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UDC 519.718

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ON-BOARD CONTROL SYSTEM FOR HIGH-RELIABILITY AND SURVIVABILITY AIRCRAFT

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Анотація. *Робота присвячена описанню методу підвищення надійності та живучості бортових систем управління. Як об'єкт дослідження обрано клас літальних апаратів — крилаті ракети, які є однією з найперспективніших систем озброєння. У статті проаналізовано сучасні структури бортових систем управління, що забезпечують високу надійність таких систем. Проведено аналіз чотириканальних відмовостійких систем для бортових комплексів управління підвищеної живучості, які забезпечують високу достовірність роботи комплексів протягом тривалого часу без фізичного обслуговування, зберігаючи стійкість до збоїв і відмов апаратури. Також розглянуто її прототип — триканальну систему з виходами синхронізації. Виділено позитивні та негативні сторони таких систем, відзначено високий рівень їх апаратної надлишковості. Для літальних апаратів із коротким терміном служби, якими є крилаті ракети та подібні до них, авторами запропоновано двоканальну квазімісткову структуру (КМС) бортової системи управління з поблоковим резервуванням і реконфігурацією. КМС загалом являє собою систему, що складається з послідовного з'єднання дубльованих вузлів однакової надійності. У разі відмови одного з функціональних субблоків дубльованого вузла схема контролю та реконфігурації виключає його з обчислювального процесу та проводить реконфігурацію структури системи в режимі роботи «Non Stop». Як інструментарій дослідження надійності бортової системи використовувався ймовірнісно-фізичний метод (ВФ-метод), в основі якого лежить дифузний розподіл напрацювання до відмови (DN-розподіл), спеціально формалізований для оцінки та прогнозування надійності електронних, електричних та електромеханічних елементів і систем. При збереженні рівня надмірності, характерного для всіх двоканальних структур, у запропонованій двоканальній резервованій КМС декомпозиція каналів на однаково надійні дубльовані вузли приводить до зростання ймовірності безвідмовної роботи системи (R-ефект), що стає більш помітним із збільшенням кількості вузлів. У роботі також описано принцип розміщення функціональних субблоків КМС, який забезпечує додатковий ефект — підвищення живучості системи в цілому.*

Ключові слова: *система з квазімістковою структурою, дубльований вузол, ймовірність безвідмовної роботи, R-ефект.*

Abstract. *The paper is dedicated to describing a method for increasing the reliability and survivability of on-board control systems. The object of the research is a class of aircraft — cruise missiles, which are considered one of the most promising weapon systems. The article analyzes modern structures of on-board control systems that ensure high reliability of such systems. The study focuses on analyzing four-channel fault-tolerant systems for on-board control complexes with enhanced survivability, which ensure high operational reliability of the complexes over extended periods without physical maintenance while maintaining resistance to equipment malfunctions and failures. Additionally, the paper examines its prototype — a three-channel system with synchronization outputs. Both positive and negative aspects of these systems are highlighted, noting their high level of hardware redundancy. For short-lifespan aircraft, such as cruise missiles and similar systems, the authors propose a two-channel quasi-bridge structure (QBS) for the on-board control system, featuring block-level redundancy and reconfiguration. In general, the*

QBS represents a system consisting of a sequential connection of redundant nodes with equal reliability. When one of the functional subunits of a redundant node fails, the control and reconfiguration scheme excludes it from the computational process and reconfigures the system structure in a non-stop mode. As a tool for studying the reliability of the on-board system, a probabilistic-physical method (PP-method) has been used, which is based on a diffusive distribution of time-to-failure (DN-distribution), specifically formalized for the assessment and prediction of the reliability of electronic, electrical, and electromechanical elements and systems. While maintaining the level of redundancy characteristic of all two-channel structures, the proposed two-channel redundant QBS, with its decomposition of channels into equally reliable redundant nodes, leads to an increase in the probability of failure-free operation (the R-effect), which becomes more significant as the number of nodes increases. The paper also describes the principle of placing functional subunits of the QBS, providing an additional effect — the overall increase in system survivability.
Keywords: *system with quasi-bridge structure, duplicated node, probability of failure-free operation, R-effect.*

DOI: 10.34121/1028-9763-2025-1-134-139

1. Introduction

The issues of improving reliability and survivability are among the most important for military equipment, especially for the most expensive types of weaponry such as ballistic and cruise missiles. This type of weaponry, along with unmanned systems, is most frequently used to target critical infrastructure areas. The primary value of such weapons lies in their high precision, allowing for the targeted destruction of specific objectives while minimizing civilian casualties.

Missiles travel at high speeds and follow complex trajectories, which presents a significant challenge for air defense systems. In this case, a direct hit on the missile is not required; it is sufficient for the air defense system to operate in close proximity to the cruise missile, affecting it with one or more damaging elements (Fig. 1).

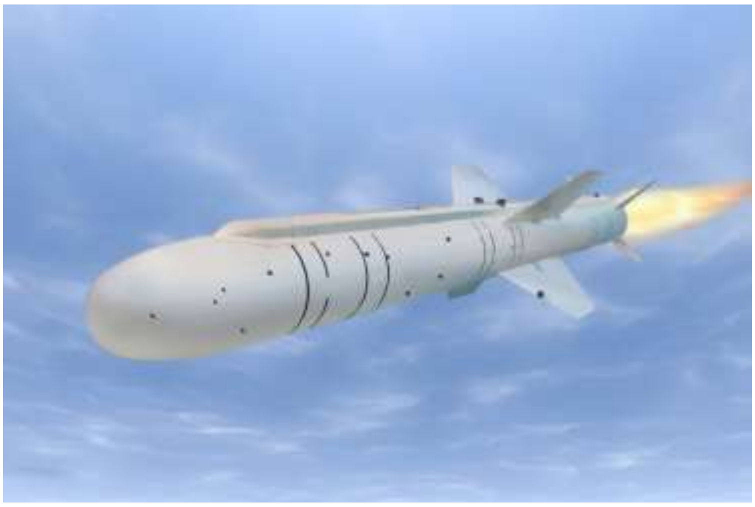

Figure 1 — Example of a cruise missile being impacted by air defense systems

The task of the cruise missile is to withstand such an impact, which, in terms of reliability theory, means demonstrating the property of survivability — continuing to perform its functions under conditions that differ from normal. Otherwise, if it sustains minor damage, the missile loses control and, without reaching its target, either self-destructs or causes damage to other civilian infrastructure objects that were not intended for attack.

The aim of this article is to improve the reliability and survivability of the on-board control systems of cruise missiles with minimal hardware redundancy by using a fault-tolerant quasi-bridge system structure.

2. Examples of on-board control system structures for aircraft

The design and functioning of electronic components (processors, memory, interfaces, etc.) used in on-board digital computing systems (ODCS) do not fundamentally differ from commercial electronic components. However, additional optimization methods are applied in ODCS [1].

There is a significant amount of recourses dedicated to the structures of ODCS for aircraft, such as [2–7].

In [3], a method for forming a four-channel fault-tolerant system for on-board control complexes with enhanced survivability is discussed. This invention can be used to create highly reliable fault-tolerant ODCS in space, aviation, nuclear, chemical, energy, and other industries.

The technical result of the proposed method and system for its implementation is a significant increase in the system's survivability and the ability to preserve its resource. This result is achieved by introducing a multiple bus organization for the interaction of the ODCS computing core with power automation blocks and peripheral devices.

The invention from [4] also relates to computing technology, ensuring high operational reliability of the ODCS complex over long periods of time, approximately 10 years, without physical maintenance while maintaining resistance to equipment malfunctions and failures. The proposed system structure also involves a multiple bus organization for the interaction of the ODCS computing core with power automation blocks and peripheral devices, ensuring high system survivability.

In the system, there are also four channels, and numerous methods and mechanisms for assessing the integrity of the system's channels have been introduced. This has allowed for increased fault tolerance by mitigating failure situations, reconfiguring the system structure in case of failures, and optimizing resources depending on operating modes. The selection of the current system configuration allows for an overall increase in the reliability and survivability of the system.

Various publications describe a method and computing system for fault-tolerant processing of critical functions in aircraft, based on fourfold hardware redundancy and majority voting of signals in the critical function implementation paths to enhance the reliability and accuracy of information processing.

The downside of this method is the complexity of real-time synchronization algorithms for the control results obtained from different channels, as well as the reduction in overall system reliability due to the fourfold increase in the total failure rate of components because all four system channels work in continuous parallel operation. Even failed components remain connected to the power supply, which is only acceptable for short-lifespan aircraft.

A known three-channel redundant control system [5] is designed to create highly reliable computing control systems. In it, information reception from subscribers, information processing, and output to subscribers are resolved using hardware signal majority voting in a three-channel redundant control system.

This maintains the detailed technical content and the comparison of different control system structures for high-reliability aircraft.

The disadvantages of such ODCS include the inability to reconfigure the system in the event of failures, which reduces the value of diagnostic procedures, the general ability to handle only one failure at a time, and increased power consumption due to the parallel operation of the three ODCS channels. This leads to reduced reliability due to the overall increase in the system's failure rate.

The closest approach to building an ODCS structure is a three-channel control system [6], consisting of three identical channels, each of which contains a computing unit (a microcontroller), an input/output block, the main and backup transceiver for the serial interface designed to organize interprocessor communication between the system channels, and the main and backup buses connected to the corresponding input/output blocks of the three channels.

When one channel fails, it is blocked and does not output anything externally (for external consumers), while the control information from the two functioning channels is sent to external consumers, where it is restored through software or hardware majority voting. The presence of signals indicating the channels' functionality allows for operation on the remaining single channel if the other two channels fail.

The «bottleneck» of the prototype is that each channel generates its own integrity signal. The low reliability of this self-check signal prevents the system from achieving high real-time control reliability, especially for systems designed for long-term operation without maintenance.

A disadvantage of the prototype [6], common to most three-channel majority voting structures, is the increased power consumption and resource depletion due to the continuous parallel operation of the three ODCS channels. This also leads to a decrease in the system's reliability due to the overall increase in failure rates.

3. Reliability and survivability of on-board control systems based on a quasi-bridge structure (QBS)

The quasi-bridge structure (QBS) of the ODCS represents a two-channel modular structure with the ability to reconfigure during operation, the properties of which have been thoroughly studied in [8].

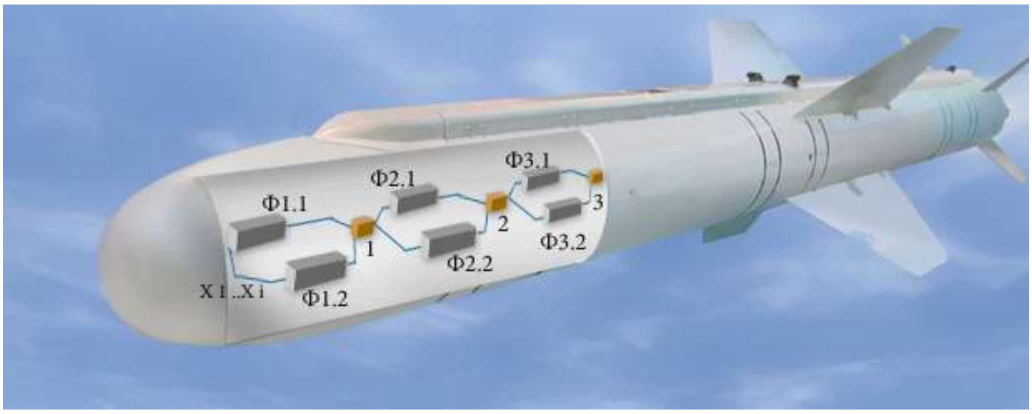

Figure 2 — Cruise missile with an ODCS based on a quasi-bridge structure

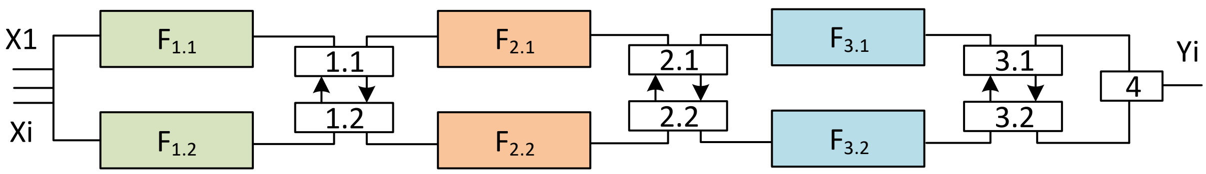

Figure 3 — Functional diagram of the quasi-bridge structure

Figure 3 shows a functional diagram of such a structure, where each computational channel X1 and X2 is divided into *n* conditionally equally reliable blocks, for example, F1.1, F1.2, F1.3 and F2.1, F2.2, F2.3, which, with the help of reconfiguration circuits (1.1, 1.2, 2.1, 2.2, 3.1, 3.2), form n redundant nodes.

A safe comparison circuit (Fig. 4) compares the output signals from channels X1 and X2. When the signals match, a control action is generated for the controlled object.

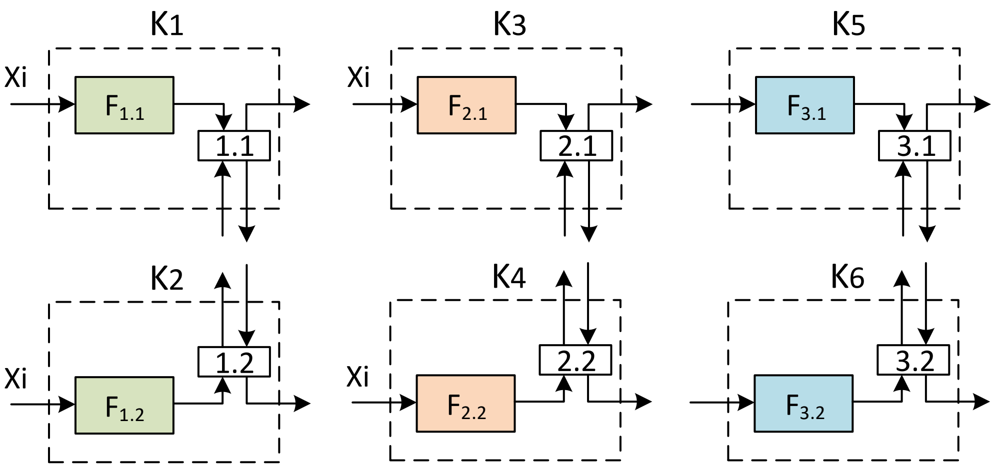

Figure 4 — Decomposition of the quasi-bridge structure into functional modules

The results of the reliability studies of a certain QBS using the PP-method [9, 10]:

– with the same number of nodes ($n = 5$) in two competing two-channel systems, the probability of failure-free operation for the system with the QBS $R_{ÊÌÑ}$ =0.8526 exceeds the probability of failure-free operation of the system with block-level redundancy $R_{ÄÑ}$=0.74809 by 14 %;

– with the same number of nodes $n = 10$ $R_{ÊÌÑ}$ = 0.9338, exceeds the probability $R_{ÄÑ}$ = 0.74809 of the system with block-level redundancy by 25 %.

Let us consider two types of damage to an ODCS based on a QBS from air defense systems.

Fragment damage to a functional module (single failure in the QBS) can occur when a fragment from a nearby exploding air defense system penetrates the protective shell of the cruise missile.

Simultaneous fragment damage to multiple functional modules (multiple failures in the QBS) can occur when several fragments from a nearby exploding air defense system penetrate the protective shell of the cruise missile.

In the event of impact from air defense systems, it is desirable for the cruise missile to retain full or partial functionality. This is achieved through the fault-tolerant properties of the QBS of the ODCS (Figs. 2–4) and the special arrangement of functional modules inside the cruise missile's body (Fig. 5).

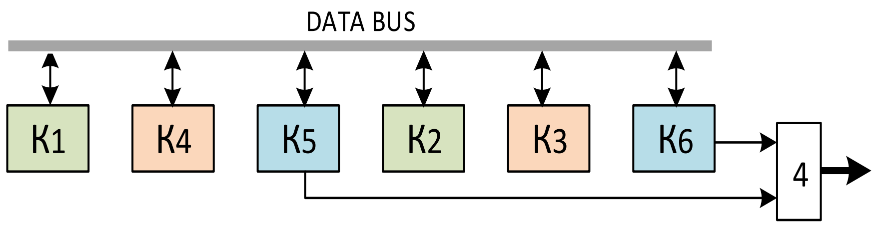

Figure 5 — Functional block connection diagram of the quasi-bridge structure

It requires no proof that, in the case of a single failure in any functional block, the ODCS based on the QBS retains full functionality. In the case of multiple failures, for instance, simultaneous damage to two functional blocks with numbers {1, 4}, {4, 5}, {5, 2}, {2, 3}, {3, 6}, or to three blocks with numbers {1, 4, 6}, {2, 3, 5}, etc., the ODCS based on the QBS also remains functional, which confirms its enhanced survivability.

4. Conclusions

At the same level of redundancy for the two-channel redundant systems with block-level duplication and the quasi-bridge structure, the decomposition of channels into equally reliable redundant nodes in the case of the QBS system leads to an increase in the probability of failure-free operation — the R-effect — both when the systems have the same number of nodes and when the QBS system has more nodes of arbitrary complexity.

The arguments given above also demonstrate the high survivability of the ODCS based on the QBS, built on a clustered structure. This structure consisting of equally reliable functional blocks is characterized by enhanced survivability, along with overall superior reliability compared to the competing two-channel system with block-level duplication.

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Стаття надійшла до редакції 15.11.2024