AUTONOMOUS VEHICLE FOR THE INVESTIGATION OF DANGEROUS ENVIROMENTS

Paul Mugur SVASTA[1], Iaroslav-Andrei HAPENCIUC[2]

Acest proiect îşi propune realizarea unui robot autonom capabil să se deplaseze pe un traseu cu minim de informații apriori. Informația necesară parcurgerii traseului dorit se va achiziționar în timpul deplasării folosind un ansamblu elaborat de senzori. Acest ansamblul de senzori a fost conceput și testat de autori. Acest sistem de navigație este compus în principal de două module: modulul inerțial şi cel de vedere stereo optică.

The project aim is to build an autonomous robot able to move on a track with minimum of priory knowledge. The information required to complete the route will be acquired during the trip by using an elaborated sensors system. This sensor system was developed and tested by the authors. The navigation system is mainly made out of two subsystems: the inertial navigation system and the stereo optic vision system

Keywords: autonomous, navigation, sensors, stereo optics, robot

1. Introduction

The interest for the autonomous vehicles has increased in the last years. The main impulse was given by the Great DARPA Challenge. Today most of the autonomous vehicles has similar configuration, most of them relaying on multiple laser telemeters. Because this sensors are extremely expensive and has a series of limitations the authors decided to build an autonomous vehicle that will use better and cheaper sensors.

After experimenting many techniques and sensors configuration the end result is relaying on two sensors: inertial and stereo optic. If inertial sensors are relatively well known and used in many applications, the stereo optic systems are still on experimental phase. Many research centres are trying to develop a reliable stereo optic system using different techniques, the authors tried one solution that proved reliable, even if are many aspects that can be improved.

2. System architecture

[1] Prof., Electronics Faculty, CETTI, University POLITEHNICA of Bucharest, Romania, e-mail: paul.svasta@cetti.ro
[2] PhD student, Electronics Faculty, CETTI, University POLITEHNICA of Bucharest, Romania

To determine the structure of an autonomous robot first it is necessary to determine on what kind of terrains will be asked to perform its tasks and secondly it's necessary to determine what kind of stimulus will act over the robot and how will it to use them to take decisions.

From the start of the project de decision was to make the robot able to move on an off-road area whit obstacles of different sizes and randomly scattered. The robot must be able to move over the small obstacles and to avoid little ones.

For this reason the platform used is a commercial available one with tracks and powerful electric engines. Electrical engines were chosen since are easier to control. The field can have different inclinations and the robot must be able to handle all situations accordingly.

Until now two senses that need to be developed for the good functioning of the robot have been indentified: sight and tilt.

The tilt sensing ability can be easily given by using a two axis accelerometer. But more sensors will be required for other senses that need to be implemented:

- The most important one for any ground based vehicle is the odometer, which is measuring the distance. This was implemented using an optical encoder mounted on the motor.
- The electronic compass will be used to determine the direction relative to the Earth magnetic field. Together with the odometer it is possible to implement "dead reckoning" navigation.
- The tri-axial accelerometer is measuring the tilt of the robot. The tilt information is especially important for the magnetic compass to compute the correct direction of the magnetic north pole even if it's not in a horizontal position.
- The tri-axial gyroscope is measuring the rotation speed of the robot, so this information needs to be integrated to obtain direction – same as the magnetic compass. The tri-axial gyroscope together with the tri-axial accelerometer is forming an Inertial Measurement Unit (IMU) that can be used for "inertial navigation".

Till now are two identified sensors, and to implement them into the structure of the robot an electronic module needs to be developed. To make a more general, multipurpose module the authors decided to add more sensors on the same PCB (printed circuit board).

The rest of the sensors will be at a first sight redundant but was noticed that in different situation some sensors are more accurate than other, and more. by corroborating the information form sensors that give information's on the same parameter in the same time more accurate results can be obtained.

To make the module more general other sensors and option have been added to this electronic module even if some of them are not used in this current project:

- Absolute pressure sensor – is acting as an electronic barometer, the main purpose is to determine the height by measuring the atmospheric pressure.
- The GPS receiver is always helpful to determine the position of the robot on the surface of Earth.
- The power digital outputs are used to drive the electric engines of the robot.

The sight was determined to be an important sense to be added to the robot in order to determine and differentiate the large obstacles to be avoided and the smalls ones over which the robot can move.

For this sense many current robots design relay on laser telemetry which has some advantages and some disadvantages, the main one from the authors point of view being the price.

The selected method of implementing sight was the stereo vision. At the beginning of the work were very few published research results in this field so the resulted stereo optic system stands out in originality.

Because the required computation power to achieve reliable obstacle detection in real time for a moving robot was very high, a powerful personal computer was used for the implementation of the image processing and for the implementation of the navigation algorithm. The size of this system can be extremely reduced by implementing the algorithm on a FPGA but this was not part of the presented project.

The block diagram of the developed robot consists from three elements (Fig. 2.1):

-the stereo vision acquisition system, the eyes of the robot;

-the computation system, the brain;

-the inertial sensing unit, the vestibular system of the robot;

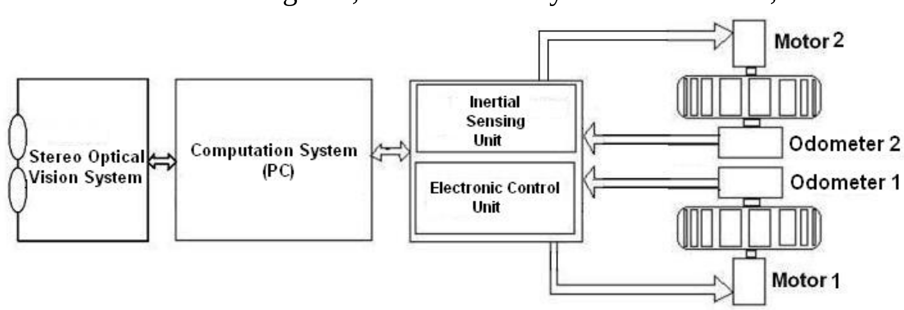

Fig. 2.2. System architecture

The resulted structure (Fig. 2.2) even if it isn't the most reliable from mechanical point of view proved sufficient to achieve autonomous navigation on shorter distances.

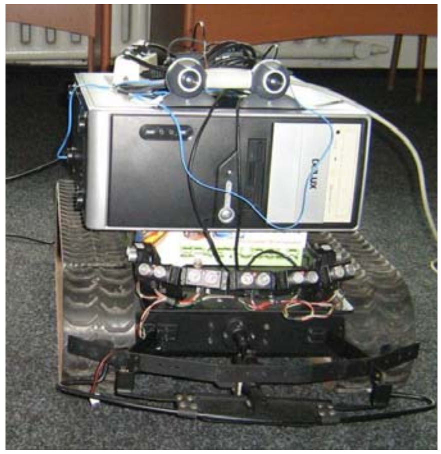

Fig. 2.2. Autonomous vehicle

3. Inertial Sensing Unit and the Electronic Control Unit

For building the electronic module responsible for inertial navigation were taken into consideration only commercial available components. The aerospace and army grade equipment were rule out for cost and availability reasons. Even if the performances will be worst, the accuracy is still good enough to achieve autonomous navigation.

Both inertial sensors and the electronic control unit were implemented on one electronic module. The electronic control unit was implemented on a DSC (digital signal controller): dsPIC30. The part was chosen mainly for its DSP core and for its 12bits ADC. The dsPIC30 feature also a compare and capture peripheral, with 8 channels for inputs and 8 channels for outputs. The outputs will be used to control the motor. The inputs will be used to read the optical encoder that is used as odometer.

The obtained electronic unit is made on one PCB (printed circuit board) and it will be referred as the “inertial bridge”. The block diagram of the inertial bridge is presented in Fig. 3.1:

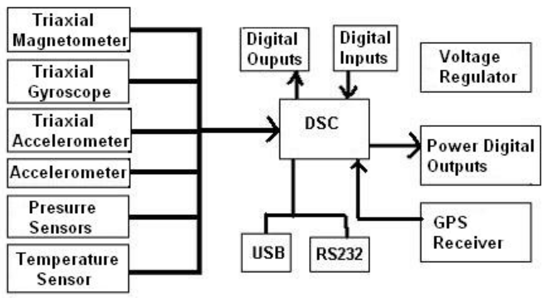

Fig. 3.1. Block diagram of the inertial and control electronic module

The resulted inertial bridge is presented in Fig. 3.2

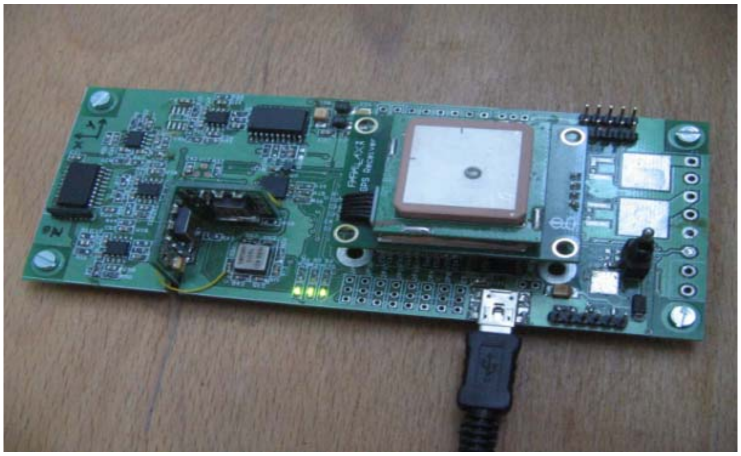

Fig. 3.2. Inertial bridge and control module

3.2 Implemented Sensors on the Inertial Bridge

The electronic compass is an essential element in navigation since it is indicating the direction of movement of the vehicle relative to the North Pole, this direction is expressed in degrees and is more often referred as heading. To build it three magnetic sensors were used, one for each axe of the 3D Cartesian system [9]. This sensors structure is required to measure the direction of the earth magnetic field in space. By making the vectors projection on the horizontal the correct direction of the north magnetic pole will be determined [4]. So the horizontal must be determined accurately by another sensor: the tri-axial accelerometer, according to Fig. 3.3.

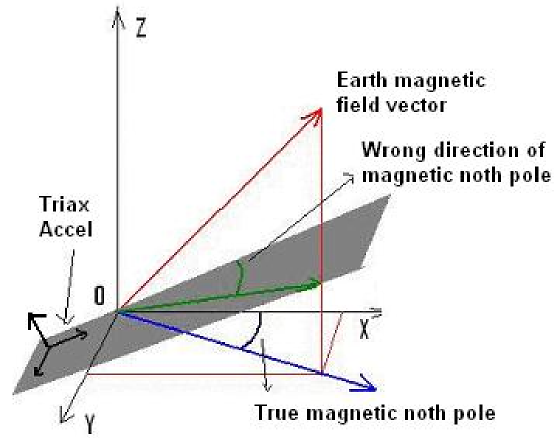

Fig. 3.3. Determination of the earth magnetic north

The tri-axial accelerometer is a vital component in any inertial navigation system. Together with other three gyroscopes it forms the inertial navigation unit. On the actual module the tri-axial accelerometer has a double role: the second one being inclinometer for the electronic compass. The accuracy of the acceleration measurement is strong related to the sensibility and the noise of the sensors as it is related on the accuracy of the analogue to digital converter. When evaluating the distance measurement through double integration of the acceleration it must be taken care of the fact the error is increasing proportional with the square of the integration time interval [5]. With the current system in 26 second the distance measurement will be 1m, so it must be periodically adjusted using a special algorithm.

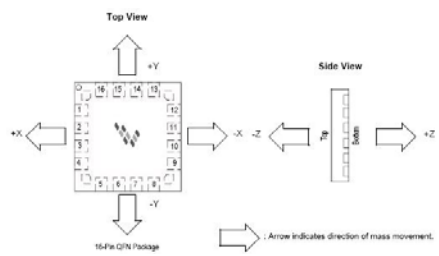

Fig. 3.4. Tri-axial accelerometer

Regarding the performances as inclinometer, the error will cause an accuracy of 0.2 degrees. Extra data from other sensors must be taken into account because accelerated movement of the vehicle will perturb the tri-axial accelerometer indication [10].

The tri-axial gyroscope is a key component from the inertial navigation system. If for the tri-axial accelerometer was used one component with this function for the tri-axial gyroscope will be used three components mounted on the desired sensitivity axes. The gyroscope used is ADXRS150 from Analog Device.

For Z axe is enough to mount the sensor on the PCB. But for the X and Y axe mini PCB board were build in attached perpendicular to the main PCB as is visible in Fig. 3.5

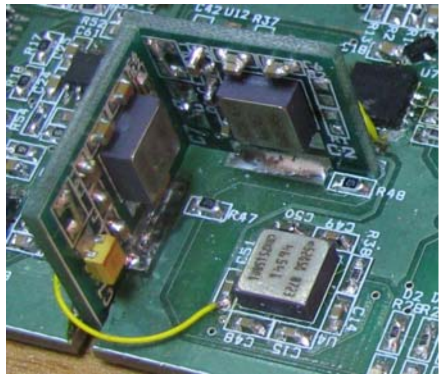
Fig. 3.5. Tri-axial gyroscope

Gyroscope measurement accuracy is especially important since these sensors are directly responsible to maintain the attitude of the system and the heading, but only if the correct quaternaries matrix is being obtained. The current system has a stability of 0.1degrees/min, which is acceptable since periodically is compensated by other sensors measurement.

The position of an object in the Cartesian space can be described by six numbers, the six degrees of freedom, three of these are linear and they are indicating the position of the object, and the other three are angles and they indicates the orientation of the object which is more often referred as attitude.

Because the information regarding attitude is extracted by integrating the value of the rotation speed measured by the gyroscope, the main error will not be given by the noise but by the gyroscope output offset stability. The Offset instability and have different reasons: thermal, power supply, etc. For this reason the ADXRS gyroscopes have an internal voltage reference available also at the output. On top of this value the rotation information is added. By measuring the voltage reference separately and taken it into consideration when computing the rotational speed indicated by the gyroscope, the measurement accuracy will be greatly improved.

As mentioned earlier, the accelerometer and the gyroscopes are forming the inertial measuring unit which is being used for inertial navigation. The mathematic form of the inertial navigation equation can be expressed as:

$$\left.\frac{d^2 r}{dt^2}\right|_i = f^i + g^i = C_b^i f^b + g^i \tag{3.1}$$

Where f^i is the acceleration of the body relative to the inertial reference frame, gi is the earth gravity acceleration, C_b^i is the cosines direction matrix which is given by the gyroscopes, f^b is the acceleration indicated by the accelerometers. The simplified inertial navigation system can be presented as in Fig. 3.6:

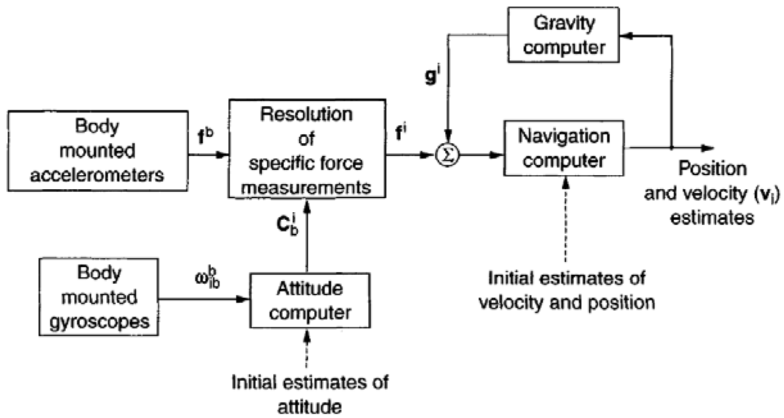

Fig. 3.6. simplified inertial navigation system

In the end, next to the process of individual calibration of the sensors, an auto calibration algorithm for the entire system was implemented that is running continuously. This auto calibration algorithm relies on the fact that for each measured parameters are available more sensors that are working in different ways.

For example for the heading indication it can be used the gyroscope, that is measuring the rotation speed and is integrating it, or it can be used the magnetic compass that is determining the direction of the magnetic north pole, or two different indication of the GPS receiver can be used. This way the compass can determine if the gyroscope has an offset variation that needs to be compensated.

The auto calibration algorithm is relying on the fact that during the vehicle movement is possible that some sensors will not be affected by the movement [13]. A flow diagram that describes the algorithm is presented in Fig. 3.7

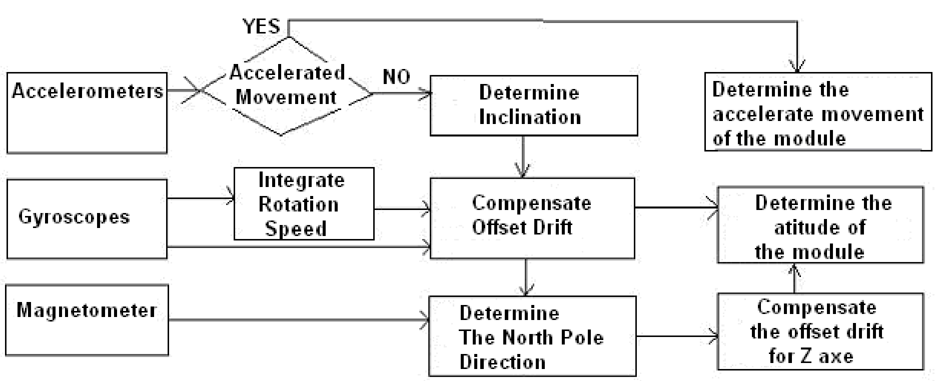

Fig. 3.7. Flow diagram of the auto calibration

4. Stereo Optic Vision System

To compensate for the limitations of the inertial navigation system, it was required another way to extract information's from the surrounding environment for achieving autonomous movement the stereo vision.

For financial reasons the authors used the most cheapest and easy available solution as image sensors: web cams. As acquisition system, after trying many ways to acquire images for both cameras the end solution required an external web cam web server. This was required because the operating system has a series of limitation regarding streaming data from two web cams because resources conflicts were happening.

The web server is commercial available at reasonable prices. The main application is in CCTV surveillance. Its role is to acquire data from the two web cams (Fig. 4.1). The two acquired images are transferred into the computing system memory through Ethernet.

Fig. 4.1. Stereo optic acquisition system

In the process of robot guidance on a certain trajectory, sight have an essential role because it is implying complex algorithms, large amount of computation power, characterization and interpretation process of the information from the images of the terrain in which the robot must move [16],[17]. This complex process implies more operations which can be separated in distinct phases:

- **Acquisition** is the process to transform de optic image in a digital image in the computer memory;
- **Preprocessing** is the process of image parameters improving: noise contrast, detail enhancement, etc;
- **Segmentation** is the process that is braking the image in smaller images;
- **Description** is the process that is computing different parameters for object identification;
- **Recognition** is the process of identifying the objects;
- **Interpretation** is the process that is giving sense to the entire picture.

The acquisition require the simple process of extracting the binary information regarding the JPEG images from the web server by using data socket, followed by the command to refresh the images.

Preprocessing consist in adjusting the level of light intensity of the two images to make them more similar from a light intensity point of view. In this phase the right image is also translated and rotated. The translation rotation process is extremely important because the mechanical system that is holding the cameras parallel is not perfect, and the mechanical imperfections will be compensated numerically in this step.

Segmentation is the process through which the big picture is divided into smaller high interest areas. Because in the case of navigation is impossible to predict the shape and the position of the obstacles, it will be used an algorithm that will detect interest area around of which the pattern recognition process will be more efficient. The image scanning is not interlaced or progressive but pseudo-random, similar with the human sight [18]. The interest areas have a size of 20x20 pixels (Fig. 4.2)

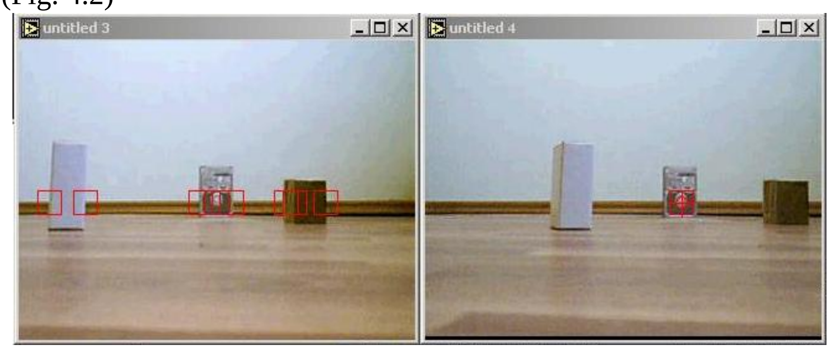

Fig. 4.2. Image segmentation

Recognition is the process of searching the interest images delimitated in the previous step in the right image. The image recognition algorithm is based on the computation of the bi-dimensional normalized cross correlation coefficient (shortly identified as R(I, j)) [11]

$$R(i,j)=\frac{\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}(w(x,y)-\overline{w})(f(x+i,y+j)-f(i,j))}{\left[\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}(w(x,y)-\overline{w})^2\right]^{\frac{1}{2}}\left[\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}(f(x+i,y+j)-f(i,j))^2\right]^{\frac{1}{2}}} \quad (1)$$

The normalized cross correlation coefficient has the value 1 for perfect mach and 0 if the two images have nothing in common. In the situation of the stereo vision the two images will never be perfectly identical since the webcams that are getting the images are in different positions. As threshold value for the

R(i,j) to separate good image matches from poor ones a value of 0.9 has given the best results.

The interest images will be slightly shifted in the two pictures because of the parallax error. The difference in horizontal position will be used to compute the distance to the obstacle [14][15].

Interpretation is the process in which the bi-dimensional map of the obstacles is being obtained. To evaluate the accuracy of the stereo vision system a series of test have been made in different situations. The measurements have been done on an area with a size of 2 by 2 meters, and three objects arranged in different positions, situation 1 is presented in Fig. 4.3.

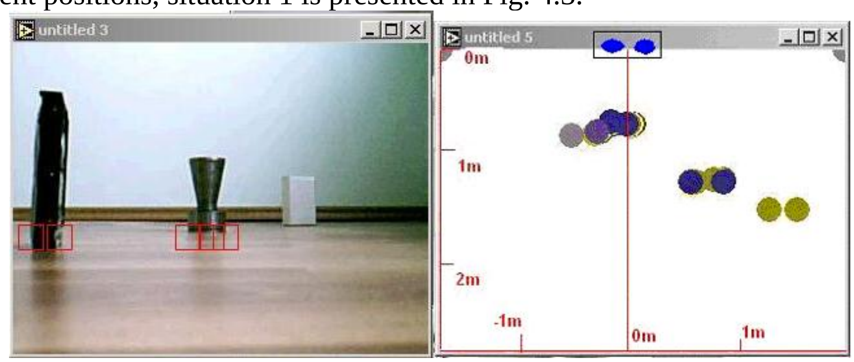

Fig. 4.3. Obstacle map

The results of the measurements are presented in table 3.1 and there is also computed the accuracy of the measurements.

		Real values		Measured values		Difference	Error
case	object	x(m)	y(m)	x(m)	y(m)	z(m)	error(%)
	a	0	1	-0.1	-0.95	0.045	4.475
	b	0.5	1.5	0.55	1.55	-0.064	-4.019
1	c	1	2	0.9	1.85	0.179	7.995
	a	-0.2	1	-0.2	1.05	-0.049	-4.812
	b	0.6	1.6	0.5	1.55	0.080	4.690
2	c	0	2.2	0.25	1.95	0.234	10.638
	a	0	1	0.05	0.95	0.049	4.869
	b	0.5	1.5	0.4	1.45	0.077	4.869
3	c	0.7	2.1	0.8	1.85	0.198	8.946

Table 4.1: Stereo optic system, accuracy evaluation

5. Navigation Algorithm

To analyze the movement on a real environment next to the two sensors systems a navigation algorithm was required to be developed. This algorithm will corroborate the information coming from al sensors to give the best decisions to avoid obstacles.

The navigation algorithm was developed also in LabVIEW environment because mainly because of the higher speed required to complete the task and because all other routines were also developed in LabVIEW and a better and easier integration in one system will be possible.

For the navigation system to work correctly, a process of calibration of the control elements of the vehicle was required. Distance is the average value of the indications of the two odometers. In the same time this value must coincide with the distances measured by the stereo optical system. The alignment was possible after a calibration process

Even if the stereo optical vision system is giving information regarding the distance to objects, because of the optical imperfections of the cheap web cams, the computed distance is not linear on a wide range, while the odometers have a good linearity.

To obtain a linear indication of the stereo optic vision system a series of measurement were required to extract the response function. Fig. 5.1 represents how the equation that is relating the output of the stereo optic vision system – pixels to the real distance – meters.

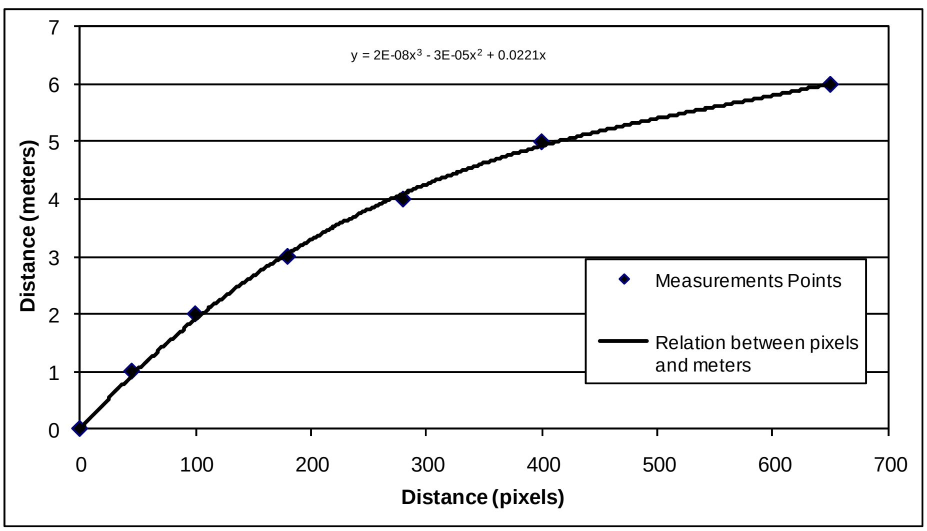

Fig. 5.1. The calibration of the stereo optic vision system

Even if for the first 3 meters the linearity is acceptable, for higher distances the measurement error becomes important. By using a linearization equation of 3rd order the measurement accuracy will be improved.

For the calibration of the odometer a simple first order equation was proven enough.

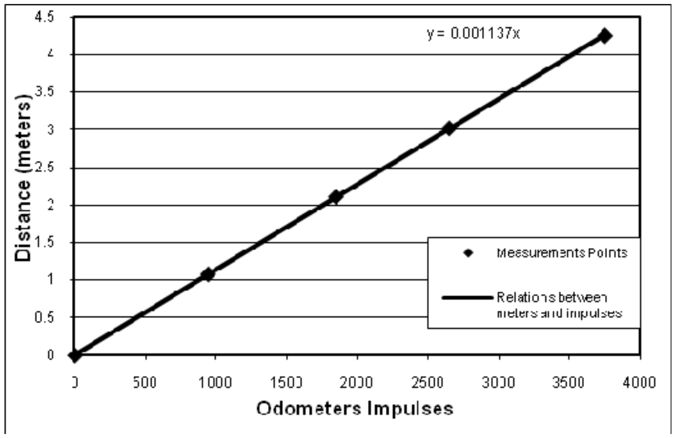

Fig. 5.2. Odometer Calibration for distance measurements

To make turns the two tracks were controlled with different speeds. For this reason it was necessary to correlate the indications of the magnetic compass with the odometers indications, more precisely with the value of the difference between the two indications. Because the friction coefficients on the two tracks are different and because the weight distribution is not similar on the two tracks, the theoretical indications were not similar with the real ones. So the equation that relates the odometers difference indication to the turn angle was obtained on the experimental way.

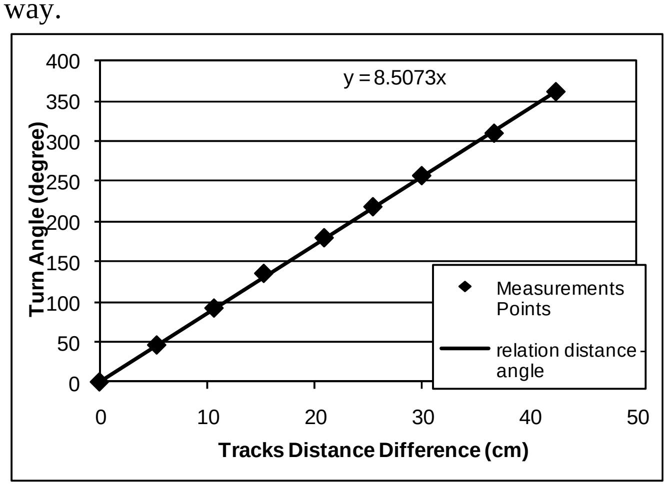

Fig. 5.3. Odometer calibration for turn angle measurement

As noticed, the main sources of information are the odometers from the engines and the stereo optic vision system. Because the different response speed of the two systems and because different errors can intervene the map picture will look blurry (Fig. 5.4) in the first steps of the signals processing, before applying the navigation algorithm that is having the role of filtering out the errors (Fig. 5.5)

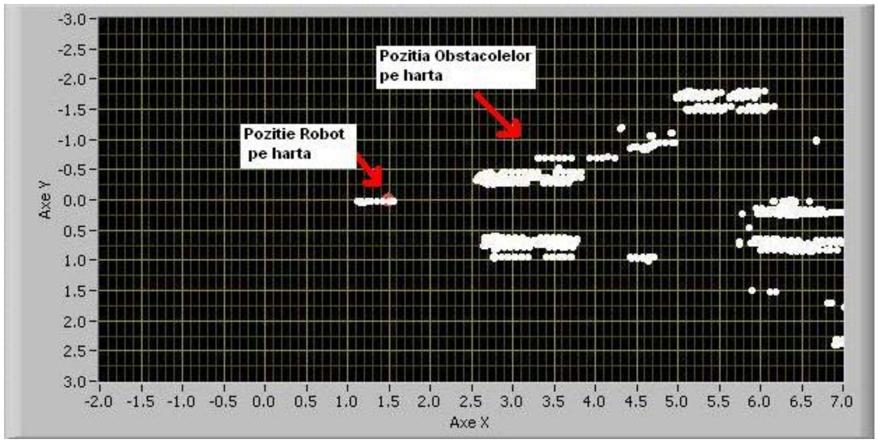

Fig. 5.4. Not filtered Obstacle map

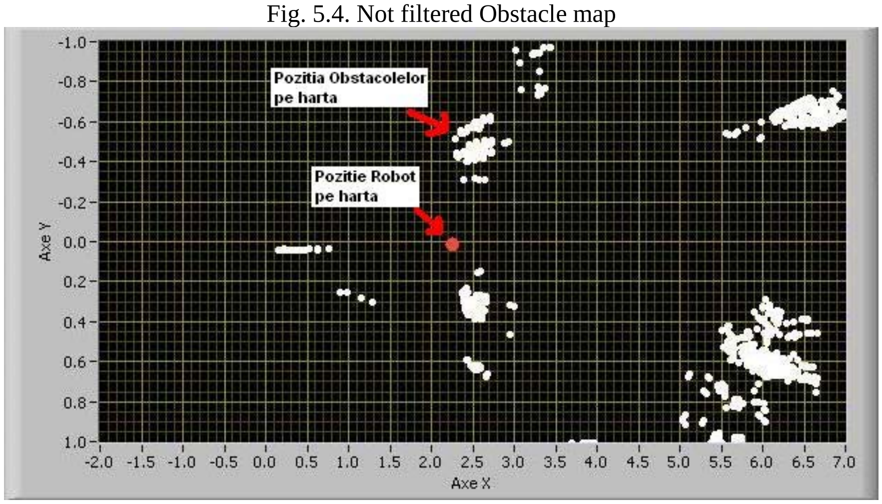

Fig. 5.5. Filtered Obstacle map

6. Conclusions

By using sensors build in MEMS technology, commercially available, it was possible to build an inertial navigation system with minimum costs. The limited accuracy of the sensors was compensated by using more sensors that are giving information about the same parameter. The information that comes from all these sensors is processed by the auto calibration algorithm that was developed by the authors.

Using surveillance equipment as stereo image acquisition system made possible to build a cheap hardware without compromising the accuracy.

The pseudo random image segmentation, which is copying the way human eyes are working, it the results of the authors work to optimize the obstacle detection algorithm for speed and accuracy.

The stereo optic vision system alone represents a cheap and reliable alternative to laser telemeters, having also the ability of detecting the light levels and colours.

On the field measurements have indicated that the developed system can be used to control a robot movement on an unknown terrain thanks to the developed navigation algorithm.

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