Acta Mechatronica - International Scientific Journal about Mechatronics
Volume: 1 2016 Issue: 1 Pages: 19-23 ISSN 2453-7306

NAVIGATION OF THE AUTONOMOUS GROUND VEHICLE UTILIZING LOW-COST INERTIAL NAVIGATION

Rastislav Pirník
Department of Control and Information Systems, Faculty of Electrical Engineering, University of Žilina, 010 26 Žilina, Slovak Republic, rastislav.pirnik@fel.uniza.sk
Marián Hruboš
Department of Control and Information Systems, Faculty of Electrical Engineering, University of Žilina, 010 26 Žilina, Slovak Republic, marian.hrubos@fel.uniza.sk
Dušan Nemec
Department of Control and Information Systems, Faculty of Electrical Engineering, University of Žilina, 010 26 Žilina, Slovak Republic, dusan.nemec@fel.uniza.sk
Pavol Božek
Department of Control and Information Systems, Institute of Applied Informatics, Automation and Mechatronics, Faculty of Materials Science and Technology, Slovak University of Technology, 917 24 Trnava, Slovak Republic, pavol.bozek@stuba.sk

Keywords: inertial navigation, automated vehicle, sensors, sensor fusion
Abstract: This article discusses usage of the inertial navigation combined with one or multiple odometers for precise navigation of the autonomous ground vehicle. Such navigation does not require any kind of external signal; therefore it is resistant against external disturbance and might be used in harsh industrial environment. Using low-cost MEMS gyroscope and accelerometer provide only attitude and heading reference; the odometers are responsible for measurement of the dislocation and the vehicle's speed.

1 Introduction

Current development in industry encounters change of focus from static robotics (automated manipulators) to the mobile robotics. Mobile robot is capable to provide its services in almost unlimited working range but does not offer such precision of the movement control. Therefore it is very suitable for basic manipulation with completed components and their transportation inside the manufacturing facility. For such purpose the autonomous ground vehicles (AGVs) utilizing some form of wheels are being widely used due to their power efficiency and simplified construction. In order to control the movement of such vehicle it is required to have precise estimation of its location in 2D space including its orientation (heading). Widely used satellite navigation systems (GPS, GLONASS) cannot be used inside buildings or underground, which restricts their usage in the mentioned industrial environment [1]. These satellite navigation systems also do not provide enough accuracy and sampling rate for real-time navigation in their civil versions. Available extensions are licensed, which makes them quite expensive. Development of the MEMS technology recently allowed manufacturing of precise and relatively low-cost inertial sensors (gyroscopes, accelerometers) [3][4]. These sensors are the basic component of any inertial navigation system.

2 Low-Cost Inertial Navigation

According to the kinematic theory it is possible to estimate the velocity vector of the object by time integration of its acceleration regarding object's attitude (lateral inclination called roll, longitudinal inclination called pitch and horizontal direction called heading). The dislocation could be then estimated by time integration of the obtained velocity. This approach requires excellent precision of the used accelerometers or special integrative accelerometers like Pendulous Integrating Gyroscopic Accelerometer (PIGA) which are complex and expensive or does not provide required precision [4]. Otherwise any error of the accelerometer's reading will be integrated into velocity and dislocation vector. In case of sensor bias (non-zero output at zero acceleration) the resultant position error will increase with square of the run-time. In case of an accelerometer with the digital output the best achievable bias varies around 1 LSB. The position error is then:

$$d_{\text{drift}}(t) \approx \frac{a_{\text{FS}}}{2^{N-1}} \frac{t^2}{2} \tag{1}$$

where $d_{\text{drift}}(t)$ - error of the position estimation in one axis [m], a_{FS} - full-scale of the accelerometer [m.s^{-2}], N - resolution of accelerometer's the digital output [bits], t - run-time of the integration since last reset [s].

On the other hand, inertial sensors can be used for very precise measurement of the attitude. Attitude (rotation of the object in 3D space) defines the rotational transformation between the static global coordinate system (in our case it is bound with the floor inside facility) and local coordinate system (bound with the vehicle). It can be computed in real time from the initial attitude and readings of 3-axial gyroscope (measures angular velocity in local system), see [7]. Since the reading of the gyroscope is integrated only once the error of the attitude estimation caused by gyroscope bias increases only linearly. If the floor were perfectly planar (not necessarily horizontal), the single-axis gyroscope mounted on the vehicle in vertical direction (with respect to the vehicle's local coordinate system) would be sufficient for estimation of the heading. If the floor is not planar the 3-axial gyroscope or 3 pieces of perpendicularly oriented single-axis gyroscopes are necessary to be used for reliable and complex attitude estimation in 3D space. Note that without knowing the initial heading it is impossible to determine actual absolute heading.

Available MEMS motion sensors sometimes incorporate 3-axis accelerometer and 3-axis gyroscope inside one integrated module. Accelerometer is not meant to be used for position estimation. Since it measures the sum of the gravitational acceleration vector (constant in global coordinate system, defines vertical direction) and the system's own acceleration (can be arbitrary but its mean value in long terms is zero) it can be used as a secondary sensor for compensation of the errors caused by gyroscope bias in horizontal axes. In order to compensate errors of the gyroscope's vertical axis and to provide absolute heading reference (with respect to the magnetic North) one can use a magnetic compass. Please note that the magnetometer is not an inertial sensor since it does not measure kinematic variable. Available magnetometers can be used for mentioned purpose but they are very sensitive to the presence of an external magnetic field or larger metal objects. In the industrial harsh environment both mentioned disturbance sources will be typically present.

Rotation of the Earth around its axis causes systematic error of the attitude estimation (orbital movement of the Earth around the Sun is negligible). This rotation influences all axes of the gyroscope (see Fig. 1) but is well defined. Therefore it can be easily compensated:

$$\boldsymbol{\omega}_{\text{comp}} = \boldsymbol{\omega}_{\text{raw}} - \boldsymbol{R}.\omega_{\text{Earth}}\left[-\cos\phi \quad 0 \quad \sin\phi\right]^{\text{T}} \qquad (2)$$

where: $\boldsymbol{\omega}_{\text{raw}}$ - angular velocity vector obtained from gyroscope [3x deg.s^{-1}], $\boldsymbol{\omega}_{\text{comp}}$ - compensated angular velocity vector in local frame of reference [3x deg.s^{-1}], ω_{Earth} - angular rate of the Earth's axial rotation (approximately 0.0042 deg.s^{-1}), $\boldsymbol{R}$ - rotational matrix expressing current attitude of the vehicle [3x3], ϕ - geographical latitude.

Our research has shown that after compensation of the Earth's rotation the heading error is not critical only if the AGV is not moving continuously longer than few minutes (depending on precision of the used gyroscope). For example, the gyroscope with 16-bit signed resolution and dynamic measurement range ± 250°/s which theoretical precision is 1 LSB drifts in heading estimation by approx. 0.5° per minute in the worst case. In order to eliminate this error it is possible to measure and reset the heading of the AGV while passing a gate or door. Since the INS is incremental the next attitude changes will be added to the precisely reset attitude.

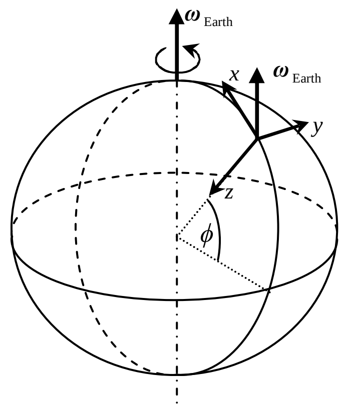

Figure 1 Influence of the Earth's rotation in specific location

Precisely estimated attitude itself is not sufficient for navigation inside the facility. It is necessary to measure distance ran by the vehicle. This can be achieved by an odometer bound with any of the vehicle's fixed wheels (which rolls along axis x). Position estimation algorithm should run in discrete time and its one step can be described by following formula:

$$\boldsymbol{d} \leftarrow \boldsymbol{d} + \Delta\boldsymbol{d} \qquad (3)$$

where $\Delta\boldsymbol{d}$ is a dislocation vector ran by the AGV during one step and is equal to:

$$\Delta\boldsymbol{d} = \boldsymbol{R}^{-1} \cdot [\Delta s \quad 0 \quad 0]^{\text{T}} \qquad (4)$$

where: $\boldsymbol{d}$ - position vector [3x m], $\boldsymbol{R}^{-1}$ - inverse rotation matrix expressing attitude of the object with respect to the global frame of reference [dimension 3x3], Δs - change of the distance measured by odometer [m].

The equation (4) does not consider position of the wheel with odometer with respect to the origin of the local coordinate system. In case of a vehicle with one steerable and one fixed axle it appears to be convenient to place the origin to the centre of the fixed axle. During turns the outer wheel runs greater distance than the inner wheel which will corrupt the overall position estimation. Equation (4) should be then modified:

$$\Delta \boldsymbol{d} = \boldsymbol{R}^{-1} \cdot \left[[\Delta s \quad 0 \quad 0]^{\mathrm{T}} - \left(\boldsymbol{\omega}_{\mathrm{comp}} \times \boldsymbol{r} \right) \Delta t \right] \tag{5}$$

where: $\boldsymbol{r}$ - dislocation vector of the wheel with odometer in local coordinate system [3x m], Δt - sampling period of the algorithm [s].

Second term expresses false velocity contribution caused by rotation of the vehicle. Equation (5) is valid only if the odometer is mounted on the fixed wheel (non-steerable). Otherwise the equation has to be modified considering the steering angle:

$$\Delta \boldsymbol{d} = \boldsymbol{R}^{-1} \cdot \left[\Delta s [\cos\psi \quad \sin\psi \quad 0]^{\mathrm{T}} - \left(\boldsymbol{\omega}_{\mathrm{comp}} \times \boldsymbol{r} \right) \Delta t \right] \tag{6}$$

where: ψ - steering angle of the wheel on which the odometer is mounted [rad].

Equations (4), (5) and (6) consider that both global and local coordinate system are Cartesian in NED convention (x – North or forward, y – East or right, z – down). If multiple wheels are equipped with odometers, it is possible to improve the precision of the position estimate by performing fusion between all odometers' readings. The differences among odometer readings are usually caused by sliding of the wheels. It is more likely that the driven wheels slide more than non-driven; therefore the fusion weight η_i of the driven wheels is lower. The equation (6) has to be applied separately to each measured wheel and the resultant dislocation vector is then equal to the weighted average of all wheels:

$$\Delta \boldsymbol{d}_{\mathrm{fusion}} = \frac{\sum_{i=1}^{n} \eta_i \Delta \boldsymbol{d}_i}{\sum_{i=1}^{n} \eta_i} \tag{7}$$

Velocity vector of the vehicle in the global coordinate system is then equal to:

$$\boldsymbol{v} = \frac{\Delta \boldsymbol{d}_{\mathrm{fusion}}}{\Delta t} \tag{8}$$

Sliding of the wheels (skid) is necessary if the mobile platform does not have any steerable or omnidirectional wheels. Such chassis is controlled by different rotation between right and left wheels (or tracks) and is suitable for off-road terrain. We can assume that the distance slid by wheels on one side of the chassis is opposite to the distance slid by the wheels on the other side. After the fusion according to the formula (7) the resultant error caused by sliding is compensated. Also note that usage of skid-controlled mobile platforms for transportation of some heavy components may cause rapid degradation of the road's surface.

3 Navigation by Waypoints

Control system of the autonomous vehicle has to affect the steering and propulsion of the vehicle in order to run along the pre-set trajectory considering possible deviations while maintaining safe distance from both static and moving obstacles. The moving obstacles are usually unpredictable and the vehicle has to incorporate non-tactile sensors (e.g. laser scanners) to detect their presence. This article discusses only navigation in the static map. The trajectory can be defined as a series of waypoints in 2D space and the vehicle has to reach each waypoint (or its close neighborhood) in given order at given speed. Proposed inertial navigation to the waypoints is different from commonly used navigation along the trajectory which is determined physically by magnetic or optic tapes (path following). Path follower does not need to know the map of the environment which makes its controller simpler. On the other hand, this approach depends on the leading tape which requires maintenance and lacks flexibility.

Waypoints have to be placed considering the physical constraints of the AGV (its dimensions and minimal turning radius). In order to optimize the trajectory (by maximizing the turning radius) the waypoint might define not just its coordinates (x, y) but also the recommended turning radius to the next waypoint. Greater turning radius allows higher speed with the stability maintained. The relation between steering S (dimensionless number from -1 to 1), vehicle's horizontal speed v_{xy} and the heading rate $d\gamma/dt$:

$$\frac{d\gamma}{dt} = k_S v_{xy} S \tag{9}$$

where k_S is constant steering gain in [rad.m^{-1}] and depends on the dimensions and construction of the vehicle. If the vehicle is running backward the steering gain is negative. The relation (9) can be used for detection of the wheel skid since the heading rate is also obtained by INS.

Now we can design the steering controller. If we label the current position of the vehicle as X = [x, y] and the next waypoint as W = [x_W, y_W], then the heading to the waypoint is:

$$\theta = \mathrm{atan2}(y_W - y, x_W - x) \tag{7}$$

Regulation error γerr is an angular difference between actual heading γ of the vehicle and heading to the waypoint θ. A proportional regulator appears to be the simplest solution. Simplified schema of the system is shown in Fig. 2. In order to avoid saturation of the steering control near the waypoint we have to define tolerance for reaching the waypoint. If the vehicle reaches the circular area around the waypoint with given radius, next waypoint has to be activated.

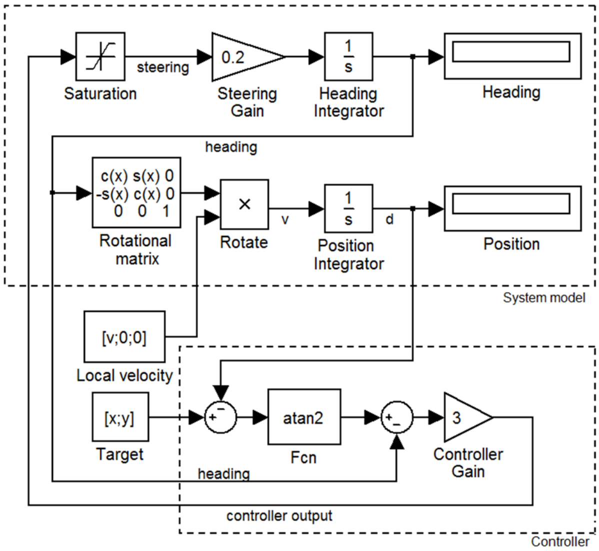

Figure 2 Simplified simulation schema of the vehicle and the controller

In order to verify proposed navigation scheme we have constructed small 4-wheeled mobile platform based on the chassis taken from R/C car. The platform is equipped with IMU unit MPU-3050 manufactured by InvenSense. Platform itself handles only wireless communication and basic hardware control, navigation and control algorithms are implemented in PC wirelessly connected to the platform. In real system the control algorithms would be implemented inside the platform; only the waypoint information would be transferred wirelessly (in road traffic a VANET could be used [8] [9]). For an illustration we have created model scene with few obstacles and pre-defined waypoints (displayed in Fig. 3).

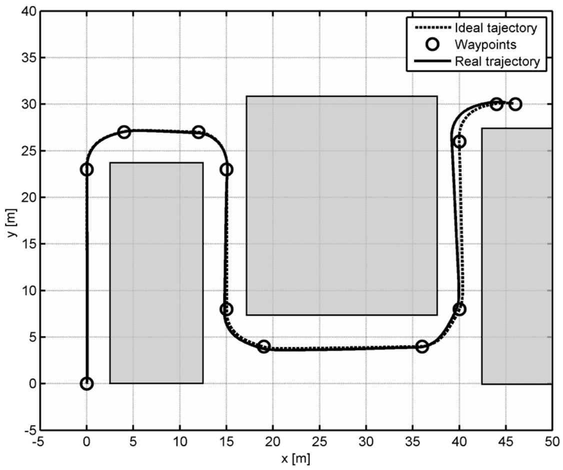

Figure 3 Example of the real and ideal trajectory among the obstacles

All dimensions in Fig. 3 are in meters and were scaled according to the scale of the mobile platform. Mobile platform successfully reached all targets. Minimal turning radius of the platform was R_{min} = 3.5m. Note that the difference between real trajectory of the vehicle and the ideal trajectory is caused by errors of the gyroscope. All errors were reset in the initial position.

4 Conclusion

Low-cost inertial navigation combined with one or multiple odometers can be used as a replacement for the industrial navigation of the mobile wheeled vehicles along some physically defined line (usually by magnetic or optical tape) inside the manufacture or storage facilities. According to the principle of the proposed navigation it does not require any external signal and is partially resistant to the wheel skid. In order to avoid increasing integrative error it is necessary to reset the error of the position and heading estimation at least in the initial location and destination. If some dynamic obstacles (persons, other unknown vehicles) might be present, it is necessary to deploy additional exteroceptive sensors to detect and avoid the collisions.

Acknowledgement
The contribution is sponsored by VEGA MŠ SR No 1/0367/15 prepared project „Research and development of a new autonomous system for checking a trajectory of a robot“.

References

[1] PINNEY, C., HAWES, M.A., BLACKBURN, J.: "*A cost-effective inertial motion sensor for short-duration autonomous navigation*", in Position Location and Navigation Symposium, 1994., IEEE , vol., no., pp.591-597, 11-15 Apr 1994
[2] SAMPAIO, S., MASSATOSHI FURUKAWA, C., MARUYAMA N., "*Sensor Fusion with Low-Grade Inertial Sensors and Odometer to Estimate Geodetic Coordinates in Environments without GPS Signal*", in Latin America Transactions, IEEE (Revista IEEE America Latina) , vol.11, no.4, pp.1015-1021, June 2013
[3] QASEM, H., GORGIS, O., REINDL, L.: "*Design and calibration of an inertial sensor system for precise vehicle navigation*", in Positioning, Navigation and Communication, 2008. WPNC 2008. 5th Workshop on , vol., no., pp.229-231, 27-27 March 2008
[4] KAISER, T.J.; ALLEN, M.G., "*A pendulous oscillating gyroscopic accelerometer fabricated using deep-reactive ion etching*" in Microelectromechanical Systems, Journal of , vol.12, no.1, pp.21-28, Feb 2003
[5] BENSER, E.T., "*Trends in inertial sensors and applications*" in Inertial Sensors and Systems (ISISS),

2015 IEEE International Symposium on , vol., no., pp.1-4, 23-26 March 2015

[6] HULSING, R., "*MEMS inertial rate and acceleration sensor*" in Aerospace and Electronic Systems Magazine, IEEE , vol.13, no.11, pp.17-23, Nov. 1998

[7] SINGLA, P., MORTARI, D.; JUNKINS, J. L. "*How to Avoid Singularity When Using Euler Angles?*" URL: http://lairs.eng.buffalo.edu/pdffiles/pconf/C10.pdf.

[8] ĎURECH, J., FRANEKOVÁ, M., HOLEČKO, P.,: "*VANET throughput model scenarios for authorized V2V communication*" In. IEEE conference INES 2015, 3.- 5. 9. 2015, Bratislava, pp.129-133,

[9] ĎURECH, J., FRANEKOVÁ, M., HOLEČKO , P., BUBENÍKOVÁ, E.,: "*Performance Analysis of Authentication Protocols used within Cooperative - Intelligent Transportation Systems with Focus on Security*" In: TST 2015, Wroclaw, Poland. Selected paper In: Journal CCIS 531 proceedings. Springer-Verlag, 2015

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