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SIMULATION MODELING OF ARTILLERY OPERATIONS IN COMPUTER GAMES: APPROACH BASED ON MARKOV PROCESSES

The object of this research is an approach to simulating the combat operation of artillery in computer games based on Markov processes. In modern computer games, an important role is played by the realism and plausibility of combat simulation. One of the most difficult and at the same time most interesting tasks is the modeling of artillery operations, where it is necessary to take into account numerous factors affecting the effectiveness of combat work.

The research was aimed at improving the methods and models of controlling the combat work of artillery under the conditions for the firing position change and the presence of external disturbances. The use of stochastic models allows more accurate modeling of the behavior of artillery units, taking into account the random nature of many parameters, such as projectile speed, reload time, and the probability of detection by enemy forces.

The proposed approach includes the development of a simulation model that allows determining optimal strategies to achieve maximum effectiveness of combat work. The model is based on Markov processes, which allows taking into account possible system states and probable transitions between them. This allows not only to simulate combat operations, but also to predict the results depending on different scenarios.

The results of the study show that the use of Markov processes in the simulation of combat operations can significantly increase the realism and efficiency of artillery operations in computer games. This opens up new opportunities for game developers to create more immersive and authentic gaming experiences.

The proposed model can be used as a basis for further research and improvement of combat simulation methods in computer games. It can also be used in military simulators and simulators where realistic combat conditions must be taken into account.

Keywords: *simulation modeling, computer games, artillery operations, Markov processes, stochastic models.*

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1. Introduction

Realism and believability of combat simulation are key aspects of modern computer games, which significantly affect the player's immersion in the virtual world. One of the most difficult and at the same time most interesting tasks is the modeling of artillery operations, where it is necessary to take into account numerous factors that affect the effectiveness of the combat work of artillery.

In traditional approaches to combat simulation, deterministic models are often used [1, 2], which do not take into account the random nature of many parameters, such as projectile speed, reload time, probability of detection by enemy forces, and others. This leads to a simplification of the model and a decrease in its realism, which negatively affects the gaming experience.

An additional complication is the need to simulate the change in firing position of artillery in response to enemy

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actions [3]. A change in position requires consideration of transportation time, possible loss of combat capability during movement, and the risk of detection and attack by the enemy. Traditional models cannot always adequately take into account these factors, which leads to inaccuracies in the simulation of combat operations.

Taking into account external disturbances, such as weather conditions, the technical condition of artillery and other factors, is also an important aspect that affects the accuracy of the simulation. The random nature of these disturbances makes it difficult to create deterministic models capable of accurately reproducing the real conditions of the combat situation.

Combat simulation in computer games and military simulators is the subject of numerous studies [4]. Developers and scientists are constantly looking for new methods and approaches to increase the realism and accuracy of these models. Let's consider the main studies related to the simulation of combat actions of artillery and the use of stochastic processes.

Deterministic models of combat operations. Most of the early work in the field of combat simulation was based on deterministic models. For example, works [5] offer models that use fixed parameters to describe the actions of artillery. These models do not take into account the random nature of many parameters, which leads to a simplification of modeling and a decrease in realism. However, they are important from the perspective of an initial approach to combat simulation and lay the foundation for further research.

Use of stochastic processes. Stochastic models, in particular Markov processes, have become widely used in modeling systems with random parameters. Works [6–8] investigate the use of Markov processes for modeling various aspects of combat operations. These models allow taking into account probable system states and transitions between them, which significantly increases the accuracy and realism of modeling. For example, in [7, 9] a model of combat operations is proposed, which takes into account the random nature of projectile speed, reloading time, and the probability of detection by the enemy.

Modeling the change of firing positions. Changing the firing positions of artillery is an important aspect that affects the effectiveness of combat operations. The works [8, 10] consider various methods of modeling this process. In particular, work [8] proposes a model that takes into account the time for transportation, possible loss of combat capability during movement, and the risk of detection and attack by the enemy.

Use of models in computer games and military simulators. Developed combat models are widely used in computer games and military simulators. For example, work [7] describes the use of stochastic models in a military simulator for training military specialists.

Thus, the literature review shows the significant interest of the scientific community in the problem of modeling the combat operations of artillery and the use of stochastic processes. However, there is a need for further research to improve methods and models, which will increase the realism and efficiency of simulations.

To solve these problems, this study proposes to use stochastic models, in particular Markov processes, to simulate the combat work of artillery in computer games. Markov processes allow taking into account probable system states and transitions between them, which significantly increases the accuracy and realism of modeling.

Thus, *the aim of this research* is to improve the methods and models of controlling the combat work of artillery under the conditions of a change in the firing position and the presence of external disturbances. The proposed approach based on stochastic models will increase the realism and efficiency of combat simulation in computer games, which will contribute to the creation of a more exciting and reliable gaming experience.

The relevance of this study also lies in the possibility of using the developed models not only in computer games, but also in military simulators and simulators. This will make it possible to increase the level of training of military specialists, ensure realistic reproduction of combat conditions, and develop effective strategies for conducting combat operations. Thus, improving the methods and models of modeling the combat work of artillery in computer games is an urgent task, which contributes to increasing the realism of the gaming experience and can be widely used in military simulators and simulators.

2. Materials and Methods

2.1. Methodology. Changing the firing positions of artillery is an important aspect of combat work that affects their effectiveness and survivability. In the context of computer games, this requires careful modeling to ensure realistic gameplay. This study examines the main elements of modeling a change in firing positions, including transport time, loss of combat capability during movement, and the risk of detection and attack by the enemy.

The time for transporting an artillery between firing positions is a critical parameter that determines the efficiency of changing positions and the ability to quickly respond to a change in the combat situation. To model this aspect, the following factors are taken into account:

– The time for transportation directly depends on the distance that the artillery must cover. For each pair of fire positions, the distance is determined based on the game map and the route of movement.
– The speed of transportation depends on the type of artillery, the technical condition of the vehicle and the terrain conditions. For example, driving off-road or in difficult weather conditions can reduce speed.
– Possible obstacles are taken into account, such as the topography of the area, the presence of enemy troops or engineering barriers. Obstructions can increase travel time or even make certain routes impassable.

During transportation, artillery may experience loss of combat effectiveness due to various factors. The following aspects are taken into account for modeling losses of combat capability:

– During the movement, technical malfunctions may occur, such as breakdown of the chassis or damage to the weapon system. The probability of such malfunctions is determined by the technical condition of the artillery and the conditions of transportation.
– During transportation, the artillery may be detected by the enemy and be attacked by enemy forces. The probability of attacks is determined by the level of artillery camouflage and the activity of enemy forces in the area of transportation.

2.2. Development of a stochastic simulation model. A detailed stochastic simulation model based on Markov processes was developed to simulate the combat operation of artillery in computer games. The main elements of this model are the states of the system, probable transitions between states, and external disturbances that affect the effectiveness of the combat work of artillery.

3. Results and Discussions

3.1. Markov processes. To simulate the combat operation of artillery in computer games, Markov processes are used, which allow taking into account the random nature of many parameters. The main components of Markov processes are system states, probabilities of transitions between states, and external disturbances affecting the effectiveness of combat operations (Fig. 1).

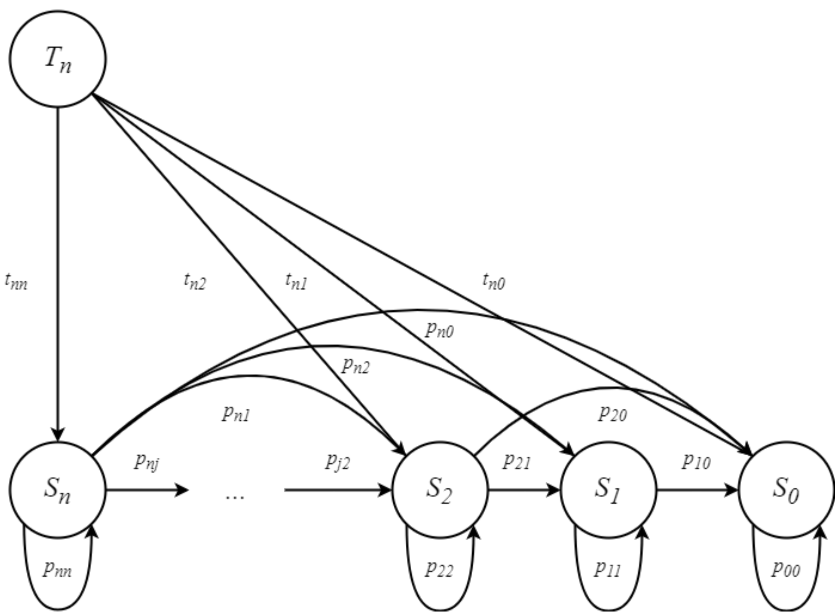

Fig. 1. Markov graph of states and transition probabilities: T_n – the starting state of the system, which corresponds to the initial position of the battery before the start of the task, with n-capable units; S_n – the state of the system during firing with n-capable units

3.2. State transition matrix. The state transition matrix describes the probabilities of transitions between different states of the system. For states and the transition matrix can be presented in the form:

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

where t_{nj} – the probability of transition from state T_n to state S_j; p_{ij} – probability of transition from state S_i to state S_j; t_{jt} – the probability of transition from state S_j to state T_n. The battery cannot return to its original position, therefore $t_{jt} = 0$.

The formulas for transition probabilities for states $t_{jt} = 0$ and S_j transition probabilities are defined as follows for $i = 1 \dots n$:

$$p_{i0} = 1 - \sum_{j=1}^{n} p_{ij},$$

$$p_{ij} = \begin{cases} C_i^j p^j q^{i-j}, & \text{if } j \le i, \\ 0, & \text{if } j > i, \end{cases}$$

where p – the probability of an effective shot and successful transportation;

$$p^j = p \cdot (1 - s),$$

where s – the probability of the battery being hit by enemy fire;

$$p = p_1 \cdot p_2 \cdot p_3,$$

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

$$p_1 = p\left(\Delta v_0^{\lambda\_chamb}\right),$$

$$p_2 = p\left(\Delta v_0^{\lambda\_barrel}\right),$$

$$p_3 = p\left(\Delta v_0^{\lambda\_charge}\right).$$

Let's present the probability of the impact of the corresponding manifestation on the disturbance as:

$$q_1 = 1 - p\left(\Delta v_0^{\lambda\_chamb}\right),$$

$$q_2 = 1 - p\left(\Delta v_0^{\lambda\_barrel}\right),$$

$$q_3 = 1 - p\left(\Delta v_0^{\lambda\_charge}\right),$$

$$t_{nn} = 1 - \sum_{j=1}^{n} t_{nj},$$

$$t_{nj} = C_i^j t^j f,$$

where t^j – the probability of maintaining the artillery effectiveness after transportation;

$$f = 1 - t^j, \; t^j = k_1 \cdot k_2 \cdot k_3,$$

where k_1 – the probability of wear of the barrel during transportation; k_2 – the probability of wear of the undercarriage during transportation; k_3 – the probability of losing the combat capability of the unit due to enemy fire during transportation;

$$k_i = 1 - e^{-q_i t},$$

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

3.3. Route selection and risk assessment. For each possible route, the risks of detection and loss of combat capability are assessed. All possible factors are taken into account, including distance, terrain conditions, enemy activity and the technical condition of the unit.

Example of calculations:

– $p_1 = 0.95$ – with the absence of disturbance in the form of wear of the charging chamber;

– $p_2 = 0.95$ – with no disturbance in the form of barrel wear;

– $p_3 = 0.95$ – with the absence of disturbance as charge uncertainty;

– $s = 0.25$ – the probability of the battery being hit by enemy fire.

Then the probability of an effective shot in the absence of all three types of disturbances:

$$p = p_1 \cdot p_2 \cdot p_3 \cdot (1-s) = 0.64303.$$

Table 1 presents the parameters that affect the combat effectiveness of an artillery when changing firing positions. The time of the march and the amount of reduction in combat capability are taken into account for different paths of movement, which makes it possible to assess the influence of external factors on the effectiveness of combat operations.

Table 1

Parameters for changing the combat capability of units when changing positions

Parameters of influence on the combat capability of the unit and the total time of its operation depending on the chosen path of movement between positions	Road number j		
	No. 1	No. 2	No. 3
March time when changing the firing position to another, s	180	720	1440
The amount of reduction in the combat capability of the AU1 due to the wear of the barrel during transportation	0.000025	0.000055	0.000075
The amount of reduction in the combat capability of the AU1 due to the wear of the undercarriage during transportation	0.00074	0.00094	0.0024
The magnitude of the decrease in the combat capability of the AU1 due to the unit wear under the influence of enemy fire during transportation	0.000055	0.00003	0.000015

This approach allows to simulate various combat scenarios and determine the optimal strategies to achieve the maximum effectiveness of the combat operations of artillery units:

– reduction of combat capability due to barrel wear during transportation;

– reduction of combat capability due to wear and tear of the chassis during transportation;

– reduction of combat capability due to wear and tear of the unit under the influence of enemy fire during transportation:

$$k = k_1 \cdot k_2 \cdot k_3 = 0.767125.$$

This approach allows to simulate various combat scenarios and determine the optimal strategies to achieve the maximum effectiveness of combat operations of artillery.

3.4. Transition probability matrix. To analyze the efficiency of transitions between different states of the system, a matrix of transition probabilities is used. This matrix allows to determine the probability of the transition of an artillery from one state to another, taking into account the random nature of various factors.

Table 2 presents the transition probability matrix for the states of the artillery. In this table, each row corresponds to the initial state of the system, and each column corresponds to the final state. The values in the cells of the table indicate the probability of transition from one state to another.

Table 2

Transition probability matrix

State	T_6	S_6	S_5	S_4	S_3	S_2	S_1	S_0
T_6	0	0.2038	0.3712	0.2817	0.114	0.0259	0.0032	0.0002
S_6	0	0.0707	0.23547	0.3268	0.24189	0.10071	0.02236	0.0021
S_5	0	0	0.10994	0.30516	0.33881	0.18809	0.05221	0.0058
S_4	0	0	0	0.17097	0.37965	0.31614	0.117	0.01624
S_3	0	0	0	0	0.26589	0.44281	0.24582	0.04549
S_2	0	0	0	0	0	0.41349	0.45908	0.12743
S_1	0	0	0	0	0	0	0.64303	0.35697
S_0	0	0	0	0	0	0	0	1

In this context, states S_0 and S_6 are represent the number of active artilleries. For example, state S_0 means that none of the settings are active, and state S_6 means that all six settings are active.

Each element of the matrix p_{ij} determines the probability of transition from state S_i to state S_j. Thus, the transition probability matrix is a key element for modeling the behavior of an artillery in various combat conditions.

For each of the routes indicated in the Table 3, it is possible to calculate the factors affecting the combat effectiveness of artillery during transportation:

– Road No. 1:

$$k_1 = 0.995;\ k_2 = 0.875;\ k_3 = 0.99;$$

– Road No. 2:

$$k_1 = 0.96;\ k_2 = 0.508;\ k_3 = 0.978;$$

– Road No. 3:

$$k_1 = 0.897;\ k_2 = 0.03;\ k_3 = 0.978.$$

Using the transition matrix, it is possible to calculate the expected number of artilleries that may lose combat capability during transportation in the form of a range.

It is possible to make calculations for three different values of the probability of the battery being hit by enemy fire: $s = 0.25$; $s = 0.4$; $s = 0.5$.

Table 3

Expected number of combat-ready units during transportation

Number	Road number j		
	No. 1	No. 2	No. 3
Units that have lost combat capability	[0; 2]	[1; 4]	[3; 6]
Combat-ready units	[4; 6]	[2; 5]	[0; 3]

Let's calculate the expected number of volleys, the number of successful and unsuccessful shots, and the time required to complete the task.

Let's consider the unit, which fired three unsuccessful shots in a row, disabled before the next salvos.

For this experiment, it is possible to determine the required number of accurate hits to complete the task – 25.

The time required for one volley of the battery – 1 minute.

Analyzing the data from the Table 4 with the results of the calculations, it is possible to draw conclusions about the potential threat of each of the routes, the probability and speed of enemy fire. For example, if the battery commander chooses road No. 3, there is a very high probability of losing the combat capability of a large number of artillery units, due to which the task takes a very long time (up to 30 minutes), which will allow the opponent to strike back.

The results of the simulations make it possible to determine the optimal strategies for the use of artillery, including the selection of firing positions. Recommendations for increasing the effectiveness of combat work are being developed.

On the basis of the conducted research and simulations, a simulation model and a method of controlling the states of the artillery gun during firing, which take into account random dynamic external and internal disturbances, were developed. The obtained results showed that the use of stochastic processes in modeling the combat work of artillery allows to achieve a significant increase in the effectiveness of combat operations.

The main results of the study include the following aspects:

1. *Effectiveness of shots:* The developed model allows taking into account the random nature of projectile speed, reloading time and the probability of detection by the enemy. The results of the simulations showed that the accuracy and effectiveness of shots are significantly increased when external and internal disturbances are taken into account. In particular, the use of stochastic processes made it possible to determine the optimal parameters to ensure the maximum effectiveness of shots.

2. *Time of execution of a combat task:* Evaluation of the time of execution of a combat task showed that the use of the developed model allows to significantly reduce the time for task execution. Simulations have shown that taking into account random disturbances and changes in firing positions allows to determine the best time to perform a combat task with minimal loss of combat capability. This is achieved by optimally allocating time for shots, reloading and transporting the unit.

3. *Loss of combat capability:* Taking into account random dynamic disturbances made it possible to reduce the loss of combat capability of artillery. The results of the simulations showed that the use of the developed model allows effective control of the states of the artillery gun, which reduces the impact of external and internal disturbances on combat capability. In particular, it was determined that the optimization of the process of reloading and changing firing positions contributes to reducing the loss of combat capability.

Comparison with real data. The obtained results were compared with real data and results of previous studies. The comparison showed high accuracy and reliability of the developed model. It was established that the model adequately reproduces real combat conditions and allows determining optimal strategies for increasing the effectiveness of combat operations.

Thus, the developed simulation model and method of controlling the states of an artillery gun when firing in the presence of random dynamic external and internal disturbances made it possible to determine the best time for completing a combat task with minimal loss of combat capability. Taking into account the frequency of changing the firing position contributed to increasing the effectiveness of combat operations and reducing the risk of detection by the enemy.

The influence of external disturbances. One of the important aspects of the study is the consideration of external disturbances, such as weather conditions and the technical condition of artillery. The results showed that these factors have a significant impact on the effectiveness of combat work. Modeling taking into account external disturbances made it possible to reduce combat losses and increase the accuracy of shots, which is important for ensuring the realism of the gameplay.

Realism of combat simulation. The developed model ensures high realism of the simulation of the combat work of artillery. The use of stochastic processes allows to take into account the random nature of the projectile speed, reload time, the probability of detection by the enemy and the technical condition of the unit. This made it possible to create a model that adequately reproduces real combat conditions and ensures the authenticity of the gameplay.

Increasing the effectiveness of shots. The proposed model makes it possible to significantly increase the effectiveness of artillery fire. Taking into account random external and internal disturbances contributes to a more accurate determination of the parameters of shots, which reduces the probability of errors and increases the accuracy of hitting. This is important to ensure the realism of combat and improve the gaming experience.

Optimization of the time of execution of combat tasks. The developed model allows to optimize the time of execution of combat tasks. Taking into account the time for reloading, transportation and changing firing positions made it possible to determine the optimal strategies for the execution of combat tasks, which ensures their quick and efficient execution. This reduces the risk of combat losses and increases the effectiveness of combat operations.

Table 4

The expected number of successful and unsuccessful shots, and the expected time required to complete the task

Parameter	Road number, *j*								
	No. 1			No. 2			No. 3		
The probability of the battery being hit by enemy fire, s	0.25	0.4	0.5	0.25	0.4	0.5	0.25	0.4	0.5
Expected number of successful shots	[25;28]	[25;26]	[10;20]	[25;27]	[24;25]	[5;15]	[0;20]	[0;10]	[0;3]
Expected number of missed shots	[10;15]	[12;20]	[20;30]	[10;15]	[15;25]	[10;20]	[0;15]	[0;10]	[0;5]
Expected number of viable units after the completion of the task	5	3	0	3	1	0	1	0	0
The time required to complete the task	~9 min	~11 min	0	~12 min	~20 min	0	~35 min	0	0

Reduction of combat losses. The use of stochastic processes in modeling made it possible to reduce the loss of combat capability of artillery. Taking into account the technical condition, weather conditions and other external disturbances made it possible to create a model that effectively manages the unit state and reduces the risk of technical malfunctions and loss of combat capability during hostilities.

Practical applications in military simulators. The developed model has wide possibilities of application not only in computer games, but also in military simulators and simulators. The use of this model will allow to increase the level of training of military specialists, ensure a realistic reproduction of combat conditions and develop effective strategies for conducting combat operations. This will contribute to improving the quality of training and increasing the readiness of the military for real combat operations.

Prospects for further research. Further research can be aimed at adapting the developed model to other types of combat operations and expanding its capabilities. This includes modeling the actions of different types of troops, integrating new parameters and external disturbances, and developing more complex strategies for managing combat operations. This approach will further increase the realism and efficiency of the simulation, providing a more exciting and authentic gaming experience.

4. Conclusions

In the course of the work, a stochastic simulation model of the combat operation of artillery was developed. The random nature of parameters such as projectile speed, reload time, probability of detection by the enemy was taken into account. But external disturbances, such as weather conditions and the technical condition of artillery, were integrated.

Simulation of changes in firing positions of artillery was carried out. The time for transportation, possible loss of combat capability during movement, the risk of detection and attack by the enemy were taken into account. Algorithms were to determine optimal strategies for changing firing positions.

Simulation and analysis of the results was carried out. A series of simulations was performed to check the effectiveness of the developed models. The results of simulations were compared with real data and results of previous studies.

The results of the obtained studies will allow to increase the realism and effectiveness of modeling the combat work of artillery in computer games, which will contribute to the creation of a more exciting and reliable gaming experience. In addition, the developed models can be used in military simulators and simulators to improve the level of training of military specialists and develop effective strategies for conducting combat operations.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The paper has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating this work.

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