ISSN 1454 - 8003
Proceedings of 2023 International Conference on Hydraulics and Pneumatics - HERVEX
November 8-10, Băile Govora, Romania

COMPARATIVE ANALYSIS OF CURRENT APPROACHES TO DIGITAL TWINS OF ELECTRO-HYDRAULIC MECHATRONIC SYSTEMS CREATIONS

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Abstract: *The aim of this study is to identify approaches and principles for creating digital twins of electrohydraulic mechatronic systems. The aim of the study was achieved by bibliometric analysis and systematic review for identification approaches and principles of creating digital twins of various electro-hydraulic mechatronic systems in all stages of their life cycles. As a result of the research, publications were systematized in accordance with the approaches and methods proposed in them for creating digital twins of electrohydraulic mechatronic systems and their elements. Namely, which stages of the life cycles of electrohydraulic mechatronic systems are covered by the approaches and methods proposed in publications. During the bibliometric analysis, no publications were identified that would offer a systematic methodology for creating different types of digital twins of electrohydraulic mechatronic systems at all stages of their life cycles. Thus, the creation of such a systematic methodology is an important scientific and practical task.*

Keywords: *Electrohydraulic mechatronic systems, heavy-duty machines, digital twins, life cycles*

1. Introduction

Heavy-duty machines, such as excavators, mining, agricultural, and military vehicles, are often operated in hazardous and harmful environments. Electrohydraulic mechatronic drives continue to be important components of such machines. The transformation of heavy-duty machines into more autonomous and robotic ones requires the creation of digital twins of electro-hydraulic mechatronic drives that would reflect their functioning at all stages of their life cycles.

2. Literature review and problem statement

The current state of development of digital twins at various stages of product life cycles is covered in publications [1-2]. The principles and approaches outlined in [1-2] can partially be applied to electrohydraulic mechatronic systems. However, they need serious adaptation and addition.
The papers [3-10] present various aspects of creating digital twins of heavy-duty machines. The papers [3-10] pay insufficient attention to electrohydraulic mechatronic systems, as important components of heavy-duty machines. In the process of creating digital twins of electrohydraulic mechatronic systems, it is necessary to take into account research [3-10] results. This is due to the fact that digital twins of electrohydraulic mechatronic systems must be suitable for integration into digital twins of heavy-duty machines.
The papers [9-10] outline approaches to creating digital twins of electrohydraulic mechatronic systems of heavy-duty machines. However, the approaches outlined in [9-10] cannot be considered comprehensive and cover all stages of the life cycles of electrohydraulic mechatronic systems.
Papers [11-13] propose results of the creation of a simplified numerical model, based on a very compact semi-empirical formulation, able to simulate the fluid dynamics behaviours of an electrohydraulic servo valve taking into account several effects due to valve geometry and operating conditions. The results [11-13] are proposed to be used to create digital twins at the stages of development and detailed design of electrohydraulic servo valves. Despite the fact that the research [11-13] concerns only electrohydraulic servo valves, they can be used to create digital twins of electrohydraulic mechatronic systems.

The article [14] presents a model for counterbalance valves which are widely used in hydraulic and electro-hydraulic drives. The model consists of parameters that account for the internal geometry, inertia, and friction characteristics of the counterbalance valves. The proposed model of the counterbalance valve satisfies the main requirements of digital twins and thus, is a suitable candidate for the digital twin of the counterbalance valves and can easily be integrated into the digital twins of larger systems where the counterbalance valves are installed [14]. The model [14] and the principles of its creation can be used in digital twins of electrohydraulic mechatronic systems.
The paper [15] presents the construction technology of the digital twinning model for the erect-fold electromechanical-hydraulic system of radar based on co-simulation. The construction technology [15] can be generalized to other electrohydraulic mechatronic systems, but it should be added with other principles of digital twins' creation.
The literature review shows a lack of research in the field of creating digital twins of electrohydraulic mechatronic systems. Publications which outline the methodology for creating digital twins of various electro-hydraulic mechatronic systems in all stages of their life cycles have not been identified. Thus, development of a methodology for creating digital twins of electro-hydraulic mechatronic systems, which covers all stages of electro-hydraulic mechatronic systems life cycles is an important scientific task.

3. The aim of the study

The aim of this study is to identify approaches and principles for creating digital twins of electrohydraulic mechatronic systems. Such digital twins should cover all stages of the life cycles of electrohydraulic mechatronic systems.

4. The study materials and methods

This study adopts bibliometric analysis and systematic review for identification approaches and principles of creating digital twins of various electro-hydraulic mechatronic systems in all stages of their life cycles. The research materials included publications on the above-mentioned scientific direction and related areas.

5. Results of comparative analysis of current approaches to digital twins of electro-hydraulic mechatronic systems creations

According to the aim of the study, each of the publications in the field of digital twins of electrohydraulic mechatronic systems and their elements were analysed to identify the methods used for creating digital twins. Also, was identified which stage of the life cycles of electrohydraulic mechatronic systems or their elements cover some publications. The results of the review are systematised in Table 1.
The papers [9, 10] propose using pressure indication in hydraulic and electro-hydraulic systems to, directly and indirectly, determine their other characteristics. The data obtained in this way is proposed to be used to create digital twins of electrohydraulic mechatronic systems mainly at such stages of their life cycles as Deployment, Operation and technical support.
The paper [11] presents an overview of low-fidelity models of the hydrodynamic behaviour of an electrohydraulic servo valve. They are designed to operate in real-time as digital twins of a physical system to enable diagnostic and prognostic algorithms. The accuracy of the simulation is assessed by comparing its results to a detailed, physics-based, high-fidelity model that calculates the equipment response based on the pressure and flow characteristics of all internal passages of the electrohydraulic servo valve.
The article [12] proposes a new simplified numerical model, based on a very compact semi-empirical formulation, able to simulate the fluid dynamics behaviours of an electrohydraulic servo valve taking into account several effects due to valve geometry and operating conditions. Although the proposed model is still based on a simplified formulation with lower computational cost, it introduces a new nonlinear approach that, by approximating the dynamic pressure and fluid flow characteristics of a servo valve with reasonable accuracy, overcomes the shortcomings typical of such models [12].

Ideas and approaches for creating digital twins of electrohydraulic servo valves based on simplified models proposed in papers [11, 12] were further developed in the article [13]. This work proposes a new simplified lumped parameter numerical model that, despite a very compact formulation and lower computational cost, simulates the internal fluid dynamics of the valve, overcoming some critical problems typical of other models available in the literature. It evaluates valve performance based on spool position and environmental conditions (e.g., supply pressure), more accurately assessing flow feedback, internal leaks, and other operating conditions (e.g., fine spool adjustment, variable supply pressure, overpressure, or water hammer). The performance of this numerical model is evaluated in comparison with other simplified models published in the literature. In addition, this is confirmed using a high-precision digital twin that simulates valve behaviour taking into account spool geometry, hydraulic fluid properties and local internal fluid dynamics (laminar or turbulent conditions, cavitation). , etc.) [13].

Table 1: Results of publications systematic review according to proposed approaches to the creation of digital twins of electro-hydraulic mechatronic systems in different stages of their life cycles

Life cycles stages of electrohydraulic mechatronic systems	Publications
Identification and analysis of needs	No publications identified
Feasibility study	No publications identified
System layout	[11], [12], [13], [14]
Design and development	[11], [12], [13], [14], [15]
Production	[15]
Deployment	[9], [10], [14]
Operation and technical support	[9], [10], [14], [15]
Disposal	No publications identified

The studies presented in the papers [11-13] are pioneering in the direction of creating digital twins of electrohydraulic servo valves based on their simplified models. However, they do not completely close the issue of creating digital twins of electrohydraulic mechatronic systems for two main reasons:

- only the electrohydraulic servo valve is considered, not the electrohydraulic mechatronic system as a whole;

- only digital twins are considered at the stage of design and development, while they need to be filled with data at all stages of the life cycles of electrohydraulic mechatronic systems.

Like the papers [11, 12, 13], the article [14] is also devoted to the creation of digital twins of a specific type of valve - counterbalance valves. The article [14] presents such a model of counterbalance valves, which are often found in various hydraulic systems. The model consists of parameters that take into account the internal geometry, inertia and friction characteristics of the counterbalance valve. To illustrate the parameter identification strategy for this model, a test setup is designed and four sets of experiments are conducted. A subset of measured data is used to systematically identify parameters. The remaining data is used to validate the counterbalance valve model and parameter identification strategy. The results show that the model is able to successfully predict the behaviour of the counterbalance valve under various operating conditions, thereby validating the model.

The proposed counterbalance valve model satisfies the key requirements of digital twins and is thus a suitable candidate for a digital twin of counterbalance valves and can be easily integrated into digital twins of larger systems where counterbalance valves are installed.

Just like the scientific results presented in the papers [11, 12, 13], the scientific results [14] are applicable to one type of valve and are limited to the following stages of life cycles, namely System layout, Design and development, Deployment, and Operation and technical support.

The paper [15] presents a comprehensive approach to creating digital twins of complex electro-hydraulic mechatronic systems, which is applicable in many stages of their life cycles. Creating a digital twin is done using an example of the erect-fold electromechanical-hydraulic system of radar. The paper [15] utilizes radar electro-hydraulic system development and digital twin technology to enhance the design, manufacturing, and comprehensive support capabilities of the system. Key technologies such as co-simulation data output, training data cleaning, reduced-order ROM model establishment, and accuracy verification are employed. The construction of a digital twin model for the radar electro-hydraulic system enables virtual-real data fusion, facilitating iteration, optimization, and improvement of electromechanical hydraulic systems throughout their life cycle. Additionally, the digital twin model allows for real-time updates of visual simulations of the radar rack and removal system, enhancing system reliability and manoeuvrability. By developing the digital twin architecture of the electromechanical hydraulic radar system based on co-simulation, a digital twin system platform for the radar installation and removal system is established. Combined with the logical connections between the subsystems of the electromechanical hydraulic system, a final digital twin model of the electromechanical hydraulic system was built and executable program code with real-time response was generated. Finally, it was analyzed and calculated on the radar structure digital twin system platform and responded to in real-time. This enables easy implementation of the digital twin model in electromechanical hydraulic system simulation without the use of traditional modelling and analysis tools [15]. The approaches and principles propoused in the paper [15] can be used to create digital twins of other complex electrohydraulic mechatronic systems.

6. Discussion of comparative analysis of current approaches to digital twins of electro-hydraulic mechatronic systems creations

The principles of creating digital twins of high-tech engineering products covering all stages of their life cycles set out in the articles [16, 17], can be used for digital twins of electrohydraulic mechatronic systems. To increase the robustness of computer networks on which models and data of digital twins will be stored, it is recommended to use the topology proposed in the [18]. To create components of digital twins of electrohydraulic mechatronic systems that would cover the initial stage of their life cycle (Identification and analysis of needs), it is recommended to use the approaches outlined in [19].

7. Conclusions

It should be noted that there are very few publications in the direction of creating digital twins of electrohydraulic mechatronic systems. During the bibliometric analysis, no publications were identified that would offer a systematic methodology for creating different types of digital twins of electrohydraulic mechatronic systems at all stages of their life cycles. Thus, the creation of such a systematic methodology is an important scientific and practical task.

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