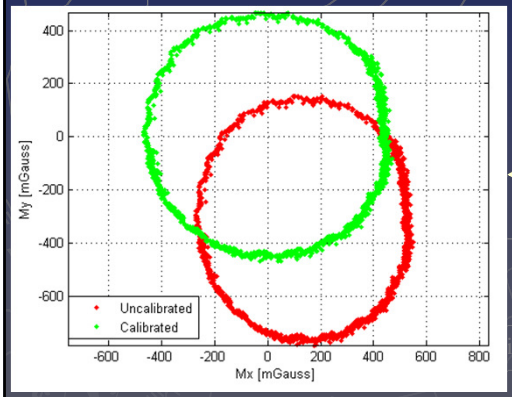
Autocalibration (hard iron effects)

Heading Calculation

Declination Correction

Scaling and Shifting

Pre-processing



Traditional autocalibration procedure: performances on simulated data.

FIG Working Week 2011: TS07F – 21 May 2011

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

Integration Algorithm

GPS coordinates (pseudoranges)

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:

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

Time Syner

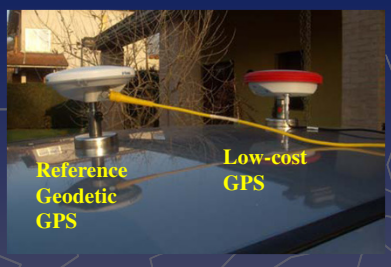
Pre-processing

Scaling and Shifting

GPS/magnetometer integration: heading computation

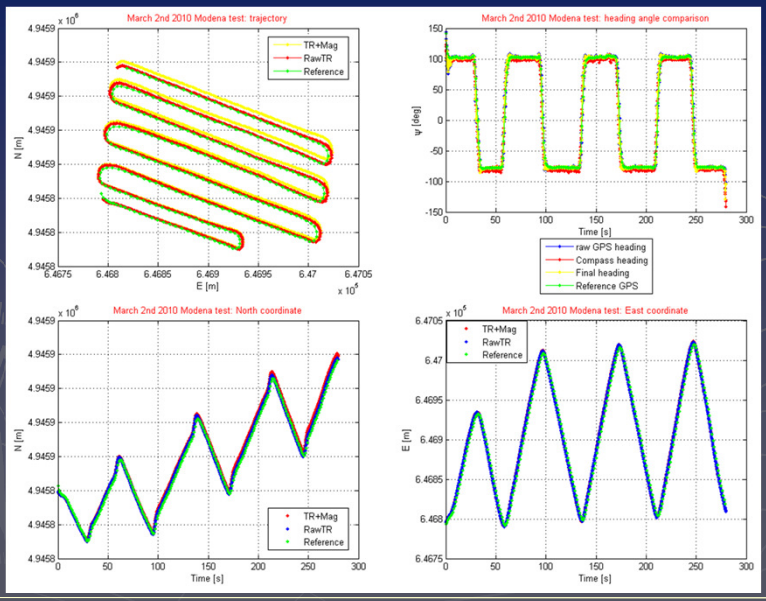
Algorithm for GPS/Magnetometer integration.

Tests



Test configuration: trajectory in a parking lot (map from Google Earth) and vehicle equipment.

Results



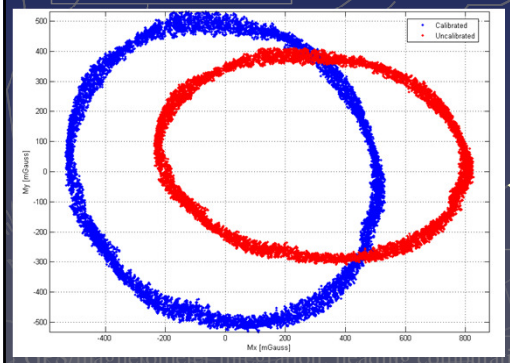
Limitations and Hypothesis

- Identified problems:
  - Deviation in North direction
  - Not proper trajectory correction
- Hypothesis:
  - Raw magnetometer data with high level of measurements noise
  - Declination correction
  - Not good autocalibration or integration

Autocalibration results

GPS coordinates (pseudoranges)

Magnetometer raw data



Wavelet-based De-noising

Manufacturer Calibration

Autocalibration (hard iron effects)

Heading Calculation

Declination Correction

Scaling and Shifting

Pre-processing

Traditional autocalibration procedure: performances on collected data.

New Autocalibration approach

GPS coordinates (pseudoranges)

Magnetometer raw data

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

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

$$\varepsilon = M - \mu$$

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

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

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

Wavelet-based De-noising

Manufacturer Calibration

Autocalibration (hard iron effects)

Heading Calculation

Declination Correction

Scaling and Shifting

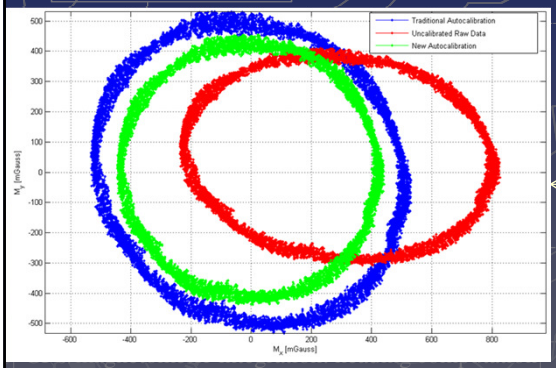
Pre-processing

New autocalibration approach for magnetometer data: the basic idea is still to change the distorted shape (ellipse) into a perfect ring. To do this the use of a well-known statistic method to transform a variable in order to normalize (e.g. to transform in an identity matrix) its covariance matrix.

New Autocalibration results

GPS coordinates (pseudoranges)

Magnetometer raw data



Wavelet-based De-noising

Manufacturer Calibration

Autocalibration (hard iron effects)

Heading Calculation

Declination Correction

Scaling and Shifting

Pre-processing

New autocalibration approach for magnetometer data: performances on collected data.

Conclusions

- Design of a low-cost guidance system
- Pseudoranges-based GPS investigation for navigation
- Precision farming applications: significant drift in time
- Proposal for a low-cost integrated guidance system
  - System configuration=GPS/magnetometer integration
  - Algorithm implementation: de-noising, autocalibration, integration
  - Performances: drift in magnetometer data (problems in the implemented algorithm? which procedure?)
  - New autocalibration approach implementation

Future developments

- New test on magnetometer data
- Algorithm optimization
- New autocalibration performances analysis
- Investigation of the integration with MEMS IMU
- Further integration with on-board sensors

cristina.castagnetti@unimore.it

FIG Working Week 2011: TS07F – 21 May 2011
Design of a Low-Cost GPS-Magnetometer System for Land-Based Navigation: Integration and Autocalibration Algorithms