

A Phase Correction Node Construction for Cyber-Physical Systems Based on All-pass Filters

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Abstract The article examines a cyber-physical system using the example of an autonomous mobile platform (AMP), which contains hardware and software components. However, AMPs have limitations regarding power consumption, computational capacity, and real-time operation independently. The uncertainty of the environment necessitates the use of means that correct sensor signals. To correct the phase of AMP sensor signals, all-pass filters are used. The paper discusses the construction of all-pass filters based on low-order LPF and HPF, as well as BPF and BRF. Phase correction improvement is achieved by increasing the order of the transfer function through the sequential connection of such filters. Schemes of correction nodes implementation are presented.

Keywords: cyber-physical system, autonomous mobile platform, all-pass filter, LPF and HPF, BPF and BSF, frequency characteristics, phase correction formation

Introduction

The modern development of society is characterized by the rapid growth of cyber-physical systems. At present, there are many definitions of cyber-physical systems [1–7]. In general, cyber-physical systems (CPS) are systems consisting of various natural objects, artificial subsystems, and controllers that manage them, which makes it possible to consider such a formation as a single whole. The interaction between computational and physical resources of the system enables active monitoring and control of physical processes based on feedback. The main technical prerequisites for the emergence of cyber-physical systems are [1–7]:

- the increase in the number of devices with embedded microprocessors and processors, as well as data storage facilities;
- integration, which allows achieving the greatest effect by combining individual components into large systems;
- the presence of a large number of sensors and actuators;
- imitations of human cognitive abilities, which evolve more slowly than machines, and inevitably comes a point when they cannot cope with the amount of information required for decision-making and event response.

Typically, this is an embedded system as a special-purpose system, in which the computational element is fully embedded in the device it controls.

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Unlike a general-purpose computer, an embedded system performs one or several predefined tasks, usually with very specific real-time requirements. Technically, an embedded system interacts with the environment in a controlled manner, meeting a number of requirements for ensuring the quality and timeliness of information necessary for control and task execution.

Cyber-physical systems integrate cybernetics, computer hardware and software technologies, qualitatively new actuators embedded in the environment and capable of perceiving its changes, responding to them, self-learning, and adapting. It should be noted that the general architecture of CPS is divided into four fundamental levels [1–3]:

- physical level (the physical level forms the foundation of the CPS architecture);
- network level (packet routing based on the transformation of the unique identifier assigned to each active equipment in the network);
- transport level (packets are divided into small fragments);
- intermediate level (terminal management, protocol conversion);
- application level (stores, analyzes, and updates information).

Autonomous mobile platforms (AMP) can also be attributed to such systems, as their structural organization corresponds to cyber-physical systems. Since the integration of physical processes and cybernetic components makes it possible to enhance the intellectual capabilities of such platforms when

performing their functions [8]. In such systems, preliminary motion modeling is often used to ensure safety within an AMP group when performing a task [9, 10]. Reliable data on the state of the AMP and the environment are required for this.

Hardware and software components must be mobile, flexible, adaptive, and able to adjust to operating conditions with limited power sources, dimensions, and weight. This is possible when using multi-functional sensors, hardware, and software components of computing systems that must operate in real time.

However, such systems also have a number of requirements and limitations. Usually, AMPs are limited in size, power supply, and computational capacity. This leads to the need to develop hardware and software components with minimal power consumption while ensuring task execution, and data processing is also limited in algorithm implementation. This fits well into modern concepts of Industry 4.0–6.0 development [11–15].

The object of the study is the process of processing and correcting AMP sensor signals within a cyber-physical system without operator involvement. With a large number of sensors and in the presence of interference, filtering and correction are required with the ability to reconfigure processing component parameters in real time. Such adaptation to operating conditions increases the reliability of decision-making data and the execution of tasks by actuators.

The subject of the study is the construction of a node for correcting the phase of AMP sensor signals onboard, with the ability to reconfigure parameters and configuration to ensure operational work.

Sensor signal correction must compensate for amplitude and phase distortions in sensor signals [16]. Such a task can be assigned to amplitude and phase correctors.

Therefore, the aim of the study is the need to use convenient and simple approaches to create digital devices that make it possible to compensate for phase distortions for AMP based on all-pass filters.

1. All-pass filter

Phase correctors, or all-pass filters, pass all signal frequencies with equal gain, but they change the signal phase [17]. Thus, these filters are used for phase correction in sensor signal processing to compensate for phase distortions.

It is known that such filters have a transfer function denominator described by the Hurwitz polynomial $Q(p)$, and its numerator by the related polynomial. If P_k - is a root of the denominator, then $(-P_k)$ - is a zero of the numerator.

$$K(p) = \frac{Q(-p)}{Q(p)}$$

For digital all-pass filters, the corresponding analogue of the Hurwitz polynomial is used. In this case, in a first-order digital all-pass filter, the zero and pole lie on the real axis of the Z -plane, so that the pole module has a value $r < 1$, and the zero module equals $-1/r$. As a result, the zero compensates for the effect of the pole. This circumstance leads to the fact that the amplitude-frequency characteristic (AFC) equals one over the entire frequency range.

2. First-order filter

Based on this description of a first-order digital all-pass filter, its transfer function will have the following form

$$H_F(z) = \frac{b_1 + z^{-1}}{1 + b_1 z^{-1}}, \quad (1)$$

where b_1 - is the transfer function coefficient.

Let us find the phase-frequency characteristic of such an all-pass filter

$$\varphi = -\arctg \frac{(1 - b_1^2) \sin(\bar{\omega})}{2b_1 + (1 + b_1^2) \cos(\bar{\omega})}$$

Thus, in general, such a filter does not change the signal amplitude but corrects its phase. However, there is one peculiarity: the closer the coefficient b_1 to one, the stronger the phase correction.

The creation of all-pass filters is not a simple task [17–19]. Therefore, simpler methods are needed for their construction.

In this work, low-order digital low-pass and high-pass filters are used for this purpose. The transfer functions of first-order normalized low-pass filters $H_L(z)$ and normalized high-pass filter $H_H(z)$ have the following form

$$H_L(z) = \frac{a_L + a_L z^{-1}}{1 + b_1 z^{-1}}, \quad H_H(z) = \frac{a_H - a_H z^{-1}}{1 + b_1 z^{-1}}. \quad (2)$$

In this case, the transfer function of the all-pass filter can be obtained by transforming the denominator of these filters to form the numerator in such a way that it has the following form $b_1 + z^{-1}$. Then, the transfer function of the all-pass filter $H_F(z)$ can be obtained as their difference.

$$H_F(z) = H_L(z) - H_H(z) \tag{3}$$

In this case, the required numerator and denominator polynomials are formed, and the phase is determined as follows.

$$\varphi_1(\bar{\omega}) = \arctg \frac{(ab_1 - d) \sin(\bar{\omega})}{(a + db_1) + (ab_1 + d) \cos(\bar{\omega})},$$

where $a=aL-aH, d=aL+aH$.

Increasing phase correction makes it necessary to increase the order of the transfer function, which can be done by sequentially connecting identical low-order all-pass filters. When connected in series, their transfer functions are multiplied, and since they are identical, this is equivalent to raising to the power equal to the number of sequentially connected filters.

$$(H_F(z))_n = \prod_{i=1}^n H_{Fi}(z) = (H_F(z))^n \tag{4}$$

It should be noted that in this case the phase changes according to the relation

$$\varphi_n = n\varphi_1, \tag{5}$$

where φ_1 - is the phase of the first-order all-pass filter.

This solution makes it possible, depending on the system operation, to automatically change the processing path configuration according to the distortion criterion.

For practical implementation, a block diagram of the correction unit has been developed, where the signal enters two channels, Fig. 1.

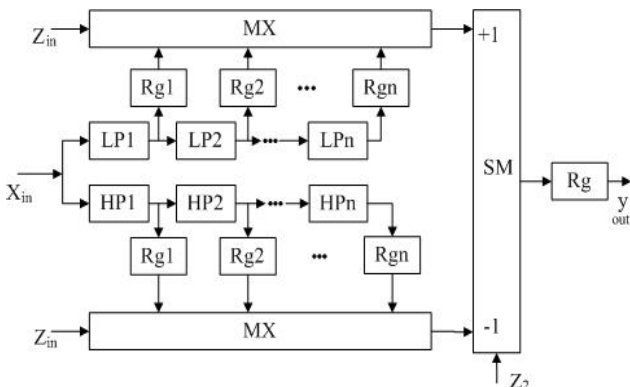


Fig. 1 Structural diagram of the formation of a first-order all-pass filter

In the first channel, n digital LP filters of the first order are connected; in the second, n digital HP filters of the first order. The outputs of each filter of such a connection in each channel go to a multiplexer (MX), which, depending on the functioning of the path and signal distortion, switches the outputs of the required number of elementary filters to an adder (SM), which performs subtraction according to relation (3). Thus, the AFC and PFC of a new connection are formed, which is equivalent to an all-pass filter of the corresponding order. In this case, the coefficient b_1 becomes the control parameter of phase correction [20].

In addition, it is possible to form the transfer function of the all-pass filter by preparing such a function in advance and creating a table of denominator coefficients b_1 . Such a coefficient table will correspond to the level of phase correction, and the increase in the degree of the transfer function, to enhance phase correction, can also be formed through the table when such an influence is studied in advance.

3. Second-order filter

The transfer function of a second-order all-pass filter, based on theory and by analogy with the first-order filter, has the following form

$$H_{F2}(z) = \frac{b_2 + b_1 z^{-1} + z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \tag{6}$$

Based on this description of a first-order digital all-pass filter, let us find the phase-frequency characteristic of the phase filter

$$\varphi = -\arctg \frac{(1 - b_2) \sin(\bar{\omega})}{b_1 + (1 + b_1) \cos(\bar{\omega})},$$

where b_1, b_2 - are the transfer function coefficients.

To form a second-order all-pass filter, one can use a band-pass digital filter and a band stop digital filter. The transfer functions of the first order (although their transfer functions are described by second-order equations) of the band stop digital filter $H_R(z)$ and the band-pass digital filter $H_B(z)$ have the following form

$$H_R(z) = \frac{a_{R0} + a_{R1} z^{-1} + a_{R2} z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}},$$

$$H_B(z) = \frac{a_{B0} + a_{B1}z^{-1} + a_{B2}z^{-2}}{1 + b_1z^{-1} + b_2z^{-2}} \quad (7)$$

In this case, the transfer function of the all-pass filter can be obtained by transforming the denominator of these filters to form the numerator so that it has the form as in (6).

Then, the transfer function of the all-pass filter HF2(z) can be obtained as their difference.

$$H_{F2}(z) = H_R(z) - H_B(z) \quad (8)$$

Increasing phase correction makes it necessary to increase the order of the transfer function, which can be done by multiplying identical all-pass filters, as in the case of first-order filters in relations (4) and (5).

For practical implementation, a structural diagram of the correction unit is proposed, where the signal enters two channels, Fig. 2.

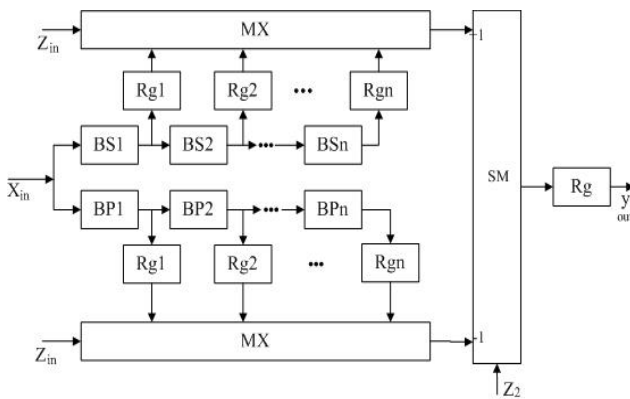


Fig. 2 Structural diagram of the formation of a second-order all-pass filter

In the first channel, n band stop filter (BS) are connected; in the second, n digital band-pass filters (BP). The outputs of each filter of such a connection in each channel go to a multiplexer (MX), which, depending on the functioning of the path and signal distortion, switches the outputs of the required number of elementary filters to an adder (SM), which performs subtraction according to relation (8). Thus, the AFC and PFC of a new connection are formed, which is equivalent to an all-pass filter of the corresponding order.

When forming the phase correction unit of sensor signals, it should be taken into account that the AMP has limited energy resources onboard. Therefore, the solution shown in Fig. 1 and Fig. 2 is not very successful from the point of view of power consumption, since 2n filters will be connected sim-

ultaneously, but on the other hand, in such an implementation, the transient process during switching is reduced, since the filters are already connected, and the multiplexer only switches the necessary signals to form correction. In this case, this contradiction must be resolved in a specific task, and the correction channel must be formed. It should also be noted that all filters are identical and need to be re-configured only once, not each individually.

However, such a solution can be implemented on an FPGA, which will be pre-programmed and embedded into the processing path, allowing, depending on platform functioning, automatic re-configuration of the correction channel according to the distortion criterion.

4. Software implementation

To build a software implementation of the all-pass filter formation, used a directed and ordered graph of the first-order transfer function (1), Fig. 3.

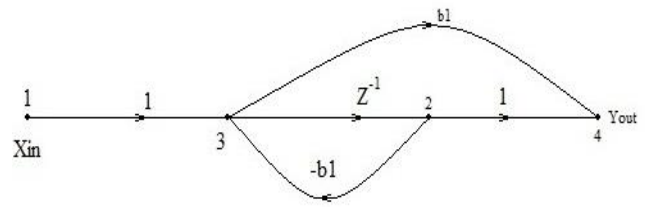


Fig. 3 Directed graph of the first-order all-pass filter

Based on this graph, a system of state equations of the graph nodes can be formed.

$$\begin{cases} x_1[i] = x_{in}[i] \\ x_2[i] = x_3[i-1] \\ x_3[i] = x_1[i] - b_1 x_2[i] \\ x_4[i] = x_2[i] + b_1 x_1[i] \\ y_{out}[i] = x_4[i] \end{cases}$$

Based on this system of equations, form a program for generating the output signal yout from the input xin, which implements the transfer function (1).

Based on the implementation of this system of equations, it is possible to form their sequential connection programmatically using recursion. A fragment of a C\C++ program looks as follows.

```
struct Parameters {
    double x3 = 0;
    double y_out = 0;
} param;
```

```

void firstOrder(const double b1, int deep, const
double value)
{
    const double x3 = value - b1 * param.x3;
    param.y_out = param.x3 + b1 * value;
    param.x3 = x3;

    if(deep-1 == 0)
        return;

    firstOrder(b1, deep-1, param.y_out);
}

```

For the second-order filter, such a graph has the following configuration, Fig. 4.

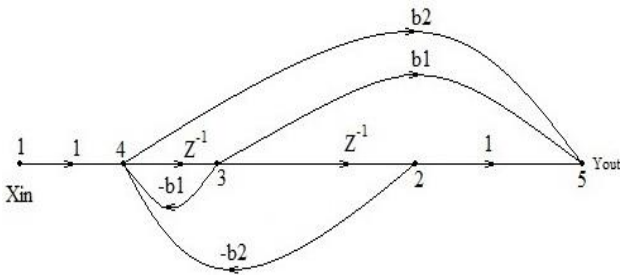


Fig. 4 Directed graph of the second-order all-pass filter

Then the system of state equations of the graph nodes will have the following form.

$$\begin{cases}
 x_1[i] = x_{in}[i] \\
 x_2[i] = x_3[i-1] \\
 x_3[i] = x_4[i-1] \\
 x_4[i] = x_1[i] - b_1 x_3[i] - b_2 x_2[i] \\
 x_5[i] = b_2 x_2[i] + b_1 x_3[i] + x_4[i] \\
 y_{out}[i] = x_5[i]
 \end{cases}$$

Based on this system of equations, we form a program for generating the output signal y_{out} from the input x_{in} , which implements the transfer function (6).

Based on the implementation of this system of equations, it is possible to form their sequential connection programmatically using recursion. A fragment of a C\C++ program looks as follows.

```

struct Parameters {
    double x3 = 0;
    double x4 = 0;
    double y_out = 0;
} param;

```

```

void secondOrder(const double b1, const double
b2, int deep, const double value)
{
    const double x4 = value - b1 * param.x4 - b2
* param.x3;
    param.y_out = b2 * param.x3 + b1 *
param.x4 + x4;
    param.x3 = param.x4;
    param.x4 = x4;

    if(deep-1 == 0)
        return;

    secondOrder(b1, b2, deep-1, param.y_out);
}

```

The software sketch simplify the implementation of the sensor signal phase correction unit.

Conclusions

The work shows that the use of digital filters makes it convenient to build an all-pass filter, and its use makes it possible to form a phase correction unit for AMP. In the authors' opinion, the software implementation of such a filter is convenient and more flexible for use and reconfiguration. The use of such a unit will automatically evaluate and change its characteristics when phase distortion occurs, in order to improve the correction of sensor signal phases and the efficiency of the system as a whole.

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Побудова вузла корекції фази для кіберфізичних систем на основі всепропускних фільтрів

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Анотація. У статті розглядається кіберфізична система, на прикладі автономної мобільної платформи (АМП), яка містить в собі апаратно-програмні компоненти. Однак АМП мають обмеження до енергоспоживання, обчислювальної потужності та функціонуванні в реальному часі самостійно. Невизначеність навколишнього середовища обумовлює застосування засобів, що коректують сигнали датчиків. Для корекції фази сигналів датчиків АМП використовують всепропускні фільтри. В роботі розглянуті питання побудови всепропускних фільтрів на основі фільтрів низького порядку ФНЧ та ФВЧ, а також СФ та РФ. Підвищення корекції фази виконується через підвищення порядку передавальної функції шляхом послідовного з'єднання таких фільтрів. Наведені схеми реалізації вузлів корекції.

Ключові слова: кіберфізична система, автономна мобільна платформа, всепропускний фільтр, ФНЧ та ФВЧ, СФ та РФ, частотні характеристики, формування корекції фази

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