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CONSTRUCTING SENSOR SIGNAL PROCESSING CHANNEL FOR AUTONOMOUS ROBOTIC PLATFORMS

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ABSTRACT

Context. The development of autonomous mobile robotic platforms has advanced rapidly, especially in cyber-physical systems where integrating physical components and computational resources is vital. A key challenge in such platforms is the efficient real-time processing of sensor signals under limited computational resources, enabling robots to operate independently of human intervention. Traditional signal processing methods demand significant power, which may limit mobile platforms constrained by energy and resources. This research focuses on restructuring sensor signal processing channels using digital bandpass filters while overcoming technical challenges posed by limited resources.

Objective. The goal is to create an efficient method for processing sensor signals in autonomous mobile platforms with constrained resources. This involves using low-order bandpass filters, capable of adjusting their characteristics and improving quality through sequential connection of identical filters. Reducing the computational load allows for enhanced overall performance of cyber-physical systems, improving efficiency under changing conditions and enabling autonomous task completion. New computational formulas are also proposed to simplify the design and better utilize onboard resources.

Method. The improved method for constructing sensor signal processing channels uses identical low-order frequency-dependent components, sequentially connected to solve challenges faced by higher-order components. This approach simplifies coefficient calculations for cutoff frequencies and improves filter performance by increasing the order and quality. The method achieves a quasi-linear phase-frequency characteristic, ensuring minimal distortion in the processed signals, while significantly reducing computational requirements.

Results. The proposed method effectively reduces computational costs while maintaining high performance in sensor signal processing. The new formulas allow for calculating filter coefficients with fewer resources, suitable for autonomous systems. Modelling and experimental verification confirm that this method lowers the computational load and enhances filter performance, enabling more efficient sensor data processing, extended battery life, and improved system reliability.

Conclusions. This research presents an efficient approach to sensor signal processing for resource-constrained autonomous robotic platforms. Sequentially connecting identical frequency-dependent components reduces computational costs while maintaining high signal processing quality. These findings are recommended for real-time applications requiring efficient resource utilization, contributing to improved autonomy and adaptability in mobile robotic systems.

KEYWORDS: autonomous mobile robotic platform, frequency-dependent components, filters, frequency characteristics, cyber-physical system.

ABBREVIATIONS

AGV is an automated guided vehicle;
AFC is an amplitude-frequency characteristic;
AMP is an autonomous mobile platform;
AMR is an autonomous mobile robot;
AMRP is an autonomous mobile robotic platform;
AP is an automated platform;
AU is an adjustment unit;
BPF is a bandpass filter;
CPS is a cyber-physical system;
EA is an evolutionary algorithm;
FDC is a frequency-dependent component;
FPGA is a field-programmable gate array;
HPF is a high pass filter;
LPF is a low pass filter;
MD is a multi-dimensional polynomial approximation;
NF is a notch filter;
OCM is an operator-controller module;
PFC is a phase-frequency characteristic;
SBC is a single-board computer.

NOMENCLATURE

a_0, a_1, a_2, b_1, b_2 are the real coefficients of the filter transfer function numerator and denominator;

c is a cutoff frequency level;

$D(\varpi)$ is a denominator of frequency response function;

f is a linear frequency;

f_0 is a central frequency of the BPF's AFC;

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f_1 is a left cutoff frequency of the BPF's AFC;

f_2 is a right cutoff frequency of the BPF's AFC;

f_d is a sampling frequency;

$H(z)$ is a transfer function in z-domain;

$H(\varpi)$ is a frequency response function;

$H_n(\varpi)$ is a frequency response function of n connected identical filters in series;

$N(\varpi)$ is a numerator of the frequency response function;

n is a number of identical connected filters;

Q is a quality factor of BPF;

z is a variable in the complex plane;

φ is a phase-frequency characteristic;

ϖ is a normalized angular frequency;

ϖ_{BP} is a bandwidth of the BPF;

ϖ_c is an AFC cutoff frequency at level c;

ϖ_p is a peak frequency of the AFC;

ϖ_{1n} is a cutoff frequency at a new level $\sqrt[n]{c}$ by main AFC for quadratic equation;

$\varpi_{cn1}, \varpi_{cn2}$ is the cutoff frequencies at a new level $\sqrt[n]{c}$ by main AFC;

1L, 1R are the left and right cutoff frequencies at the level c;

2L, 2R are the left and right cutoff frequencies at the level $\sqrt[n]{c}$;

3L, 3R are projections of the left and right cutoff frequencies 2L and 2R onto the new AFC.

INTRODUCTION

The modern development of society is characterized by the increasing use of robotic systems in production processes and society. Such systems include AMPs, mobile robots, and mobile manipulators, which are actively used in factories and enterprises to perform complex and monotonous tasks such as assembly, welding, painting, loading and unloading operations. In the social environment, they are employed for various service tasks: domestic, office, medical, monitoring, inspection, and search operations. It is especially important to note the role of AMPs in the military field, where they are used for both reusable and single-use specific tasks, as well as for reconnaissance, search, monitoring, escorting, and so on [1].

Within the framework of AMPs, it is possible to distinguish between AGV and AMR. APs are portable robots that use floor markings for movement and employ radio waves, video cameras and surveillance systems, magnets, and lasers for navigation. In the presence of obstacles, they typically stop. AMRPs, on the other hand, are platforms controlled by software based on signals from a large number of sensors and actuators, allowing them to identify their position and surroundings in space and move without operator intervention [2–5]. Moreover, modern AMRPs use elements of artificial intelligence to make decisions during task execution.

Recently, there has been intense development in CPS across various fields. To date, different definitions of such systems exist, but many authors agree that they represent a fusion of physical processes and cybernetic components. This combination enhances the intellectual capabilities of AMRPs in performing their functions [6–8]. In such systems, preliminary motion modelling is often used to ensure the safety of movement within a group of AMRPs and the completion of tasks [9, 10]. Reliable data on the state of the AMRP and its surrounding environment are essential for this purpose.

Typically, AMRPs are constrained by size, power supply, and computational capacity. This necessitates the development of software and hardware components with minimal energy consumption while ensuring task performance, as data processing is also limited by the implementation of processing algorithms. This fits well with modern concepts of AMRP development – Industry 4.0–6.0 [11, 12].

The object of study is the process of sensor signal processing in AMRPs without operator intervention. With a large number of sensors and the presence of interference, filtering is required, with the ability to adjust the parameters of the processing components in real-time. This need for adaptation to operating conditions enhances the reliability of the data for decision-making and task execution by the actuators.

The subject of study is the model and method for constructing the signal processing channel for sensors with the ability to adjust the characteristics and configuration to ensure the operational functionality of the path. Known methods [13–19] are complex, time-consuming, and costly, especially for single-use AMRPs.

The purpose of the work is to improve the efficiency of the FDCs of an AMRP, as a CPS, by reducing the computational complexity of their reconfiguration through the analysis and improvement of the sequential connection model of the components, taking into account the features of their frequency characteristics.

1 PROBLEM STATEMENT

Let's assume a CPS is given in the form of an AMRP interacting with natural objects. This platform consists of set of sensors, set of hardware components, set of software components, and set of actuators, all of which must operate in real-time to perform a given task. The primary constraints for such a platform are power supply limitations and computational resource limitations. The platform has both high-level and low-level subsystems, which prioritize the allocation of these resources.

For this platform, the task of constructing a sensor signal processing channel, which belongs to the low-level subsystems, can be represented as the problem of finding the components of the channel, determined after researching the possible structures and components of the channel. The components of the processing channel must meet the

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requirements of simplicity, the ability for quick and minimal adjustments, and minimal costs for improving the quality of the channel while maintaining limited power consumption.

In this formulation, it is necessary to find formulas for calculating new cutoff frequencies for the channel component when n identical low-order components are sequentially connected with a transfer function $H(z)$, in other words, $\varpi_{cn1,cn2} = f(a_i, b_i, n, c)$, and also show which phase distortions occur with such a connection $\varphi_n f(n)$.

2 REVIEW OF THE LITERATURE

Development a processing channel based on FDCs, several tasks are usually addressed: approximation, developing, and implementation. To create tunable components, various approaches and methods are used by the authors, allowing for control over the frequency characteristics of the components. Let's consider these approaches and methods using the example of digital filters, as standard control system links are described by similar transfer functions.

Many authors start the process by approximating and normalizing the transfer function. In [13], the authors propose transitioning to state space and adjusting characteristics there, using the Faust language to achieve the Chamberlin form. This approach is quite complex to implement in AMRP.

Another approach introduces additional parameters into the transfer function to control the cutoff frequency [14, 15]. Retuning is easily done on non-recursive filters since they do not have roots in the denominator of the transfer function. This idea of controlling the cutoff frequency then applied to recursive filters. Another approach involves using MD polynomial approximation for recursive filters with the introduction of additional parameters into the transfer function. These approaches require prior preparation, and with each retuning, the transfer function needs to be checked for stability.

It is known that digital non-recursive filters are always stable and have a linear PFC. However, since it is also necessary to change the filter order to improve its quality factor, higher-order filters are often required, which leads to increased delay, and this is a problem for real-time signal processing. Therefore, moving to recursive filters, the filter's numerator coefficients are approximated using polynomials with variable parameter. To solve this problem, the transfer function is transformed using semi-definite programming in the frequency domain [16].

The problem of developing a recursive filter has proven complex due to the presence of poles in its transfer function. This leads to a non-linear phase characteristic of the transfer function, and the amplitude characteristic is also shifted due to the quantization of the denominator polynomial coefficients, which leads to instability. In [17], numerous efforts were made to achieve an optimal filter characteristic using several optimization methods. A task was formulated and solved to develop a recursive filter with various constraints using gradient methods, which led to an optimal passband characteristic with an almost linear phase, and in some cases, absolute linearity was achieved. However, the obtained solutions were suboptimal in many cases due to the conversion of the multimodal filter design problem into convex optimization. To overcome suboptimality, the authors used EA. It should be noted that system identification was conducted in the time domain, while in the frequency domain, various error functions were developed for the obtained amplitude characteristics, bringing them closer to the desired one.

This approach resulted in an optimal recursive filter characteristic; however, the linearity of the phase characteristic was not improved. The EA approach was applied to lower-order recursive filters. This approach is the most suitable since the filter characteristic is stable, almost linear, and the amplitude characteristic is also accurate. However, there is a significant error at the edges of the bandpass. The retuning process is complex, and requires significant computational resources, though it provides a satisfactory characteristic, and stability must be checked during retuning.

The recursive filter structure has unique advantages and disadvantages. The main advantage of this filter structure is that it provides a frequency characteristic comparable to that of a higher-order non-recursive filter, resulting in fewer computations needed to implement the filter. However, recursive filters can be unstable due to the presence of feedback. As a result, they are more challenging to design, and caution is needed to prevent instability. Recursive filters have a non-linear phase characteristic, which may make them unsuitable for certain applications requiring a linear phase. Additionally, because recursive filters take into account past outputs due to feedback, they are typically more sensitive to quantization noise, making them harder to implement using 16-bit controllers or fixed-point microprocessors. Generally, 32-bit resources are preferable for implementing recursive filters.

For this reason, non-recursive filters are often recommended for microprocessor-based implementations due to their simplicity in description and realization [15, 16, 18]. However, many open questions remain regarding parameter retuning and increasing filter order.

When implementing AMRPs, several tasks need to be solved simultaneously. This requires developing a modular AMRP structure, often designed to solve current tasks and expand for future capabilities. Using multiple microprocessor blocks leads to a distributed system within a single AMRP.

For instance, in [19], a concept of a modular and distributed architecture for a robotic system is presented. The architecture is based on the OCM, which describes the adaptation of distributed OCM for AMRP, taking into account the requirements for such robots, including real-time constraints and safety. The presented architecture hierarchically divides the system into a three-layer structure of controllers and operators. Controllers directly in-

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teract with all sensors and actuators in the system, requiring strict real-time constraints. However, the reflexive operator processes information from the controllers, which can be done using model-based principles with finite state machines. A cognitive operator is used to optimize the system.

Further development of AMRPs is connected to the advent of small SBCs as more energy-efficient and suitable solutions for mobile robot processor blocks. Multiple SBCs or microcontrollers are combined into a distributed system for greater computational power or better reliability, and modular solutions make it easy to expand AMRP capabilities. This approach positions AMRP as a CPS capable of making decisions to improve signal processing quality in the processing path under uncertainty, without operator involvement.

At present, there are many definitions of CPS. In general, CPS are systems consisting of various natural objects, artificial subsystems, and control controllers, allowing such a formation to be considered a unified whole. CPS provide close coordination between computational and physical resources. Computers monitor and control physical processes using feedback loops, where events in the physical systems influence the computations and vice versa. The main technological prerequisites for the emergence of CPS are [20–24]:

– growth in the number of devices with embedded microcontrollers, microprocessors and data storage;

– integration that achieves maximum efficiency by combining individual components into larger systems;

– availability of numerous sensors and actuators;

– limitations in human cognitive abilities, which evolve more slowly than machines, leading to a point where they can no longer handle the volume of information required for decision-making.

Typically, this is an embedded system, a special-purpose system where the computational element is entirely integrated into the device it controls. Unlike a general-purpose computer, an embedded system performs one or several predefined tasks, usually with very specific real-time requirements.

From a technical perspective, an embedded system interacts with its environment in a controlled manner, meeting several requirements for ensuring the quality and timeliness of information necessary for task control and execution.

CPS integrate cybernetics, hardware and software technologies, and qualitatively new actuators embedded in their environment, capable of sensing changes, reacting to them, self-learning, and adapting.

It is worth noting that the general CPS architecture is divided into five fundamental levels [20–22]:

– physical level (lays the foundation for CPS architecture);

– network level (packet routing based on transforming a unique identifier assigned to each active device into network-based identifiers);

– transport level (packets are fragmented into smaller parts);

– intermediate level (terminal management, protocol conversion);

– application level (stores, analyzes, and updates information).

Thus, the development of the sensor signal processing channel fits into this CPS architecture, interacting actively with sensors to provide the decision-making system and actuators with reliable information. The path must be able to adjust its properties according to the operational conditions of the AMRP.

3 MATERIALS AND METHODS

In building the sensor signal processing path for AMRP, there are two main tasks: adjusting the cutoff frequency or bandpass and increasing the quality factor of the AFC or enhancing the slope of the AFC rise and fall.

In addressing the first task, adjusting the cutoff frequency for LPF and HPF, as well as the centre frequency and bandwidth (rejection) for bandpass and NF, an analysis of methods for adjusting recursive filters of various orders was conducted. Several methods for tuning both analog and digital filters were considered, some of which are reflected in the works [13–19]. Particular attention was paid to the simplicity of the method, the computational load for recalculating new filter coefficients, stability, and the interdependencies between filter coefficients. It should be noted that as the filter order increases, the interdependence of coefficients during re-tuning grows. This leads to a complex recalculation process, the range limitations, and the need for mandatory stability checks. For digital filters, the quantization of coefficients also plays a significant role. Based on this analysis, the low-order digital filters (first and second order) and an analytical method for calculating new coefficients are recommended [25].

To utilize the analytical method, models of FDCs were developed, allowing the creation of systems of equations from which calculation formulas for retuning were derived. The limited number of coefficients simplified the calculations and reduced computational costs, and the stability check was found to be fairly straightforward.

Enhancing the "intellectual capabilities" of the channel during retuning is possible based on an adaptive approach, as shown in [14]. The peculiarity of controlling the main filter lies in the AU, which also defines its intelligent properties. Currently, AUs widely use comb filters for analyzing the input and output signals of the main filter.

Based on the obtained theoretical and practical data, the task of improving the quality factor of the AFC or increasing the steepness of the rise and fall of the AFC is proposed to be solved using similar FDCs of a low order.

It is known that when components are connected in series, the resulting transfer function is the product of the individual transfer functions of the components. If these components are of the same type, this multiplication turns into raising the individual transfer function to a power. Moving to the complex transfer coefficient based on complex variable theory, it is possible to point out that the

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module, i.e., AFC is raised to the corresponding power, and the phase, i.e., PFC is multiplied by the indicator of the degree.

It is also known that the quality factor of BPFs is determined by the AFC. To do this, the bandwidth is defined as the difference between the cutoff frequencies at a level of 0.707 (approximately 3 dB) from the peak of the AFC, as half of the signal's power is concentrated at the filter's output at this level. Thus, the quality factor Q is determined as follows

$$Q = \frac{f_0}{f_2 - f_1}. \quad (1)$$

Naturally, the higher the quality factor, the steeper the AFC, i.e., the rate of rise and fall of the characteristic. Let's consider such a configuration using first-order identical BPFs as an example since they are often used in AMRP. When connecting such filters in series, the AFC of the new configuration becomes "compressed", with the cutoff frequencies shifting toward the central frequency, and the AFC slope increases, thus improving the quality factor of this configuration (Fig. 1) [26].

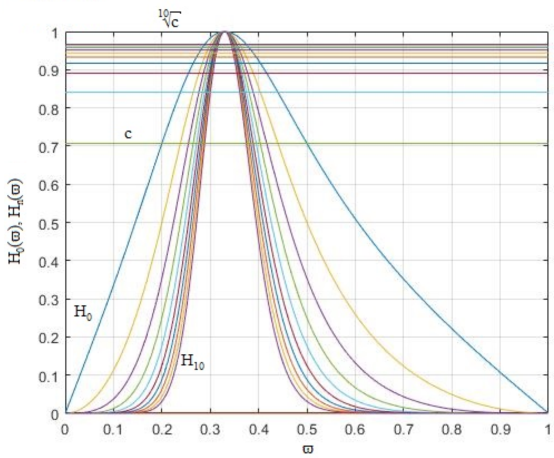

Figure 1 – AFC of first-order Butterworth digital BPFs connected in series

The transfer function of the main first-order BPF in z-domain is described as follows

$$H(z) = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}}. \quad (2)$$

For $z = e^{j\varpi}$, $a_1 = 0$ and $a_2 = -a_0$, the transfer function (2) can be transformed into the following frequency response function

$$H(\varpi) = \frac{N(\varpi)}{D(\varpi)}, \quad (3)$$

where

$$N(\varpi) = 2a_0 \sin(\varpi),$$

$$D(\varpi) = \sqrt{(1-b_2)^2 + b_1^2 + 2b_1(1+b_2)\cos(\varpi) + 4b_2\cos^2(\varpi)}.$$

It should be noted that the peak frequency of the AFC remains unchanged and is determined by the equation

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

Usually, the cutoff frequency level is defined as $c = 0.707$, then solving equation $H(\varpi_c) = c$, we determine the two cutoff frequencies 1L and 1R (Fig. 2).

When multiplying identical AFCs or raising them to a power, the level remains the same, but to determine the cutoff frequencies of the AFC of the new configuration, when connected in series, it is necessary to extract the corresponding root from the level c, i.e., $\sqrt[n]{c}$ (Fig. 2). In Fig. 1, these levels are shown as horizontal lines.

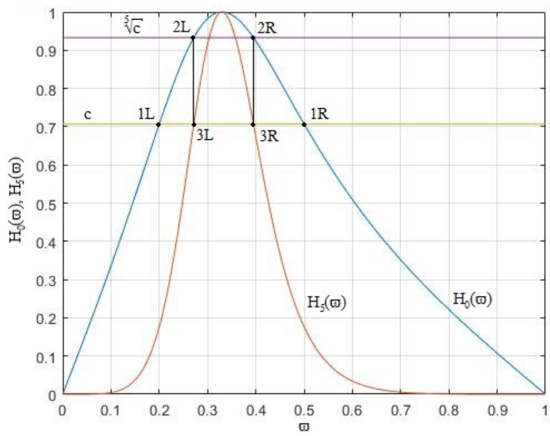

Figure 2 – AFC of the main first-order Butterworth filter and AFC when connecting five identical first-order Butterworth filters in series

In this case, from the AFC of the main filter, it is possible to calculate the cutoff frequencies of the AFC of the new configuration. Figure 2 shows the correspondence between the cutoff frequencies of the main first-order AFC at the level c and the AFC when five identical first-order AFCs are connected in series. These cutoff frequencies are determined by the main AFC, whose parameters are known, and by the new level equal to $\sqrt[n]{c}$. Figure 2 shows the level c for the main filter and its cutoff frequencies 1L and 1R, then the new level is determined from the number of connections $\sqrt[n]{c}$ and based on it, the new cutoff frequencies 2L and 2R are determined. Based on these, as a projection onto the new AFC of the connection, it can be possible to get 3L and 3R [27].

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To determine the cutoff frequencies of the new AFC after connecting n identical filters based on the main AFC, it is necessary to solve the equation (4):

$$H^2(\varpi) = \frac{N^2(\varpi)}{D^2(\varpi)} = \sqrt[n]{c^2}. \quad (4)$$

The substitutions $a_0 = (1-b_2)/2$ and $\sin(\varpi) = \sqrt{1-\cos^2(\varpi)}$ to the numerator of (3) yield the following expression for $N^2(\varpi)$:

$$N^2(\varpi) = (1-b_2)^2(1-\cos^2(\varpi)).$$

After transforming equation (4) can be written in the form of a quadratic equation for $\cos(\varpi)$:

$$[4b_2 c^{\frac{2}{n}} + (1-b_2)^2]\cos^2(\varpi) + 2b_1(1+b_2)\cos(\varpi) + \\ + c^{\frac{2}{n}} b_1^2 + (1-b_2)^2(c^{\frac{2}{n}} - 1) = 0. \quad (5)$$

Solving this equation gives formulas for determining the cutoff frequencies when n identical filters are connected in series:

$$\varpi_{cn1,cn2} = \arccos\left(\frac{-b_1(1+b_2)c^{\frac{2}{n}}}{4b_2 c^{\frac{2}{n}} + (1-b_2)^2} \pm \\ \pm \frac{(1-b_2)\sqrt{\left(1-c^{\frac{2}{n}}\right)\left[\left(4b_2 - b_1^2\right)c^{\frac{2}{n}} + (1-b_2)^2\right]}}{4b_2 c^{\frac{2}{n}} + (1-b_2)^2} \right). \quad (6)$$

When creating such a new signal processing path for sensors, a question arises as to how the PFC will look compared to the direct calculation of a filter of the given order and how linear it will be. The research of changes in the PFC was based on the transfer function of the main filter (2). For this, an analytical mathematical description of the PFC was obtained, which after transformation looks as follows

$$\varphi = \arctan\left(\frac{b_1 + (b_2+1)\cos(\varpi)}{(1-b_2)\sin(\varpi)} \right). \quad (7)$$

As mentioned earlier, when connecting n identical filters in series, the PFC of the new configuration is the multiplication of the PFC of the main filter and the number of main filters connected, i.e.,

$$\varphi_n = n \cdot \varphi. \quad (8)$$

For other filters, when similar components are connected in series, the AFC changes as follows:

– for the LPF, it shifts to the left, i.e., towards lower frequencies with the quality factor increases;

– for the HPF, the characteristic shifts to the right, i.e., towards higher frequencies with the quality factor increases;

– for the NF, unlike BPF, the characteristic does not shift toward the central frequency, meaning it “expands” outward from the central frequency rather than “compressing”.

Such AFC behavior is not always suitable for solving the signal processing tasks required for sensor data.

4 EXPERIMENTS

As a result of theoretical research, corresponding calculations, modelling, and experimental verifications were carried out using real AMRP.

In solving the first task of retuning, the computational costs for recalculating the transfer function coefficients were assessed. The computational load was evaluated by the number of operations required to implement the proposed formulas. The results were compared with the method based on variable substitution. Each processor has its own values for the execution of addition operations. Raspberry Pi 4 was chosen for evaluation. The results were experimentally verified using it. Based on the results obtained, the proposed method of recalculating transfer function coefficients is 27% more efficient for first-order LPF and HPF, 29% for second-order LPF and HPF, and 13% for BPF and NF.

Modelling and experimental verification of serially connected similar BPFs resulted in a quasi-linear PFC compared to equivalent filters calculated directly.

5 RESULTS

When verifying the obtained relationships, for example, Fig. 3 shows the cutoff frequency dependencies derived from formula (7).

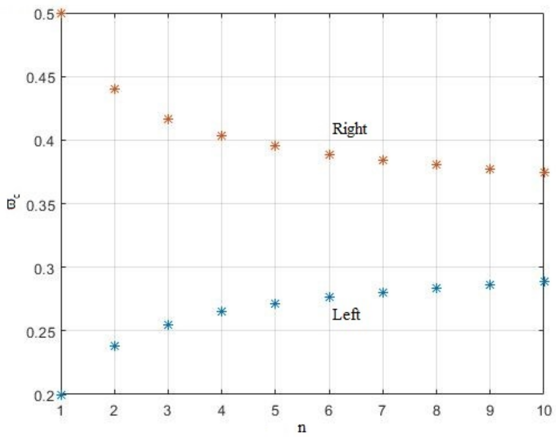

Figure 3 – Graph of the cutoff frequency dependence on the number of connected identical filters when filters connected in series

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Based on these ratios, the bandwidth of such a connection is determined as $\varpi_{BP} = |\varpi_{cn1} - \varpi_{cn2}|$ (Fig. 4).

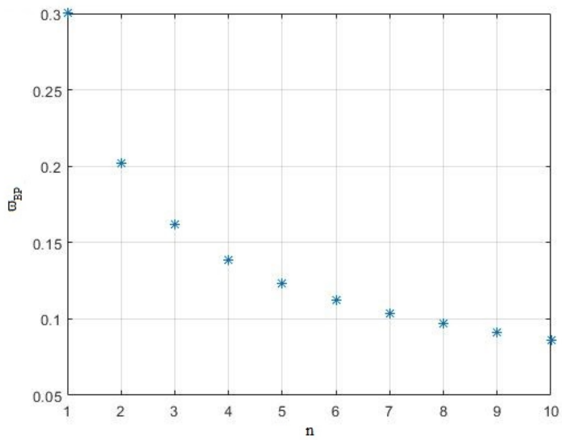

Figure 4 – Graph of bandwidth ϖ_{BP} dependence on the number of connections

As seen in Fig. 4, the bandwidth decreases exponentially. At the same time, it can be shown how much the bandwidth decreases with a series connection, and accordingly, the quality factor of such a configuration increases in accordance with (1) (Fig. 5).

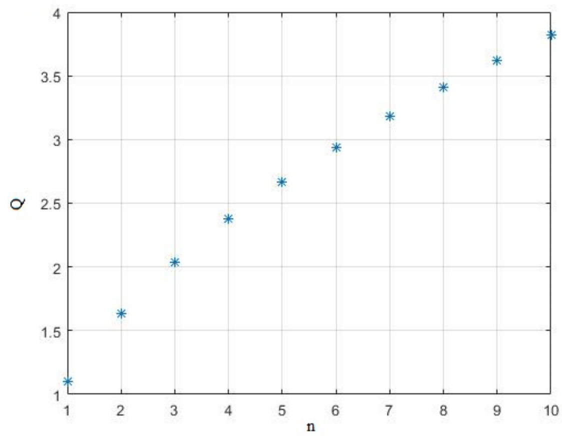

Figure 5 – Graph of the quality factor Q dependence on the number of connections

For example, with connecting four identical components, the bandwidth decreases by more than twice, with connecting eight – by more than three times, with ten – the bandwidth is reduced by 3.5 times. At the same time, the quality factor increases by 2.4 times, 3.4 times, and 3.8 times, respectively.

Modelling and experimental verification of the series connection of identical BPFs lead to a quasi-linear PFC compared to similar directly calculated filters (Fig. 6).

Figure 6 shows that the PFC of the new configuration, according to equation (8), i.e., $\varphi_5 = 5 \cdot \varphi$, five identical filters, is quasi-linear compared to the PFC of a fifth-order filter calculated directly. Additionally, when calculating an identical filter, only three coefficients are computed, whereas the fifth-order filter requires six coefficients in the numerator and ten in the denominator, totaling 16 coefficients that need recalculating and verification for stability. For filters of this order, this is a challenging task. Verifying the stability of first-order BPFs is a well-known and straightforward task. Moreover, the serial connection of stable filters results in the stability of the entire configuration.

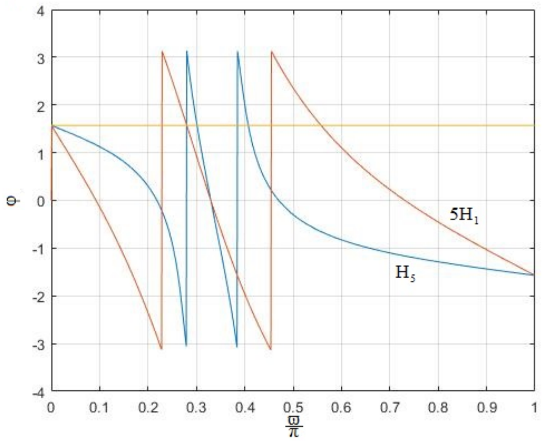

Figure 6 – Graph comparing the PFC of a series connection of five identical filters with the transfer function (1) ($5H_1$ is the transfer function after connecting five main filters) and the PFC of a fifth-order directly calculated filter H_5

When analyzing the PFC of the serial connection of identical components, it was found that the PFC of the new configuration is significantly more linear compared to the directly calculated PFC of the required order. Under limited computational capabilities, the proposed approach is considerably better than the traditional one.

6 DISCUSSION

The technical implementation of this approach in digital form can be both hardware and software-based. The hardware implementation relies on the serial connection of n identical components. The main component is calculated based on data stream information and operating modes. Cutoff frequencies, bandwidth, and gain coefficients are determined from this.

In the hardware implementation, one option considered was the serial connection of multiple identical filters with registers at the outputs of these components. A commutator handles the commutation of register outputs to the device output, which reduces filter switching time and the transition process time since the necessary data is already in the registers. This implementation could also be realized on an FPGA. However, this approach increases the energy consumption of the entire processing pipeline.

The software implementation was applied for processing data from the ultrasonic obstacle sensor on an AMRP using identical first-order components. This solution was convenient for both implementation and operation, reducing computation time since some constants were precomputed and stored in memory cells. Additionally, there were written a program for increasing filter order and the steepness of the AFC. However, the transition process time increased.

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CONCLUSIONS

A relevant problem has been solved: the comprehensive retuning of sensor signal processing characteristics with limited computational capabilities onboard AMRP without operator involvement. This was demonstrated using digital BPFs.

The scientific novelty of the results lies in the fact that, based on a model of serially connected identical FDCs described by first- and second-order transfer functions with specific frequency characteristics, new calculation formulas for such a connection were obtained for the first time. These formulas reduce computational costs when calculating coefficients based on given cutoff frequencies. Moreover, this connection allows for an increase in the order and quality factor of the new configuration, as well as achieving a quasi-linear PFC.

The practical significance of the results is that the obtained relationships enable the calculation of new cut-off frequency values with lower computational costs. Modelling and experimental verification results recommend this method and its formulas for practical use in AMRP with limited real-time computational resources.

Prospects for further research include extending this method to a wide range of practical tasks in robotics.

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ПОБУДОВА КАНАЛУ ОБРОБКИ СИГНАЛІВ ДАТЧИКІВ ДЛЯ АВТОНОМНОЇ РОБОТОТЕХНІЧНОЇ ПЛАТФОРМИ

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АНОТАЦІЯ

Актуальність. Розвиток автономних мобільних роботизованих платформ швидко прогресує, особливо в області кіберфізичних систем, де важлива інтеграція фізичних компонентів і обчислювальних ресурсів. Одним із ключових викликів для таких платформ є ефективна обробка сигналів датчиків у режимі реального часу за умов обмежених обчислювальних ресурсів, що дозволяє роботам діяти незалежно від втручання людини. Традиційні методи обробки сигналів вимагають значних ресурсів, що може стати проблемою для платформ з обмеженою енергією та ресурсами. Це дослідження зосереджене на перебудові каналу обробки сигналів за допомогою цифрових смугових фільтрів, долаючи технічні труднощі, що виникають через обмеження ресурсів.

Мета роботи – створення ефективного методу обробки сигналів датчиків на автономних мобільних платформах з обмеженими ресурсами. Це включає використання низько-порядкових смугових фільтрів, які можуть змінювати свої характеристики і підвищувати якість за допомогою послідовного з'єднання однакових фільтрів. Зниження обчислювального навантаження покращує загальну продуктивність кіберфізичних систем, підвищуючи ефективність роботи в умовах змін та дозволяючи автономне виконання завдань. Запропоновані нові розрахункові формули спрощують процес проєктування фільтрів та дозволяють ефективніше використовувати обмежені ресурси платформи.

Метод. Покращений метод побудови каналів обробки сигналів використовує однакові низько-порядкові частотно-залежні компоненти, послідовно з'єднані для вирішення проблем, характерних для високопорядкових компонентів. Такий підхід спрощує обчислення коефіцієнтів для заданих частот зрізу та підвищує продуктивність фільтра завдяки збільшенню порядку та якості. Метод досягає квазілінійної фазо-частотної характеристики, що мінімізує спотворення сигналу, і значно знижує обчислювальні вимоги.

Результати. Запропонований метод ефективно знижує обчислювальні витрати при збереженні високої продуктивності в обробці сигналів датчиків. Нові формули дозволяють розраховувати коефіцієнти фільтрів з використанням меншої кількості ресурсів, що робить їх придатними для автономних систем. Моделювання та експериментальна перевірка підтверджують, що цей метод знижує навантаження та покращує частотні характеристики фільтрів, дозволяючи роботам більш ефективно взаємодіяти з оточенням у режимі реального часу. Підвищена ефективність обробки сигналів також подовжує час роботи та підвищує надійність системи.

Висновки. Це дослідження пропонує ефективний підхід до обробки сигналів для автономних мобільних платформ з обмеженими ресурсами. Метод послідовного з'єднання однакових частотно-залежних компонентів знижує обчислювальні витрати та підтримує високу якість обробки сигналів. Результати моделювання та експериментів підтверджують ефективність нових розрахункових формул для покращення продуктивності системи. Цей підхід добре підходить для кіберфізичних систем, де критично важлива робота в реальному часі та ефективне використання ресурсів.

КЛЮЧОВІ СЛОВА: автономна мобільна робототехнічна платформа, частотно-залежні компоненти, фільтри, частотні характеристики, кіберфізична система.

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