OPTIMIZATION OF A SMART ACCELEROMETER BASED ON AMPLITUDE-FREQUENCY CHARACTERISTICS CONSTRAINTS

Teodor Lucian Grigorie, Nicolae Jula, Petre Negrea, Radu Obręja
University of Craiova, Faculty of Electrical Engineering, Department of Avionics
107 Decebal Blvd., Craiova, Dolj, Romania, 200440
lgrigore@elth.ucv.ro, nicolae.jula@gmail.com, negreapetre@yahoo.com, radu@sistemeuroteh.ro

Ruxandra Mihaela Botez
ETS-LARCASE Laboratory of Active Controls, Aeroservoelasticity and Avionics, Department of Automated Production Engineering
1100 Notre Dame West, Montreal, Que., Canada, H3C1K3
ruxandra@gpa.etsmtl.ca

ABSTRACT
The paper deals with a smart inertial sensor architecture optimization by using a tuning algorithm related to some constraints imposed to the sensor amplitude-frequency characteristics. To test the optimization criterion the model of a close loop accelerometer is used. Starting from the basic architecture of the sensor, based on classical control at the loop closing, a new smart architecture is proposed. In this way, a fuzzy logic controller is added on the direct path of the accelerometer in order to replace an amplification and filtering block used initially to create the control the feedback force acting on the proof mass. Further, a Matlab/Simulink model is developed for accelerometer and a method to plot its amplitude-frequency characteristics based on this model is described. An optimization subroutine for the tuning of derivative gain of the fuzzy logic controller is presented and tested on the simulation model.

KEY WORDS
Inertial navigation, smart inertial sensors, optimization, fuzzy logic, control tuning, accelerometer.

1. Introduction
The strap-down inertial navigator was at first put in the category of the dead-reckoning navigation systems and it began to be used to its full value in the 90s, a period when the performances of the calculus systems with a possibility of boarding increased very much. In the beginning it was used as a stand-alone navigation system, but it shortly became, together with the GPS, an essential part of the complex navigators founded on aircrafts, submarines, spaceships and land vehicles [1]-[5]. Generally, the three basic functions of the strap-down inertial navigation system (INS) are: sensing, calculation and output [1]-[5] (Fig. 1). The sensing function is performed by the accelerometers and by the gyros, their measurements being transmitted to the navigation computer. The computer uses this data to generate speed, position, attitude, attitude rates, altitude and the distance to destination. If the real speed is provided to the computer by an aerodynamic system, INS can also calculate the wind speed and the drift angle. The output function is limited to transmit calculated data to the flight control systems, weapon systems, recognizing sensors or display and control unit, as is required for the specific missions.

Figure 1. Simplified diagram of a strap-down INS

From the point of view of the sensing component, inertial navigation systems have evolved from low precision electromechanical inertial sensors, that guided first V2 missiles, to the solid-state sensors conception of today, performed in MEMS (micro - electro - mechanical systems), NEMS (nano - electro - mechanical systems), MOEMS (micro - opto - electro - mechanical systems) or NOEMS (nano - opto - electro - mechanical systems) technologies, equipping most modern vehicles. Besides the size reduction, these technologies offer more benefits, such as series production, cost reduction, energy consumption reducing, robustness increasing and flexibility in design. However, reducing the size of the sensing elements creates new challenges to improve their performance, considering that, generally, the reduction of the sensor size entail the decrease of the sensitivity, the increase of the noise and the decrease of the control capacity of the sensing elements. Therefore, the research...
in the field aims at discovering accurate technologies to build inertial sensors, the implementation of better inertial sensors models with new technologies, establishing numerical algorithms and dedicated architectures of assembling the sensors which could allow the obtaining of inertial detection units with high accuracy and a high degree of redundancy, optimizing the pre-existent numerical algorithms, of sensors data processing and the creation of new ones as well as the increase of the performances of the boarding calculus systems while considering their miniaturization [6]-[9]. In this context, at University of Craiova is currently developed a research project aiming to found some design technologies allowing the development of High-precision micro and nano smart sensors for space inertial navigation applications, project financed by Romanian Space Agency (ROSA).

At this time, the research team of the project developed some smart architectures based fuzzy logic controllers for a series of miniaturized inertial sensors. At the next step, some optimization procedures for the new architectures are desired to be developed. The paper presents an inertial sensor smart architecture optimization, which should improve the static and dynamic characteristics. The optimization criterion is based on some constraints related to the sensor amplitude-frequency characteristics. Usually, the control is hardware developed and embedded in the sensor structure, being obtained a sensor with unchangeable frequency characteristics. The smart part of the accelerometer is related to the fact that it uses a software programmable fuzzy logic controller, which allow the user to make some adjustments in its coefficients in order to modify its frequency characteristics as a function of the specificity of the application desired to be developed (i.e. inertial navigation (cutting frequency under 100 Hz), vibrations detection (measurement of higher frequencies), …). This new reconfigurable structure allows user to personalize the sensor, in order to limit the amplitude and phase distortions as a function of the developed application technical characteristics.

2. Sensor smart architecture

It is very well known that a fuzzy logic controller may improve significantly the rise time of an automatic system when it replaces its classical controller. Generally, the fuzzy logic controllers presents a lot of advantages instead of classical control techniques, becoming more and more used in industrial applications to model highly non-linear, multidimensional systems, including those with parameter variations, or where the sensors’ signals are not accurate enough for other models. On the other way, the control technique based on the linguistic rules elaboration, come in support to the easy implementation of these control systems [10]-[14]. The literature already offers some studies related to this subject, i.e. the development of sensors, miniaturized or not, that address this type of control [15]-[19]. The here exposed study uses an already developed model of a closed loop accelerometer based on a classical control ([19], [20]), and propose a new smart architecture, which uses a fuzzy logic controller, and an optimization procedure for this new architecture.

The accelerometer basic structure (Fig. 2 [19], [20]) includes a displacement transducer, on the direct path, and, an amplification and filtering block and a permanent magnet whereon slides a coil, on the feedback path. Starting from this structure, and having in mind the physical model of the accelerometer ([19], [20]), we propose the replacement of the amplification and filtering block by a fuzzy logic controller, acting on the direct path of the accelerometer as in Fig. 3. On the other way, a quick analyze of the system block scheme suggests us that the fuzzy logic control architecture can be limited at a basic one of the PD type. In this way, the control structure in Fig. 4 was chosen to be used.

![Figure 2. Basic structure of the accelerometer](image-url)

![Figure 3. Smart architecture of the accelerometer](image-url)

![Figure 4. Architecture of the fuzzy logic controller](image-url)
To design the fuzzy logic control system four principal components should be considered: a fuzzifier, a fuzzy rule base, a fuzzy inference engine and a defuzzifier ([10]-[14]). In the fuzzifier stage the crisp inputs \((u \text{ and } \Delta u)\) are transformed through the fuzzification into linguistic variables, which further are translated into linguistic concepts represented by fuzzy sets. Considering \([-0.1, 0.1]\) interval as universe of discourse for both inputs of the controller and for the output, we choosing three membership functions \((mf)\) for each of the two inputs \((A_1^1, A_1^2, A_1^3)\). In the same time, five constant membership functions were chosen for the fuzzy logic controller output. The linguistic terms for the inputs are N (negative), Z (zero), and P (positive), while for the output are NB (negative big), NS (negative small), Z (zero), PS (positive small), and PB (positive big). The inputs \(mf\) were considered by the Gaussian-type, defined with the following expression ([21], [22])

\[
A_i^q(x) = \exp \left\{ -0.5 \left( \frac{x-c_i^q}{\sigma_i^q} \right)^2 \right\},
\]

where \(c_i^q\) is the cluster center and \(\sigma_i^q\) is the dispersion of the cluster; the parameters characterizing the membership functions of the inputs are given in Table 1.

Table 1. The parameters of the input’s membership functions

<table>
<thead>
<tr>
<th>Input</th>
<th>Parameter</th>
<th>(mf1)</th>
<th>(mf2)</th>
<th>(mf3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in1 &amp; in2</td>
<td>(\sigma/2)</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>(c)</td>
<td>-0.1</td>
<td>0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

According to the values in the Table 1, the membership functions for the inputs are by the form depicted in Fig. 5. Starting from the inputs’ and output’s membership functions, a set of 5 inference rules were obtained \((N=5)\)

Rule 1: If \(u\) is \(A_1^i\) and \(\Delta u\) is \(A_2^i\), then \(u_i = -0.1\).
Rule 2: If \(u\) is \(A_1^i\) and \(\Delta u\) is \(A_1^i\), then \(u_i = -0.05\).
Rule 3: If \(u\) is \(A_1^i\) and \(\Delta u\) is \(A_1^i\), then \(u_i = 0\).
Rule 4: If \(u\) is \(A_1^i\) and \(\Delta u\) is \(A_1^i\), then \(u_i = 0.05\).
Rule 5: If \(u\) is \(A_1^i\) and \(\Delta u\) is \(A_1^i\), then \(u_i = 0.1\).

The rule-based inference chosen for each consequent is presented in Table 2 and Fig. 6. With the previous considerations, the fuzzy control surface results by the form presented in Fig. 7 (two views for different angles).

Table 2. Rule-based inference for the fuzzy logic controller

<table>
<thead>
<tr>
<th>(u/\Delta u)</th>
<th>N</th>
<th>Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>NB(-0.1)</td>
<td>NS(-0.05)</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>-</td>
<td>Z(0)</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>PS(0.05)</td>
<td>PB(0.1)</td>
</tr>
</tbody>
</table>

3. Optimization of the smart architecture

The time response of the smart architecture versus the classical structure revealed a decrease by approximately 150 times of the system rise time (Fig. 8); the step signal was applied at 0.5 ms for both characteristics in Fig. 8. The assessment of the accelerometer precision, with design in the classical variant, made in [20], led to the conclusion that if it is used in an inertial navigation system, the resulted positioning errors are strongly influenced by the transient regime of the accelerometer. Therefore, the using of the fuzzy controller creates a
significant improvement of the positioning error when the accelerometer operates in a strap-down IMU.

On the other way, we demonstrate in [20], that a non-monotone amplitude-frequency characteristic means that the system has oscillatory tendencies. The system is underdamped. In the other case, the system is overdamped. At limit, between the two ranges, there is an optimal value for damping. If the derivative gain \( K_D \) is changed, then the characteristics in Fig. 9 are obtained for its various values; for simulation the Matlab/Simulink model of the accelerometer in Fig. 10 was used. Therefore, the optimization of the system means finding \( K_D \), in order to achieve the critical damping of the system.

The critical damping is appreciated using the amplitude-frequency characteristic of the system. Thus, the optimization supposes two steps: firstly, we draw the amplitude-frequency characteristic and secondary we pick the optimal value of \( K_D \). In this way, the simulation scheme of the system may be reconfigured as in Fig. 11, and includes a part which helps us to draw the amplitude-frequency characteristic. Practically, the used method consists in the simulation of a voeboscope. In this way, we had to solve two problems. Firstly, we have to generate a signal with increasing frequency, while the second problem consists in the rectification of the output signal in order to select only its maxims.

At the input of the system, we generate a cosine signal with the amplitude equals to 1 and with the frequency rising in respect to time. We consider the variation of the frequency as

\[
f = 10^{600t}.
\]

Then, the angular frequency of the signal will be

\[
\omega = 2\pi f = 2\pi 10^{600t}.
\]

The Eq. (4), in agreement to [20], leads to

\[
\varphi(t) = \int_0^t \omega(t) \, dt = \int_0^t 2\pi 10^{600t} \, dt = \frac{2\pi(10^{600t} - 1)}{600\ln 10}.
\]

Figure 8. Transient response: fuzzy vs. classical

Figure 9. Transient response for various values of \( K_D \)

Figure 10. Accelerometer’ Matlab/Simulink model with fuzzy controller

Figure 11. Accelerometer’ Matlab/Simulink model with fuzzy controller

The latest relation is used at the input of the scheme depicted in Fig. 11. This generator block supplies a signal of a frequency that attends about \( 10^9 \) Hz in 0.01 s simulation time. At this final frequency, the simulation runs with very small steps and this takes a lot of time. But, if we choose a linear variation of the frequency, then \( 10^9 \) Hz will be attended in \( 10^6 \) s, with a very small step.
This would take a longer time than the other method, presented in [20].

To draw the amplitude-frequency characteristic, we must extract, from all values of the output voltage vector $\mathbf{U}_\text{fuzzy}$, only the local maximums, which represents the amplitude of the output signal. The final part of scheme from Fig. 11 is designed to establish the maximum values. These are stored in the vector $\mathbf{y}$. In order to be able to draw the characteristic, we form two vectors. One of the vectors ($\mathbf{x}$) contains the maximum values of the output voltage vector $\mathbf{U}_\text{fuzzy}$, after the system performs a normal operation (at some time after start up). The other vector contains the frequencies. The lengths of these vectors must be the same, every frequency corresponding to a maximum value of the output voltage vector $\mathbf{U}_\text{fuzzy}$.

This algorithm runs for several values of $K_D$. The variation speed of the frequency is chosen so as a rise of 1 Hz is made in approximately $10^{-3}$ times longer than the transient regime of the system. For example, for different values of $K_D$, the vector $\mathbf{y}$ looks as in Fig. 12.

The input signal, with variable frequency is presented in Fig. 13. The obtained amplitude-frequency characteristics are depicted in Fig. 14.

We can see in Fig. 14, with no additional computation, that the optimal value for $K_D$ is somewhere between 0.5 ms and 3 ms.

Considering the above, we start with the range 0.5 ms to 3 ms and we check if, for $K_D$ in the middle of the interval, $\mathbf{x}(i)$ is smaller than $\mathbf{x}(i-1)$. Depending on the result, we chose the next value for $K_D$ in the middle of the upper interval, or in middle of the lower one. In other words, we use the successive approximation method. The program stops when $K_D$ is obtained with $10^{-14}$ tolerance. Running this program, we obtained the optimal value $K_{D,\text{opt}} = 1.20994447$ ms.

In Fig. 15 is draw the amplitude-frequency characteristic when $K_D = K_{D,\text{opt}}$, while Fig. 16 shows the transient performance of the system.
4. Conclusion

The paper presented a numerical study related to the optimization of the architecture of a smart accelerometer. The results validated the proposed method based on some amplitude-frequency characteristics constraints, and highlighted a new possibility to realize the final tuning of a fuzzy logic PD controller. Also, the study showed a way to draw the amplitude-frequency characteristics of a Matlab/Simulink modeled automatic system, by using a variable frequency signal at the input of the model with an exponential dependence by the time, in order to avoid the mixing with the transient regime of the system.

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References