Proceedings of the IASTED International Conference
Robotics and Applications 2000
August 14-16, 2000 – Honolulu, Hawaii, USA

Experimental Results with the KVH C-100 Fluxgate Compass in Mobile Robots

by
Lauro Ojeda and Johann Borenstein
The University of Michigan
Dept. of Mechanical Engineering and Applied Mechanics
Ann Arbor, MI 48109-2110
lojeda@eecs.umich.edu; johannb@umich.edu

ABSTRACT

This paper presents a discussion on the use of electronic compasses in mobile robots. Different error sources are considered, and solutions are proposed to correct these errors. Experimental results show the effectiveness of some of the error reduction measures. The results also show what performance can be expected from a well-calibrated compass system.

The overall most important result is that errors due to external magnetic interferences are the most severe and hard-to-correct ones.

Keywords: Mobile Robots, Compass, Navigation, Sensors

1. INTRODUCTION

Accurate position estimation is one of the foremost concerns in mobile robotics. Position estimation methods can be divided into two categories: absolute and relative positioning [1].

1. *Absolute positioning* typically relies on external references, such as beacons, reflectors, or other environmental landmarks. If the position of these external references is known, then the position of the mobile robot can be computed, usually with good accuracy. The problem with most absolute positioning methods is that they require modifications of the environment prior to utilizing the system.
2. *Relative positioning* relies on sensors that do not require external references, such as encoders for odometry and gyroscopes or accelerometers for inertial measurements. The advantage of these systems is that they do not require modifications of the environment. The disadvantage is that they tend to accumulate errors without bound.

One sensor that is formally part of the first category, but in practice can be used as though it was part of the second, is the compass. The compass is somewhat distinct from other absolute positioning sensors in that it does not require environmental modification. That is, of course, because the earth's magnetic field is readily available virtually anywhere on earth.

1.1 The Earth's Magnetic Field[1]

Figure 1 shows how the earth's magnetic field (F) is composed of a vertical (V) and horizontal (H) component. The magnetic field is perfectly vertical in the magnetic poles (horizontal intensity is zero) and perfectly horizontal in the magnetic equator (vertical intensity is zero). Everywhere else there is a combination of vertical and horizontal components. The angle between the magnetic field and the horizontal component is known as *Inclination* (I) or magnetic dip angle.

It is well known that the earth's magnetic poles do not correspond with its geographic poles (see Figure 2). Furthermore the magnetic field is not perfectly uniform, it is irregular and it must be measured in many places to get a satisfactory picture of its distribution (see Figure 3). This phenomenon is called *Variation*.

The variation is defined as the difference between the local magnetic meridian and the local geographic meridian at any particular point on the earth.

A good compass should point in the directions of the horizontal component of the magnetic field where the compass is located. *Declination* (D) is the angle between true north and the horizontal trace of the magnetic field (see Figure 4).

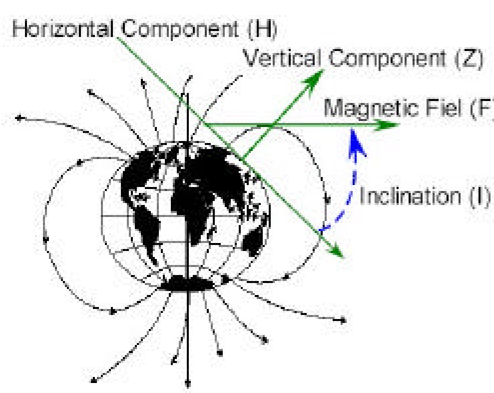


Figure 1: *Relationship between the magnetic field and inclination. (Adapted from [2]).*

[1] Most of the material in Section 1.1 is based on information from [3], [4], and [5].

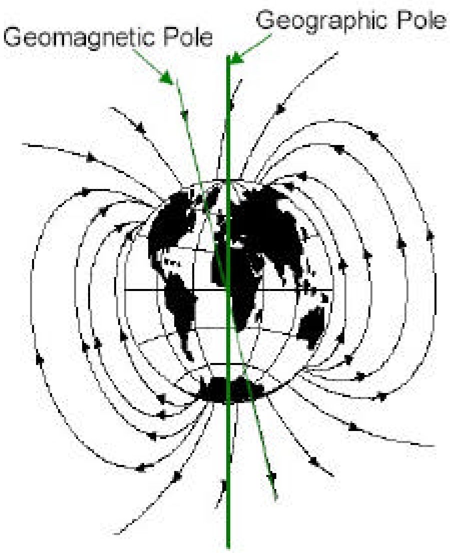


Figure 2: Discrepancy between the earth's magnetic and the geographic poles. (Adapted from KVH).

1.2 The KVH C-100 Fluxgate Compass

The compass used in the experiments described throughout this paper is the KVH C-100 Fluxgate compass made by KVH [2]. The C100 Compass Engine (see Figure 5) is a versatile low-cost (less than $700) developer's kit that includes a microprocessor-controlled stand-alone fluxgate sensor subsystem based on a two-axis toroidal ring-core sensor.

The C100 can accommodate tilt angles of up to ±45°. It provides internal gimballing by floating the sensor coil in an inert fluid inside the lexan housing and a 2-degree-of-freedom pendulous gimbal in addition to the internal fluid suspension. The sensor PC board can be separated as much as 122 centimeters (48 in) from the detachable electronics PC board with an optional cable if so desired.

The resolution of the C100 is ±0.1°, with an advertised accuracy of ±0.5° (after compensation, with the sensor card level) and a repeatability of ±0.2°. Separate ±180-degree adjustments are provided for *declination* as well as index offset (in the event the sensor unit cannot be mounted in perfect alignment with the vehicle's axis of travel). System damping can be user-selected, anywhere in the range of 0.1 to 24 sec. settling time to final value.

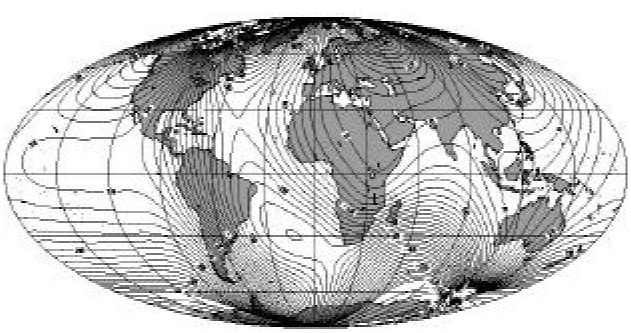


Figure 3: World Magnetic Field Model – 1995. Courtesy of the National Geophysical Data Center [3].

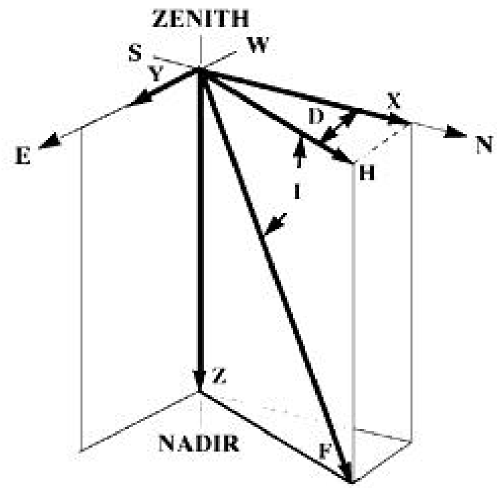


Figure 4: Vector magnetic components: Declination (D), Inclination (I), Horizontal Intensity (H), Vertical Intensity (Z), North-South Intensity (X), East-West Intensity (Y), Total Intensity (F). Courtesy of the U.S. Geological Survey [4].

An innovative automatic compensation algorithm employed in the C100 is largely responsible for the high accuracy obtained by such a relatively low-priced system. This software routine runs on the controlling microprocessor mounted on the electronics board and corrects for magnetic anomalies associated with the host vehicle. Three alternative user-selectable procedures are offered for compensation.

Correction values are stored in a look-up table in non-volatile EEPROM memory. The automatic compensation routine also provides a quantitative indicator of the estimated quality of the current compensation and the magnitude of any magnetic interference present [2].

The C100 configured with an SE-25 coil assembly weighs just 62 grams (2.25 oz) and draws 40 mA at 8 to 18 VDC (or 18 to 28 VDC). The combined sensor and electronics boards measure 4.6×11 centimeters (1.8×4.5 in). RS-232 (300 to 9600 baud) and NMEA 0183 digital outputs are provided, as well as linear and sine/cosine analog voltage outputs.

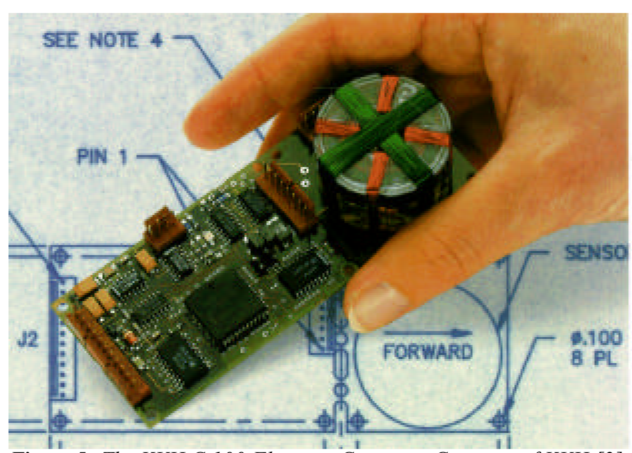


Figure 5: The KVH C-100 Fluxgate Compass. Courtesy of KVH [2].

2. COMPASS ERRORS

Compass errors can be classified as absolute and relative errors, as shown in Figure 6. This section presents a detailed analysis of each type of error.

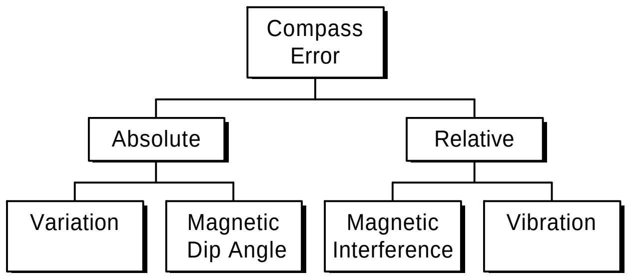


Figure 6: *Compass error classification.*

2.1 Absolute Errors

Absolute errors are defined as the difference between the compass reading and the real north (geographic north) direction on earth. There are two main factors that affect the magnitude of absolute errors: variation and inclination.

2.1.1 Error introduced by the Variation

The variation might introduce large errors and the correction factor varies depending where the compass is located. This error can be eliminated using a compensation table based on the World Magnetic Model (see Figure 3). A new International Geomagnetic Reference Field is adopted every five years; this model was developed by the U.S. Department of Defense and the British Geological Survey.

2.1.2 Error introduced by Inclination

The inclination or magnetic dip angle could be a source of error, especially with some compasses that are not able to determine exactly the horizontal component of the magnetic field. The problem is even worse when the compass is located near the magnetic poles, because the vertical component of the earth's magnetic field is bigger than the horizontal component. Modern compasses use complex algorithms and techniques to reduce the effects of the magnetic dip angle. The two prevalent approaches for compensation are:

- to place the magnetic sensor in a fluid (gimbals) to ensure that the sensor element is always aligned with the horizontal component of the earth;
- to keep the magnetic sensor fixed and use an inclinometer (tilt sensor) to measure the inclination of the sensor with respect to the horizon of the earth, while the corrections are calculated using a compensation algorithm.

2.2 Relative Errors

When the main objective is to get only a referential orientation in a relative small area (10 Km), one can ignore the effects of the variation and inclination since their effects will be very similar in two close locations. However there are other factors that can affect the correct measurement of the compass.

2.2.1 Magnetic Interference

Local magnetic interference produces a deviation in the earth's magnetic field, and, consequently erroneous readings in the compass (see Figure 7). This interference might cause large errors and most of the effects are unpredictable. Magnetic interference can be produced in many ways. For example

- **Natural interferences:** sunspots, solar magnetic storms, etc.
- **Man-made interferences:** bridges, passing vehicles, buildings, high-voltage wires, transformers, large metal structures, the host platform, etc.

2.2.1.1 Correction of constant deviations produced by the host platform

The effects produced by the host platform can be compensated for if the resulting error is constant. To implement the compensation procedure it is important to find a place free of local magnetic interference and it is recommended to have an extra compass for comparison. The basic procedure is:

- Position the compass on the robot at its intended location.
- Position the robot at a location that is free of known magnetic interference.
- Orient the robot so that it points to 0º (the magnetic north) and collect several readings from the compass.
- Repeat the previous step at 45º, 90º, 135º, 180º, 225º and 270º.

The next step is the analysis of the collected data. Figure 9 shows the output of the compass versus the reference direction. When *no* magnetic interference is introduced by the host platform the graph is a straight line with a slope of 45º.

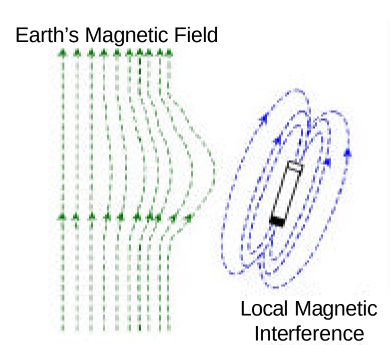


Figure 7: *Deviation produced in the earth's magnetic field by local magnetic interference.*

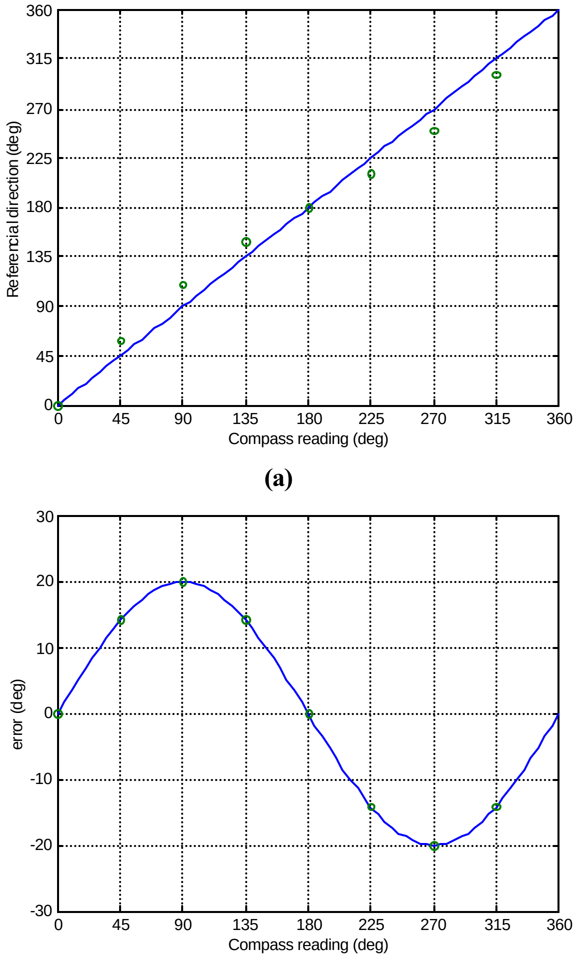


Figure 8: Example of measurement errors caused by the host platform. (a) line: ideal output; small circles: actual sampled output. (b) Error, shown as the interpolated difference between the small circles and the line in (a).

In practice, the body of the robot, the motors, the electric cables, and other onboard components introduce magnetic interferences, resulting in a difference between the actual orientation and the orientation measured by the compass (see Figure 8a and Figure 8b)

2.2.1.2 Correction of variable deviations produced by the host platform

Some electronic compasses have built-in algorithms that automatically calibrate the compass and compensate for the constant interferences that affect the compass at its location. For example, the KVH G100 has incorporated two procedures for performing this calibration: a) the so-called "8-point calibration" and b) the so-called "circular calibration." It is important to mention that the same procedure can be performed to compensate the compass due to the errors produced by variation (KVH calls this procedure "three-points calibration").

Using a compensation function as described above is practical only if the magnetic interference is constant. However, some on-board interferences are not constant. For example, Figure 10 shows the interference observed

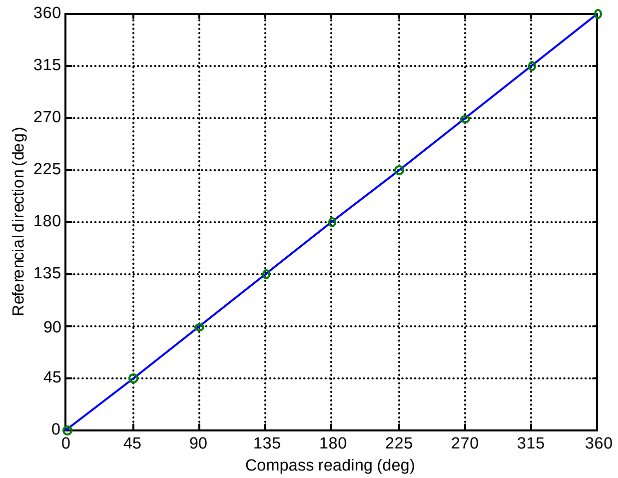


Figure 9: Ideal output of the compass with no deviation produced by the host platform.

in the vicinity of an electric motor. Electric motors cause two kinds of interference: a) a (constant) magnetic interference caused by the permanent magnet and b) a (varying) electro-magnetic interference that depends on the momentary load and speed of the motor.

To overcome the problem of varying interferences one can apply magnetic shielding to all major sources of interferences [7]. There is no known material that blocks magnetic fields without itself being attracted to the magnet. However, magnetic fields can be redirected using high-permeability shielding alloys known as "mu-metal," "newmetal," "moommetal" or "mewmetal." These materials are able to divert the magnetic flux to themselves, so the magnetic fields around them can be reduced significantly.

The deviation produced by the host platform (motors, wires, etc.) can be reduced with the use of *magnetic shielding* made from mu-metal. To be effective, the magnetic shielding must provide a complete path for the magnetic field lines, in order to prevent the magnetic field

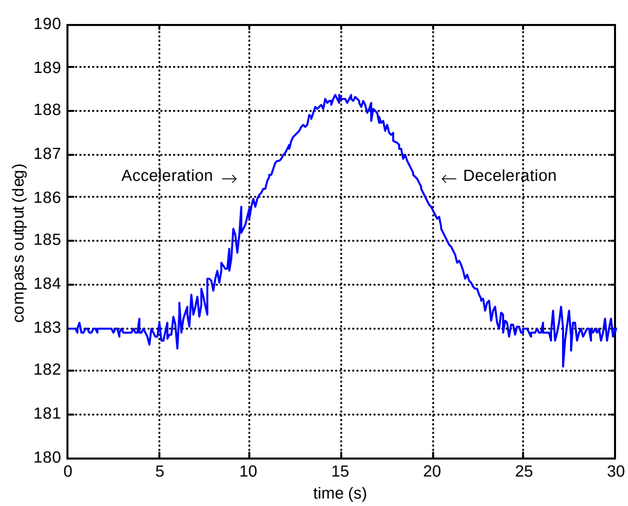


Figure 10: Interference caused by an on-board electric motor. In the case here the robot was oriented in an fixed direction of 150°. The motor's permanent magnet introduced a constant deviation of 33°, while the momentary load and speed of the motor caused an additional, time-varying interference.

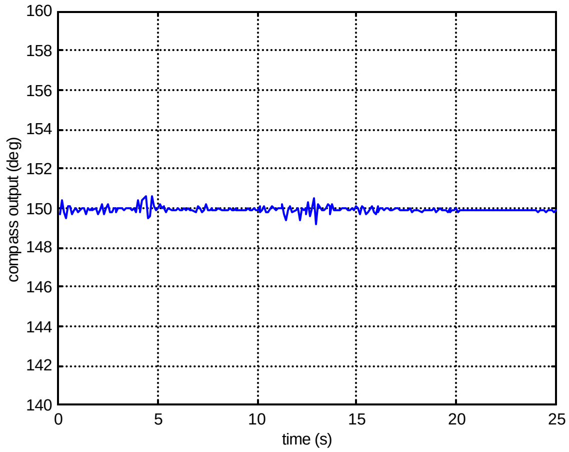


Figure 11: *Same conditions as in Figure 10, but now with mu-metal shielding of the motors.*

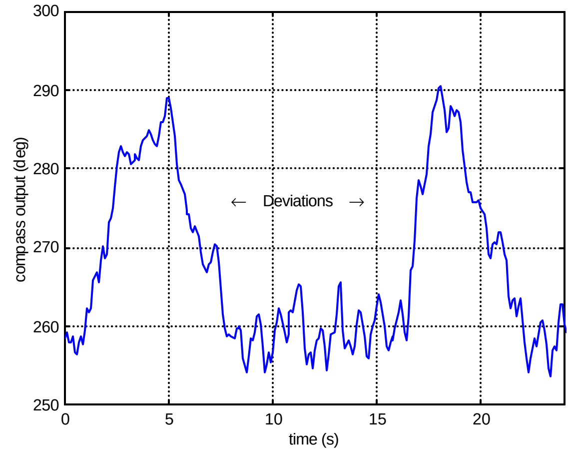


Figure 12: *Deviations in compass readings of up to 30° produced by an external magnetic interference as the robot passes the disturbance. The actual orientation was 258°.*

from causing interference outside of the shielding. Closed shapes like cylinders with caps around the motors, boxes with covers on power supplies, tubes around wires, etc. are the most effective. In addition, some physical separation between the mu-metal housing and the compass is still necessary to avoid magnetic interference. Figure 11 shows the result of a test performed under the exact same conditions as the test in Figure 10, but now with mu-metal shielding of the motors.

2.2.1.1 Deviation caused by other magnetic sources

When the deviation in the compass is produced by external magnetic interference, the problem is more severe since the amount and direction of the magnetic interference is unpredictable and cannot be calibrated for or modeled mathematically.

For this reason errors due to external magnetic interference may be much more critical than errors that can be eliminated through calibration (see Figure 12). The difficulty of modeling external magnetic interference makes it less practical to fuse compass data with data from other sensors using common Kalman Filter approaches, as done, for example, in [7].

Although external magnetic interference cannot be compensated, there are some properties of magnetic fields that can be used to detect the interference. In that case at least the user will know if the measures are or not correct. We have identified two practical methods for detecting such disturbances:

- Redundant sensors
- Differential compass

It is important to mention that both techniques are complementary and can be implemented together.

Redundant sensors

This approach attempts to determine the presence of magnetic interference using another orientation sensor (i.e., gyroscope, encoders, etc.) for reference, in order to ratify or reject the measure of the compass. The main problem with this approach is that the reference sensor may be in error.

Differential compass

As is well known, the strength of a magnetic field is inversely proportional to the square of the distance from the source. This means that at different points, the extend of the magnetic interference will be different. Based on this premise we have developed the differential compass system (to the best of our knowledge this method has not been suggested elsewhere).

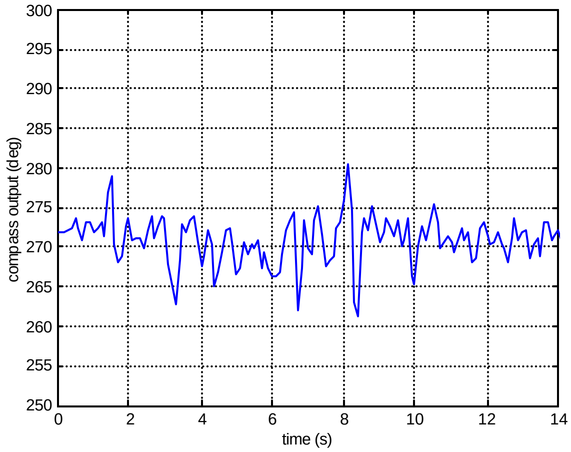
The differential compass system uses two identical compasses aligned in the same direction but separated from each other by a fixed distance. In the absence of external disturbances both compasses are affected only by the earth's magnetic field and should show the same measurement output. If the compasses move into the vicinity of a magnetic disturbance one compass will be more affected than the other (except for the singular case of both compasses moving parallel to an elongated source of disturbance, i.e., an electrical wire). We have built a prototype differential compass and have verified the validity of this approach (see Figure 13).

Vibration

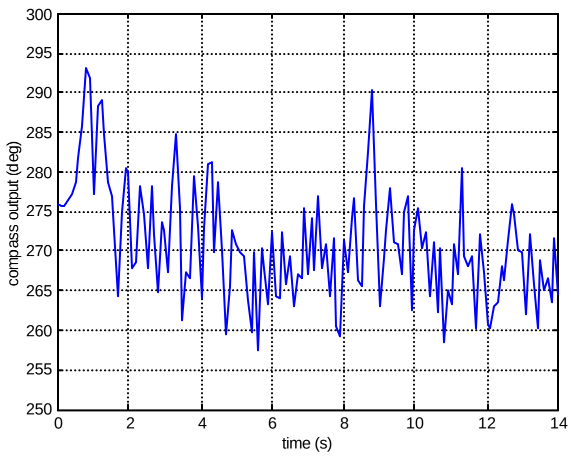
When the compass has to be used in a mobile platform and the movement introduces vibration, it is possible that the vibration produces errors in the output of the compass. The error is dependent of the type of floor (regular or irregular terrain) and the speed of the robot (see Figure 14 and Figure 16).

The effects of the vibration can be reduced using low pass digital filters. Four different kind of low pass filter were tested, two type IIR (Infinite Impulse Response) and two type FIR (Finite Impulse Response):

Figure 13: *An early prototype of a differential compass developed at the University of Michigan.*

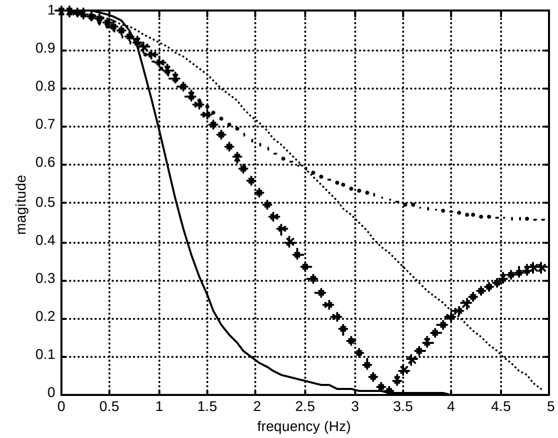


(a)

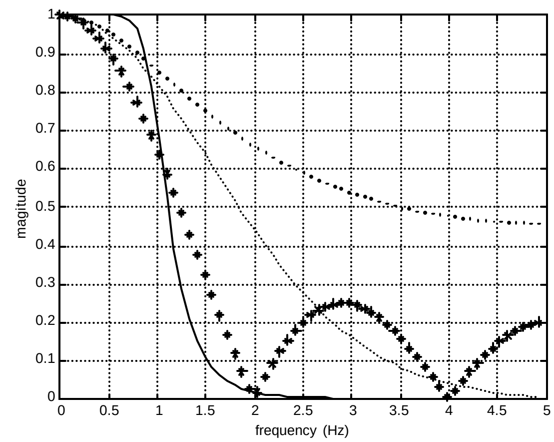


(b)

Figure 14: *Output of the compass while the robot was moving at: a) 100 mm/s., std. dev.=2.632 and b) 500 mm/s., std. dev.=7.175.*



(a)



(b)

Figure 15: *Digital filters cut-off =1 Hz. (a) 3rd-order (b) 5th order. Legend: ¾Butterwod ----Hamming *** Moving Average xxxxxx RC*

IIR Filters: Resistor & Capacitor Net (RC); Butterworth

FIR Filters: Hamming window; Moving Average

The filters were designed and tested with a cut-off frequency of 1 Hz (and F_{max} = 5 Hz) and with orders between 1-5 (except for the RC filter, which is always of 1st order). The frequency response of the digital filters (Figure 15) suggest that the IIR Butterworth has the better characteristics in the pass band, however the transient response of the FIR filters were more appropriate since they produce smaller delays in the signal (Figure 17).

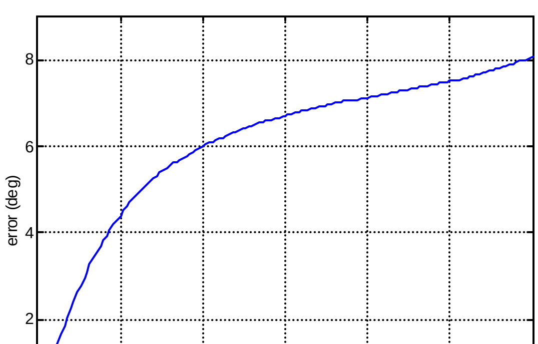


Figure 16: *Compass errors at different speeds of the mobile platform.*

After an exhaustive analysis and tests of each filter, we selected the Moving Average Filter (MAF) (Figure 18). The MAF also offers the unique advantage that the output can be used from the first reading. It is also possible to increase the order using only the last output of the filter and the new reading of the compass (i.e., it does not need to be recalculated using all the past values).

3. Conclusions

An examination of the performance of the compass in mobile applications has been presented. Error analysis of the compass and possible solutions have been developed and tested.

The error due to magnetic interference is the most distracting one – it can be up to ±180°. This report discussed techniques for reducing these errors. One technique, called host platform calibration, was implemented in our system. Another technique, believed to be proposed here for the first time, uses two compasses in an arrangement we call "differential compass." We have implemented at

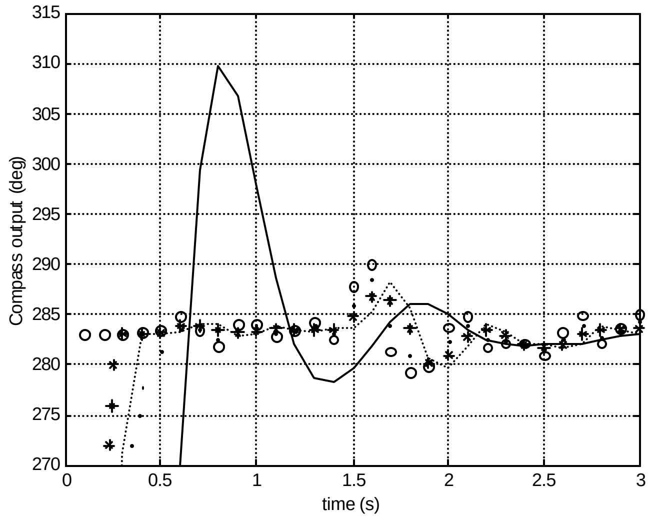


Figure 17*: Transient response of the digital filters.*
Legend: oooo *Original ¾ ¾ Butterwod ----Hamming*

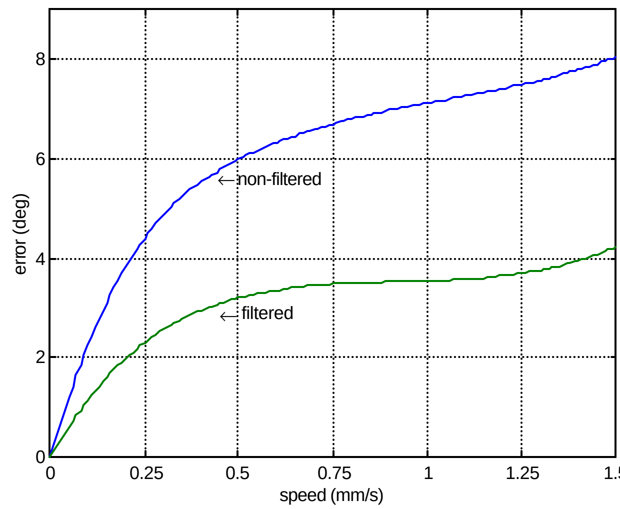


Figure 18: *Comparison of the error in the compass before and after apply a Moving Average Filter (MAF) of 3rd order.*

our lab the proof-of-concept prototype of a differential compass.

Our experiments show that when compasses are used on mobile robots, carefully tuned digital low pass filters are very effective in minimizing errors produced by vibration (which can produce errors up to 10°).

In summary, we conclude that electronic compasses have good potential to be useful in mobile robot positioning, especially as part of a multi-sensor system, in which other sensor modalities can take over when needed.

Acknowledgements

This material is based upon work supported by DARPA under Award No DAAE07-98-C-L029 and by DOE under Award No. DE-FG04-86NE37969.

4. References

1. Borenstein, J., Everett, B., and Feng, L., 1996, "*Navigating Mobile Robots: Systems and Techniques*." A. K. Peters, Ltd., Wellesley, MA, ISBN 1-56881-058-X, February 1996.
2. KVH Industries, Inc., 50 Enterprise Center, Middletown, RI 02842, Ph.: 401-847-3327. White paper at http://www.kvh.com/support/product_docs/oemcomov.pdf.
3. NGDC'99 – National Geophysical Data Center web site at http://www.ngdc.noaa.gov/seg/potfld/faqgeom.shtml.
4. USGS/NGIC'99 – National Geomagnetic Information Center, U.S. Geological Survey web site at http://geomag.usgs.gov/frames/mag_mod.htm.
5. CNGP'99 – Canadian National Geomagnetism Program web site at http://geomag.usgs.gov/frames/mag_mod.htm.
6. MSC'99 – Magnetic Shield Corporation. Perfection Mica Company, 740 N. Thomas Dr., Bensenville, IL. 60106, U.S.A., Ph.: 888-766-7800. Magnetic Shield Corporation web site at http://www.magnetic-shield.com/faqs.html.
7. Abbott, E., Powell D., 1995, "An Examination of the Relative Merits of Various Sensors for Vehicle Navigation." Presented at *ION GPS '95*, Palm Springs, California. September 1995.