Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 2, 2015, vol. LXI
article No. 2001

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NAVIGATION AND CONTROL OF A VEHICLE TO THE PARKING PLACE USING INS

NAVIGÁCIA A RIADENIE VOZIDLA NA PARKOVACIE MIESTO POMOCOU INS

Abstract

This article discusses possibility of usage of the inertial navigation system for an autonomous navigation of a vehicle to the parking place inside intelligent parking house. Our research has shown that inertial navigation is suitable only for heading and attitude estimation. In order to achieve reliable and precise position estimation the additional odometer sensor is required. Article also describes control algorithm which can be used for steering control of the car according to pre-set waypoints. Waypoints have to be placed with respect to the dimensions and overall maneuverability of the vehicle.

Abstrakt

Článok sa zaoberá možnosťou nasadenia inerciálneho navigačného systému pre autonómnu navigáciu vozidla na parkovacie miesto vo vnútri inteligentného parkovacieho domu. Náš výskum ukázal, že inerciálna navigácia je vhodná iba na určenie kurzu a náklonu. Na spoľahlivé a presné určenie polohy je nutné použiť prídavný odometer. Článok taktiež popisuje algoritmus určený pre riadenie smeru auta podľa preddefinovaných bodov trajektórie. Body musia byť umiestnené s prihliadnutím na rozmery a manévrovacie schopnosti konkrétneho vozidla.

Keywords

inertial navigation, automated parking, sensors, sensor fusion, motion control

1 INTRODUCTION

Current development in the area of the road traffic encounters larger deployment of intelligent traffic systems. These systems are designed to improve traffic efficiency and safety and increase throughput capabilities of the road network. Increasing number of car owners uses their vehicles for everyday transportation especially inside cities. This raises serious concern about parking. More and larger parking houses are about to be built and intelligent parking systems are deployed in order to improve their efficiency.

One of the basic tasks in intelligent parking is the automated navigation of an intelligent car to some available free parking place. In order to navigate the vehicle trough the parking house, 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

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underground, which restricts their usage inside parking houses [1] [2]. These 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) [4]. These sensors are the basic component of the inertial navigation systems.

2 INERTIAL NAVIGATION FOR VEHICLES

Our research has shown that low-cost inertial sensors do not provide sufficient accuracy of the acceleration measurement therefore they cannot be used directly for position estimation. For example, if the digital output of the accelerometer has resolution of 14 bits including sign, bias of the sensor equal to 1 LSB will cause an increasing error of the position estimation approximately equal to:

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

where:

$d_{\mathrm{drift}}(t)$ - error of the position estimation in one axis [m],

a_{FS} - full-scale (dynamic range) of the accelerometer [m.s^{-2}],

N - resolution of accelerometer’s the digital output [bits],

t - run-time of the integration algorithm since last reset [s].

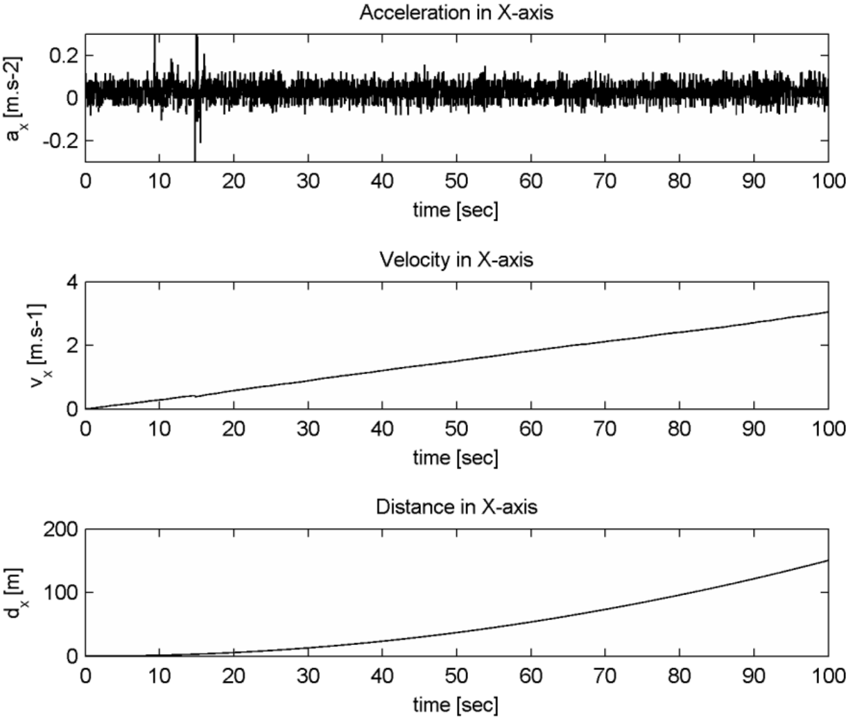

Fig. 1 Increasing drift of the position estimation utilizing only accelerometer (single axis movement)

According to the formula (1) the position estimation error of the mentioned example accelerometer with dynamic range of ±8 g and minimal accelerometer bias after t = 100 seconds of runtime will produce error of the position estimation $d_{\mathrm{drift}} \approx 200\,\mathrm{m}$. This error shows that using only accelerometer for position estimation is not reliable in longer term operation. Real measured drift characteristics are shown in Fig 1. Experimental results are obtained just after sensor calibration and are slightly better than the calculated value (distance error was approximately 150 meters).

On the other hand, inertial sensors can be used for very precise measurement of attitude (lateral inclination called roll, longitudinal inclination called pitch and horizontal direction called heading). Attitude (rotation of the object in 3D space) defines the rotational transformation between the global coordinate system (in our case it is bound with the parking house) 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 [6]. If the parking 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. However the real parking floors are usually not planar due to the draining system. Therefore only 3-axial gyroscope or 3 pieces of perpendicularly oriented single-axis gyroscopes are necessary to be used for reliable heading estimation. 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 one can use a magnetic compass. Available magnetometers can be used for such purpose but they are very sensitive to the presence of an external magnetic field or larger metal objects. In the environment of the parking house both mentioned disturbance will be present. Many vehicle parts are made of metal and future deployment of electromobiles implies presence of strong permanent magnets in the propulsion electromotors. However, without using magnetometer the drift of the heading estimation is much slower than the distance drift:

$$\gamma_{\mathrm{drift}}(t) \approx \frac{\omega_{\mathrm{FS}}}{2^{N-1}}t \tag{2}$$

where:

$\gamma_{\mathrm{drift}}(t)$ - error of the heading estimation [deg],

ω_{FS} - full-scale (dynamic range) of the gyroscope [deg.s^{-1}],

N - resolution of gyroscope's the digital output [bits].

Dynamic range of the gyroscope mounted on vehicle can be set to lower values (around 200 deg.s^{-1}) in order to obtain higher precision of the angular velocity measurement. If we use gyroscope with 16-bit signed resolution the heading drift will be approximately 0.006 deg.s^{-1}.

Resultant attitude can be expressed not just in the form of Euler angles (in Z-Y-X convention they are equal to above mentioned roll, pitch and heading), but also as a rotational matrix or quaternion. In our algorithms we usually use rotational matrix because it allows fast transformation between global and local system and can be easily used in MATLAB® environment. Coordinate systems (both global and local) are Cartesian with North-East-Down (abbr. NED) axis orientation.

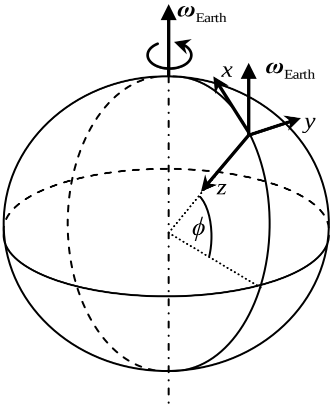

Fig. 2 Influence of the Earth's rotation in specific location

Above equation (2) considers only error caused by gyroscope bias. Another source of the attitude estimation error is rotation of the Earth around its axis (orbital movement of the Earth around the Sun is negligible). This rotation influences all axes of the gyroscope (see Fig. 2) but is well defined. Therefore it can be easily compensated:

$$\boldsymbol{\omega}_{\mathrm{comp}} = \boldsymbol{\omega}_{\mathrm{raw}} - \boldsymbol{R}.\omega_{\mathrm{Earth}} \left[-\cos\phi \quad 0 \quad \sin\phi\right]^{\mathrm{T}} \tag{3}$$

where:

$\boldsymbol{\omega}_{\mathrm{raw}}$ - angular velocity vector obtained from gyroscope [3x deg.s^{-1}],

$\boldsymbol{\omega}_{\mathrm{comp}}$ - 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.

Precisely estimated attitude itself is not sufficient for navigation to free parking place in the parking house. 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:

$$\boldsymbol{d} \leftarrow \boldsymbol{d} + \boldsymbol{R}^{-1} \cdot [\Delta s \quad 0 \quad 0]^{\mathrm{T}} \tag{4}$$

where:

$\boldsymbol{d}$ - position vector [3x m],

Δs - change of the distance measured by odometer [m].

This equation does not consider position of the wheel with odometer with respect to the origin of the local coordinate system. In case of a car with one steerable and one fixed axle it appears to be convenient to place the origin to the centre of the fixed (rear) 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:

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

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. If multiple wheels are equipped with odometers, it is possible to improve the precision of the position estimation by performing fusion between all readings (which can also compensate errors caused by sliding).

2 NAVIGATION OF THE VEHICLE TO THE PARKING PLACE

Parking house is a closed system usually separated from the outside traffic by the entrance gate. Every parking place has its defined state (taken or free) and defined position expressed as coordinates x_P, y_P of the centre of the parking place portal (in Fig 3 displayed as a white cross), and horizontal orientation γ_P of the parking place's axis, all measured in global coordinate system. All lanes can be defined by the coordinates of their corners. There are no restrictions about placement and orientation of the 2D global coordinate system. However, it is convenient to bind its origin with the entrance gate of the parking house and to orientate its axes along parking lanes.

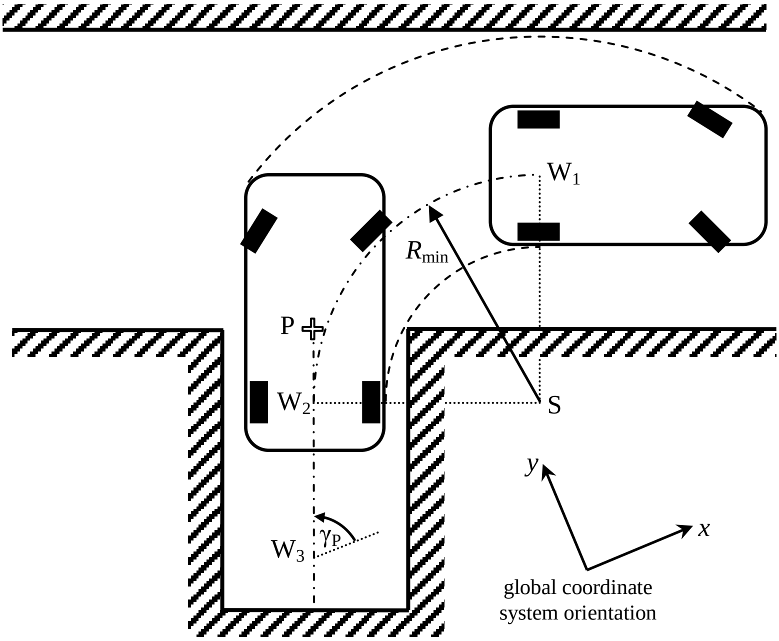

Fig. 3 Parking maneuver and navigation waypoints

In order to navigate to the parking place the vehicle has to approach the parking place via selected lanes (by reaching their corners) and then cross three characteristic waypoints W_1, W_2, W_3 displayed in Fig. 3. Trajectory of the local coordinate system's origin is marked by dot-dashed line. Coordinates of these waypoints can be calculated from point P, considering minimal turning radius and dimensions of the vehicle. If the steering angle is constant the Ackerman steering geometry ensures that every point of the vehicle rotates around the same centre of rotation S. Minimal turning radius $R_{\min}$ of the centre of the rear axle is specific for each car and might be calculated by following formula:

$$R_{\min} = \sqrt{R^2 - a^2} - \frac{b}{2} \tag{6}$$

where:

R - minimal turning radius of the outer tire [m],

a - wheelbase of the vehicle [m],

b - track of the vehicle [m].

All above parameters can be obtained directly from the technical documentation. In order to achieve better maneuverability it is recommended to use greater value of $R_{\min}$ than the actual physical limit of the vehicle.

Control system of the vehicle has to regulate steering angle in order to follow selected trajectory. 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 γ_{err} is the angular difference between actual heading of the vehicle γ and heading to the waypoint θ. Steering output φ (from -100% to 100%) is given by a non-linear function:

$$\varphi = \begin{cases} \mathrm{sign}(\gamma_{\mathrm{err}}) & \text{if } K \cdot \mathrm{abs}(\gamma_{\mathrm{err}}) > 1 \\ K\gamma_{err} & \text{otherwise} \end{cases} \tag{8}$$

where:

K - steering controller gain [% / deg].

In order to verify proposed control algorithm we have constructed small 4-wheeled mobile platform based on the chassis taken from toy 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. One of the model situations (entering parking house, navigation via lanes, final parking maneuver) is displayed in Fig. 4. Mobile platform successfully reached all targets. All dimensions in Fig. 4 are in meters and were scaled according to the scale of the mobile platform. Initial position corresponds to the entrance gate position where all errors of the position and heading estimation were reset.

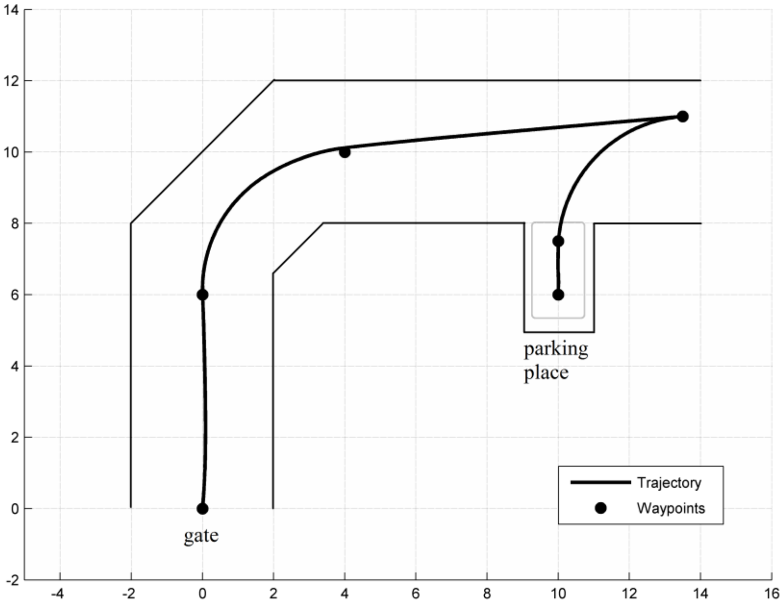

Fig. 4 Model situation during experiment.

3 CONCLUSIONS

Inertial navigation is a suitable motion sensor system for navigation of vehicles in the area of the parking house. Since it does not require any kind of external signal, it is capable to provide reliable readings in harsh environments including strong magnetic fields. However, the precision of available low-cost MEMS accelerometers is not sufficient for position estimation. Therefore the additional odometer sensor is required and the inertial navigation provides only heading and attitude reference. Resultant estimate of the position obtained by the sensor fusion is precise enough to be used in real-time control of the vehicle. Since the inertial sensors provide only relative reference of the heading and position, heading bias and estimated position has to be reset when the vehicle is passing the entrance gate. Therefore the gate has to be equipped with sensors which can precisely measure the position and heading of the passing vehicle with respect to the parking house. This information supplemented by the approach trajectory waypoints has to be provided back to the vehicle in order to successfully navigate to the parking place without collisions with other cars.

ACKNOWLEDGEMENT

This paper is supported by the following project: University Science Park of the University of Zilina (ITMS: 26220220184) supported by the Research&Development Operational Program funded by the European Regional Development Fund.

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