Information & Security

D. Markov, A. Kolev & V. Ivanova
vol. 53, no. 1 (2022): 89-101
https://doi.org/10.11610/isij.5307

Published since 1998

ISSN 0861-5160 (print), ISSN 1314-2119 (online)

Research Article

An Enhanced Solution for Automated Fire Control Systems

Dilyan Markov, Alexander Kolev (✉), Vania Ivanova

Bulgarian Defence Institute, Sofia, Bulgaria, https://www.di.mod.bg

ABSTRACT:

In this article, the authors consider problems that affect the combat characteristics in the combat use of self-propelled artillery systems. With the understanding that one of the important characteristics is the speed of setting the firing data and aiming the gun at the target, the aim is to reduce the needed time while maintaining or even increasing the accuracy compared to the traditionally used methods. The authors' proposal is to introduce automatic compensation taking into account the longitudinal and transverse tilt of the machine at the firing position when determining the direction of the gun body of the self-propelled artillery installation, the determination of the elevation angle, and the angle between the main direction of fire and the direction of the target. The authors consider two options for determining the self-propelled artillery system's own spatial position: using an inertial navigation sensor and using digital terrain height data. In the case of applying digital terrain data, the authors present results from simulation experiments conducted in laboratory conditions.

ARTICLE INFO:

RECEIVED: 28 JUNE 2022
REVISED: 24 AUG 2022
ONLINE: 21 SEP 2022

KEYWORDS:

inertial navigation sensor, digital terrain elevation data, spatial position, self-propelled howitzer, artillery, fire support

Introduction

Already in the 70s of the last century, the requirements for modern artillery to accurately hit a large number of targets, coordination of actions, and decentralization of battle formations, through automation of activities caused a search for ways of their implementation.[3] The past years of implementation of a number of means to improve speed and accuracy marked the path of development of artillery, which even in the present finds its main purpose in hitting targets on the battlefield.

✉ Corresponding Author: E-mail: a.kolev@di.mod.bg

The use of self-propelled artillery systems from indirect fires is associated with a number of challenges, which are specified as requirements for them in the Manual for combat work of artillery fire units. Analyzing them in the field of view, the decisive factor in the differences between self-propelled and towed systems stands out: the possibility of firing at large deviations from the main direction and, if necessary, conducting circular fire. Precisely because of the speed of conducting a circular fire from the self-propelled guns, they will be the focus of the present report.

The used 122 mm Gvozdika 2C-1 self-propelled artillery mount has a 360^0 range of fire without changing its location. In order to lead accurate fire from the firing position, the requirement is made that the tilt of the pivot axis of the cradle should not exceed 30 Mils Soviet Union (32 NATO-MIL), and for powerful guns – 15 Mils Soviet Union (16 NATO-MIL).[9] A characteristic feature is that during a circular fire, the pivot axis changes its location, but there is no requirement regarding the longitudinal inclination of the axis of the machine, and it is stated that the location of the firing position must be horizontal level. In reality, this inaccuracy is compensated for by aligning the gun gauges. Even so, differences are obtained when firing at large angles of deviation from the main direction, especially reaching 90^o from the main direction of fire, when in reality the longitudinal and transverse inclination of the machine at the firing position change their positions.

With the study, the main objective of the report is to find the speed in setting the data for firing and pointing the gun after conducting fire from one target to another regardless of the deviation from the main direction, so-called. maneuver with trajectories. Reducing the time by a few seconds (10-15) will make a difference in the rate of artillery fire.

Proposing Advanced Solutions in Determining Shooting Data

As shown in Figure 1, the general model of the automated fire control system (AFCS) in the case of a Self-propelled Artillery Unit (SAU) consists of a sensor subsystem, a subsystem for processing the primary sensor data, predefined tabular data, and a general computing unit. The purpose of the AFCS is to determine the main firing data, which are the angle between the main firing direction and the direction to the target and the elevation angle of the gun body when the self-propelled gun position and coordinates of the hit target are set.

The sensor subsystem provides the required set of additional data, with which greater speed and accuracy is achieved in determining the basic firing data. In this material, we dwell on the possibilities for automated determination of input parameters related to the self-propelled gun position and, more specifically, the determination of the longitudinal (pitch) and transverse (roll) inclination of the chassis of the machine in the determined firing position. An assessment was made for the degree of the practical application of the two considered approaches for determining the slope of the chassis of the self-propelled guns.

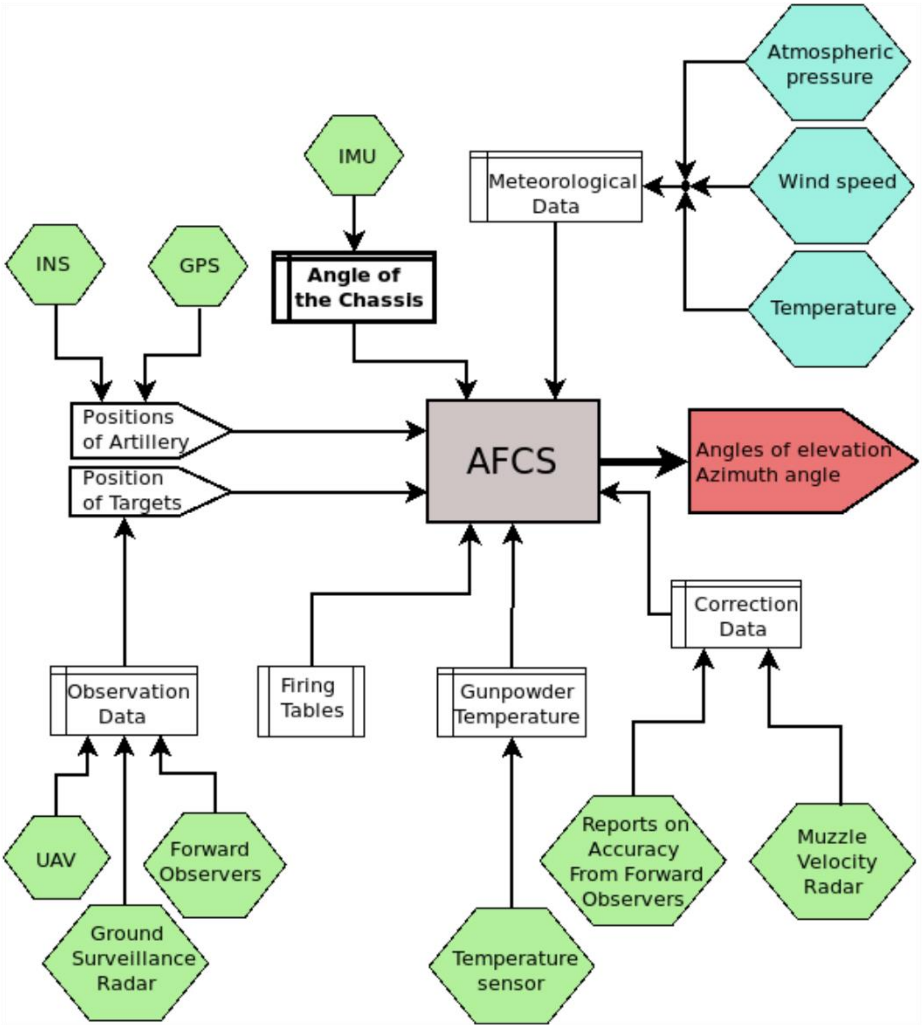

Figure 1: General model of AFCS).

Methodology

The applicable methods for determining pitch and roll are by applying an Inertial Measured Unit (IMU) rigidly attached to the chassis of the machine and oriented strictly along the longitudinal and transverse geometric axes, and a second possible method is by applying Digital Terrain Elevation Data (DTED) in the immediate vicinity of the already determined firing position.

For the purposes of subsequent consideration, we introduce the following notations (Figure 2):

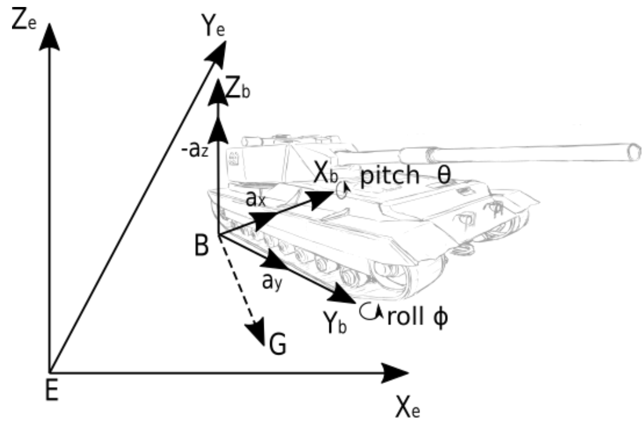

Figure 2: Spatial relations in the arrangement of the firing position of the self-propelled artillery installation

- Inertial coordinate system (E), right-oriented, in the considered cases coinciding with the applied geographic coordinate system in ENU notation, with axes X_e - East direction, Y_e - Nord direction, Z_e - Up direction;
- Local coordinate system of the ACS chassis, right-oriented, indicated in the Figure 2 by (C) with axes X_b – axis of longitudinal inclination, Y_b – axis of transverse inclination, Z_b – axis of azimuthal rotation;
- Spatial angles in the local coordinate system: relative to the X_b axis pitch θ, relative to the Y_b axis roll φ, and course angle yaw ψ.

Applying IMU

The determination of the pitch θ of the angle and roll φ, with the application of an inertial sensor, rests on the physical fact that when the machine is stationary, the vector of the direction of the ground acceleration, indicated in Figure 2 with G, in the general case there are projections along the axes in the local coordinate system C. These projections, denoted in Figure 2 with a_x, a_y, and a_z measured by the IMU at the rest of the machine in a normalized form are numerical values in the range [-1, 1] and, at the same time ,are functionally dependent on the sought angles pitch θ and roll φ. The determination of the pitch of the angle θ and roll φ can be carried out by applying the mathematical apparatus of rotational coordinate transformations.

In accordance with the adopted Tait-Bryan sequence,[10] the rotation matrix R_C in the local coordinate system of the SAU chassis in a sequence of performing the individual XYZ rotations is presented as:

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\theta & -s\theta & 0 \\ 0 & s\theta & c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

$$R_y = \begin{bmatrix} c\Phi & 0 & s\Phi & 0 \\ 0 & 1 & 0 & 0 \\ -s\Phi & 0 & c\Phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

$$R_z = \begin{bmatrix} c\psi & -s\psi & 0 & 0 \\ s\psi & c\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

$$R_C = R_z \times R_y \times R_x =$$

$$= \begin{bmatrix} c\Phi c\psi & c\psi s\Phi s\theta - c\theta s\psi & s\theta s\psi + c\theta c\psi s\Phi & 0 \\ c\Phi s\psi & s\Phi s\theta s\psi + c\theta c\psi & c\theta s\Phi s\psi - c\psi s\theta & 0 \\ -s\Phi & c\Phi s\theta & c\Phi c\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

The thus obtained rotation matrix R_C from expression (4) is applied to determine the normalized components $a=[a_x\ a_y\ a_z]^T$ of the ground acceleration vector. In the normalized form of representation, we assume the usual value of the ground acceleration of G = 9.81 m/s^2 with G_n = -1, taking into account the assumed in Figure 2 directions of the axes of the local coordinate system C.

$$\begin{bmatrix} a_x \\ a_y \\ a_z \\ 1 \end{bmatrix} = R_C \times \begin{bmatrix} 0 \\ 0 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} -s\Phi \\ c\Phi s\theta \\ -c\Phi c\theta \\ 1 \end{bmatrix}. \tag{5}$$

In expressions (1 ... 5) the symbol s denotes the function sin(), and the symbol c denotes the function cos(). As a result, for values of the desired angles of longitudinal slope pitch θ and of transverse slope roll φ, expressed by means of the normalized components of ground acceleration a_x, a_y and a_z , we obtain:

$$\phi = -\sin^{-1}(a_x), \tag{6}$$

$$\theta = -\tan^{-1}\left(\frac{a_y}{a_z}\right). \tag{7}$$

Applying DTED

The data for building a digital terrain model were acquired from a freely available source. [6]

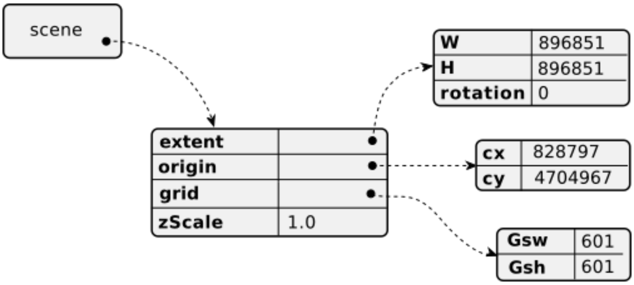

Figure 3: Georeferencing of the data from the digital model of the terrain.

The files containing the height of the earth's surface are in ASCII GRID format, in rectangular matrix form, and their basic parameters correspond to the U.S. standard. Military Specification Digital Terrain Elevation Data (DTED – level 1), MIL-PRF-89020B in the WGS84 geodetic reference coordinate system. By applying the specialized Quantum GIS software, the data were converted to the Universal Transverse Mercator (UTM) projection reference coordinate system. Data preparation for work in a 3D virtual scene was performed using the qgis2threejs functional extension.[11]

An important and practical valuable feature of the thus synthesized virtual spatial scene is the preservation of the inherent geo-referencing of the virtually represented geographic objects. The georeferencing data carrier is the automatically created information structure in json file format. The more important parameters required to perform georeferencing are shown in Figure 3.

The modeled earth surface is in ENU notation coordinate system – positive x-axis direction is East, positive y-axis direction is North, the z-axis is directed upwards Up. The coordinate system is right-oriented with linear units of meters and angular units of radians.

As shown schematically in Figure 4 firing position of the SAU is denoted by P(x, y), where the values of x and y are coordinates in the actual coordinate system of the digital elevation model. Within the general modeled space of dimensions W and H, the upper left corner has fixed coordinates denoted by c_x and c_y. The height matrix {M} is accessed with the index I,j. The firing position of the self-propelled guns falls within the rectangle {M_0, M_1, M_2, M_3}, the corresponding indices are determined by applying the dependencies:

$$i = floor\left(\frac{P_x - c_x}{\frac{W}{G_{sw}} + 1}\right), \qquad (8)$$

$$j = floor\left(\frac{c_y - P_y}{\frac{H}{G_{sh}} + 1}\right). \tag{9}$$

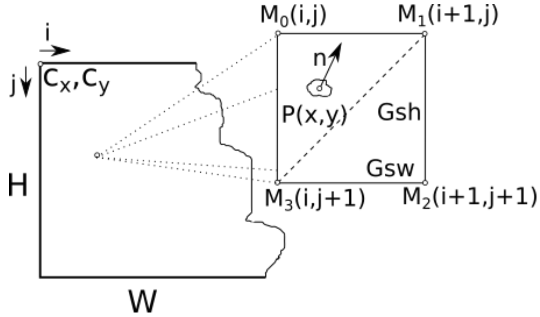

Figure 4: Determination of the slope in the firing position of the SAU.

The possible placement of the firing position P is in one of the triangles $\Delta M_0M_1M_3$, $\Delta M_1M_2M_3$ or occupies an intermediate position. Belonging to one of these two triangles can be accurately determined by applying the "barycentric coordinates" method. [8] If we assume that $P \in \Delta M_0M_1M_3$ and we have $M_0(x_0, y_0, z_0)$, $M_1(x_1, y_1, z_1)$, $M_3(x_3, y_3, z_3)$, then the vector normal to the plane of $\Delta M_0M_1M_3$ vector $\vec{n}$ is expressed by:

$$\vec{v} = \overrightarrow{M_1} - \overrightarrow{M_0}\,; \vec{u} = \overrightarrow{M_3} - \overrightarrow{M_0}\,; \tag{10}$$

$$\vec{n} = \vec{v} \times \vec{u} = \\ = \begin{bmatrix} (y_1 - y_0)(z_3 - z_0) - (y_3 - y_0)(z_1 - z_0) \\ (x_3 - x_0)(z_1 - z_0) - (x_1 - x_0)(z_3 - z_0) \\ (x_1 - x_0)(y_3 - y_0) - (x_3 - x_0)(y_1 - y_0) \end{bmatrix} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix}. \tag{11}$$

In normalized form, the normal vector is represented as:

$$\hat{n}_x = \frac{n_x}{|n|}, \hat{n}_y = \frac{n_y}{|n|}, \hat{n}_z = \frac{n_z}{|n|}, \tag{12}$$

where:

$$|n| = \sqrt{n_x^2 + n_y^2 + n_z^2}. \tag{13}$$

Experiment Setup and Achieved Results

To assess the practical applicability of the proposed approaches, an error assessment was performed for determining the slope of the chassis of the SAU.

The experimental work was carried out using the created by specialists of the Defense Institute "Prof. Tsvetan Lazarov" virtual spatial scene.

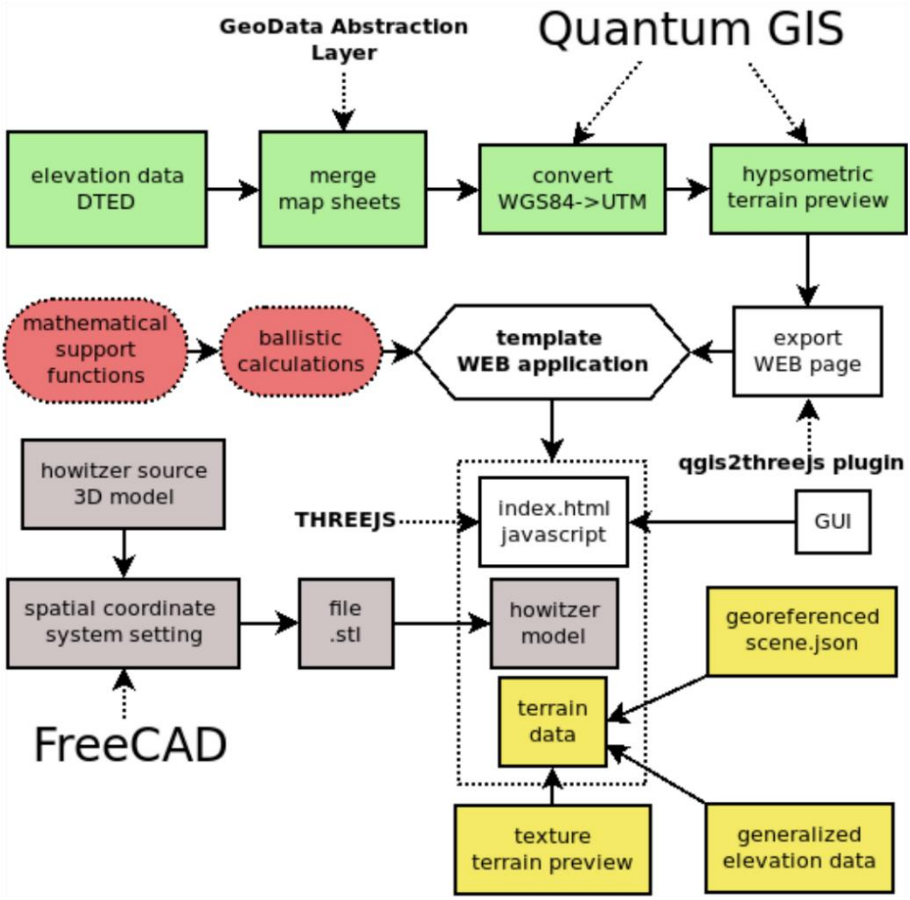

Figure 5: Spatial virtual scene diagram for laboratory experiment.

Open source software products and data from freely available sources, Creative Commons - Attribution - Non-Commercial license, were used to synthesize a realistic virtual spatial scene.[6, 1, 2] In Figure 5 schematically shows the sequence of work and interconnections in the process of creating the virtual scene.

The software solution allows simulating complex artillery tasks for firing from closed firing positions. The three-dimensional map base is organized according to the method described above in the text. A graphical user interface has been created, with the help of which the positioning of a self-propelled gun model is controlled, the targeting process is simulated, and the basic firing data is determined.

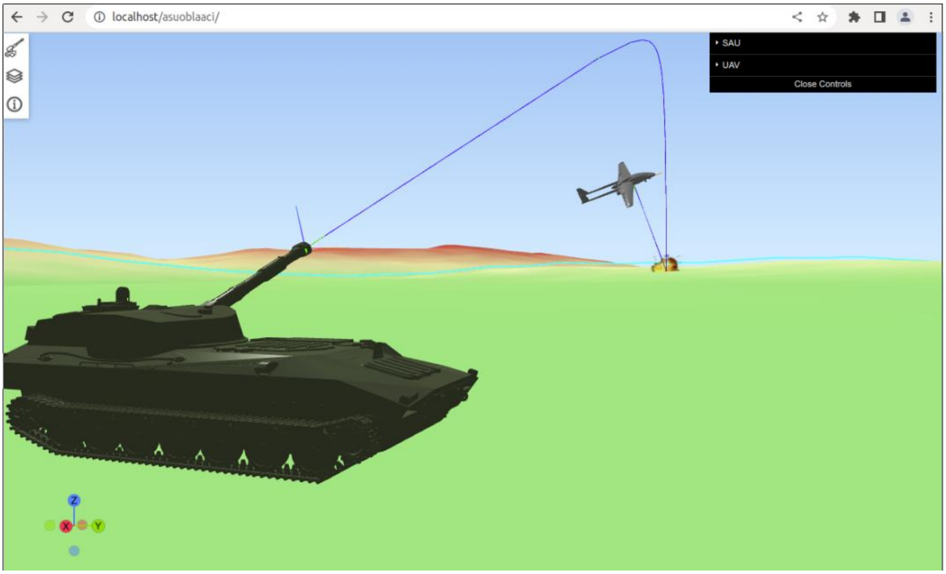

Figure 6: Screen from the experimental setup.

Determination of the angle to the direction of the target is determined geometrically using data on the coordinates of the firing position and the target. In the process of determining the elevation angle of the gun body (in the case without chassis tilt compensation), the distance to the target measured in the virtual scene and polynomially approximated data from the standard firing table of the relevant artillery system are used.

Given the set coordinates of the firing position and the thus determined elevation angle of the gun body, a three-coordinate simulated calculation of the ballistic curve of the shot is performed. For this purpose, a computational procedure for solving a system of differential equations has been introduced as a program function of the JavaScript programming language, with results comparable to the theoretical ones from the corresponding shooting table. The intersection of the ballistic curve with the three-dimensional model of the earth's surface is the impact position of the artillery shell. Hit coordinates are determined by applying the "raycaster" method from the object-oriented model of the TREEJS software library. [7]

In Figure 6 shows a screenshot of the experimental setup for simulating artillery fire in a realistic spatial scene. The situation in the figure was created exclusively for the purpose of the experiment and does not reflect the actual placement of an artillery system in the area.

At a specified distance to the target of 10320 m, a series of 10 simulated shots were conducted with an elevation angle ranging from 15054' to 17030'. The exact numerical data from the experiment are shown in Table 1. The reported distances of artillery hits are from 10310 m, which corresponds to a hit accuracy error of 0.09% to 10542 m, which corresponds to a hit accuracy error of 4.93%.

If we assume that the allowable error in the accuracy of the first shot when firing from a closed firing position is no more than 5%, then the error in determining the elevation angle of the gun body can possibly reach 10.06%. The latter conclusion can be considered valid when firing in the range of tested distances to the target, which are 2/3 of the maximum engagement distance for the given artillery system.

Table 1. Numerical data from the experiment .

DMS	Thousands	Distance[m]	Error [%]
15.54	266	10310	0.09
16.06	269	10376	0.55
16.18	272	10443	1.19
16.23	274	10476	1.52
16.36	277	10542	2.15
16.48	281	10606	2.77
16.53	282	10638	3.08
17.06	286	10703	3.71
17.18	289	10766	4.33
17.30	292	10828	4.93

Conclusions

The methods proposed by the authors for compensation of the elevation angle of the gun body depending on the slope of the chassis of the self-propelled guns in the coordinates of the firing position are applicable as long as the compensation angle of slope is determined with an error within 10%.

Possible DTED implementation error

Digital terrain elevation data obtained by the Space Radar Topography Mission (SRTM) method at different representation levels are characterized by different height representation errors. In the most favorable cases, the relative height error is defined as ±6 m. [13] If we assume the maximum size of the chassis of the SAU of 7.26 m [12], then the determination of longitudinal and transverse inclination using the expressions (12) will lead to an unacceptable error of approximately 58^0. The method of compensation using DTED in the modern accuracy of the digital model in height is not applicable in practical conditions.

The created virtual spatial scene works with a generalized three-dimensional representation model of the earth's surface, in the case experimented by the authors, it is a cell of a rectangular matrix with a side size of 601m. In laboratory conditions, the simulation environment can provide an error of 1.14^0 when determining the compensation angle of elevation, which, according to Table 1, is sufficient to simulate the first shot with a deviation of no more than 5% from the desired distance to the target. Developed at the Defense Institute "Prof. Tsvetan Lazarov" a realistic spatial virtual environment is applicable for conducting simulation experiments on researching the combat capabilities of artillery systems.

Possible IMU implementation error

Micro Electro-Mechanical System (MEMS) inertial navigation sensors combine accelerometer, gyroscope, and magnetometer hardware components in their housing. Examples of such commercially available devices are the product MPU-9250[5] and the relatively more precise electronic gyroscope STIM210.[14] Each of the hardware components makes measurements of a characteristic physical quantity with inherent error. For the accelerometer, the measurement error is due to rapidly changing signal deviations due to electro-mechanical noise of the device, vibrations in the mechanical structure, and geometric inaccuracies in manufacturing and assembly. The gyroscope is characterized by a slowly changing deviation of the measured signal, also called drift. Known methods for overcoming measurement error are applying digital processing of the primary signal with Kalman filters. A published study[4] reported a maximum error in the determination of transverse or longitudinal slope of no more than 5^0. With reference to the expressions (6, 7), it can be argued that the measurement error of the STIM210 type IMU in the range $0^0 \div 30^0$ will not exceed 6%. The latter allows drawing the conclusion that correcting the elevation angle of the self-propelled gun body using the IMU to determine the tilt of the chassis in the place of the firing position is applicable in practice.

The research of the authors in this report shows a real practical focus on the following main activities:

- Shortening the time to select the location of the cannon on the terrain, especially for uneven terrain. This activity, carried out by the artillery reconnaissance groups without the presence of self-propelled guns, is a labor-intensive task for personnel with little or no practical experience;
- Increasing the accuracy of artillery fire at large angles of deviation from the main direction;
- Reduction of the time for alignment of the measuring instruments at large angles of deviation from the main direction.

Testing the results in real field conditions is possible when developing automation, calculating corrections for shooting data from the tilt of the pivot axis in its different locations in a circle. The application can be carried out not only for the specified 2C-1 system but also for the 122 mm multiple rocket launcher BM-21, where, together with increasing the range, the application of this type of automation will also have a positive effect.

Acknowledgements

This work was supported by the NSP DS program, which has received funding from the Ministry of Education and Science of the Republic of Bulgaria under the grant agreement no. D01-74/19.05.2022.

References

1. Enver Avcı, "Bayraktar TB2 Tactical UAV," May 04, 2020, https://www.thingiverse.com/thing:4336517.
2. Stephen Miller, "Carnation 2S1," August 20, 2021, https://www.thingiverse.com/thing:4936827.
3. R. Chalakov, "Field artillery – from the cherry ball to automated fire control systems," *Collection of reports from an international scientific conference of the "Georgi Stoykov Rakovski" Military Academy – 105 years of knowledge in the interest of security and defense,* 2018, pp. 192-195, in the Bulgarian language.
4. Shi Gang, Xisheng Li, and Zhengfu Jiang, "An Improved Yaw Estimation Algorithm for Land Vehicles Using MARG Sensors," *Sensors* 18, no. 10 (2018): 3251, https://doi.org/10.3390/s18103251.
5. IvenSense, "MPU-9250 Product Specification Rev 1.1," June 20, 2016, https://invensense.tdk.com/wp-content/uploads/2015/02/PS-MPU-9250A-01-v1.1.pdf.
6. A. Jarvis, Hannes Reuter, Andy Nelson, and Edith Guevara, "Hole-filled seamless SRTM data V4," *International Centre for Tropical Agriculture (CIAT),* January 2008, https://srtm.csi.cgiar.org.
7. Jeremie Bourque, "JavaScript 3D Library," accessed January 16, 2022, https://threejs.org.
8. Juyong Zhang, Bailin Deng, Zishun Liu, Giuseppe Patanè, Sofien Bouaziz, Kai Hormann, and Ligang Liu, "Local Barycentric Coordinates," *ACM Transactions on Graphics* 33, no. 6 (November 2014): 1–12, https://doi.org/10.1145/2661229.2661255.
9. *Manual for Combat Work of Artillery Fire Units* (Military publishing house, 1994), in the Bulgarian language.
10. Philipp Allgeuer and Sven Behnke, "Fused Angles and the Deficiencies of Euler Angles," *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* 2018, https://doi.org/10.1109/IROS.2018.8593384.
11. Minoru Akagi, "Qgis2threejs, 3D visualization powered by WebGL technology," 2022, https://plugins.qgis.org/plugins/Qgis2threejs/.
12. Military history WikiProject, "SAU 2S1 Gvozdika," accessed March 17, 2022, https://en.wikipedia.org/wiki/2S1_Gvozdika.
13. Michaela Wagner, "SRTM Digital Terrain Elevation Data (DTED) Format," 2003, https://geoservice.dlr.de/web/dataguide/srtm/pdfs/SRTM-XSAR-DEM-DTED-1.1.pdf.

14. Sensonor, "Ultra-high performance gyro module STIM210," accessed January 2022, https://www.sensonor.com/.

About the Authors

Dilyan Markov is an Associate Professor of military affairs. He holds an M.S. Degree and a Ph.D. from the "G. S. Rakovski" National Defense Academy in Sofia. His current research interests are in the use of artillery in operations.

Alexander Kolev is an Associate Professor in "Automated Systems for Information Processing and Control" and secretary of the Scientific Council of the Department "Development of C4I Systems" of the Bulgarian Defence Institute "Prof. Tsvetan Lazarov," Sofia, Bulgaria. He holds an M.S. Degree in Mechanical Engineering from the Technical University of Sofia and a Ph.D. degree in Informatics from the "G. S. Rakovski" National Defense Academy in Sofia. His current research interests are in information technologies.
https://orcid.org/0000-0002-9211-2717

Vania Ivanova graduated with a Master's Degree in Mechanical Engineering from the Technical University of Sofia, Bulgaria. She is currently pursuing a Ph.D. degree at "Prof. Tsvetan Lazarov" Defence Institute on the topic "Data Model of the Automated Fire Control Systems." Her research interests include computer graphics, automated systems, and web-based information systems.