

## Sensor Signal Processing unit in an Autonomous Mobile Platform Using Bandpass Frequency-Dependent Components

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**Abstract.** *The article discusses the features of a sensor signal processing unit in an autonomous mobile platform using bandpass frequency-dependent components. A series connection of low-order components is proposed for rapid retuning of the processing unit components. It is shown how the frequency characteristics of the new connection change. It is shown how to use allpass filters for phase correction of the signal and also allpass filters application to obtain a bandstop filter. In addition, the formation features related to the number of connected components are shown.*

**Key words:** *autonomous mobile platform, frequency-dependent components, bandpass and bandstop filters, allpass filter, frequency characteristics*

### Introduction

At present, the use of autonomous mobile platforms (AMP) for goods delivery, servicing people in everyday life, as public transport, as systems for surveying areas with anomalies, for search and reconnaissance of remote areas and others. The construction of such complex platforms is associated with certain requirements and limitations.

AMPs, as autonomous systems, have limitations on power supply, dimensions and computational resources. Such limitations require the development of hardware–software components with minimal power consumption while ensuring task execution. Data processing must operate in real time and be limited in algorithm processing duration. In addition to limitations, such systems must be flexible to the environment and the internal state of the platform. These circumstances are well aligned with modern development concepts of the Industry 4.0–6.0 [1–5].

It should be noted that AMPs, by structural organization, correspond to cyber-physical systems. Since the integration of physical processes and cybernetic components allows increasing the intellectual capabilities of such platforms in performing their functions [6]. In such systems, pre-modeling of movement is often used to ensure safety within a group of AMPs during task execution [7, 8]. For this purpose, reliable data on the state of the AMP and the environment are required.

The hardware–software components of AMPs are limited, but must be flexible, adaptive, and able

to adjust to operating conditions under the above-mentioned constraints. Such platform properties are possible with the use of multifunctional sensors, hardware and software components of computing equipment.

The object of research is the process of sensor signals processing in the AMP processing block within a cyber-physical system without operator involvement. While an interference is present in the environment with a large number of sensors, filtering and correction with the ability to retune the characteristics of processing components in real time are necessary. This needs to adapt to operating conditions increases the reliability of data for decision-making and task execution by actuators.

The subject of research is the construction of a sensor signal processing unit on the board of AMP with the ability to retune characteristics and configure bandpass frequency-dependent components. Signal processing should reduce distortions in sensors motion and distance-to-obstacle measurement signals [9].

The aim of the research is the quest of using convenient and simple methods for creating digital devices that make it possible to process distorted signals for AMPs.

First-order frequency-dependent components require to calculate three coefficients and for seventh order it is require 15 coefficients. In order to simplify the implementation of the signal processing tract, increase speed by reducing computation time and retuning coefficients of frequency-dependent components, it is proposed to use identical low-order components. It should be noted that frequency-dependent components include both filters and typi-

cal control system circuits. So, to simplify let's consider this issue using digital filters.

When identical digital filters are connected in series, their transfer functions are multiplied

$$H(p) = \prod_{i=1}^n H_{oi}(p),$$

where  $H_{oi}(p), H(p)$  — respectively the  $i$ -th and the final transfer functions.

Since transfer functions  $H_o(p)$  consist of amplitude-frequency and phase-frequency characteristics, and the components are identical, one can write

$$H_o(j\omega) = H_o(\omega) \cdot e^{j\varphi_o(\omega)},$$

where  $H_o(\omega), \varphi_o(\omega)$  — respectively the amplitude-frequency and phase-frequency characteristics of the main identical filter.

Then, when identical filters are connected in series, their multiplication becomes exponentiation

$$H(p) = \prod_{i=1}^n H_{oi}(p) = (H_o(p))^n,$$

and the AFC and PFC characteristics transform accordingly as follows

$$H(j\omega) = [H_o(j\omega)]^n = [H_o(\omega)]^n \cdot e^{jn\varphi_o(\omega)}$$

The main changes in such a connection occur in the AFC [10].

When filters are connected in parallel, their transfer functions add up, what is equivalent to increasing the gain coefficient by the amount of the connected identical filters. When an identical filter is included in negative feedback to the main filter, the connection order increases, and the shape of the frequency characteristics changes significantly. Thus, for AMPs it is advisable to use a series connection of identical filters.

### 1. Research of AFC changes of identical filters when connected in series

Few issues are solved when building a sensor signal processing unit in an AMP with bandpass filters: retuning the center frequency and the pass-band, and also increasing the steepness of the AFC rise and fall.

Special attention was paid to the simplicity of calculation methods, the amount of computations for

new filter coefficients, its stability and the interrelationships of the filter coefficients. It should be noted that as the filter order increases, the interrelationships of coefficients during retuning grow, which leads to a complex dependency in calculations, limits the range of change of values, and requires mandatory stability checking. Coefficient quantization also matters for digital components. Based on this analysis, the use of low-order digital filters — first and second order — and an analytical method for calculating new coefficients is recommended for AMPs [11].

Based on the research, the task of increasing the steepness of the AFC rise and fall is proposed to be solved using of sequential connection of identical low-order components.

When components are connected in series, the resulting transfer function is the multiplication of the particular transfer functions of the components, as shown above.

Consider such a connection using as an example the identical first-order bandpass filters, since they are more convenient to use in AMPs. When such filters are connected in series, the AFC of the new connection is somewhat "compressed", with the cutoff frequencies shifting toward the center frequency and the steepness of the AFC increasing, Fig. 1 [12].

The transfer function of the basic first-order bandpass filter is mathematically described by a second-order equation

$$H(z) = \frac{a_o + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}}, \quad (1)$$

where  $a_o, a_1, a_2, b_1, b_2$  — with real coefficients of numerator and denominator respectively.

When transitioning to the complex transfer coefficient using Euler's formula

$$z^{-1} = \cos(\varpi) - j \sin(\varpi),$$

$\varpi$  — where the normalized angular frequency,

$$\varpi = 2\pi \frac{f}{f_d},$$

$\varpi \in [0, \pi], f, f_d$  — respectively linear frequency and sampling frequency. On its basis we will further

obtain the AFC at  $a_2 = -a_0, a_1 = 0$ . Obtain the square of the AFC in the form

$$H^2(\varpi) = \frac{(2a_o \sin(\varpi))^2}{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi) + 4b_2 \cos^2(\varpi)}$$

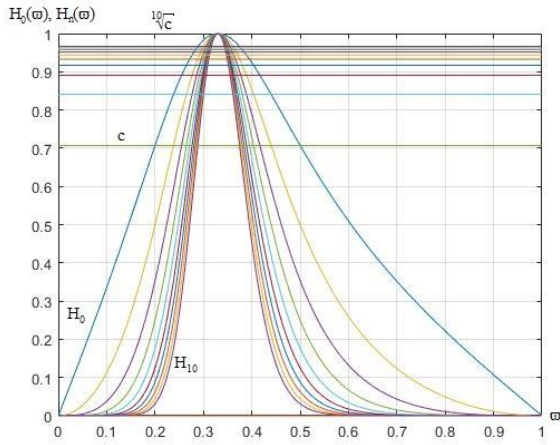


Fig. 1 - AFC of digital first-order Butterworth bandpass filters when connected in series.

At the same time, the center frequency (AFC peak) does not change and is determined from the equation, Fig. 2

$$\varpi_p = \arccos\left(-\frac{b_1}{1+b_2}\right)$$

The level which the cutoff frequency is determined equals

$$c = \frac{1}{\sqrt{2}} = 0,707$$

, then solves the equation

$$H(\varpi_c) = c,$$

where  $\varpi_c$  - the AFC cutoff frequency at the level  $c$ .

Let's determine respectively two cutoff frequencies 1L and 1R, Fig. 2.

When multiplying identical AFCs or raising them to a power the level does not change. To determine the cutoff frequency of the AFC of the new connection, it is necessary to extract the root of the corresponding order from the level  $c$ , that is  $\sqrt[n]{c}$ , Fig. 2. In Fig. 1 these levels are shown by horizontal lines.

$$H^2(\varpi) = \frac{(2a_0 \sin(\varpi_{1n}))^2}{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi_{1n}) + 4b_2 \cos^2(\varpi_{1n})} = \sqrt[n]{c^2}$$

where  $\varpi_{1n}$  — the cutoff frequency at the new level  $\sqrt[n]{c}$  from the main AFC.

$$a_0 = \frac{1-b_2}{2}$$

After substituting

$$\text{and } \sin^2(\varpi_{1n}) = 1 - \cos^2(\varpi_{1n}) \text{ obtain}$$

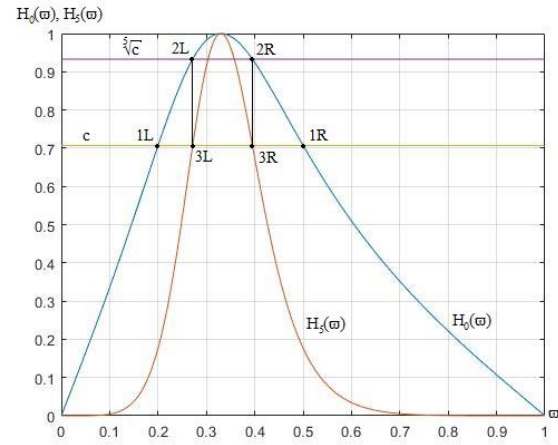


Fig. 2 - AFC of the basic first-order Butterworth filter and AFC when five identical first-order Butterworth filters are connected in series

In this case, from the AFC of the basic filter it is possible to calculate the cutoff frequencies of the AFC of the new connection. Fig. 2 shows respectively the cutoff frequencies of the basic first-order AFC at the level  $c$  and the AFC when five (5) identical first-order components are connected in series. These cutoff frequencies are defined from the main AFC, whose parameters are known, and by the new level, which equals  $\sqrt[n]{c}$ . The level  $c$  for the basic filter and its cutoff frequencies 1L and 1R are shown in Fig. 2; then the new level from the number of

connected components  $\sqrt[n]{c}$  is determined and on its basis the new cutoff frequencies 2L and 2R are determined. On their basis, as projections onto the new AFC of the connection, obtain 3L and 3R.

To determine the cutoff frequencies of the new AFC after connecting  $n$  identical filters from the basic AFC it is necessary to solve the following equation

$$H^2(\varpi) = \frac{(1-b_2)^2 (1-\cos^2(\varpi_{1n}))}{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi_{1n}) + 4b_2 \cos^2(\varpi_{1n})} = c^{\frac{2}{n}}.$$

Solving this equation find formulas for determining the cutoff frequencies for the n-th connection of identical filters. To simplify the presentation of the result, new notations introduced

$$A = 4b_2 c^{\frac{2}{n}} + (1-b_2)^2; \quad B = -b_1(1+b_2)c^{\frac{2}{n}};$$

$$C = (1-b_2) \sqrt{\left(1-c^{\frac{2}{n}}\right) \left[ (4b_2 - b_1^2) c^{\frac{2}{n}} + (1-b_2)^2 \right]}.$$

Then the cutoff frequencies of the AFC for the n-th connection of identical filters will have the following form

$$\varpi_{cn1} = \arccos\left(\frac{B+C}{A}\right);$$

$$\varpi_{cn2} = \arccos\left(\frac{B-C}{A}\right).$$

With such a connection in the new sensor signal processing unit, the question arises of how the PFC of the new connection will look compared to the direct calculation of a filter of the given order and how linear is it? The research of PFC changes was carried out based on the transfer function of the main filter (1). The analytical mathematical relation of the PFC was obtained, which has the following form

$$\operatorname{tg} \varphi = \frac{b_1 + (b_2 + 1) \cos(\varpi)}{(1-b_2) \sin(\varpi)}.$$

Based on this relation and modeling of the series connection of identical bandpass filters leads to a quasi-linear PFC compared to the equivalent filter of direct calculation, Fig. 3.

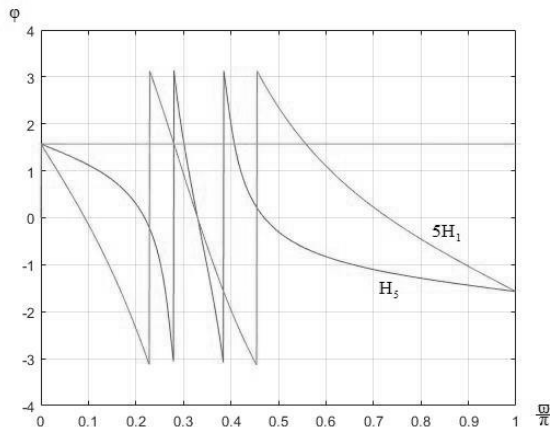


Fig. 3 - Graph comparing the PFC of a connection of five identical filters with transfer function (1) (5H1 — this is the transfer function after connecting five basic filters) and the PFC of the 5th-order filter of direct calculation H5.

From Fig. 3 it is seen that the PFC of the new connection of five identical filters is quasi-linear compared to the PFC of the directly calculated 5th-order filter. In addition, when calculating an identical filter only 3 coefficients are computed, whereas a 5th-order filter has six in the numerator and five in the denominator, so in total it is necessary to recalculate 11 coefficients and required to be checked for stability. For filters this is not a simple task. For checking the stability of first-order bandpass filters the task is known and simple; moreover, the series connection of stable filters leads to the stability of the entire connection.

Allpass filters are widely used on board AMPs for phase correction of sensor signals. The formation of such a phase correction block is described in the research [13]. This work shows how to form an allpass filter and increase their order by serially connecting identical low-order allpass filters [14].

Usage of allpass filters is not limited only by resolving of this issue. It is known that on the basis of an allpass and a bandpass filter a bandstop filter can be constructed [15].

The research showed that depending on the number of serially connected low-order components a bandstop filter  $H_{BS}(z)$  of the corresponding order can be constructed on the basis of the following relations:

- for an odd number of connections

$$H_{BS}(z) = H_{BP}(z) + H_{AF}(z),$$

- for an even number of connections

$$H_{BS}(z) = H_{BP}(z) - H_{AF}(z),$$

where - are, respectively, the transfer functions of the bandstop, bandpass and allpass filters.

At the same time, the cutoff frequencies of the new bandstop filter will be located inside the cutoff frequencies of the bandpass filter, Fig. 4.

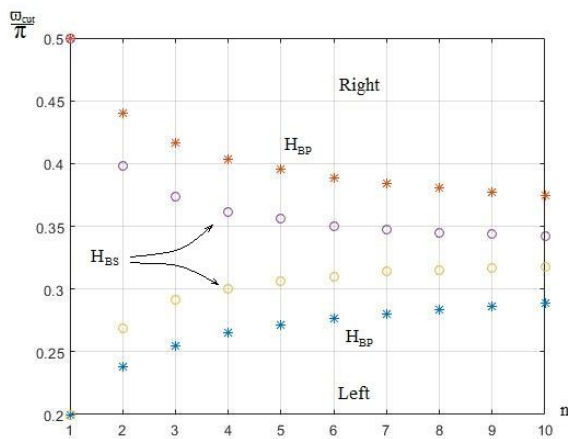


Fig. 4 - Graph of cutoff frequencies of bandpass (stars) and bandstop (circles) filters.

### Conclusion

The work shows that the sensor signal processing unit for an autonomous mobile platform can be built on the basis of a low-order digital bandpass filter with the serial connection of identical filters to increase its order. The processing unit may include an allpass filter for phase correction of sensor signals. On the basis of low-order digital bandpass and allpass filters it is also possible to obtain a bandstop filter of the corresponding order.

As a result of the series connection of identical components it is shown that the PFC in the new connection is significantly more linear compared to the PFC of the directly calculated required order. With limited computational capabilities, this option of the sensor signal processing unit is significantly better than the traditional one.

A software implementation of this approach in digital form is preferable to hardware. The main component is calculated based on information about data streams and operating modes and its cutoff frequencies and passband, as well as the gain coefficient, are determined.

A software implementation was applied for processing data from an ultrasonic obstacle sensor in an AMP based on identical first-order components. This solution made it possible to reduce computation time, since some constants were precomputed and stored in memory cells.

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## Вузол обробки сигналів датчиків у автономній мобільній платформі з використання смугових частотно-залежних компонентів

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**Анотація.** У статті розглядаються особливості вузла обробки сигналів датчиків у автономній мобільній платформі з використанням смугових частотно-залежних компонентів. Для швидкої перебудови компонентів вузла обробки запропоновано послідовне з'єднання компонентів низького порядку. Показано як змінюються частотні характеристики нового з'єднання. При використанні всепропускних фільтрів для корекції фази сигналів, показано їх застосування для отримання режекторного фільтру на основі смугового. Крім того показані особливості формування, які пов'язані зі кількістю з'єднаних компонентів.

**Ключові слова:** автономна мобільна платформа, частотно-залежні компоненти, смуговий та режекторні фільтри, фазовий фільтр, частотні характеристики

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