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STOCHASTIC AND INTELLIGENT MODELS IN DIAGNOSTIC AND CONTROL SYSTEMS OF ARTILLERY COMPLEXES

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Abstract. This paper explores the application of stochastic and intelligent modeling approaches for enhancing the diagnostic and adaptive control efficiency of modern artillery systems. Particular attention is devoted to stochastic models based on Markov chains, which enable the probabilistic representation of state transitions, system degradation, and uncertainties affecting artillery performance. In parallel, the study introduces a generalized fuzzy model capable of addressing critical challenges such as barrel wear diagnostics, sight correction under uncertain conditions, optimization of higher-level battery control by integrating environmental factors within the firing zone with per-gun operating parameters, and automatic aiming drive regulation through the integration of fuzzy reasoning with advanced control methodologies. The combined use of these approaches is shown to yield a synergistic effect, where the predictive rigor of Markov models complements the adaptive decision-making power of fuzzy logic. This integration offers a robust framework for increasing accuracy, reliability, survivability, and operational efficiency in dynamically changing combat environments. The results highlight the importance of hybrid modeling architectures in advancing next-generation artillery systems and outline future research directions aimed at real-time implementation, large-scale system integration, and experimental validation.

Keywords: artillery systems; diagnostics; automatic control; stochastic models; intelligent models; Markov chains; fuzzy logic.

Introduction

Modern military conflicts worldwide, and particularly the ongoing Russian–Ukrainian war, have vividly demonstrated the decisive role of artillery in contemporary warfare. Artillery remains one of the most effective means of delivering systematic, long-range fire damage to enemy positions, serving as a cornerstone for achieving tactical, operational, and, in some cases, even strategic objectives [1–3]. Its capacity for sustained firepower and wide-area coverage ensures its indispensability in shaping the battlefield environment.

The recent integration of unmanned aerial vehicles (UAVs) into reconnaissance and fire adjustment processes has significantly amplified the precision and effectiveness of artillery operations [4]. UAVs provide near-real-time intelligence and enable adaptive targeting, thereby increasing the lethality and efficiency of artillery fire. This synergy between traditional artillery systems and modern autonomous technologies marks a fundamental transformation in the way fire support missions are conducted.

Nevertheless, the intensive deployment of artillery under combat conditions has exposed a range of critical technical and operational challenges. Issues such as accelerated barrel wear, overheating of components, and the degradation of aiming accuracy have increasingly been reported [5, 6]. These factors not only undermine the reliability of artillery systems but also reduce their combat readiness during prolonged engagements. In conditions where operational tempo is high and uninterrupted functionality is crucial, such vulnerabilities can critically affect mission success.

At the same time, the existing diagnostic and control methods employed for assessing the technical state of artillery installations remain inadequate. Many of these approaches are limited by their lack of timeliness, reliance on bulky auxiliary equipment, and susceptibility to measurement errors, all of which hinder accurate assessment of system condition [6]. Such limitations complicate preventive maintenance and timely decision-making, ultimately reducing the operational efficiency, shooting accuracy and resilience of artillery forces.

Against this backdrop, there arises a pressing scientific and practical need to develop advanced diagnostic and control methodologies that combine stochastic modeling and intelligent approaches. These innovations have the potential to ensure higher accuracy in fault detection, improve predictive maintenance, and enhance overall system robustness under combat stressors. By addressing the shortcomings of traditional techniques, such models can significantly contribute to strengthening the effectiveness and survivability of artillery complexes in modern warfare.

Analysis of modern foreign and domestic research and publications

Contemporary advances in artillery fire control and system reliability have been driven by the development of sophisticated computational methods and modern information technologies aimed at enhancing accuracy, responsiveness, and operational robustness. Precision trajectory prediction using advanced ballistic models now relies on specialized rapid-assessment algorithms that facilitate on-site estimation and forecasting of strike accuracy under variable field conditions [7, 8]. Concurrently, purpose-built software tools and geographic information systems have been widely adopted to generate firing tables and produce cartographic materials that support commanders and fire-control personnel in planning and executing missions with increased situational awareness [9–11].

A crucial avenue for improving both accuracy and survivability of artillery units lies in minimizing exposure time on firing positions and enabling in-service diagnostics of barrel wear and system degradation without withdrawing the cannon from operational use. Such improvements hinge on more effective verification of shot outcomes — namely, prompt confirmation of projectile impact or precise assessment of deviation from the aim point — which forms the basis for closed-loop correction of subsequent firings [12]. Implementations of this concept typically instantiate an information feedback contour linking successive shots, whereby initial firing parameters are adjusted iteratively and the condition of the firing system is continuously reassessed [13, 14]. Two canonical feedback paradigms are commonly distinguished: the “shoot-look-shoot” loop for visible targets and the “shoot-adjust-shoot” loop for concealed or indirect engagements; both approaches require accurate determination of burst coordinates, which complicates and lengthens verification procedures.

To address the limitations of traditional post-impact verification, recent work has proposed and experimentally validated methods for pre-impact shot verification that operate prior to projectile impact or detonation [15, 16]. These approaches exploit the registration of ballistic and acoustic signatures generated by a projectile in flight, captured via networks of spatially distributed acoustic sensors. By analyzing the recorded waveforms, it becomes possible to estimate trajectory parameters in near real time, thereby substantially reducing engagement duration and ammunition expenditure when compensating for stochastic perturbations relative to conventional aiming procedures. Moreover, such techniques enable in-flight diagnosis of artillery system state, facilitating maintenance interventions and tactical adjustments without interrupting mission flow.

Despite these advances, significant challenges persist in adequately accounting for various sources of uncertainty that affect artillery complexes: propellant degradation and batch variability, deviations in projectile mass, and progressive multi-component wear of barrels and associated mechanical systems. These uncertainties propagate through diagnostic chains and control algorithms, undermining the reliability of existing assessment and decision-support methods and limiting their applicability in high-tempo operations. Consequently, purely deterministic models and rule-based procedures often fail to capture the full spectrum of stochastic behavior observed in operational environments.

Against this backdrop, stochastic modeling and intelligent computational paradigms emerge as promising frameworks for robust diagnostics and adaptive control. In particular, Markovian models offer a natural formalism for representing probabilistic transitions of system states under cumulative wear and random perturbations, providing tractable means for prognostics and maintenance scheduling [17]. Complementarily, intelligent models grounded in fuzzy logic enable the formalization and processing of expert knowledge under conditions of incomplete and imprecise information, allowing for linguistic rule-based reasoning and graceful handling of ambiguity in sensor data and human assessments [18].

In summary, the literature indicates a clear trajectory toward hybrid methodologies that integrate rapid ballistic estimation, distributed sensing (including acoustic and RF modalities), and intelligent stochastic modeling to enhance verification, diagnostics, and closed-loop control of artillery systems. The confluence of these approaches motivates further research into novel methodologies, models, and information technologies that can reconcile probabilistic uncertainty with expert knowledge, thereby improving the effectiveness and resilience of diagnostic and control processes in modern artillery complexes.

The primary objective of this study is to conduct a comprehensive analysis of the specific features and prospective applications of stochastic models based on Markov chains and intelligent models founded on fuzzy logic for addressing the wide spectrum of uncertainties that affect artillery complexes. The research emphasizes the integration of these modeling approaches into diagnostic frameworks and adaptive control systems, with the overarching goal of enhancing the overall effectiveness, accuracy, survivability, and reliability of artillery systems operating under dynamic and uncertain conditions.

Main material

Markov chains in artillery diagnostic and control systems. Most studies of combat modeling have traditionally employed deterministic frameworks. For example, the works cited in [13, 19] propose models that describe the behaviour of artillery units using fixed, time-invariant parameters. While analytically tractable, such deterministic formulations neglect the inherently stochastic nature of many operational variables, producing simplified representations that can markedly reduce the realism and predictive fidelity of simulation results.

In contrast, stochastic approaches, particularly those founded on Markovian processes, offer a natural and powerful formalism for modeling systems whose parameters evolve randomly. Markov chains permit explicit representation of probable system states and the transition probabilities between them, thereby substantially increasing model adequacy when studying diverse aspects of combat dynamics [15, 19, 20]. For instance, the model presented in [15] accounts for random variability in projectile velocity, reloading intervals, and the probability of enemy detection. These inclusions materially improve the model's capability to reproduce observed operational outcomes. Similarly, the study reported in [17] develops a stochastic framework for analyzing the random processes associated with repositioning towed artillery systems, including transit times to firing positions, loss of combat capability during movement, and the attendant risks of detection and enemy engagement in the route.

The main components of Markov processes are the states of the system, the transition probabilities between the states, and external disturbances that affect the effectiveness of combat work. Fig. 1 shows the Markov graph of states and transition probabilities when changing the firing positions of artillery installations.

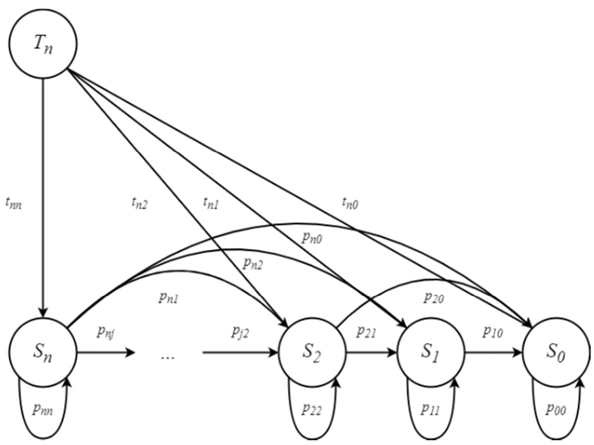

Figure 1 – Markov graph of states and transition probabilities taking into account the transportation of cannons

In Fig. 1, the following notations are introduced: T_n is the initial state of the system, which corresponds to the initial position of the battery, in a hidden position, before the start of the task, with n combat-ready installations; S_n is the state of the system during firing with n combat-ready installations.

The state transition matrix, which describes the probabilities of transitions between different states of the system (Fig. 1), is presented in the form:

$$P=\begin{vmatrix} t_{tt} & t_{nn} & \cdots & t_{n2} & t_{n1} & t_{n0} \\ t_{nt} & p_{nn} & \cdots & p_{n2} & p_{n1} & p_{n0} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ t_{2t} & 0 & \cdots & p_{22} & p_{21} & p_{20} \\ t_{1t} & 0 & \cdots & 0 & p_{11} & p_{10} \\ t_{0t} & 0 & \cdots & 0 & 0 & 1 \end{vmatrix}, \quad (1)$$

where t_{nj} is the probability of transition from state T_n to state S_j (logistics operations); p_{ij} is the probability of transition from state S_i to state S_j (combat operations); t_{jt} is the probability of transition from state S_j to state T_n. Since the battery cannot return to its initial position (t_{jt} = 0), after completing combat work, it always takes a new position.

In turn, the transition probabilities for i =1, …, n are determined as follows:

$$p_{i0}=1-\sum_{j=1}^{n}p_{ij}; \quad (2)$$

$$p_{ij}=\begin{cases} C_i^j p^j q^{i-j}, \ if \ \ j\le i; \\ 0, \ if \ \ j>i, \end{cases} \quad (3)$$

where p^j is the probability of an effective shot and successful transportation.

Moreover,

$$p^j=p\left(1-s\right), \quad (4)$$

where s is the probability of the battery being hit by the fire of the enemy.

In turn, the probability p consists of:

$$p=p_1p_2p_3, \quad (5)$$

where p_1 is the probability of a shot with no disturbance in the form of chamber wear; p_2 is the probability of a shot with no disturbance in the form of barrel wear; p_3 is the probability of a shot with no disturbance in the form of charge uncertainty.

The probability of the influence of the corresponding disturbance can be represented as follows:

$$q_1=1-p_1; \quad (6)$$

$$q_2=1-p_2; \quad (7)$$

$$q_3=1-p_3; \quad (8)$$

$$t_{nn}=1-\sum_{j=1}^{n}t_{nj}; \quad (9)$$

$$t_{nj}=C_i^j t^j f, \quad (10)$$

where t^j is the possibility of preserving the effective usage of artillery after the transportation process.

In turn,

$$t^j=k_1k_2k_3; \quad (11)$$

$$f=1-t^j, \quad (12)$$

where k_1 is the probability of barrel wear during transportation, k_2 is the probability of chassis wear during transportation,and k_3 is the probability of the installation losing its combat capability under enemy fire during transportation.

Herewith,

$$k_i=1-e^{-q_i t}, \quad (13)$$

where t is the time required to cover the route, q_i is the coefficient of influence of the i-th factor per unit of time during transportation along the selected route.

In general, this example illustrates how Markovian and related stochastic models enable more nuanced, probabilistically grounded analyses that better reflect the uncertainties inherent to modern artillery operations.

Intelligent models based on fuzzy logic in artillery diagnostic and control systems. Intelligent models founded on fuzzy logic offer a promising avenue for enhancing the autonomy and resilience of artillery systems by providing a mathematically tractable means to encode and process imprecise expert knowledge and noisy sensor information; their graded membership functions and rule-based inference enable graceful handling of ambiguous states (e.g., partial barrel degradation, variable propellant performance, or degraded visibility) that defy crisp thresholding. In practice, fuzzy controllers and decision-support modules can be applied to adaptive fire-control tuning, progressive shot-to-shot correction, target prioritization under incomplete information, and in-situ fault diagnosis, while preserving interpretability, an essential property for

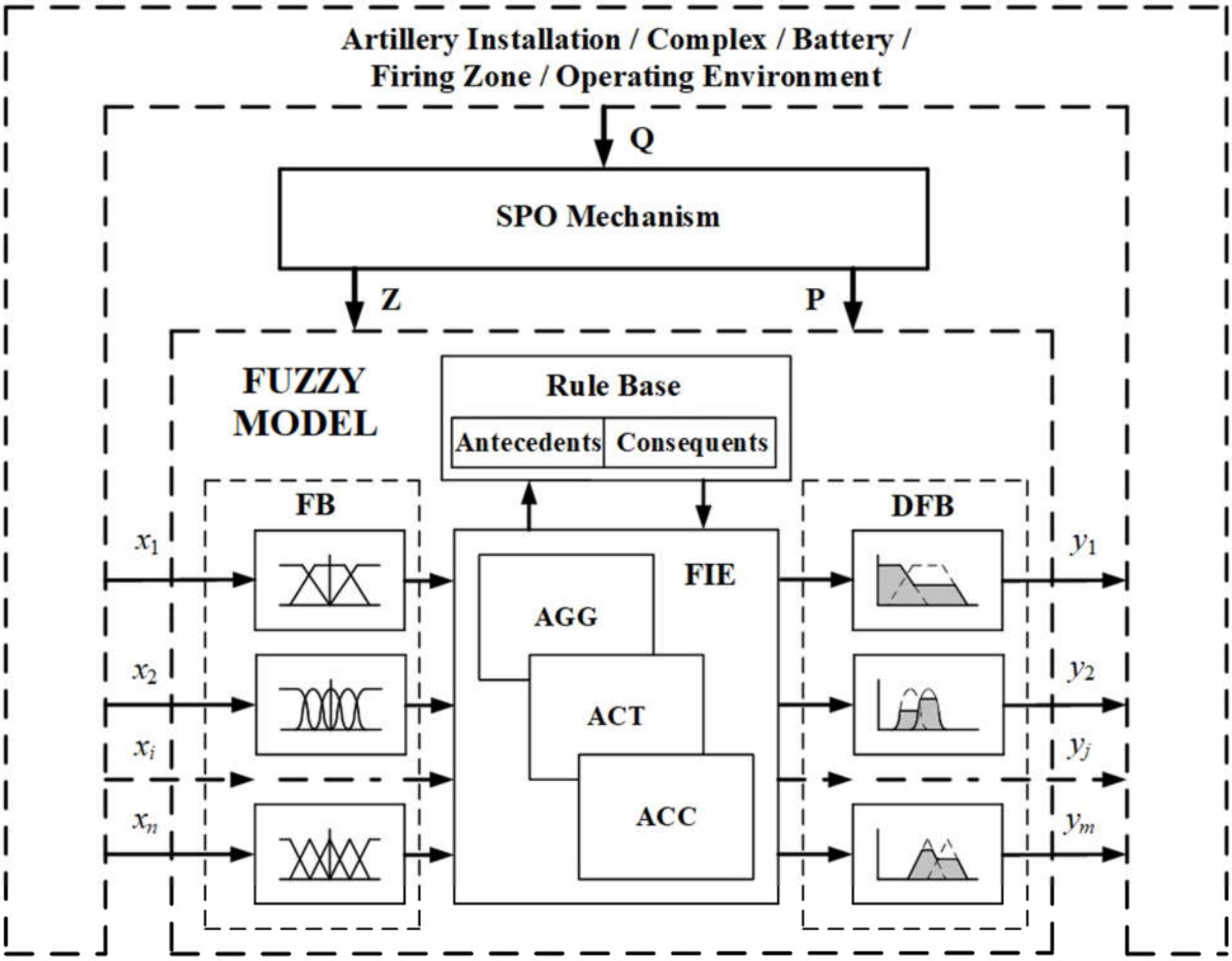

Figure 2 – Generalized fuzzy model for diagnostics and control of artillery systems

operator trust and human-machine teaming. Hybridizing fuzzy architectures with data-driven techniques (such as online learning, evolutionary optimization of membership parameters, or integration with Markovian prognostics) allows these systems to refine rules and adapt to evolving wear patterns and environmental conditions, supporting predictive maintenance and improved mission endurance. Furthermore, when embedded in multi-sensor fusion frameworks, fuzzy models facilitate the assimilation of heterogeneous signals (acoustic, RF, inertial, thermal) into compact, actionable assessments of system state and engagement quality. Realizing these prospects requires rigorous methods for systematic rule elicitation, robust parameter tuning, computationally efficient implementations for real-time operation, and extensive validation with field data; nonetheless, the combination of robustness to uncertainty, adaptability, and explainability positions fuzzy-based intelligent models as a strategically valuable component of next-generation artillery diagnostic and control systems.

The functional structure of the generalized fuzzy model for implementation of diagnostics and control processes of artillery systems is shown in Fig. 2, where the following abbreviations are used: SPO Mechanism is the mechanism of structural-parametric optimization; FB is the fuzzification block; FIE is the fuzzy inference engine; AGG is the aggregation block; ACT is the activation block; ACC is the accumulation block; DFB is the defuzzification block; $x_1, x_2, \ldots, x_i, \ldots, x_n$ are the fuzzy model's input variables; $y_1, y_2, \ldots, y_j, \ldots, y_m$ are the fuzzy model's output variables; **S** is the vector of structure variants of the fuzzy model; **P** is the vector of parameters of the fuzzy model; **Q** is the vector of output variables of the artillery installation, complex, battery, firing zone, or operational environment, that are used for structural-parametric optimization of the fuzzy model.

The presented generalized fuzzy model implements the following dependence [21]

$$\mathbf{Y} = f_{\mathrm{FS}}(\mathbf{X}),$$
$$\mathbf{Y} = (y_1, y_2, ..., y_j, ..., y_m), \qquad (14)$$
$$\mathbf{X} = (x_1, x_2, ..., x_i, ..., x_n),$$

where **X** is the vector of n input variables x_1, x_2, …, x_i, …, x_n; **Y** is the vector of m output variables y_1, y_2, …, y_j, …, y_m of the fuzzy model.

The FB defines the degree of membership of the numerical values of all n input variables of the vector **X** to the corresponding fuzzy input linguistic terms of the model [21]. The FIE, in turn, based on fuzzified signals and received data from the rule base sequentially performs the operations of aggregation, activation, and accumulation [22].

The rule base includes a set of rules made up of specific antecedents and consequents. So, for example, to implement functional dependence (14) by the fuzzy model, using the corresponding linguistic terms, one of the rules for any variable x_i (i = 1...n) or y_j (j = 1...m), can be represented by (15) [21]

IF "$x_1 = A_1$" AND "$x_2 = A_2$" AND …
AND "$x_i = A_i$"... AND… AND "$x_n = A_n$"
THEN "$y_1 = B_1$" AND "$y_2 = B_2$" AND … (15)
AND "$y_j = B_j$"... AND… AND "$y_m = B_m$",

where A_1, A_2, A_i, A_n, B_1, B_2, B_j, B_m are the corresponding linguistic terms of the input and output variables of the model.

The DFB converts the consolidated fuzzy inference into a clear numerical signal for each j-th (j = 1, 2, …, m) output variable [22].

Moreover, the presented fuzzy model can be developed in the automated mode using the built-in mechanism of structural-parametric optimization (SPO). Herewith, the given mechanism should determine such vectors of structure options **S** and parameters **P**, which will ensure sufficiently effective use of the model for solving the stated problem (diagnostics, correction, or automatic control). At the same time, the efficiency of the fuzzy model can be assessed using a specified objective function, which is calculated based on the obtained values of the vector of measured output variables of the artillery complex, outlined firing zone, or the operating environment **Q** [21].

The presented intelligent model based on fuzzy logic is most appropriate for solving the following complicated problems of modern artillery systems:

1) robust diagnostics of barrel wear for individual cannons by fusing heterogeneous modalities (visual inspection data, acoustic emissions recorded during firing, and measured muzzle velocities);

2) sight correction and ballistic compensation by explicitly accounting for stochastic perturbations (deviations in projectile mass, progressive degradation of propellant charges, and component wear);

3) higher-level battery control, integrating environmental factors within the firing zone (e.g., wind, temperature, terrain-induced disturbances) with per-gun operating parameters to optimize task allocation, sequencing of fire, and survivability measures for grouped artillery assets;

4) automatic control of the aiming drives of individual guns by hybridizing fuzzy inference with advanced control paradigms (adaptive, predictive, sliding-mode, combined, etc.) that can provide smooth, interpretable control actions, resilient to measurement noise and model uncertainty.

Joint application of Markov chains and fuzzy models in artillery systems. The integrated application of Markovian stochastic models and fuzzy-logic–based intelligent systems creates a synergistic paradigm that substantially elevates the diagnostic, prognostic, and control capabilities of modern artillery complexes. Markov chains supply a rigorous probabilistic scaffold for representing state transitions, cumulative wear processes and uncertainty propagation over time, thereby enabling quantitative prognostics, risk-aware maintenance scheduling, and formally grounded assessments of system reliability under random perturbations.

Complementarily, fuzzy models excel at encoding imprecise expert knowledge, assimilating noisy multisensor inputs and producing interpretable, rule-based control and decision recommendations in real time.

When combined, these formalisms bridge the gap between probabilistic prognostics, and linguistically driven operational reasoning: stochastic estimators can inform and update fuzzy membership functions and rule weights with posterior likelihoods, while fuzzy inference can translate probabilistic state assessments into actionable, human-comprehensible control directives and maintenance advisories.

The hybrid architecture thus yields robust, adaptive behavior, improving shot-to-shot correction, optimizing resource allocation across batteries, and enabling anticipatory interventions that reduce downtime and enhance survivability. Beyond performance gains, the approach preserves transparency and operator trust through explainable rules, while affording formal metrics of uncertainty from the Markovian layer for decision assurance. Realising this synergistic potential demands careful model integration, efficient real-time algorithms, and comprehensive validation with field data, but promises a decisive step toward resilient, intelligent artillery systems capable of operating effectively in the stochastic and ambiguous conditions of contemporary battlefields.

Conclusions

1. The comprehensive analysis of the distinctive features and prospective applications of stochastic models based on Markov chains and intelligent models founded on fuzzy logic for addressing the broad spectrum of uncertainties inherent in artillery complexes was carried out. The findings underscore the necessity of integrating these modeling paradigms into diagnostic frameworks and adaptive control systems, with the overarching aim of increasing operational effectiveness, improving firing accuracy, extending system survivability, and ensuring higher reliability under dynamically changing and uncertain battlefield conditions.

2. Special attention was devoted to the application potential of Markov processes, which serve as a robust mathematical tool for modeling probabilistic state transitions, system degradation, and stochastic disturbances. Their use enables quantitative assessments of artillery system reliability, prediction of long-term performance trends, and the development of effective maintenance and control strategies. By capturing the inherent randomness of operational parameters, Markov models significantly enhance the realism and adequacy of artillery simulations.

3. A generalized fuzzy model was introduced as an intelligent framework for artillery systems, with particular emphasis on its ability to address complex diagnostic and control challenges. This model demonstrates promise in diagnosing barrel wear, correcting gun sights under multiple uncertainty factors, optimizing higher-level battery control, integrating environmental factors within the firing zone with per-gun operating parameters to optimize task allocation, sequencing of fire, and survivability measures for grouped artillery assets, and enabling automatic aiming drive control through the integration of fuzzy reasoning with advanced control methodologies. These capabilities highlight the wide-ranging adaptability and practicality of fuzzy models in real-world artillery applications.

4. The paper further presented an integrative approach that leverages the complementary strengths of Markov chains and fuzzy models, yielding a pronounced synergistic effect. While stochastic models provide probabilistic rigor and predictive accuracy, fuzzy logic systems offer interpretability, adaptability, and resilience to imprecise data. Their combined use creates a hybrid diagnostic and control paradigm that unites probabilistic foresight with intelligent decision-making, thereby enabling artillery complexes to function more effectively in the face of uncertainty, operational noise, and environmental complexity.

5. Future research should focus on refining hybrid Markov–fuzzy architectures through advanced algorithmic integration, efficient real-time computation, and comprehensive experimental validation using both simulated and field data. Particular emphasis should be placed on extending these models to networked artillery systems, multi-agent coordination, and cyber-physical defense platforms, where the interplay of stochastic uncertainties and intelligent control

demands novel methodological solutions. Such efforts will not only advance theoretical knowledge but also provide practical tools for the development of next-generation artillery systems capable of maintaining superiority in increasingly complex operational environments.

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СТОХАСТИЧНІ ТА ІНТЕЛЕКТУАЛЬНІ МОДЕЛІ В СИСТЕМАХ ДІАГНОСТИКИ ТА КЕРУВАННЯ АРТИЛЕРІЙСЬКИМИ КОМПЛЕКСАМИ

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Анотація. У статті розглянуто застосування стохастичних та інтелектуальних моделей для підвищення ефективності систем діагностики та адаптивного керування сучасними артилерійськими комплексами. Особлива увага приділена стохастичним моделям на основі ланцюгів Маркова, які забезпечують імовірнісне відображення переходів між станами, деградації системи та невизначеностей, що впливають на ефективність функціонування артилерії. Паралельно представлено узагальнену нечітку модель, здатну вирішувати такі ключові завдання, як діагностику зношення стволів, корекцію прицілу в умовах невизначеностей, оптимізацію управління батареєю з урахуванням факторів середовища у зоні ведення вогню та параметрів окремих гармат, а також автоматичне керування приводами наведення шляхом інтеграції нечіткого виведення з сучасними принципами керування. Показано, що поєднане використання цих підходів створює синергетичний ефект, коли прогностична строгість марківських моделей доповнюється адаптивними можливостями прийняття рішень на основі нечіткої логіки. Така інтеграція формує надійну основу для підвищення точності, надійності, живучості та ефективності артилерійських систем в динамічних умовах бойових дій. Отримані результати підкреслюють важливість гібридних моделей у розвитку артилерійських комплексів нового покоління та визначають перспективні напрями подальших досліджень, зокрема їхню реалізацію в режимі реального часу, масштабну системну інтеграцію та експериментальну верифікацію.

Ключові слова: артилерійські системи; діагностика; автоматичне керування; стохастичні моделі; інтелектуальні моделі; ланцюги Маркова; нечітка логіка.