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UNCERTAINTY IN GROUND VEHICLE DYNAMICS MEASUREMENT SYSTEM

This paper gives an overview of uncertainty analysis of inertial measurement system intended for characterizing and comparing ground vehicle driving abilities in real world condition tests. For constructing measurement function and model, sources of system uncertainty are mapped and their effects described. Method finding acceleration sensor output systematic effects and standard deviation is discussed. Data processing algorithms add additional combined uncertainty to system, which can also be estimated. An overview of calibration method and experimental results are presented and eventually further accuracy improvements suggested.

Keywords: *vehicle dynamics measurement, uncertainty, calibration method.*

Introduction

Motorized ground vehicles have been around more than 100 years already and their performance calculations have long history. Nowadays also unmanned ground vehicles (UGV) are developed, mainly for the military use. On the last decade UGV-s are breaking into the civilian market and the interest of using UGV for various tasks is growing rapidly. This paper studies the possibilities to use the performance analysis methods for the unmanned vehicles focusing on the uncertainty issue. The research is a part of general model-based mechatronic system design methodology framework, which provides simulation algorithms for different types of mobile robotic platforms. The current measurement method development is important for verifying the mobile robot simulation algorithms and is used to develop autonomous navigation scenarios for unmanned ground vehicles [1].

Ground vehicle driving performance can be analyzed and compared between each other based on real condition measurements while recording their position and acceleration performance during time test. Real-time data measured during driving reflects the real world and are essential to verify dynamic simulations [2], tests with dynamometers or analyze vehicle condition changes from wear over time. Same data can simultaneously be used for tuning mobile platform parameters affecting driving performance. If the vehicle is unmanned, the driving algorithms decision-making abilities, flexibility and versatility can be evaluated.

The most important measure of dynamical performance is driving acceleration that can be measured at minimum with inertial navigation system (INS) and speed or position can be calculated. GPS based system alone is not suitable because of low data acquisition rate and position measure high uncertainty, which disables to calculate starting, stopping accelerations and precise test timing. INS is self-contained measurement system, which is most suitable for measuring fast dynamic processes but it has a drawback of velocity and position uncertainties, which are growing cumulatively during test. Acceleration sensors built using MEMS technology are best for practical measuring because they are rugged, miniature and inexpensive, therefore also suitable for small robotic platforms, which cannot carry heavy equipment.

For testing and improving measurement method, the practical electronic device was constructed for carrying on tests in real world conditions on different vehicles [3]. The device is a combined measurement system [4] that includes ±19,6 m/s^2 MEMS acceleration sensor with 12-bit analog-digital converter (ADC), timing system and microcontroller for data recording, processing and submitting for further analysis. The current research has the aim to consider the possible uncertainty contributors, which are essential in estimating a reliability of measurement results and improving measurement method.

Sources of uncertainty in measurement system

Main source of data is provided by 3-axis acceleration sensor that is mounted into vehicle in unknown position. Therefore the measurement system output y (acceleration, speed and covered distance for driving direction) (Fig. 1) [5] at every time stamp depends on several variables and constants x_i and is determined with measurement function:

$$y = f(g, a_q^x, a_q^y, a_q^z, a_{1g}^x, a_{1g}^y, a_{1g}^z, a_t^x, a_t^y, a_t^z), \quad (1)$$

where g is natural acceleration, a_q^x, a_q^y, a_q^z are axes quiescent values before test, a_{1g}^x, a_{1g}^y, a_{1g}^z are axes values encountering only natural acceleration and a_t^x, a_t^y, a_t^z are axes values in time stamp t of test.

All variables in function (1) a_i^x, a_i^y, a_i^z are affected by effects, which are divided into four groups (Table 1). This particular type of MEMS sensor includes an inner 12-bit ADC, which minimizes negative noise effects on sensor analog signal transfer. Sensor data is processed by microcontroller, which unavoidably uses rounding in calculations. The measurement test time stamps are set by 32,768 kHz quartz clock whose frequency also deviates from ideal (about ± 4 s deviation in a day). Natural acceleration real value is also unknown and calculations assume its typical value (9,81 m/s^2).

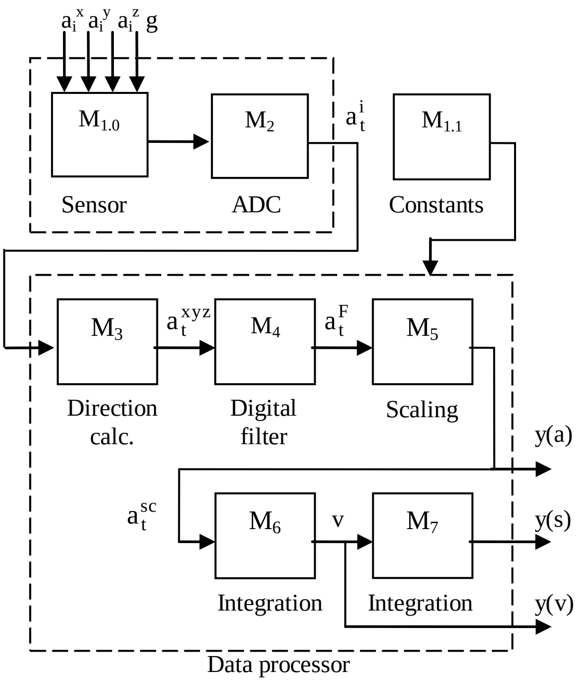

Fig. 1. The measurement system setup

Table 1

Uncertainty contributors

Device	Vehicle	Driver	Environment
Sensor	Start bounce	Handling	Track homogeneity
ADC	Heating	Trajectory	Wind
Time	El-magn. noise		Natural acc. difference
Calculations	Vibration		Air temp.
			Atm. pressure

If the measurement device is attached to a vehicle body having suspension, it will encounter suspension bounce when starting. Although inner combustion engine adds more noise and vibration into measurements (ignition wires, generator), electric motor has also negative electromagnetic effects. Some unavoidable effects are affecting only test repeatability. These are for example engine temperature variations affecting maximum output power and vehicle driver or driving system behavior. Other similar effects are from real world counteractions, like variable wind, air temperatures and track properties. These effects can only be minimized if tests are carried out quickly before conditions change or carried out inside buildings. Due to calibration procedure, they have equal effect on etalon measurement device and therefore can be compensated.

Sensor outputs uncertainty

All deviations in measurement process origin from the uncertainty of sensor output. The output value recorded into memory at every time stamp t is acceleration arithmetic mean value $\bar{a}_i^t$ measured and calculated for time stamp:

$$\bar{a}_i^t = \frac{1}{n}\sum_{i=1}^{n} a_i^t , \qquad (2)$$

with standard deviation estimate $u\left(\bar{a}_i^t\right)$ is established with statistical analysis:

$$u\left(\bar{a}_i^t\right) = \sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}\left(a_i^t - \bar{a}_i^t\right)^2} . \qquad (3)$$

The sources of uncertainty for sensor axes are output bias, scale factor, nonlinearity and asymmetry of axes and sensitivity [6]. Sensor is calibrated at nominal voltage in factory and therefore precision voltage regulator must be used. Sensor zero acceleration level bias systematic effect ε_B causes constant linear growth of velocity systematic effect depending on measurement time t when integrated [7]. Double integrating causes the position systematic effect $\varepsilon_s(t)$ to grow quadratically in time:

$$\varepsilon_s\left(t\right) = \varepsilon_B \cdot \frac{t^2}{2} . \qquad (4)$$

Additional systematic effect affecting output is bias ε_{tmp} caused by environment temperature that is highly nonlinear. The sensor is calibrated at temperature 25 °C by manufacturer. The effect to speed and position is equal with previous assumptions. All systematic effects are compensated with correction δ_i.

Sensor output random deviation is caused by thermo-mechanical white noise whose mean value is zero, correction $\delta_{wn} = 0$ and experimental standard deviation is s_{wn} which estimates standard deviation σ. Noise raises velocity standard deviation proportionally to measurement time $t^{1/2}$ when integrated and position standard deviation $s_s(t)$ proportionally to measurement time $t^{3/2}$ when double integrated:

$$s_V\left(t\right) = s_{wn}\cdot t^{1/2}\cdot\sqrt{\Delta t} ; \qquad (5)$$

$$s_S\left(t\right) = s_{wn}\cdot t^{3/2}\cdot\sqrt{\frac{\Delta t}{3}} , \qquad (6)$$

where Δt is time between measurement points. Similar is sensor zero acceleration level systematic effect ε_B change over time that raises velocity standard deviation proportionally to $t^{3/2}$ and position standard deviation to $t^{5/2}$.

All output values a_i^x, a_i^y, a_i^z in Eq. (1) measured with sensor are affected by aforementioned effects. Therefore correction function to these values is given:

$$a_i^k = f\left(x_{res}, x_{wn}, x_g, x_{temp}, x_b, x_{sc}, x_{nl}\right) \qquad (7)$$

and 3-axis acceleration sensor measurement model can be expressed which includes all corrections δ_i added to output y.

$$y = \bar{a}_t^{sc} + \sum_{i=1}^{n} \delta x_{sens}^i + \delta x_{res} + \delta x_{wn} + \\ + \delta x_g + \delta x_{tmp}, \tag{8}$$

where:

$$\sum_{i=1}^{n} \delta x_{sens}^i = \sum_{i=1}^{n} \left(\delta x_b^i + \delta x_{sc}^i + \delta x_{nl}^i \right), \tag{9}$$

where δx_{res} is the ADC sensitivity correction, δx_{wn} is white noise correction, δx_g is natural acceleration change correction, δx_{temp} is environment temperature correction, δx_b is axis bias correction, δx_{sc} is axis scale factor correction and δx_{nl} is axis nonlinearity correction.

Subsequently combined standard deviation to sensor outputs can be expressed:

$$u(y) = \sqrt{u^2 \left(\bar{a}_t^{sc} \right) + \sum_{i=1}^{n} u^2 \left(\delta x_i \right)}. \tag{10}$$

Data processing uncertainty

Following data processing is carried out after test and is based on recorded data. The vehicle longitudinal acceleration without natural acceleration effect is calculated from 3-axis sensor data saved for each time stamp. As the sensor position in vehicle is unknown, it is assumed that ground vehicle driving on even track, is moving translatory compared to its initial position. Then the longitudinal acceleration vector has constant angles with acceleration sensor measurement axes and its projections to axes can be found. This simplifies measurement system and special algorithm is developed for microcontroller calculations:

$$a_t^{xyz} = \left(a_t^x - a_q^x \right) \cdot K_v^x + \left(a_t^y - a_q^y \right) \cdot K_v^y + \\ + \left(a_t^z - a_q^z \right) \cdot K_v^z, \tag{11}$$

where K^i_v is a coefficient representing axis positioning rate relative to driving direction that is found using all axes maximum achieved speeds [3]. This is experimentally found to be a good way for determining longitudinal driving direction after test, as it is undetectable before. Once K^i_v is found, it is used in test as a constant. Uncertainties for coefficients K^i_v are cumulative as for velocity and are affected by acceleration measures (a_q^i and a_t^i) before and during the test. High enough measurement frequency enables to replace them with their mean values. As the algorithm requires quiescent acceleration mean measures before driving test a_q^i, this can be calculated from much more set of measures because of freely available time. This minimizes random noise effect from possible periodic vehicle idling vibration.

During vehicle driving test, device encounters different vibrations, that sensor measures together with longitudinal acceleration. This creates the need for digital filtration of calculated values. Filter is using measured data and estimates its possible true values, therefore being the only tool to compensate negative random effects caused by interaction between vehicle and environment. The Kalman filter is useful and common for filtering dynamic movements [8].

Finally the filtered longitudinal acceleration is transformed into real measurement units. This is based on mean values $\bar{a}_{1g}$ of only natural acceleration applied to sensor axes determined in calibration procedure and natural acceleration typical value $g \approx 9{,}81$ m/s^2 as a constant:

$$a_t^{sc} = \frac{g}{\bar{a}_{1g}} \cdot a_t^{xyz}. \tag{12}$$

Using this equation, the measurement system first output y(a) (Fig. 1) – longitudinal driving acceleration a_t^{sc} is calculated. If independent input values x_i are estimated in Eq. (1), then combined uncertainty is the square root of variance:

$$u(y) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^2 u^2 \left(x_i \right)}. \tag{13}$$

If the acceleration value is found, longitudinal velocity and covered distance cumulative uncertainty are depending from test time t:

$$\int_0^t \varepsilon_v \cdot d\tau = \delta t \sum_{i=1}^{n} \varepsilon_a^i ; \tag{14}$$

$$\int_0^t \int_0^t \varepsilon_s \cdot d\tau \cdot d\tau = \delta t \sum_{i=1}^{n} \delta t \sum_{i=1}^{n} \varepsilon_a^i . \tag{15}$$

Calibration

Although the manufacturer has calibrated acceleration sensor at certain voltage and temperature, it is necessary to verify the measurement system and adjust correction values as the parameters are noticed to be different and natural acceleration is not always the same. The measurement system at first is calibrated using natural acceleration to find our sensor output bias and scale factor for transforming measured values into real units. Practical method is to mount the device on a turntable whose orientation can be controlled accurately. For 3-axis sensor 6 orientations must be measured to calculate mean acceleration values a_{1g}^i for natural acceleration. Sensor axis nonlinearity and asymmetry is harder to found, instead manufacturer specifications are used for corrections.

Final general calibration method is based on comparing the object with etalon device (Figure 3) [8]. The etalon device is proposed to be special built infrared laser based timing system installed into suitable length even road track. The vehicle is accelerated at its maximum performance and elapsed times compared from vehicle wheels interrupting infrared beams. However the most significant deviations are here uncertainty of track length, sensor positions and vehicle position in starting line.

Suitable track length for a car size vehicle would be 400 m with sensors on start and finish line. The measurement distance uncertainty can be less than 10 cm with careful vehicle positioning on starting line and timing system uncertainty less than 1 ms.

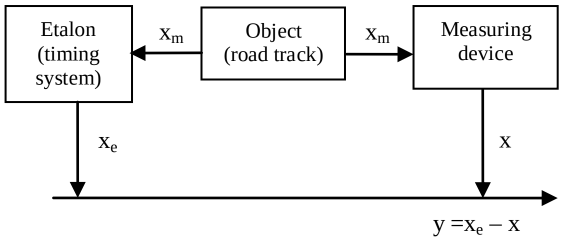

Fig. 2. Device calibration model

Experimental results

When measurement system output value combined uncertainty is calculated based on Eq. (13) it will estimate 0,1% uncertainty. As acceleration values accuracy is critical, velocity cumulative expanded uncertainty was tested to grow to 0,5 m/s after 15 s driving test. This is sufficiently precise for powerful enough vehicles reaching above usual speed limit during test, but requires improvement for longer tests of slower vehicles. It is also seen (Fig. 2) that digital filtering effectively decreases driving vibration rate to under 0,05 m/s^2.

Practical testing of measurement system was carried out with regular cars because of the ability of better test and driving control. Measurement system outputs were recorded (Fig. 3 – 5) and compared with laser based motosports timing system being different under 2 %. The main influence factor here might be the inertial suspension bounce, which increases longitudinal acceleration during starting. For attaining different speeds and measuring track length elapsing times, the good repeatability with (1 – 2)% deviation was achieved depending on driver's success.

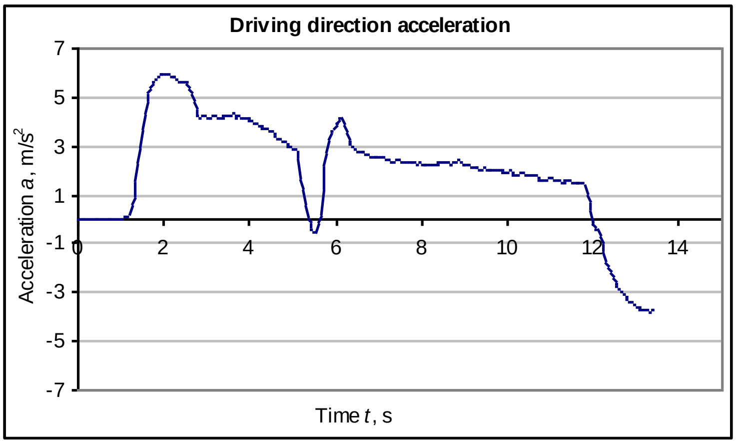

Fig. 3. Acceleration data after digital filtration (car acceleration with one gear change)

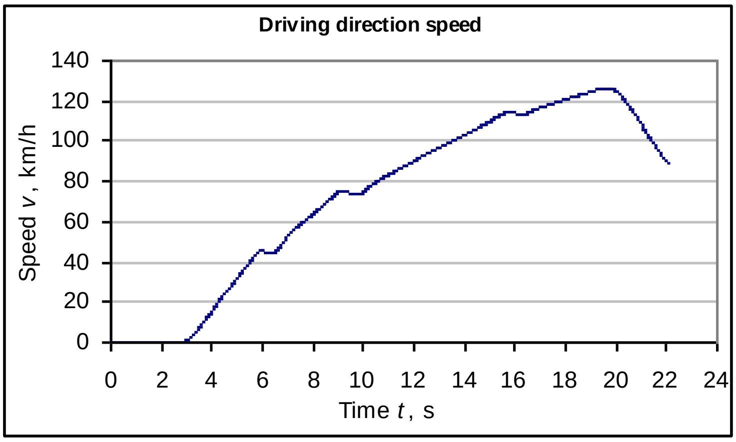

Fig. 4. Calculated car speed with gear changes

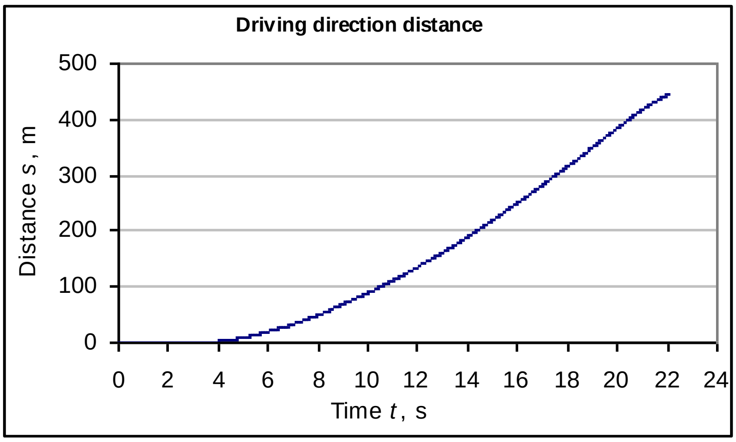

Fig. 5. Calculated car covered distance

Accuracy improvement

Because of INS cumulative error, it is necessary for testing longer distances to use additional GPS module or incremental odometer to compensate their disadvantages. GPS module enables to keep uncertainty invariable during time. Small GPS modules alone are not precise enough to measure acceleration and disables position measurement in buildings, where best testing conditions can be met. There are several methods of fusing different sensors data [9], where good error control can be achieved using improved techniques in Kalman filter [8, 10].

For ground vehicle, it is also possible to use additional encoders mounted on wheel shafts. The uncertainty of covered distance measured with encoder, is growing cumulatively as in INS. Critical uncertainty contributors are here time measurement accuracy between encoder interrupts and wheel slipping.

Conclusion

The measurement system was investigated for sources of uncertainty and the measurement model proposed based on this. The levels of uncertainty are, at first sensor output and its calibration, the data processing algorithms and finally the interactions of environment and vehicle. However, the measurement system can be composed with satisfying accuracy when taking into account of proposed model. This model will be applied for the UGV development and its behavior control algorithms.

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НЕВИЗНАЧЕНІСТЬ ВИМІРЮВАЛЬНОЇ СИСТЕМИ ДЛЯ ВИМІРЮВАННЯ ДИНАМІКИ РУХОМОГО ЕКІПАЖА

Е.Е. Вяльяотс, Р.А. Лаанеотс, Р.С. Сель

Стаття дає огляд про аналіз невизначеності інерціальної вимірювальної системи. Описувана система знаходить застосування для вимірювання величин, які характеризують властивості рухомого по земній поверхні екіпажа в реальних умовах. Для складання вимірювальної моделі і функції вимірювання знайдені джерела невизначеності і описано їх вплив на вихідні величини. Представлено методику для визначення поправок і стандартних відхилень для датчика швидкості. Обробка результатів спостережень додає додаткову невизначеність, яку також можна оцінити. Надано опис про методику калібрування вимірювальної системи, представлено результати дослідження і оцінено можливості для удосконалення вимірювальної системи.

Ключові слова: *вимірювання динаміки рухомого екіпажа, невизначеність, методика калібрування.*

НЕОПРЕДЕЛЕННОСТЬ ИЗМЕРИТЕЛЬНОЙ СИСТЕМЫ ДЛЯ ИЗМЕРЕНИЯ ДИНАМИКИ ДВИЖУЩЕГОСЯ ЭКИПАЖА

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Статья дает обзор об анализе неопределенности инерциальной измерительной системы. Описываемая система находит применение для измерения величин, которые характеризуют свойства движущегося по земной поверхности экипажа в реальных условиях. Для составления измерительной модели и функции измерения найдены источники неопределенности и описано их влияние на выходные величины. Представлена методика для определения поправок и стандартных отклонений для датчика скорости. Обработка результатов наблюдений прибавляет дополнительную неопределенность, которую также можно оценить. Дано описание о методике калибровки измерительной системы, представлены результаты исследования и оценены возможности для усовершенствования измерительной системы.

Ключевые слова: *измерение динамики движущегося экипажа, неопределенность, методика калибровки.*