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GPS-free navigation based on using inertial and odometry, data fusion and map matching algorithm.

Piotr Prusaczyk[1, a)], Jarosław Panasiuk[1, b)] and Leszek Baranowski [1, c)]

[1]*Faculty of Mechatronics & Aerospace, Military University of Technology, Urbanowicza 2, 00-908, Warsaw, PL*

[a)]Corresponding author: Piotr.Prusaczyk@wat.edu.pl
[b)]Jaroslaw.Panasiuk@wat.edu.pl
[c)]Leszek.Baranowski@wat.edu.pl

Abstract. This paper discusses the capability to create GPS-free navigation system for land vehicles, using integrated data from inertial and odometer sensors coupled with the road map data. The data from accelerometers and gyros embedded in low cost strapdown IMU units are combined with differential odometry data provided by the wheels' speed sensors using dedicated filter. The INS exponential growing errors over time can be eliminated or significantly reduced by using the Zero Update Velocity (ZUPT) method based on a dedicated filter. The aim of the problem is to use merged data with map-matching algorithm to accomplish mapping the computed trajectory onto the road network for determination of the position of the vehicle in two dimensional space.

INTRODUCTION

Knowledge of actual position and velocity of the object is a crucial task in many land applications. Old times of using the paper's maps are gone. Nowadays GPS (Global Positioning System) is widely used for navigation purposes for aircraft, vehicles and pedestrians because of its affordability and convenience. Unfortunately pure GPS localization can be highly inaccurate in urban environments such as tunnels and urban canyons. In specific situations the GPS can be jammed or turned off by the owner which are United States of America. This are the reasons that other countries making its own alternatives navigation systems based on satellites. The final users of that systems are still dependent on devices that fly many kilometers above their heads.

GLOBAL POSITIONING SYSTEM

Global Positioning System (GPS) use satellites to obtain current geographic location of the object equipped with receiver on the globe. The system contains of 28 satellites that orbit the Earth which is shown on FIGURE1. The location accuracy is from 100 meters up to few meters, and it depends on the factors that include satellite geometry, signal blockage, atmospheric conditions and receiver quality.

The GPS is based on the time measurement of the receiving signal between satellite and receiver. Knowing the speed of electromagnetic wave and the exact time when the signal has been send it is available to calculate the distance between satellite and receiver. At least 4 satellites are required to obtain the position in three dimensional space. The navigation message received from each satellite contains date, time, ephemeris and almanac data. The satellite use atomic clock to hold precise date and time. The ephemeris is orbital information which allows the receiver to calculate the position of the satellite. The almanac data contains information and status concerning all the satellites.

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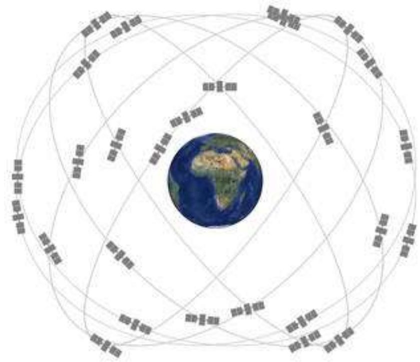

FIGURE 1 GPS constellation.[Source: NASA]

INERTIAL NAVIGATION SYSTEM

The Inertial Navigation System (INS) unlike GPS, are entirely self-contained within the object, they do not depend on external radiation and optical information. The INS use the inertial properties of sensors mounted in the object to proceed the navigation function. The system process the data obtained from force and inertial angular velocity measurements. The system calculate the position and orientation change in time. Knowledge of the position and orientation at the start of navigation is crucial for inertial navigation system to be able to continuously determinate the vehicle position and velocity without the usage of external data. The INS consists of gyroscopes and accelerometers. The gyroscopes can measure angular-velocity based on conservation of the angular momentum principle. Three structurally mounted gyroscopes determine the relative orientation between the initial and present object coordinate frame. The accelerometer measures the specific force, using sophisticated variations of the simple pendulum. The motion of the pendulous element is related to the motion of the object upon which the accelerometer is mounted via Newton’s second law of motion. Motion of the pendulous element is correlated with the inertial acceleration. As FIGURE 2 shows, the first time integration of the inertial acceleration gives velocity information. The second time integration gives the position information. [1]

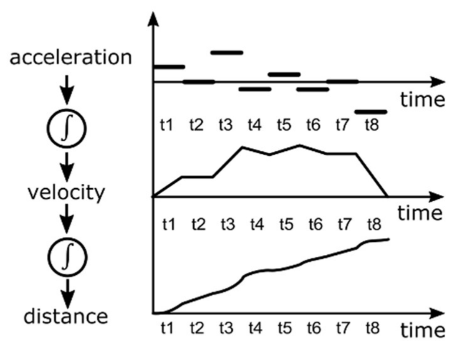

FIGURE 2 Double integration process.

STRAPDOWN TECHNOLOGY

Modern systems have removed most of the mechanical complexity of platform systems, by attaching the sensor to the body of the object. This reduces the cost, size and weight of the inertial navigation systems. The major disadvantage is increasing computing complexity, and necessity to use sensors capable of measuring at higher rates of turn. New applications that demand low-cost sensors for providing measurements of acceleration and angular motion push the development of micro-machined electromechanical system sensors (MEMS). Usage of silicon as the base material drastically reduced the size and number of elements that leads to reducing the cost. MEMS gyroscope is non-rotating device that use the Coriolis acceleration effect on a vibrating proof mass to detect inertial angular rotation. MEMS accelerometer operates similar to the pendulous open-loop and force-feedback accelerometers, that are described in [2]. The MEMS sensors are usually made of silicon. The Strapdown Inertial Navigation System can achieve very high accuracy and high autonomy. Unfortunately the accuracy of INS system depends on the quality of the IMU sensors. The nonlinearity, bias, drift and noise of the sensor affect on the measurements, which are integrated once and twice for velocity and position calculation, causing the accuracy of the predicted values valid for short period of time. The navigation signal will be divergence with the accumulation of time in the long-range time and long-movement [3][5]. For error minimalisation it is crucial to know the model of the sensor. The generalized inertial sensor model was presented in [3]:

$$ {}^{b}\tilde{y} = {}^{b}y + {}^{b}b + n \tag{1} $$

where ${}^{b}y^{T} = [{}^{b}f^{T} \;\; {}^{b}\omega_{ib}^{T}]$ and ${}^{b}f = {}^{b}a + {}_{n}^{b}Rg^{n}$ is the specific force vector. The vector ${}^{b}y$ is corrupted by a slowly changing bias ${}^{b}\mathrm{b}^{T} = [{}^{b}\mathrm{b}_{a}^{T} \;\; {}^{b}\mathrm{b}_{g}^{T}]$ and measurement noise *n*. The symbols ${}^{b}\mathrm{b}_{a}$ ${}^{b}\mathrm{b}_{g}$ are accelerometer and gyrometer biases. ${}^{b}a$ denotes the body frame acceleration and the ${}^{n}g$ is the gravity vector in navigation frame ${}^{b}\mathrm{g}^{T} = [0 \; 0 \; \mathrm{g_e}]$. According to inertial sensor model the INS error state vector is:

$$ \delta x^{T} = \left[{}^{n}\delta p_{b}{}^{T} \;\; {}^{n}\delta v_{b}{}^{T} \;\; {}^{n}\rho^{T} \;\; {}^{b}\delta b_{a}{}^{T} \;\; {}^{a}\delta b_{g}{}^{T}\right] \tag{2} $$

${}^{n}\delta p_{b}$ − position error, ${}^{n}\delta v_{b}$ − velocity error, ${}^{b}\delta b_{a}$ – accelerometer bias, ${}^{b}\delta b_{g}$ –gyroscope bias, ${\rho_{n}}^{T}$ −estimated angle variation

Thus, error state differential equations are [3]:

$$ {}^{b}\delta\dot{p}_{n} = {}^{b}\delta v_{n} \tag{3} $$
$$ {}^{b}\delta\dot{v}_{n} = -[{}^{n}f \times]^{n}\rho + {}_{b}^{n}R^{b}\delta b_{a} + {}_{b}^{n}R\, n_{a} \tag{4} $$
$$ \dot{\rho}_{n} = {}_{b}^{n}R^{b}\delta b_{g} + {}_{b}^{n}R\, n_{g} \tag{5} $$
$$ {}^{b}\delta\dot{b}_{g} = n_{b_g} \tag{6} $$
$$ {}^{b}\delta\dot{b}_{a} = n_{b_a} \tag{7} $$

qhere b_{a} and b_{g} are the accelerometer and gyroscope measurement noise respectively.

ODOMETRY

Another kind of localization method is dead-reckoning, wheel encoder based odometry. For land navigation, odometry is a cost-effective and convenient method of determining the position change. The data from the motion sensors is used to estimate change in position over time. This method is widely used in robotics[4]. In classical approach, the distance is calculated from the angle displacement measurement of the rotating wheel on the surface without slipping. Like for INS the knowledge of the initial position and orientation is important for determination the actual position. The major disadvantages of the odometry are connected with the instability of the scale factor linking the distance traveled with the measured wheel angle. This errors grows potentially with travelled distance. The errors that come with the changing environmental conditions are called non-systematic deviation. That errors can be generated by nonlinear surface or wheel slippery. For two-dimensional navigation the differential odometry can be used[5]. Given a two wheeled robot, odometry estimates position (8)(9) and orientation (10), from left and right velocities as a function of time. The velocities are calculated by counting the encoders' signals edges in specific period of time. Monitoring of the encoder channels can be performed by external interruptions of the microcontroller.

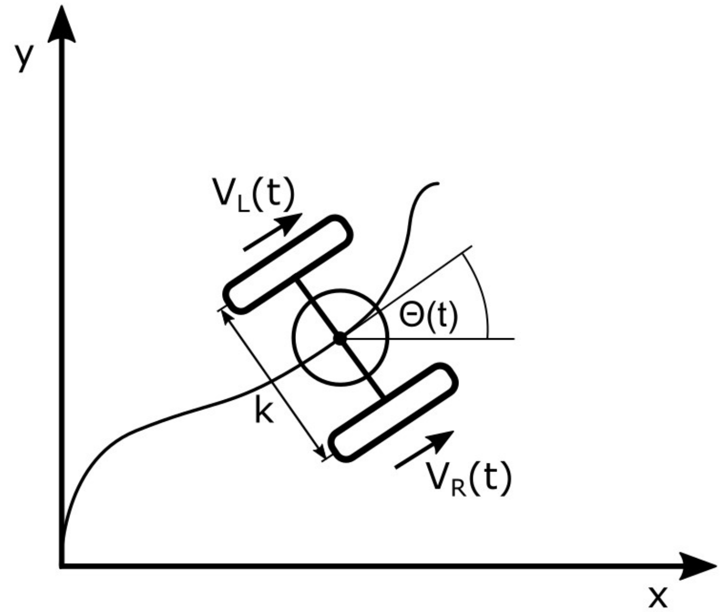

FIGURE 3 Differential odometry.

$$x(t) = x(0) + \int_0^t \left(\frac{V_R(\tau)+V_L(\tau)}{2}\right) \cos\Theta(\tau) d\tau \tag{8}$$

$$y(t) = y(0) + \int_0^t \left(\frac{V_R(\tau)+V_L(\tau)}{2}\right) \sin\Theta(\tau) d\tau \tag{9}$$

$$\Theta(t) = \Theta(0) + \int_0^t \left(\frac{V_R(\tau)-V_L(\tau)}{k}\right) d\tau \tag{10}$$

where: V_R – right wheel velocity, V_L – left wheel velocity, k – wheel separation

ERROR MINIMIZATION COMBINING DIFFERENT LOCALIZATION METHODS

GPS & INS

Inertial Navigation system has high accuracy in short period of time. This is caused by integration of noise-contaminated inertial measurements that leads to an unbounded drift. To mitigate the error drift other absolute sensor can be used. GPS can be treated as an absolute updating sensor with a long-term stability with homogenous accuracy. GPS combined with INS have been used intensively in aeronautics [7] and become a standard approach in modern navigation area. There are three main coupled integration approaches: loosely coupled integration, tight coupled integration and ultra-tight coupled integration. All methods are based on the INS error dynamic model that uses the GPS information to calibrate INS accumulation error with dedicated navigation filters. Kalman filter are commonly used as a standard data fusion method. [8]

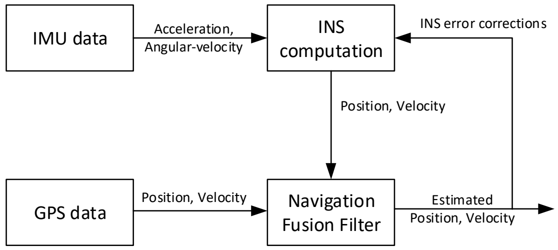

FIGURE 4 Block diagram of example GPS/INS integration method.

INS & ODOMETRY

Dead reckoning navigation estimates a relative position from the initial starting point information. As it was written earlier, it uses an inertial measurement unit or a control variable, such as a wheel encoder and so there is no necessity to depend on external signals. Simplicity, low cost, and easier time estimating the position in real time compared to absolute positioning (GPS) are big advantages of dead reckoning methods. In odometry, position and yaw angle of the travelling mobile robot can be estimated by encoders attached to the robot's wheels. Unfortunately, odometry generates unbounded errors because of slippage, mismatches in the system parameters, measurements inaccuracies, and noise from the encoder signals. These errors accumulates over travelled distance. The INS, provides the position and orientation at high rate with high short-term precision but low long-term precision. By the double integrate process, low frequency noise and sensor biases are amplified. Standalone working odometry and INS generates accumulated errors over long periods of time. In the article [9] authors combine odometry and INS in order to reduce the accumulated errors of those navigation methods. Data fusion process and position and orientation estimation was performed by designed Kalman filter. When the object is stationary the inertial, compass data estimates the bias of the inertial. In moving state inertial data is used for calculation velocity and orientation corrected by state estimation kalman filter that uses encoder data. [9]

ZUPT

Zero velocity update is effective technique of error suppression and compensation for high-precision inertial positioning and orientation system (INS). When the object is in standstill state (zero speed) the velocity observation is set to zero, and the velocity and position of the inertial navigation systems are corrected. The detection of the stopping time intervals of INS is very crucial for this method. Bad precision of navigation will bring the mistakenly detected stationary state. There are several types of zero-velocity detectors, like acceleration moving variance detector, acceleration magnitude detector, and angular rate detector. [6][10]

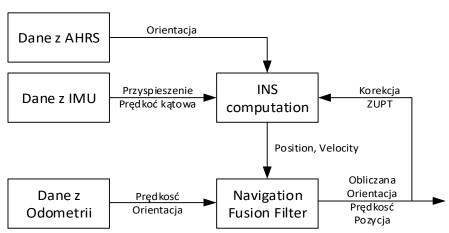

FIGURE 5 Block diagram of example of INS/ODOMETRY method.

MAP MATCHING TECHNIQUE FOR MAINTAINING GLOBAL POSITION

GPS systems or even combined methods of navigation do not always provide the location of a vehicle in road map with the required accuracy. This is caused by various error sources. Many methods were presented to reduce these errors. Another approach in reducing the navigation error is Map Matching algorithm. In this technique the estimated position of the object in map is computed by comparison of the real position and the road network of digital map. [13] There are multiple map matching algorithms, which can be divided to geometric and topological algorithms.

Geometric information is used in a geometric map matching algorithms. Point-to-point map matching algorithm uses GPS coordinates that are matched to the nearest shape point of a road segment. This method can be easily and fast implemented. Point-to-curve map matching algorithm uses coordinates that are matched to the closest curve in the road network. The geometry of the road network is used in topological algorithm. In this method the links that have no connectivity with previous matched road network are exluded from the checking algorithm.[14]

CONCEPTION

In order to downgrade the dependency on the GPS signal, other navigation methods need to be used. The independent from the external radiation and optical information, dead reckoning methods, generates accumulated errors, when working separately. In paper [9] and [11] authors perform tests that combine the INS with the odometry and confirm that position estimation error can be significantly reduced. Nevertheless, remaining errors need to be suppressed. The map-matching algorithm is very promising in correcting actual calculated position by attaching the position to the most probable place on the digital road network map. The authors propose different approach to navigation problem.

Navigation is used in order to reach some specific destination in the world, moving along the route calculated by the navigation algorithm (figure 6). The route is represented by a succession of road centerline points. The reference trajectory (figure 7) is generated from the route, constrained by geometric and dynamic limitations of the vehicle, using mathematical models of the vehicle.

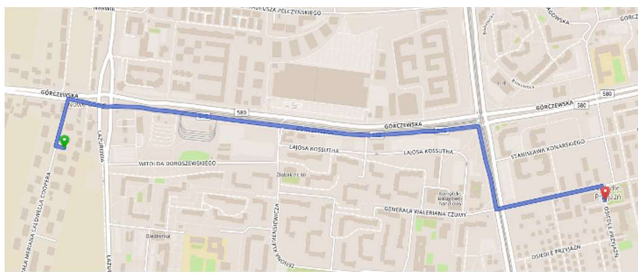

FIGURE 6 Calculated path.

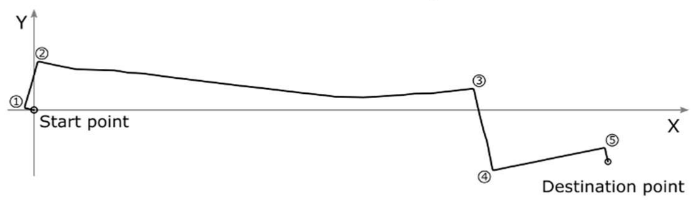

FIGURE 7 Ideal trajectory generated from calculated path.

The trajectory can be described as continuous sequence of reachable configurations q=(x, y, Θ, φ) defined by Wheeled Rolling System's (figure 9) Centre of Gravity coordinates (x, y), Centre of Gravity orientation (Θ) and curvature of the path (k). Reaching destination point $(x_n, y_n, \Theta_n, \varphi_n)$ is possible performing that reference trajectory from start point $(x_0, y_0, \Theta_0, \varphi_0)$. [17]

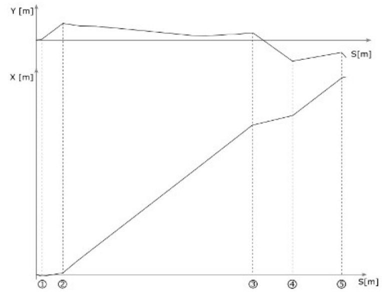

FIGURE 8 Global X and Y coordinates depending on covered distance of ideal trajectory.

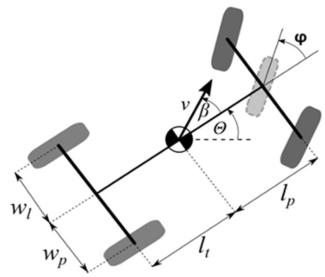

FIGURE 9 Wheeled Rolling System model

The real trajectory of the vehicle is obtained by the combined dead reckoning methods like inertial navigation system and wheel speed sensors (rotational encoder). The inertial navigation system equipped with the magnitude sensor, creates the attitude and heading reference system (AHRS). There are several approaches to velocity and distance measuring using odometry that have been proposed [15]. Using high accuracy optic encoders, the current velocity and travelled distance can be obtained. The odometry can also be used as a trigger to Zero Velocity update method for the inertial measurement unit calibration.

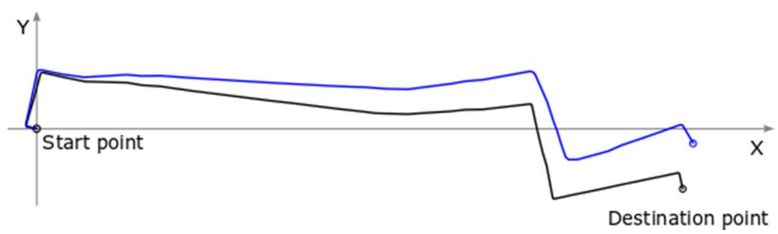

FIGURE 10 The deviation of the trajectory (blue line), reference (real) trajectory (black line).

Using dead reckoning methods, the errors of the position increase on each meter while driving along generated trajectory. Thus the false trajectory appear and false position coordinates are the calculated.

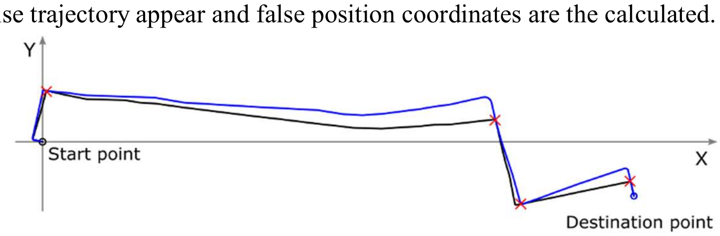

FIGURE 11 The correction of the deviation using intersection matching method.

The real trajectory compared with the reference one gives the deviation that should be decreased in navigation process. The conception is based on natural landmarks, which for the road can be curvature, intersections and etc. Those characteristic points are used for trajectory matching and trajectory progress detection.

CONCLUSION

In this paper, different types of navigation strategies were described as well as position deviation minimization using different navigation techniques. Most of the navigation techniques using GPS satellite signal for positioning process. Some of them are assisted with odometry and inertial systems for increasing the accuracy in short period of time. The next stage can be the development of navigation systems that operate independently of the GPS signal. In these techniques, odometry, inertial and the matching algorithms systems play a crucial role. The authors propose the conception of a navigation system based on a trajectory generated from digitized road network map. The real trajectory is compared with the generated ideal trajectory in order to calculate the deviation that can be used in the navigation process. In further studies, the real time measuring platform will be developed and adapted in car vehicle.

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