International Journal of Engineering & Technology, 7 (4.38) (2018) 1615-1619

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Strategic Level of Mobile Robot Control System Based on Fuzzy Logic

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Abstract

As autonomous mobile objects become more complex and the range of tasks for which they are used widens, existing navigation systems are beginning to lag behind requirements for accuracy, weight and size, cost and other characteristics. The use of intelligent algorithms capable of reasonable data integration taking into account not only the design but also both the situational features of the sensors used and their noise characteristics, which determine the nature of the mobile object's movement, can improve the navigation system's accuracy. This article describes the operation of a tightly-coupled navigation system based on inertial low-cost MEMS sensors and GNSS navigation, as well as an adaptive Kalman filter based on an expert system with fuzzy logic technology. To implement the expert system's knowledge base with the help of fuzzy logic, the Takagi-Sugeno model was chosen, as it is an effective tool for describing systems with a priori-known character of transformations between input and output signals. In the framework of the resulting algorithm, we propose refining the noise covariance matrix using fuzzy logic, based on analysis of the inertial sensors' noise readings. In the paper the necessary calculations, a test simulation was carried out, which shows the results and operating time of the classic Kalman filter and the proposed algorithm on the microcontroller Cortex M4 by STMicroelectronics (Stm32f407).

Keywords: *Tightly-Coupled Navigation System, MEMS Sensors, GNSS, Kalman Filter, Fuzzy Logic*

1. Introduction

As autonomous mobile objects become more complex and the range of tasks for which they are used widens, existing navigation systems are beginning to lag behind requirements for accuracy, weight and size, cost and other characteristics [8, 9]. Current efforts to modernize navigation systems are based on improving the characteristics of inertial sensors, or developing new promising software-algorithmic complexes to process navigation information [2, 14, 18]. The use of intelligent algorithms capable of reasonable data integration taking into account not only the design but also both the situational features of the sensors used and their noise characteristics, which determine the nature of the mobile object's movement, can improve the navigation system's accuracy [10-12,15, 20, 21]. Additionally, the use of micromechanical performance sensors (MEMS sensors) significantly reduces the mobile object's cost and improves its weight and size indicators [3, 17, 19].

This article proposes a tightly-coupled navigation system with an adaptive Kalman filter [5, 13] based on an expert system using fuzzy logic.

2. Method Description

The tightly-coupled system method is realised based on data taken from a single-frequency receiver of the global navigation satellite system (GNSS) and inertial MEMS sensors, while the information is integrated by a modified Kalman filter. In the framework of the resulting algorithm, shown in figure 1, we propose refining the R_k noise covariance matrix using fuzzy logic, based on analysis of the inertial sensors' noise readings.

Readings from the accelerometer and angular rate sensor (ARS) are the physical parameters input into the expert block, and the output coefficient is the measurement *R*, which is used in the calculation of the noise covariance matrix.

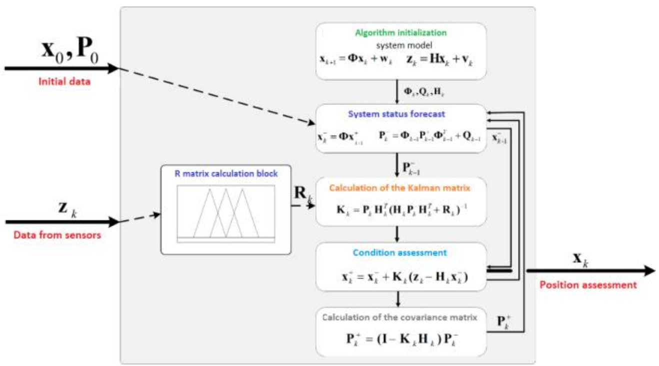


Fig. 1. Adaptive Kalman filter algorithm

According to the analysis, the inertial sensors' noise measurements correlate with sharp changes, with the maximum effect of the relationship observed at the acceleration/deceleration stages. Analysis of these inertial sensor areas is shown in figure 2.

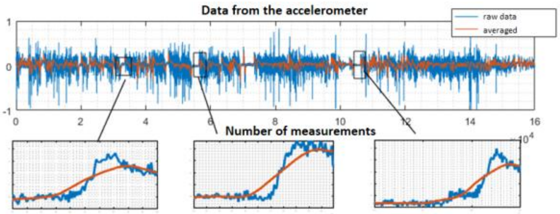


Fig. 2. Analysis of the speed of acceleration change during acceleration

3. Stages of movement

Based on the analysis of inertial sensor data, with reference to the nature of the mobile object's movement, the following stages of movement were identified:

● *mobile object immobile* – at this stage, readings from the inertial sensors are minimally susceptible to noise and the elements $r_{i,j}$ of matrix R_k have the following values:

$$r_{i,j} \approx \sigma^2_{\min(acc,gyro)} \tag{1}$$

where $\sigma^2_{\min(acc,gyro)}$ is the minimum RMS (standard deviation) from the accelerometer or ARS sensor pair;

● *mobile object at maximum acceleration / deceleration* – at this stage, the readings from the inertial sensors are most susceptible to noise and the elements $r_{i,j}$ of matrix R_k have the following values:

$$r_{i,j} \approx \sigma^2_{\max(acc,gyro)} \tag{2}$$

where $\sigma^2_{\max(acc,gyro)}$ is the maximum RMS from the accelerometer or ARS sensor pair;

● *mobile object at intermediate stage (uniformly accelerated smooth motion)* – at this stage, the elements $r_{i,j}$ of matrix R_k have the following values:

$$r_{i,j} \approx (a_1\alpha + a_2\beta + a_3)\sigma^2_{acc,gyro} \tag{3}$$

where $a_1\alpha + a_2\beta + a_3$ is the linear law of RMS change from the accelerometer or ARS sensor pair, α and β are values from the sensors.

The ratio between the real physical parameters' ranges of change and the linguistic values of the variables used is determined by the membership functions presented in figure 3.

In turn, the form, location and slope of the membership functions depend on the following parameters:

to prepare input value terms, two linguistic values, "small" and "large", were used (due to the value's changes); since analysis of the experimental data enables identification of the RMS maximum and minimum values' extreme positions, two terms are sufficient to draw up the rules;

x-axis values correspond to the range of boundaries determined by sensor information movement of the mobile object, and are calculated by the formula

$$x_{\min} = \min(x_1), x_{\max} = \max(x_1) \tag{4}$$

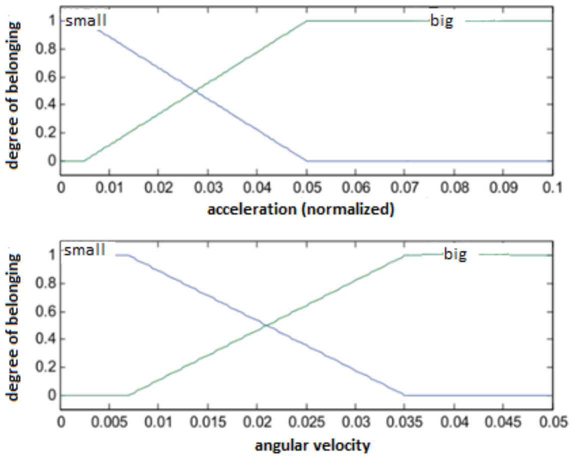


Fig. 3. The form of representation of the input term for the variables α and β

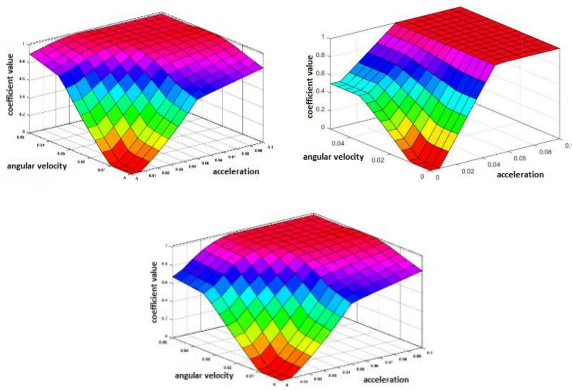
where the value range depends on each individual inertial sensor and the type of mobile object in motion.

To implement the expert system's knowledge base with the help of fuzzy logic, the Takagi-Sugeno model was chosen [6, 16], as it is an effective tool for describing systems with a priori-known character of transformations between input and output signals.

The ratio between input and output membership functions is determined by the following production rules base:

1. If α SMALL, and β SMALL $z = 0$;
2. If α SMALL, and β BIG, $z = a_1\alpha + a_2\beta + a_3$;
3. If α BIG and β SMALL $z = a_1\alpha + a_2\beta + a_3$;
4. If α BIG and β BIG, $z = 1$.

Since the measurements from the accelerometer and ARS generate different types of data and, taking into account the situational significance, have different effects on the system's accuracy of the system, our approach proposes introducing weights a1,a2,a3, which will determine the a particular sensor's degree of interference, as shown in figure 4.



a b c

Fig. 4. Sugeno-model nonlinear transformation. a) a_1=0, a_2=0, a_3=0.5; б) a_1=3,5; a_2=8; a_3=0,5; в) a_1=3,5; a_2=8; a_3=0,5

At the same time, the value of the z coefficient is formed determined at the expert block's output. It is then used to calculate the covariance matrix R by the formula:

$$r_{i,j} = (k_1 z^2 + k_2) \tag{5}$$

where k1, k2 are the adjustment coefficients that are calculated by the following formulas:

$$k_2 = \min(\sigma^2_{acc}, \sigma^2_{gyro}) \tag{6}$$

$$k_1 = \max(\sigma_{acc}^2, \sigma_{gyro}^2) \quad (7)$$

The covariance matrix of the following type is constructed on the basis of relations 5 and 7:

$$R = \begin{pmatrix} (k_1 z + k_2) I_{14} & 0 \\ 0 & 1 \end{pmatrix} \quad (8)$$

The measurements' vector will take the form:

$$\vec{z} = (P_i, ..., g_x^{IMU}, g_y^{IMU}, g_z^{IMU}, a_x^{IMU}, a_y^{IMU}, a_z^{IMU}, v_x^{IMU}, v_y^{IMU}, v_z^{IMU}, m_x^{IMU}, m_y^{IMU}, m_z^{IMU})$$

where P_i is the pseudo-distance from satellite number i (multiple pseudo-distances are possible),

$g_x^{IMU}, g_y^{IMU}, g_z^{IMU}$ - angular velocity (gyro readings);

$a_x^{IMU}, a_y^{IMU}, a_z^{IMU}$ - acceleration (accelerometer reading);

$m_x^{IMU}, m_y^{IMU}, m_z^{IMU}$ - vector declination of the magnetic field (magnetometer readings).

The *IMU* index designates data obtained from inertial sensors.

According to Newtonian mechanics, the coordinates will change according to the equation:

$$\begin{cases} x_k = x_{k-1} + dt v_{x,k-1} + \dfrac{a_{x,k-1} dt^2}{2} \\ y_k = y_{k-1} + dt v_{y,k-1} + \dfrac{a_{y,k-1} dt^2}{2} \\ z_k = z_{k-1} + dt v_{z,k-1} + \dfrac{a_{z,k-1} dt^2}{2} \\ v_{x,k} = v_{x,k-1} + dt a_{x,k-1} \\ v_{y,k} = v_{y,k-1} + dt a_{y,k-1} \\ v_{z,k} = v_{z,k-1} + dt a_{z,k-1} \end{cases} \quad (9)$$

Also in the physical model we believe that

$$a_k = a_{k-1} \quad (10)$$

Calculation of rotation angles is made by the following equations:

$$\begin{cases} v_{x.k} = arctg\left(\dfrac{y_k - y_{k-1}}{z_k - z_{k-1}}\right) \\ v_{y.k} = arctg\left(\dfrac{x_k - x_{k-1}}{z_k - z_{k-1}}\right) \\ v_{z.k} = arctg\left(\dfrac{y_k - y_{k-1}}{x_k - x_{k-1}}\right) \end{cases} \quad (11)$$

Thus, the magnetic declination readings will be calculated by the equations:

$$\begin{cases} m_{x,k} = m_{x,k-1} + (v_{x,k} - v_{x,k-1}) \\ m_{y,k} = m_{y,k-1} + (v_{y,k} - v_{y,k-1}) \\ m_{z,k} = m_{z,k-1} + (v_{z,k} - v_{z,k-1}) \end{cases} \quad (12)$$

The acceleration error accumulates proportionally to the time interval dt, therefore, the matrix Q will look like this:

According to the algorithm shown in figure 1, the remaining matrices required for the Kalman filter operation have the following form:

$$\vec{x} = (x, y, z, v_x, v_y, v_z, a_z, a_y, a_z, v_x, v_y, v_z, m_x, m_y, m_z)$$

\- state vector

where x, y, z are the coordinates; vx, vy, vz — speeds; ax, ay, az- receiver acceleration; dt — seconds elapsed between steps (k − 1) and k step.

$$Q_k = const \times \begin{pmatrix} \frac{dt^3}{6} I_3 & O_3 & O_3 & O_3 & O_3 \\ O_3 & \frac{dt^2}{2} I_3 & O_3 & O_3 & O_3 \\ O_3 & O_3 & dt I_3 & O_3 & O_3 \\ O_3 & O_3 & O_3 & arctg\left(\frac{dt^3}{6}\right) I_3 & O_3 \\ O_3 & O_3 & O_3 & O_3 & arctg\left(\frac{dt^3}{6}\right) I_3 \end{pmatrix} \quad (13)$$

where I3 is the unit matrix of dimension 3;

O3 — the null matrix of dimension 3.

The pseudo range associated with the coordinates in accordance with the following equation:

$$P_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} + E_i \quad (14)$$

where xi, yi, zi are the coordinates of the satellite at the time of sending the packet (known numbers), Ei is the summand containing the counted errors.

The accelerometer and magnetometer readings are related to the state vector by the following equations:

$$\begin{cases} \vec{a} = T \times R\vec{a} \\ \vec{m} = T \times R\vec{m} \end{cases} \quad (15)$$

where R is the transformation matrix from the coordinate system bound to the inertial sensors to the local coordinate system. The matrix R is found by DCM algorithm [7].

T is a matrix of transformations from the local coordinate system to THE ecef coordinate system [1]. R and T are orthogonal rotation matrices.

The gyroscope readings are related to the state vector by the following equations:

$$\begin{cases} g_{x,k} = \dfrac{v_{x,k} - v_{x,k-1}}{dt} \\ g_{y,k} = \dfrac{v_{y,k} - v_{y,k-1}}{dt} \\ g_{z,k} = \dfrac{v_{z,k} - v_{z,k-1}}{dt} \end{cases} \quad (16)$$

where, $\overrightarrow{g_k} = TR\overrightarrow{g_k}$

Presented modified algorithm of tightly-coupled navigation system has been implemented in the Scilab mathematical environment, for the transfer of pseudorange in the coordinates of the involved library RTKLIB [4].

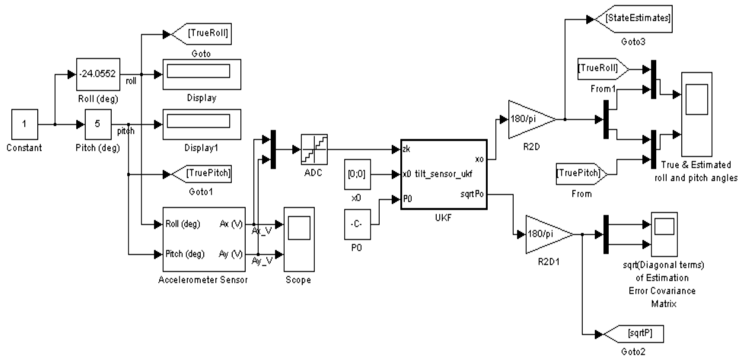


Fig. 5. Implementation of Kalman filter algorithm in Scilab mathematical environment

After performing the necessary calculations, a test simulation was carried out, which shows the results and operating time of the classic Kalman filter and the proposed algorithm on the microcontroller Cortex M4 by STMicroelectronics (Stm32f407) (table 1).

Table 1: The execution time of the algorithms on the microcontroller Stm32F407

Maximum execution time	Average execution time	Maximum time per call	Average time per call
The Extended Kalman Filter			
Initialization of the algorithm			
13244	13244	9179	9179
Time to complete one iteration			
385917	381554	203649	200022
Time to stop algorithm			
935	935	935	935
Modified Kalman Filter			
Initialization of the algorithm			
52030	52030	46100	9179
Time to complete one iteration			
540140	425757	341800	14708
Time to stop algorithm			
1860	1860	1860	1860
Units of measurement are presented in nanoseconds, measurements were carried out on the STM32F407 microcontroller (Cortex M4)			

4. Conclusion

Summarizing the simulation results of the developed algorithm, we can talk about a slight increase in the operating time in comparison with the extended Kalman filter.

On the basis of the proposed algorithm, a hardware and software complex was developed that has been tested in the tasks of high-precision agriculture in the creation of a parallel driving system to reduce the cost of sowing crops (figure 6).

Fig. 6. The result of the passage of mobile agricultural machinery on the site of the field with the display of the area of arable land and floors

Its implementation provided an increase in the accuracy of maintaining the inter-row distance within 40%, which allowed to reduce grain costs by 20% compared to other competitive samples.

Acknowledgments

This work is supported by the Russian Science Foundation, according to research project No. 16-19-00052 of 2016.

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