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Mobile robot controlling possibilities of inertial navigation system

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Abstract

The paper explain analysis of inertial navigation system and accelerometric, gyroscopic sensors and describe possibilities of their application for inertial navigation of mobile robot. Such controlling system allows to monitor exact position of robot. These information can be applied for robot controlling, its autonomous control or its tracking. Inertial navigation is completely autonomous and independent from surroundings, i.e. the system is resistant from external influences as magnetic disturbances, electronically disturbance, signal deformation, etc. For mobile robots to be successful, they have to move safely in environments populated and dynamic. While recent research has led to a variety of localization methods that can track robots well in static environments, we still lack methods that can robustly localize mobile robots in dynamic environments.

Keywords: inertial navigation system, robots, gyroscop, accelerometer

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1. Introduction

Inertial navigation is a self-contained navigation technique in which measurements provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a known starting point, orientation and velocity. Inertial measurement units (IMUs) typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration respectively. By processing signals from these devices it is possible to track the position and orientation of a device. Inertial navigation is used in a wide range of applications including the navigation of aircraft, tactical and strategic missiles, spacecraft, submarines and ships. Recent advances in the construction of MEMS devices have made it possible to manufacture small and light inertial navigation systems. These advances have widened the range of possible applications to include areas such as human and animal motion capture [1].

Inertial navigation systems have been widely used in aerospace applications but have yet to be seriously exploited in robotics applications where they have considerable potential. In the integration of inertial and visual information is investigated. Methods of extracting the motion and orientation of the robotic system from inertial information are derived theoretically but not directly implemented in a real system. Inertial sensors are used to estimate the attitude of a mobile robot. With the classical three-gyro, two-accelerometer configuration, experiments are performed to estimate the roll and pitch of the robot when one wheel climbs onto a plank using a small inclined plane. One reason that inertial systems are widely used in aerospace applications but not in robotics applications is simply that high-quality aerospace inertial systems are comparatively too expensive for the budgets of most robotics systems. However, low-cost solid-state inertial systems, motivated by the needs of the automotive industry, are increasingly being made commercially available. Although a considerable improvement on past systems, they clearly provide substantially less accurate position information than equivalent aerospace systems.

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Inertial Navigation Systems (INS) have been developed for a wide range of vehicles. Sukkarieh [2] developed a GPS/ INS system for straddle carriers that load and unload cargo ships in harbors [3]. Bennamoun et al [4] developed a GPS/INS/SONAR system for an autonomous submarine. The SONAR added another measurement to help with accuracy, and provided a positional reference when the GPS antenna got submerged and could not receive a signal [3]. Ohlmeyer et al [5] developed a GPS/INS system for a new smart munitions, the EX-171. Due to the high speed of the missile, update rates of 1 second from a GPS only solution were too slow, and could not provide the accuracy needed. Jorge Lobo et al [6] describes a prototype of an inertial navigation system for use in mobile land vehicles, such as cars or mobile robots. Dieter Fox et al [7], describes operate autonomously, mobile robots must know where they are. Mobile robot localization, that is the process of determining and tracking the position (location) of a mobile robot relative to its environment, has received considerable attention over the past few years [8]. Robot localization has been recognized as one of the most fundamental problems in mobile robotics [9, 10]. Pirník et al [11] uses INS for control of wheel chassis from inertial sensors based on data. Abramov and Božek [12] used INS for application of inertial measurement system in machinery.

2. Inertial Navigation System

Inertial navigation uses gyroscopes and accelerometers to measure rate of rotation and acceleration. Measurements are integrated once (or twice, for accelerometers) to yield position. Inertial navigation systems have the advantage that they are self-contained, that is, they don't need external resources. However, inertial sensor data drift with time because of the need to integrate rate data to yield position. Inertial sensors are thus mostly unsuitable for accurate positioning over an extended period of time [13]. Self-contained inertial navigation is a navigation technique provided by accelerometers and gyroscopes are used to track the position and orientation of an object relative to a starting point, direction and velocity.

An IMU is a "clump" of six inertial sensors. Three linear accelerometers and three rate gyros make up an IMU. Usually, an IMU also contains a computational unit to do the position calculations based off of the sensors. The operation to combine information from such multi-modal sensors is called sensory fusion [14].

An IMU is sufficient to navigate relative to inertial space (no gravitation present), given initial values of velocity, position and attitude:

- Integrating the sensed acceleration will give velocity.
- A second integration gives position.
- To integrate in the correct direction, attitude is needed. This is obtained by integrating the sensed angular velocity.

In terrestrial navigation (close to the Earth) we compensate for gravitation, and rotation of the Earth. Equations integrating the gyro and accelerometer measurements into velocity, position and orientation are called navigation equations [15]. The combination of an IMU and a computer running navigation equations is called an Inertial Navigation System (INS).

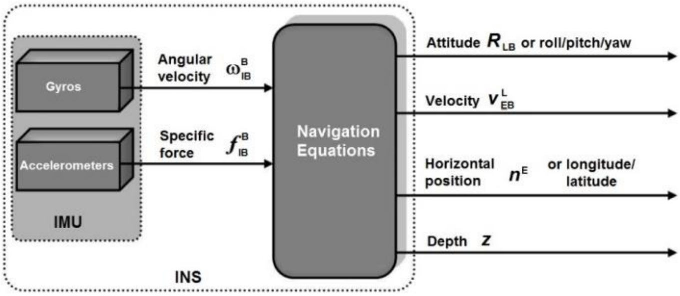

Fig. 1: Inertial navigation system [15]

2.1. Navigation Equations

The principle of inertial navigation laws are managed by classical mechanics, which defined by Newton. Looking at Newton's second law of movement, a change in motion occurs as a force is applied to a body. Now, dividing both sides of the equation by the mass of the object results in the certain force. In inertial navigation, accelerometers detect accelerations due to forces exerted on the body [3].

$$\frac{f}{m} = a = S \tag{1}$$

Typically these forces as special forces called (S). Thus reading from the IMU will be referred to as specific forces, which are independent of the mass [3].

3. Accelerometer

Accelerometers are used to measure acceleration along one or more axis and are relatively insensitive to orthogonal directions.

Accelerometer is electromechanical device to measure acceleration forces:

- Static forces like gravity pulling at an object lying at a table
- Dynamic forces caused by motion or vibration

Accelerometer Applications:

- Automotive: monitor vehicle tilt, roll, skid, impact, vibration, etc., to deploy safety devices (stability control, anti-lock breaking system, airbags, etc.) and to ensure comfortable ride (active suspension)
- Aerospace: inertial navigation, smart munitions, unmanned vehicles
- Sports/Gaming: monitor athlete performance and injury, joystick, tilt
- Personal electronics: cell phones, digital devices
- Security: motion and vibration detection
- Industrial: machinery health monitoring
- Robotics: self-balancing

3.1. Types of Accelerometer

Accelerometer can be broadly classified either a mechanical or solid state device.

3.1.1. Mechanical Accelerometer

A mechanical accelerometer include of a mass suspended by springs, as shown in Figure 2. The displacement of the mass is measured using a movement pick-off, giving a signal that is proportional to the force F acting on the mass in the orientation of the input axis. Newton's second law *F = ma* is then used to calculate the acceleration acting on the device.

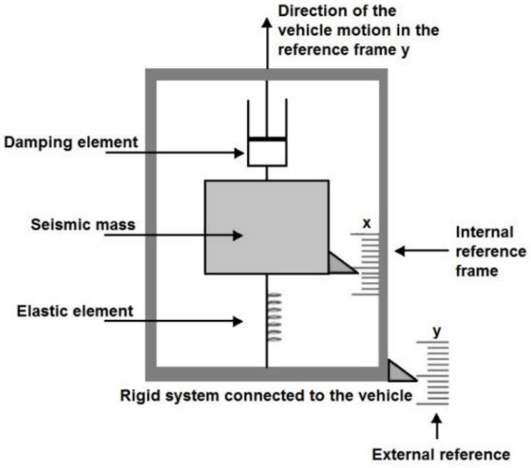

Fig. 2: Accelerometer structure. Proof mass is attached through springs [16]

3.1.2. Solid State Accelerometer

Solid state accelerometer can be divided to various subgroups, including surface vocal wave, vibratory, silicon and quartz devices. Solid state accelerometers are small, trustworthy and rough. An example of a solid-state accelerometer is the surface acoustic wave (SAW) accelerometer. A SAW accelerometer consists of a linchpin beam which is resonated at a specific frequency, as shown in Figure 3. A mass is depended to one end of the beam which is free to move. The other end is hardly attached to the case. When an acceleration is applied along the input axis the beam curved. This causes the frequency of the surface acoustic wave to change symmetrically to the applied strain. By measuring this change in frequency the acceleration can be specified.

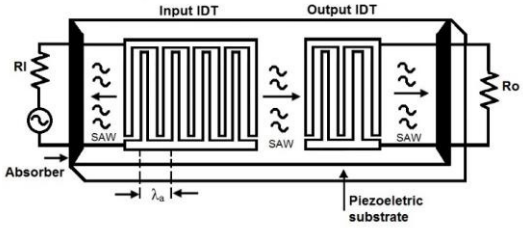

Fig. 3: Surface acoustic wave (SAW) [17]

3.1.3. MEMS Accelerometers

Abbreviation MEMS based on the "microelectromechanical systems". What means systems in which there are implemented on one chip micromechanical structures forming sensor as such, with controlling and evaluation electronical circuits.

Silicon micro-machined accelerometer using the same principles of mechanical and solid state sensors. There are two main category of MEMS accelerometer. The first category consists of mechanical accelerometers (i.e. devices which measure the displacement of a supported mass) manufactured using MEMS techniques. The second class consists of devices which measure the change in frequency of a vibrating element caused by a change of traction, as in SAW accelerometers. They are small, light and contain low power consumption and start-up times. Their basic disadvantage is that they are not currently as accurate as accelerometers manufactured using traditional techniques, although the implement of MEMS devices is improving quickly [1].

Typical MEMS accelerometer is composed of movable proof mass with plates that is attached through a mechanical suspension system to a reference frame, as shown in Figure 4. Movable plates and fixed outer plates show capacitors. The deviation of proof mass is measured using the capacitance difference [1]. Proof mass is attached through springs (k_S: spring constant) at substrate. It can move only up and down. Movable and fixed plates construct capacitors.

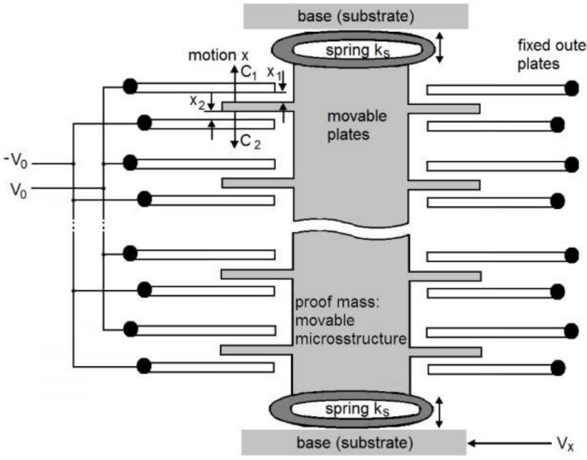

Fig. 4: Accelerometer structure [18]

The free-space (air) capacitances between the movable plate and two stationary outer plates C_1 and C_2 are functions of the corresponding displacements x_1 and x_2:

$$C_1 = \varepsilon_A \frac{1}{x_1} = \varepsilon_A \frac{1}{d+x} = C_0 - \Delta C \tag{2}$$

$$C_2 = \varepsilon_A \frac{1}{x_2} = \varepsilon_A \frac{1}{d-x} = C_0 + \Delta C \tag{3}$$

If the acceleration is zero, the capacitances C_1 and C_2 are equal because $x_1 = x_2$. The proof mass displacement x results due to acceleration. If $x \neq 0$, the capacitance difference is found to be:

$$C_2 - C_1 = 2\Delta C = 2\varepsilon_A \frac{1}{d^2-x^2} \tag{4}$$

Measuring ΔC, one finds the displacement x by solving the nonlinear algebraic equation:

$$\Delta C x^2 + \varepsilon_A x - \Delta C d^2 = 0 \tag{5}$$

This equation can be simplified. For small displacements, the term ΔCx^2 is negligible. Thus, ΔCx^2 can be omitted. Then, from

$$x \approx \frac{d^2}{\varepsilon_A}\Delta C = d\frac{\Delta C}{C_0} \tag{6}$$

one concludes that the displacement is approximately proportional to the capacitance difference ΔC [18].

3.2. Working principle of typical accelerometer

The principle of working of an accelerometer can be explained by a simple mass (m) attached to a spring of stiffness (k) that in turn is attached to a casing, as illustrated in Figure 5. The mass used in accelerometers is often called the seismic-mass or proof-mass. In most cases the system also includes a dashpot to provide a desirable damping effect. The dashpot with damping coefficient (c) is normally attached to the mass in parallel with the spring. When the spring mass system is subjected to linear acceleration, a force equal to mass times acceleration acts on the proof-mass, causing it to deflect. This deflection is sensed by a suitable means and converted into an equivalent electrical signal. Some form of damping is required, otherwise the system would not stabilize quickly under applied acceleration. To derive the motion equation of the system Newton's second law is used, where all real forces acting on the proof-mass are equal to the inertia force on the proof-mass. Accordingly a dynamic problem can be treated as a problem of static equilibrium and the equation of motion can be obtained by direct formulation of the equations of equilibrium. This damped mass-spring system with applied force constitutes a classical second order mechanical system. From the stationary observer's point of view, the sum of all forces in the z direction [19].

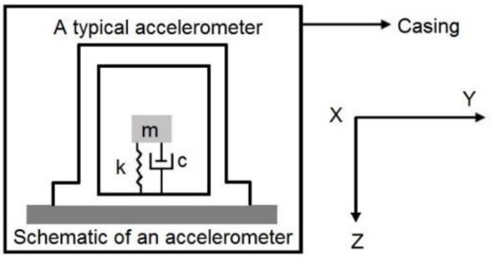

Fig. 5: Schematic of an accelerometer [19]

$$mx + kx + cx = F \tag{7}$$

where: m – mass of the proof-mass, x – relative movement of the proof-mass with respect to frame, c – damping coefficient, k – spring constant, F – force applied

The equation of motion is a second order linear differential equation with constant coefficients. The general solution $X(t)$ is the sum of the complementary function $X_C(t)$ and the particular integral $X_P(t)$.

$$X = X_c(t) + X_p(t) \tag{8}$$

The complementary function satisfies the homogeneous equation.

$$mx + kx + cx = 0 \tag{9}$$

The solution to $X_C(t)$ is:

$$X_c(t) = C\,e^{st} \tag{10}$$

Substituting (10) in (9)

$$(ms^2 + cs + k)C\ e^{st} = 0 \tag{11}$$

As $C\,e^{st}$ cannot be zero for all values of *t*, then,

$$(ms^2 + cs + k) = 0 \tag{12}$$

called as the auxiliary or characteristic equation of the system. The solution to this equation for values of *S* is:

$$S_{1,2} = \frac{1}{2}m(-C \pm \sqrt{C^2 - 4mk}) \tag{13}$$

From the above equation 6, the following useful formulae are derived

$$\omega_n = \sqrt{\frac{k}{m}} \tag{14}$$

$$\frac{c}{m} = 2\xi\omega_n \tag{15}$$

$$\xi = \frac{c}{2} \tag{16}$$

where ω_n – undamped resonance frequency, *k* – spring constant, *m* – mass of proof-mass, *c* – damping coefficient, ξ – damping factor

$$F_{applied} - F_{damping} - F_{spring} = m\ddot{x}$$

$$m\ddot{x} + F_{damping} + F_{spring} = F_{applied} \tag{17}$$

4. Gyroscopes

A gyroscope is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum.

There exist a few basic types of gyroscopes.

4.1. Mechanical gyroscopes

A conventional gyroscope contains of a spinning wheel mounted on two gimbals which allow it to rotate in all three axes, as show in Figure 6. An effect of the safekeeping of angular momentum is that the spinning wheel will resist changes in orientation. Thus when a mechanical gyroscope is expose to a rotation the wheel will remain at a constant global orientation and the angles between adjacent gimbals will change. To measure the orientation of the device the angles between adjacent gimbals can be read using angle pick-offs. Note that a conventional gyroscope measures orientation. In contrast nearly all modern gyroscopes (including the optical and MEMS types) are rate-gyros, which measure angular velocity. The main disadvantage of mechanical gyroscopes is that they contain moving parts. Moving parts cause friction, which in turn causes the output to drift over time. To minimize friction high-precision bearings and special lubricants are used, adding to the cost of the device. Mechanical gyroscopes also require a few minutes to warm up, which is not ideal in many situations.

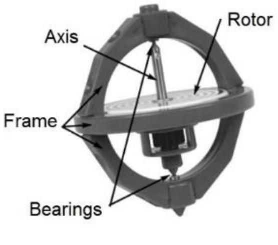

Fig. 6: Gyroscope [20]

4.2. Optical Gyroscope

A fiber optic gyroscope (FOG) uses the interference of light to measure angular velocity. A FOG consists of a large coil of optical fiber. To measure the rotation of the two light beams are fired into the coil in opposite directions. If the sensor is undergoing a rotation then the beam travelling in the direction of rotation will experience a longer path to the other end of the fiber than the beam travelling against the rotation, as illustrated in Figure 7. This is known as the Sagnac effect. When the beams exit the fiber they are combined. The phase shift introduced due to the Sagnac effect causes the beams to participate, resulting in a combined beam whose intensity depends on the angular velocity. It is therefore possible to measure the angular velocity by measuring the intensity of the mixed beam. Ring laser gyroscopes (RLGs) are also based on the Sagnac effect. The difference between a FOG and RLG is that in a RLG laser beams are directed around a closed path using mirrors partly than optical.

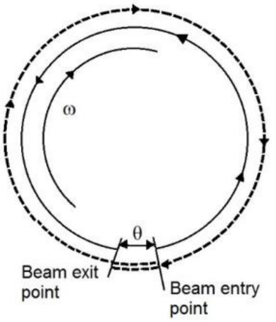

Fig. 7: The Sagnac effect
The dashed line is the path taken by the beam travelling in the direction of rotation. The solid line is the beam travelling against the rotation. θ is the angle through which the gyro turns whilst the beams are in flight [1]

4.3. MEMS Gyroscopes

Notwithstanding years of expansion, mechanical and optical gyroscopes still have high part counts and a requirement for parts with high-precision tolerances and intricate assembly techniques. As a result they remain expensive. In contrast MEMS (Micro-Electro-Mechanical system) sensors built using silicon micro-machining techniques have low part counts and are relatively cheap to manufacture. MEMS gyroscopes make use of the Coriolis effect, which states that in a frame of reference rotating at angular velocity ω, a mass m moving with velocity v experiences a force:

$$F_c = -2m(\omega \times V) \tag{18}$$

MEMS gyroscopes contain vibrating elements to measure the Coriolis effect. Many vibrating element geometries exist, such as vibrating wheel and tuning fork gyroscopes [1].

Micromachined (MEMS) gyroscopes based on piezoresistive nano-gauge sensing have potentialities of compactness [21]. The test and characterization of each individual manufactured MEMS structure is of major importance, both from the economic and quality standpoints [22].

4.4. Properties of gyroscopes

Rigidity and Precession, these properties are defined as follows:

- Rigidity: The axis of rotation (spin axis) of the gyro wheel tends to remain in a fixed direction in space if no force is applied to it.
- Precession: The axis of rotation has a tendency to turn at a right angle to the direction of an applied force.

The fundamental equation describing the behavior of the gyroscope is:

$$\tau = \frac{d\boldsymbol{L}}{dt} = \frac{d(I\omega)}{dt} = I\alpha \tag{19}$$

where the vectors τ and *L* are, respectively, the torque on the gyroscope and its angular momentum, the scalar *I* is its moment of inertia, the vector ω is its angular velocity, and the vector α is its angular acceleration.

It follows from this that a torque τ applied perpendicular to the axis of rotation, and therefore perpendicular to *L*, results in a rotation about an axis perpendicular to both τ and *L*. This motion is called **precession**. The angular velocity of precession w_P is given by the cross product:

$$T = w_p X_1 \tag{20}$$

Thus if the gyroscope's spin slows down (for example, due to friction), its angular momentum decreases and so the rate of precession increases. This continues until the device is unable to rotate fast enough to support its own weight, when it stops precessing and falls off its support, mostly because friction against precession cause another precession that goes to cause the fall.

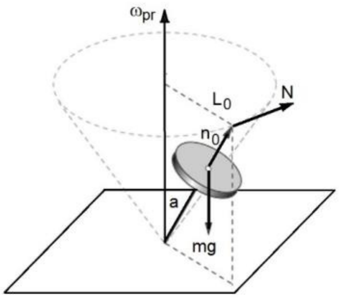

Fig. 8: Steady (regular) precession of the gyroscope under the force of gravity [23]

5. Using inertial navigation systems in Mobile robots

Obviously navigation is one of the most complicated issues in mobile robots, Each mobile object that is free to move in space has six "degrees of freedom" – or ways it can move. There are three linear degrees of freedom (*x*, *y*, *z*) that specify its position and three rotational degrees of freedom (theta (pitch), psi (yaw), and phi (roll)) that specify its attitude. If we know these six variables, we know where it is and which way it is pointed. If we know them over a period of time, then we can also figure out how fast it is moving, and what its acceleration rate is. In fact Navigation System is part of a mobile object to tell it where it is and what it is its' attitude. From inertial measurements we can determine an estimate for linear accelerations and angular velocities. By integrating these quantities we determine the velocity vector and the body attitude. Position can be calculated by integration of the velocity vector. Inertial navigation is thus based on the dead-reckoning principle [14].

One of the commonly used relative positioning system is Inertial Navigation System (INS). Dead reckoning positioning with gyros and accelerometers is called inertial navigation. The gyro measures the angular rate and the accelerometer senses the accelerations. Integration of angular velocity with time yields angle data. Distance data could be obtained by double integration of acceleration with time. INS is a self-contained device which requires no external electromagnetic signals. Thus, INS does not have the signal coverage problem found in GPS. Moreover, the data output rate of INS could be much faster than GPS. However, the disadvantage of INS is the bias drift problem. These errors would be accumulated and the accuracy deteriorates with time due to integration [24].

Gyroscopes are of particular importance to mobile robot positioning because they can help compensate for the foremost weakness of odometry. An odometry-based positioning method, any small momentary orientation error will cause a constantly growing lateral position error. For this reason it would be of great benefit if orientation errors could be detected and corrected immediately. Until recently, highly accurate gyros were too expensive for mobile robot applications [13].

In the form of an autonomous, mobile robots must know where they are. Mobile robot localization, that is the process of specify and tracking the position of a mobile robot relative to its environment, has received significant attention over the past few years. Accurate localization is a key prerequisite for successful navigation in large-scale environments, spatially when global models are used [7]. Localization, that is the estimation of a robot's location from sensor data, is a fundamental problem in mobile robotics. The purpose of localization is to estimate the position of a robot in its environment, given a map of the environment and sensor data [8].

Local approaches to localization are planed to compensate odometric error based on sensor data. They often require that the initial location of the robot is known, and are only capable of navigate the location of a robot. Global dealing are more general. They can localize a robot globally, that is, they can determine its location without knowledge of the initial location and therefore can handle the "kidnaped robot problem". Recently, several researchers proposed a new localization sample, called Markov localization, which enables robots to localize themselves under global uncertainty. Global approaches have two important advantages over local ones: First, the initial location of the robot does not have to be specified and, second, they provide an additional level of robustness, due to their ability to recover from localization failures [7].

A second dimension along which localization methods can be grouped is interested with the nature of the environment which they can master. Most methods can only deal with one's surroundings, with static environments, that is, environments where, according to the robot's sensors, the only aspect that may change over time is the robot's own location. However, these methods usually fragile in environments where the dynamics are perceived through the robot's sensors. Uses of cameras pointed towards the ceiling and thus cannot perceive most of the changes that occur in typical office environments. Unfortunately, such an approach is only applicable if the ceiling contains enough structure for accurate position estimation. Thus, the development of methods that can localize a robot in dynamic environments is still an important goal of research on mobile robot navigation. a localization algorithm that can localize robots in the most difficult of all situations, namely localization under global uncertainty and in highly dynamic environments [7].

6. Conclusion

Inertial navigation is based on a continuous evaluation of object position wait using of the navigation sensors which are sensitive to movement, ie. gyroscopes and accelerometers which are considered primary inertial sensors, or other sensors, placed on the navigated object. Through navigation computing and data from sensors position, orientation, direction and velocity of movement without information external sources on movement is continuously determined. Current location of object is measured based on knowing of the initial position and subsequent measurement of acceleration and orientation of motion in reference system [25].

Autonomous robot navigation was one of the main problems, but at the same time of aims since starting of robotics. Despite already existing independently working robots in different industries and in different applications, robots still lack ability of self-localization in space but also of separate robot navigation respectively specified in an unspecified area. System based on robot self-management is more accurate but as well as faster access in robot navigating than in with the control system application [26].

This paper presented an overview of inertial navigation system and accelerometric, gyroscopic sensors and describe possibilities of their application for inertial navigation of mobile robot.

In important component of any operational mobile robot system is the ability for the robot to localize itself; that is, to explain its position in space consistently and accurately from sensor data.

Acknowledgements

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References

[1] Woodman O. J. An introduction to inertial navigation. Technical Report, Number 696, University of Cambridge, 2007

[2] Sukkarieh S. Low Cost, High Integrity, Aided Inertial Navigation Systems for Autonomous Land Vehicles. Ph.D. Thesis, University of Sydney, 2000

[3] Walchko K. J., Mason P. A. C. Inertial Navigation. Florida Conference on Recent Advances in Robotics, 2002

[4] Bennamoun M., Boashash B., Faruqi F., Dunbar, M. The Development of an Intergrated GPS/INS/Sonar Navigation System for Autonomous Underwater Vehicle Navigation. IEEE Symposium on Autonomous Underwater Vehicle Technology, Washington, DC, 1990; 256–261

[5] Ohlmeyer E., Pepitone T., Miller B. Assessment of Integrated GPS/INS for the EX-171 Extended Range Guided Munition. Naval Surface Warfare Censter.

[6] Lobo J., Lucas P., Dias J., Traça de Almeida A. Inertial Navigation System for Mobile Land Vehicles. IEEE International Conference on Industrial Electronics, Athens, Greece, 1995, 843–848

[7] Fox D., Burgard W, Thrun S, Cremers A. B. Position Estimation for Mobile Robots in Dynamic Environments. In: Proc. of the Fifteenth National Conference on Artificial Intelligence, Madison, Wisconsin, 1998

[8] Fox D., Burgard W, Thrun S. Markov Localization for Mobile Robots in Dynamic Environments. Journal of Articial Intelligence Research 11: 1999; 391–427

[9] Cox I. J., Wilfong G. T. Autonomous Robot Vehicles. Springer Verlag, 1990

[10] Borenstein J., Everett B, Feng L. Navigating Mobile Robots: Systems and Techniques. A. K. Peters, Ltd., Wellesley, MA, 1996

[11] Pirník R., Hruboš M., Nemec D. Navigation and Control of a Vehicle to the Parking Place Using INS. Transactions of the VŠB - Technical University of Ostrava, Mechanical Series. vol. LXI (2): 2015; 35–41

[12] Abramov A., Božek P. Aplikácia inerciálneho meracieho systému v obrábaní. Strojárstvo/Strojírenství 15 (12); 2011

[13] Borenstein J., Everett H. R., Feng L., Wehe D. Mobile Robot Positioning – Sensors and Techniques. Journal of Robotic Systems, Special Issue on Mobile Robots. 14 (4): 2002; 231–249

[14] Saderzadeh A., Sanaatiyan M. M., Korayem M. H., Shahri A., Shahri H. R. Mobile Robot Navigation Error Handling Using an Extended Kalman Filter. Journal of Advances in computer Research 1 (1): 2010; 61–76

[15] Gade K. Introduction to Inertial Navigation and Kalman Filtering. Tutorial for IAIN World Congress, Stockholm, 2009

[16] Nisticò A. Working principle of a capacitive accelerometer. University of Roma Tor Vergata, 2013

[17] Abracon Corporattio, A Worldwide Leading Supplier of Electronic Components. Saw devices. California, 2005

[18] Andrejašic M. MEMS accelerometers. University of Ljubljana, 2008

[19] Prasad S. Desidn simulation and fabrication of micromachined acceleration sensor: Accelerometer Theory & Design. Jawaharlal Nehru Technological University, 2010

[20] Przybilla K. The Amazing Power of Spin. Duncan Toys 2005

[21] Giacci F., Dellea S., Langfelder G. Capacitive vs Piezoresistive MEMS Gyroscopes: A Theoretical and Experimental Noise Comparison. Procedia Engineering 120: 2015; 406–409

[22] Britoa N., Alvesb F. S., Cabrala J., Gasparc J., Monteiroa J., Rochab L. A. Embedded MEMS Platform for Structure Test and Characterization. Procedia Engineering 120: 2015; 67–70

[23] Butikov E. Precession and nutation of a gyroscope. St. Petersburg State University, St. Petersburg, Russia

[24] Liu H., Pang G. Accelerometer for Mobile Robot Positioning. Proceedings of the 1999 IEEE Industry Applications Society Conference Phoenix, Arizona, USA, 1999

[25] Soták M. Inerciálny navigačný systém v Simulinku. Mezinárodní konference Technical Computing Prague 2009, 93–98

[26] Chynoradský L. Riadenie robota pomocou inerciálneho navigačného systému. Diplomová práca. Slovenská Technická Univerzita v Bratislave, 2015