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Development of a universal binary classifier of the state of artillery barrels by the physical fields of shots

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ABSTRACT

An artillery shot is accompanied by the release of combustion products of powder gases from the barrel. It is proposed to use muzzle ejection to classify the level of barrel wear during firing. A full-scale experiment was carried out with high-speed video recording in the visible and infrared ranges of the dynamics of the development of muzzle ejection when firing guns with a defect-free and worn barrel. Muzzle ejection when fired from a large-caliber gun consists of three spatial regions: frontal and two side, associated with the emission of powder gases through the openings of the compensators. A technique for analyzing three synchronized video streams has been developed. The technique made it possible to quite fully investigate the processes of muzzle ejection development dynamics in defect-free and worn barrels. Informative signs are chosen, which are different for the dynamics of muzzle ejection from defect-free and worn barrels. This made it possible to build a binary classifier of the condition of the trunks by the level of wear based on the support vector machine with least squares. In contrast to the classical SVM classifier, this allowed us to reduce the calculation time and reduce the required size of the training set. To assess the quality of classification, it is proposed to rely on only errors of the first and second kind, but also an integral indicator – the probability of error-free classification. To increase the reliability of the classification, the concept of a universal binary classifier is proposed, which uses both video recording of the muzzle ejection and acoustic fields of the shot – ballistic and muzzle waves – to diagnose the state of the barrel. On the basis of experimental data, it is shown that the use of all physical fields accompanying an artillery shot for the binary SVM classification allows obtaining a high value of the error-free classification probability.
Keywords: Barrel wear; muzzle blast; highspeed video; universal classifier; classification quality

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INTRODUCTION

Intense military operations in the liberation war of the Armed Forces of Ukraine against the aggressor state once again demonstrated the decisive role of large-caliber artillery in achieving combat success. Combat experience showed hitherto unprecedented intensity of artillery fire. The high intensity of fire is associated with high
wear of artillery gun barrels, which requires constant monitoring of wear [1, 2]. A special role is played by methods of monitoring barrel wear, which do not require the removal of the gun from combat formation and do not require the use of expensive this regard, wear assessment methods based on the special equipment for the operational assessment of wear. In registration of physical fields accompanying the shot are especially promising. From this point of view, the study of such methods for assessing the wear of artillery barrels is an important scientific and practical task.

LITERATURE REVIEW

The task of diagnosing the state of the trunk can have two approaches. The first of them is the examination of the barrel itself as an element of the tool that is subject to wear [3]. Various endoscopic methods for examining the trunks require moving the tool to the technical unit [4]. Despite the high quality of diagnostics, such methods reduce the combat power of an artillery unit and cannot be considered operational. Another variant of barrel diagnostics is based on the assessment of the initial velocity of the projectile at the moment of its exit from the muzzle of the barrel. This option is based on the fact that eventually the wear of the gun barrel or charging chamber leads to a decrease in the muzzle velocity of the projectile [5]. The most modern way to estimate the initial velocity of the projectile is the use of artillery ballistic stations (ABS) [6, 7]. Artillery ballistic stations are centimeter-wave Doppler radars. Their shortcomings are well known. Artillery ballistic stations are active devices, which increases the unmasking effect of the firing position. In order to accurately measure the muzzle velocity of a projectile, ABS requires precise installation, which requires additional time. Finally, ABS are quite expensive equipment. An alternative approach to diagnosing the state of barrels is the registration and processing of physical fields that occur during an artillery shot. Consistently physical fields look like this. When the projectile exits the muzzle of the gun at supersonic speed, a ballistic wave arises and moves along with the projectile, the parameters of which depend on the initial velocity of the projectile and, consequently, the state of the gun barrel. Then there is a muzzle ejection (ME) of the combustion products of gunpowder in the barrel and combustion chamber and unburned carbon. Muzzle ejection parameters also depend on the state of the trunk. Muzzle ejection generates an acoustic low-frequency muzzle wave. In [8, 9], [10], it was proposed to use ballistic and muzzle waves to assess the level of barrel wear. For this, it is proposed to use a trainable binary SVM classifier [11, 12], [13, 14]. An analysis of the literature showed that ME analysis was not used anywhere to determine the state of the trunk, although ME is accompanied by a powerful optical flash and can be recorded quite simply. The most effective option for diagnosing the condition of the barrel could be an automatic classifier based on the analysis of all the listed types of physical fields, including the visual manifestation of muzzle blast.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the study is to develop a universal automated classifier of the state of barrels in terms of wear level based on the analysis of all types of physical fields accompanying an artillery shot, including video recording and analysis of muzzle ejection.

To achieve this goal, the following tasks were solved:

– a preliminary field experiment was carried out with firing from guns with a high level of barrel wear and a practically unworn barrel with multi-view video recording of muzzle ejection, as well as registration of a ballistic wave and muzzle wave;

– a technique was developed for analyzing video recordings of muzzle ejection with the formation of informative signs for diagnosing the state of the barrel;

– a universal classifier was built based on the use of informative features formed on the basis of physical fields of various origins.

VIDEO RECORDING OF MUZZLE EJECTION

Muzzle ejection when firing from a modern large-caliber gun has a rather complex three-lobed shape (Fig. 1).

Fig.1. **Muzzle ejection formed when firing from a 152 mm gun 2A36 "Hyacinth-B"[10]: 1 – projectile; 1a – mach cone accompanying the projectile; 2 – frontal ejection of powder gases; 3 – side ejection of powder gases through the holes of the compensator (muzzle brake) tools**
***Source*: compiled by the [10]**

The frontal ejection of powder gases is associated with their eruption from the barrel, the left and right side ejections are formed when the combustion products exit through the holes of the gun compensators. From the point of view of diagnosing the state of the barrel, it is important to extract maximum information from the observed dynamics of the development of the muzzle burst. This can be achieved by high-speed video recording of the muzzle burst from various angles.

A field experiment was set up during training firing of 152 mm 2A36 "Hyacinth-B" trailed guns. In the experiment, shots were fired from two guns:

gun No.1, from which 91 shots were previously fired, i.e. a gun with a practically new barrel, and gun No.2, from which 1968 shots were previously fired, i.e. a gun with a barrel that has a very high level of wear. Further, in the process of training firing, physical fields from 59 shots were recorded, namely, 34 shots were fired from gun No.1 from a defect-free barrel, and 25 shots from gun No. 2 with wear exceeding the allowable.

The shooting video recording scheme is shown in Fig. 2.

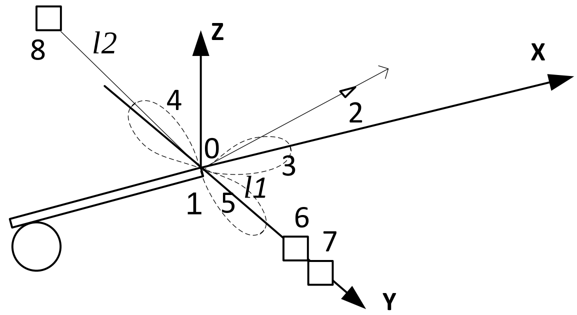


Fig. 2. **Scheme of video recording of muzzle ejection during a shot:**

1 – gun barrel; 2 – projectile; 3 – frontal ejection; 4 and 5 – left and right side ejections; 6 – visible range ground video camera for recording a horizontal side view; 7 – infrared range video camera; 8 – visible video camera for recording vertical angle
***Source*: compiled by the authors**

In the scheme (Fig. 2) the origin of coordinates *O* is aligned with the muzzle of the gun barrel (1). The axis *OX* is aligned with the direction of fire. Projectile (2) leaves the muzzle of the gun at an initial speed v_0 and moves along the trajectory. When the projectile exits, frontal (3) and lateral (4,5) muzzle ejections are formed. On a line perpendicular to the direction of fire at a distance of l_1=60–100 m, a ground-based high-speed wide-angle video complex is located. The video complex consists of a video camera in the visible range (6) and an infrared (IR) video camera (7). The task of the video complex (6,7) is to record the dynamics of muzzle burst development in the ground side view. A high-speed wide-angle video camera (8) is placed on an inclined line lying in a plane perpendicular to the horizontal one at an inclined distance of l_2=60–100m. In the experiment, video camera 8 was located on an unmanned aerial vehicle in the hovering mode. The task of the video camera 8 is to register muzzle ejection in a vertical perspective. Video streams from cameras (6,7,8) are synchronized and transmitted via radio and wire channels to the processing computer.

The following equipment was used in the experiment:

1. IR Camera: High-Speed MWIR Science-Grade Camera FLIR X6980; resolution 640x512px; shooting frequency up to 1004 Hz; a standard ND2 filter was used: (250…2000)°C; dynamic range 14 bits; real time connection via Ethernet port.

2. Visible spectrum cameras: blast-proof FASTCAM MINI WX camera, resolution 1920x1080 px; shooting frequency from 240 Hz; linear image (no lens and perspective distortion); connection of a video signal in real time.

3. Computer for processing the recorded information: video card: RTX 3080, processor: 4.5 GHz, 12 cores, storage: SSD 4 TB M.2 NVME RAM: 64GB, OS: Windows 10.

Note that for all shots, acoustic fields were also recorded – a ballistic wave and a muzzle wave. Since the issues of their registration are covered in sufficient detail in [8, 9], [10], here the detailed issues of registration of the acoustic fields of shots are omitted.

Fig. 3 shows sequential frames of muzzle burst development dynamics in the upper vertical view. Analysis of sequential frames demonstrates the obvious difference between muzzle bursts from shots from a defect-free barrel and a worn barrel. This gives grounds for constructing an automatic classifier of the state of the barrel based on the analysis of the video recording with the recorded dynamics of the development of the muzzle burst.

ANALYSIS AND METHOD OF FORMING A VIDEO RECORDING OF MUZZLE EJECTION

Step 1. Video recording starts synchronously with all video cameras, and then a shot is fired with a slight delay. Two digital video streams of the visible spectrum are transmitted to the processing computer from cameras (6) (file_1) (horizontal view) and (8) (file_2) (vertical view) and an infrared spectrum video stream from IR camera (7) (file_1ir).

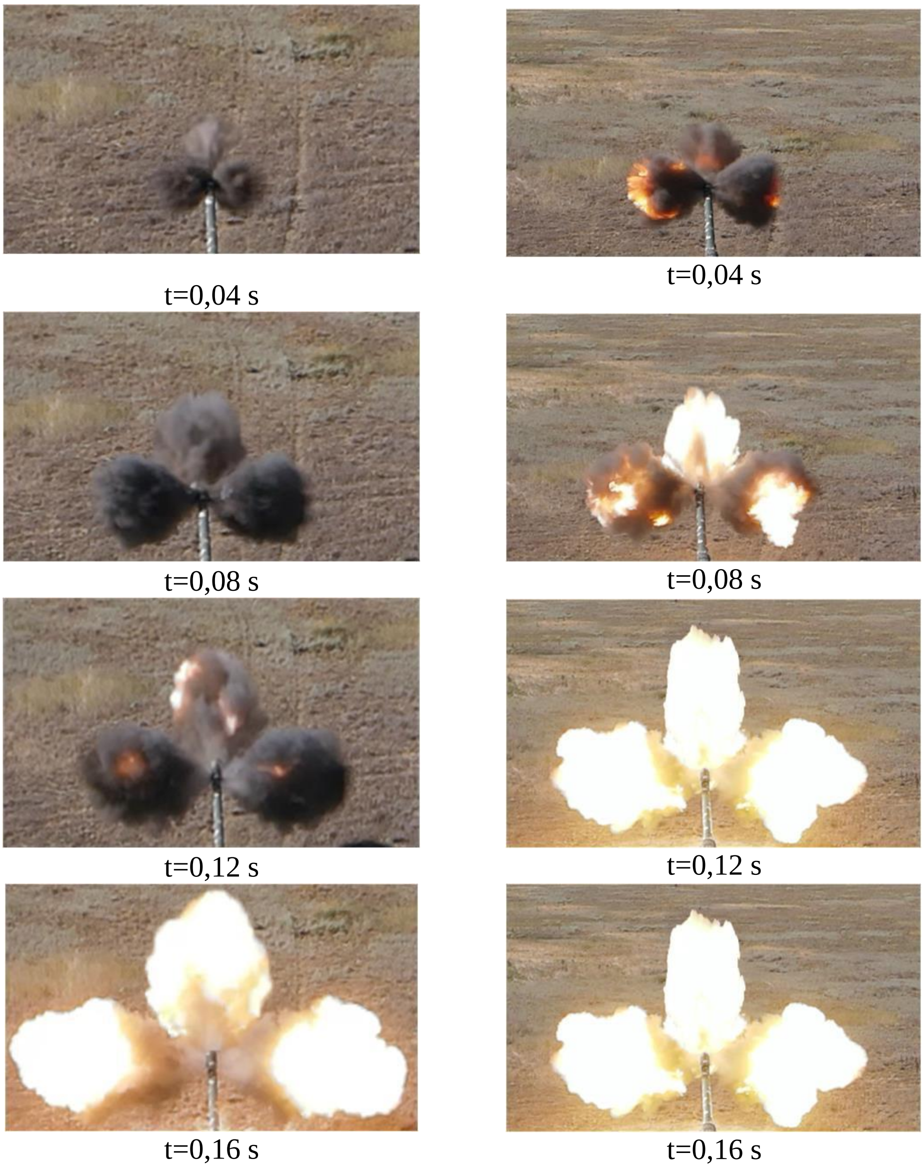
Step 2. The specified video streams (file_1), (file_2), (file_1ir) are converted into a synchronous sequence of frames grouped by discrete time counts.

Step 3. Each frame is analyzed in order to find a projectile display in the frame. Further, those time frames are selected into a separate array, on which the image of the projectile is located from the moment of its separation from the image of the cut of the gun barrel or exit from the cloud of powder gases of the muzzle ejection to the moment where the image of the projectile is absent.

Step 4. For each time frame, the projection of the temperature zone is analyzed if the required information is found in the frame after processing the infrared video stream from video camera (7) (file_1ir). All time frames of the three video streams are synchronized in time and represent two geometric projections of the muzzle blast, in addition, if available, a geometric view of the average temperature field of the current volume of muzzle blast powder gases is possible.

Step 5. A search is being made on the side view frame for the location of the center of mass of the projectile. At this point, the coefficient of geometric conversion of linear quantities is determined by a priori known projectile dimensions (diameter and length).

Step 6. The natural linear distance between the center of mass of the projectile and the cut of the cannon barrel bore is determined from the image of the cut of the bore of the gun barrel and the point of the center of mass of the projectile, taking into account the geometric conversion factor. The average speed of the projectile in this segment is determined.



a b

Fig.3. **Sequential frames of muzzle burst development dynamics in the upper vertical view:**
a – shot from a barrel with wear exceeding the allowable level;
b – shot from a defect-free barrel
***Source*: compiled by the authors**

Step 7. The statistically reliable initial linear velocity of the projectile is calculated after analyzing all the side view frames.

Step 8. From the time frame of the video stream of infrared radiation, the length of the curved line is determined - the boundary between the projection of the surface of free carbon and powder gases and the atmosphere that got from the cannon barrel into the atmosphere and the area of this projection, if they exist.

Step 9. From the time frames of video cameras (6) and (8), the current areas of projections of the volume of muzzle blast gases are estimated and, based on them, the current volume of muzzle blast gas is calculated.

Step 10. For each time frame, the current pressure of powder gases at the front of the shock muzzle wave is calculated. The current pressure of the muzzle blast gases is determined by the average temperature, the current volume of gas, and the thermodynamic characteristics of the gas concentrated in the muzzle blast. The equality of the design pressure and atmospheric pressure indicates the disappearance of the shock muzzle wave in the understanding of the loss of the sound source as a diagnostic feature.

Step 11. Analysis of the received calculated vectors. During the entire analysis of video streams, two vectors of values are formed. The first vector is the value of the current pressure of the muzzle gas volume for each frame from the video sequence. The general property of such a vector is inherent only in a monotonic decrease in pressure to the atmospheric value. The second vector is the value of the current temperature of the muzzle gas volume for each frame from the video sequence. The general property of such a vector is characterized by: a monotonic decrease in temperature; a jump followed by a monotonic decrease in temperature; monotonous decrease in temperature with current temperature stabilization in a separate area.

The presence of the formed volume of free carbon in muzzle powder gases is determined either by a jump in temperature or by its stabilization. This property of the temperature of the volume of muzzle powder gases confirms that when they expand and mix with atmospheric oxygen, additional oxidation of free carbon is formed with the release of additional energy, which leads to such a temperature characteristic.

Fig. 4 shows the processing diagram of the information video stream corresponding to the above methodology.

Below are the individual operations of the methodology that require an illustrative explanation.

Fig. 5 shows a typical video sequence of combined synchronized images of vertical and side views. After reformatting the video stream files (file_1) and (file_2) into frame sequences, for each joint pair of frames file_1_1.i and file_2_2.i using the Open CV library, which implements a filtering method based on the gradient method and a closed loop detection method based on chain approximation of the contour, and determining their geometric dimensions according to the

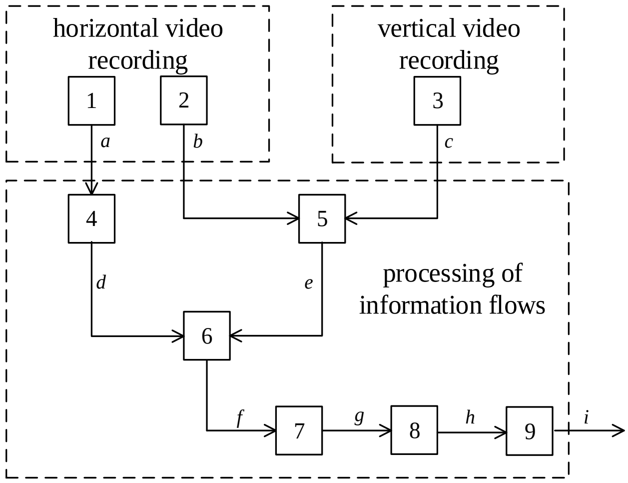


Fig.4. **Scheme for processing information video streams:**
1 – IR video camera; 2 – side view vide camera; 3 – vertical view video camera; 4 – preprocessing of the IR video stream; 5 – pre-processing of the visible spectrum video stream; 6 – combi-nation of frame images; 7 – detection in frame of analysis regions; 8 – detection in the image frame of the IR spectrum of the region of powder gases of muzzle ejection;
9 – calculation of the perimeter and area of the volume of powder gases of muzzle ejection:
a – horizontal video stream of the IR spectrum; b – vertical video stream of the visible spectrum; c – horizontal video stream of the visible spect-rum; d – a normalized set of IR image frames; e – a normalized set of visible spectrum image frames; f – an array of time sets (time, frame, position); g – an array of numerical characteris-tics; h – an array of numerical characteristics; i – two generated vectors characteristics
Source: **compiled by the authors**

accepted base (the outer diameter of the bore), the current values of the dimensions of the muzzle ejection elements were determined. By processing the camera frame file_1_1.i, the values of the diameter D_1 and length L_1 of the frontal muzzle ejection were determined. The values of the diameter D_2 of the muzzle ejection to the left side from the muzzle brake were also determined. It was assumed that the diameters of the right and left outliers are the same on the current frame. By processing the frame of the vertical camera file_2_2.i, the values of the length L_2 of the muzzle ejection to the left side of the gun from the muzzle brake and L_3 to the right side of the gun from the muzzle brake were determined (Fig. 6).

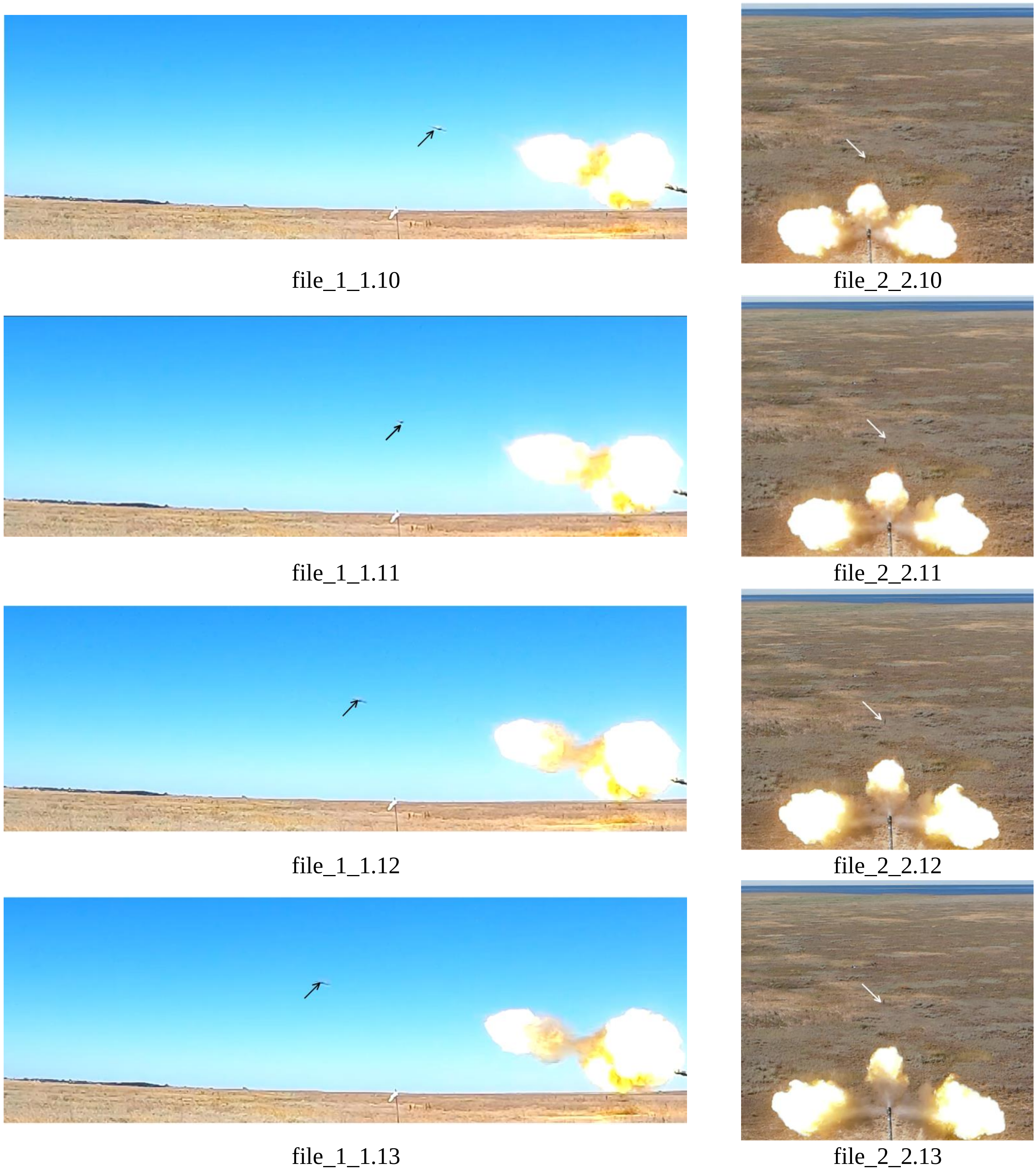


Fig.5. **A typical video sequence of combined synchronized images of vertical and side views (the arrows on the images mark the projectile)**
***Source*: compiled by the authors**

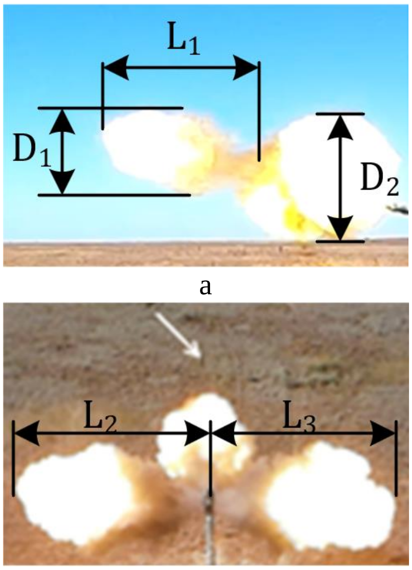
It was assumed that the obtained geometric dimensions of the "petals" of the muzzle ejection correspond to bodies that have the shape of ellipsoids of revolution. Then the total current muzzle ejection volume was determined as the sum of the volumes of three geometric bodies:

$$V_i = 4/3\pi(L_1 \cdot D_1^2 + L_2 \cdot D_2^2 + L_3 \cdot D_2^2).$$

The current pressure P_i in the volume of gas V_i with an average temperature T_i is determined from the following assumptions.

The model is based on the state of an ideal gas, for which the Mendeleev-Clapeyron equation is applicable [15]:

$$P_i \cdot V_i = \frac{m}{M} R \cdot T_i.$$



a

b

Fig. 6. **Determining the size of muzzle ejection gases:**
a – determination of geometric dimensions from a side view video camera; b – determi-nation of geometric dimensions from a video camera of a vertical view
***Source*: compiled by the authors**

As long as the gas expands after exiting the barrel into the air atmosphere, it is assumed that no chemical reactions occur in the muzzle blast gas, that is, the mixture of vent gases has a constant gas composition. For this reason, the molar mass (M) of the gas mixture in the charging chamber, bore, muzzle blast system is unchanged. Therefore, the mass of the gas mixture (m) of the muzzle ejection located in the entire muzzle system "charging chamber + bore + muzzle ejection" is unchanged. For the same reasons, the universal gas constant is unchanged. The product $\frac{m}{M}R$ is a constant for calculation, and its detailed calculation is shown in [16]. At the same time, it should be borne in mind that for each value of the shot, this product has its own value and depends on the charge, brand of gunpowder, its gerontological properties and the state of wear of the barrel system.

The temperature T_i is determined by horizontal recording with an infrared video camera, which records the temperature in a file (file_1ir). From the correspondence of video frames file_1_1.i and file_1_1ir.i, the property of the measured temperature extends to the entire area of muzzle blow gases of this fragment.

Fig. 7 shows the results of joint processing of frames from the video sequences (file_1), (file_2), (file_1ir), demonstrating changes in the pressure and temperature of gases in the muzzle blast. Note that Fig. 7 corresponds to the video sequence processed according to the above method, shown in Fig. 3. (the left column corresponds to a shot from a barrel with high wear, the right column corresponds to a shot from a defect-free table).

The results of joint processing of frames from video sequences (file_1), (file_2), (file_1ir), demonstrating changes in pressure and temperature of gases in the muzzle ejection (lines a, b, c, d) for two different states of the barrel, line shows the gas pressure gradient in muzzle ejection, in the first case, the shock wave turned into a sound wave in the time interval from 0.08 to 0.12 s after the exit of the projectile, and in the second case from the beginning of the exit to 0.04 s.

THE CHOICE OF INFORMATIVE SIGNS FOR THE CLASSIFICATION OF THE CONDITION OF ARTILLERY BARRELS

By analogy with classification by acoustic fields, for classification by video recording of a muzzle ejection, the main task of analyzing a video recording is to select informative sign (IS) that are different for a worn and defect-free barrel. The analysis of the obtained video sequences made it possible to select the following informative parameters for the binary classification of defect-free and worn shafts.

The following were chosen as the main features for classification:

$IS_{1,i}^{video}$ – is the perimeter of the curved line that limits the area of muzzle ejection on the frame recorded at the time t s after the shot – L_t; the perimeter was calculated for the time points t=0.04 s, 0.08 s, 0.12 s, 0.16 s, thus forming four IS $IS_{1,004}^{video1}$, $IS_{1,008}^{video2}$, $IS_{1,012}^{video3}$, $IS_{1,016}^{video4}$.

$IS_{2,i}^{video}$ – is the projection area of the muzzle ejection area on the frame plane at the time moment t s after the shot – S_t, it was calculated for the same time moments, four IS were formed: $IS_{2,004}^{video5}$, $IS_{2,008}^{vsdeo6}$, $IS_{2,012}^{video7}$, $IS_{2,016}^{video8}$.

The volume of the muzzle ejection area at the time points t=0.04 s, 0.08 s, 0.12 s, 0.16 s was chosen as information features from the ninth to the twelfth: $IS_{3,004}^{video9}$, $IS_{3,008}^{video10}$, $IS_{3,012}^{video11}$, $IS_{3,016}^{video12}$ – $\hat{V}_t$.

Since in preliminary experiments there is a difference in the dynamics of changes in the volume of the muzzle ejection area, the following derived features were formed:

$IS_{4,40\_120}^{video13}$ – estimation of the growth rate of the volume of the muzzle ejection area from 40 ms to 120 ms;

$IS_{4,120\_160}^{video14}$ – estimation of the growth rate of the volume of the muzzle ejection area from 120 ms to 160 ms.

These signs were calculated as follows:

$$\dot{V}_{40\_120} = \frac{V_{120} - V_{40}}{80},$$

$$\dot{V}_{120\_160} = \frac{V_{160} - V_{120}}{40}.$$

For all video recordings of shots, the indicated fourteen information signs were calculated.

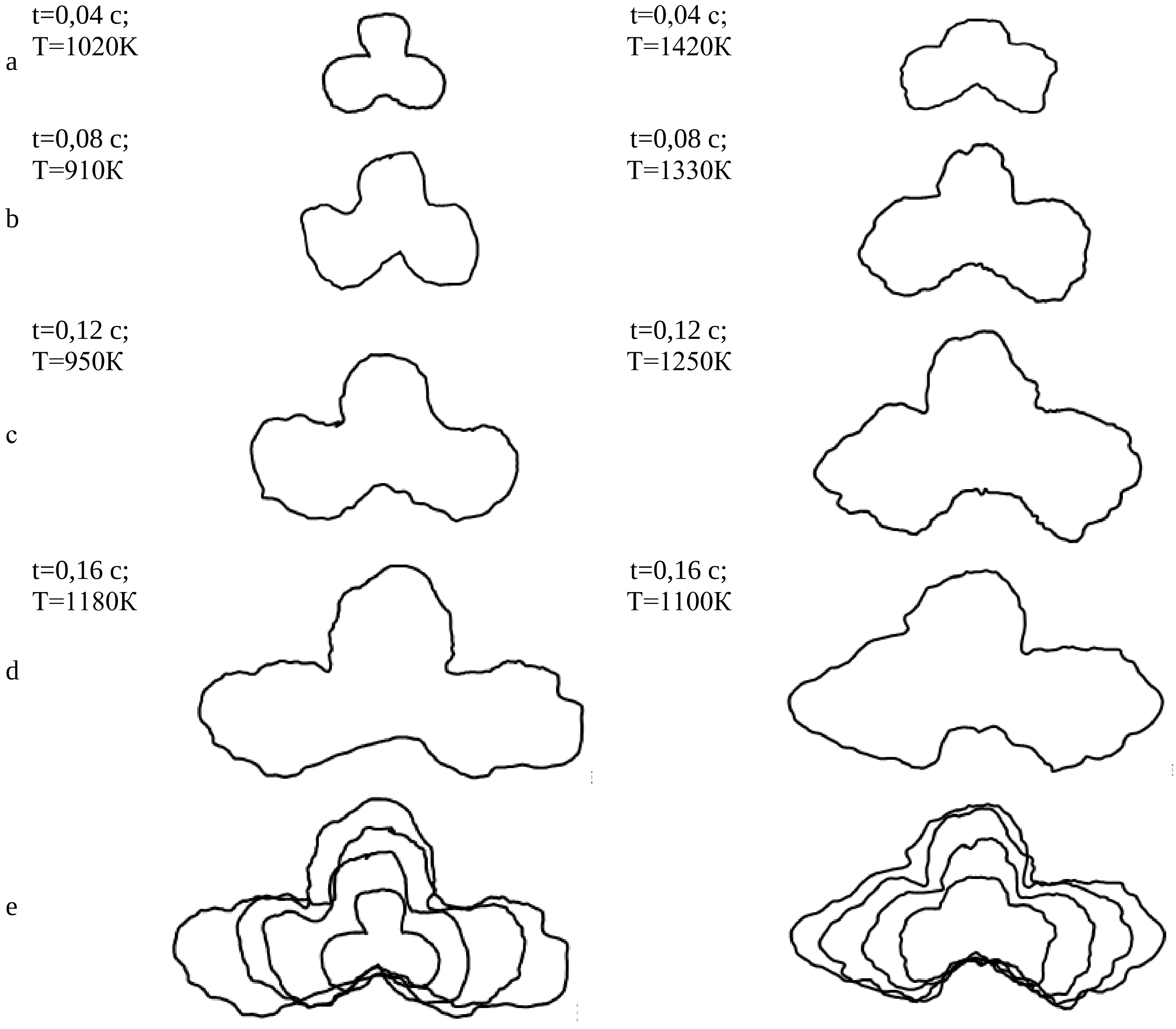


Fig.7. **Results of joint processing of frames**
***Source*: compiled by the authors**

BINARY CLASSIFIER FOR DIAGNOSING THE CONDITION OF BARRELS

Since a classifier based on the SVM (Support Vector Machine) [10] has proven itself well in classifying the state of the barrel according to the acoustic fields of the ballistic and muzzle waves [10], the same classifier was tested to assess the state of the barrel from the video recording of the muzzle burst. In contrast to [10], in this case, a more efficient type of SVM was chosen – the Least Squares Support Vector Machines (LSSVM) method [17]. LSSVM is a modified SVM method that reduces to solving linear systems of equations and ultimately leads to solving a linear programming problem, while the classical SVM method leads to solving a quadratic programming problem. The LSSVM method reduces the computational time by almost an order of magnitude with the same classification quality indicators. The use of the LSSVM method also makes it possible to significantly (2-4 times) reduce the size of the training set [18]. The LSSVM method is implemented as a toolbox of the Matlab system [19].

For a binary classification of the state of the barrels according to video recordings of the muzzle burst dynamics for 59 records obtained as a result of the experiment, vectors of informative sign were calculated. Next, the standard procedure for training, tuning and testing the LSSVM classifier was performed [17, 18]. All the informative signs listed above are normalized to the interval [0;1]. The training sample for setting up and training the classifier was formed from vectors of informative signs with a size of 30 randomly selected records. After training the classifier, an experiment was conducted to assess the quality of the classification. To do this, a test sample of vectors of informative signs for 25 records was fed to the input of the classifier, 13 of which were recorded when shooting from a defect-free barrel, and 12 from a worn barrel.

Until now, the quality of projectile barrel wear classification has been quantitatively evaluated by one quantitative indicator – reliability, which is the ratio of correctly classified objects to the total number of objects [20]. This assessment is not complete enough. The logic and results of the classification are presented in Table. 1. In columns 2 and 3 of the Table 1 shows the true classes to which the state of the trunk belongs. In the rows of the Table Fig. 1 shows the classifier's decisions showing which of the two classes the classifier classifies the shot to. In the cells of the table at the intersection of the corresponding rows and columns, the number of true or false solutions of the classifier is given. Since the main task of the classification is to identify barrels with wear above the allowable level (worn artillery barrels), the “Barrel is really worn out” state is taken as a true positive state. Then the opposite state – “The barrel is really operable” is truly negative. The classifier's decisions can be: “Barrel worn” is a true positive decision, and the classification result: “Barrel serviceable” is a true negative decision. The meaning of erroneously positive and erroneously negative solutions is clear from Table. 1. Corresponding cells of the Table 1 show the quantitative results of the classification of the studied sample.

Table 1. **Logic of wellbore condition classification results**

Barrel states	True positive state	True negative state
Classifier decisions	“The barrel is really worn out”	“The barrel is really workable”
Classified as: “Barrel is worn”	True Positives *(TP)*	Fa1se Negatives *(FN)*
Classified as: “Barrel is worn”	Fa1se Positives *(FP)*	True Negatives *(TN)*

***Source*: compiled by the authors**

The classification quality was assessed by three indicators. The first indicator is a classification error of the first kind – the share of decisions of the classifier that determines the worn barrel as workable

$$F_1 = FP/N_{real},$$

where N_{real} is the actual number of worn barrels.

The second indicator – the classification error of the second kind is defined as the proportion of decisions of the classifier that defines a workable shaft as worn

$$F2=FN/N_{work},$$

where N_{work} is the actual number of workable barrels.

Of course, a mistake of the first kind is more critical in terms of consequences, but in combat conditions an erroneous decision of the second kind is associated with the removal of a defect-free artillery gun from the battle formation and transporting it to a technical unit for diagnostics.

Therefore, a third indicator was introduced, which is a generalized indicator of the quality of classification and shows the probability of error-free classification of the state of the barrel

$$P_0=1-(F_1+F_2).$$

The results of barrel condition classification based on muzzle blast video recording are presented in Table 2.

Table 2. **The results of barrel condition classification based on muzzle blast video recording**

Barrel states	True positive state	True negative state
Classifier decisions	"The barrel is really worn out"	"The barrel is really workable"
Classified as: "Barrel is worn"	True Positives *(TP)* 8	Fa1se Negatives *(FN)* 2
Classified as: "Barrel is worn"	Fa1se Positives *(FP)* 4	True Negatives *(TN)* 11

***Source*: compiled by the authors**

Quantitative indicators of classification: error of the first kind F_1=0.33; error of the second kind F_2=0.15; probability of error-free classification P_0=0.52. Quantitative indicators confirm the possibility of a fairly accurate classification of the state of the barrel by analyzing the video recording of the dynamics of the muzzle burst.

DISCUSSION OF THE RESULTS OF THE STUDY OF THE UNIVERSALITY OF THE CLASSIFIER

Of great practical interest is the study of the possibility of classifying the state of the trunk according to various physical fields and their combination. Below are the results of classification by acoustic fields of ballistic and muzzle waves, and their combinations. At the same time, for training and testing the classifier, informative features were used, which are detailed in [8, 9], [10]. The training and test samples coincide with the classification based on the video recording of the muzzle burst dynamics. The results of classification by the acoustic field of a ballistic wave are presented in Table 3.

Quantitative indicators of classification: error of the first kind F_1=0.33; error of the second kind F_2=0.38; probability of error-free classification P_0=0.29.

Table 3. **Classification results for the acoustic field of a ballistic wave**

Barrel states	True positive state	True negative state
Classifier decisions	"The barrel is really worn out"	"The barrel is really workable"
Classified as: "Barrel is worn"	True Positives *(TP)* 8	Fa1se Negatives *(FN)* 5
Classified as: "Barrel is worn"	Fa1se Positives *(FP)* 4	True Negatives *(TN)* 9

***Source*: compiled by the authors**

The results of classification by the acoustic field of the muzzle wave are presented in Table 4.

Table 4. **Classification results according to the acoustic field of the muzzle wave**

Barrel states	True positive state	True negative state
Classifier decisions	"The barrel is really worn out"	"The barrel is really workable"
Classified as: "Barrel is worn"	True Positives *(TP)* 9	Fa1se Negatives *(FN)* 4
Classified as: "Barrel is workable"	Fa1se Positives *(FP)* 3	True Negatives *(TN)* 9

***Source*: compiled by the authors**

Quantitative indicators of classification: error of the first kind F_1=0.25; error of the second kind F_2=0.31; probability of error-free classification P_0=0.44.

The results of classification by acoustic fields of ballistic and muzzle waves are presented in Table 5.

Table 5. **Classification results for acoustic fields of ballistic and muzzle waves**

Barrel states	True positive state	True negative state
Classifier decisions	"The barrel is really worn out"	"The barrel is really workable"
Classified as: "Barrel is worn"	True Positives *(TP)* 10	Fa1se Negatives *(FN)* 3
Classified as: "Barrel is workable"	Fa1se Positives *(FP)* 2	True Negatives *(TN)* 10

***Source*: compiled by the authors**

Quantitative indicators of classification: error of the first kind F_1=0.17; error of the second kind F_2=0.23; probability of error-free classification P_0=0.60.

To demonstrate the versatility of the classifier, the LSSVM classifier was trained and tested on a set of information features of all three physical fields that occur during a shot – the acoustic field of a ballistic wave, the acoustic field of a muzzle wave, and informative sings extracted from a video recording of the muzzle ejection dynamics. The results of such a combined classification are given in Table 6.

Table 6. **Results of classification by acoustic fields of ballistic and muzzle waves and video recording of muzzle burst dynamics**

Barrel states	True positive state	True negative state
Classifier decisions	“The barrel is really worn out”	“The barrel is really workable”
Classified as: “Barrel is worn”	True Positives *(TP)* 11	Fa1se Negatives *(FN)* 2
Classified as: “Barrel is workable”	Fa1se Positives *(FP)* 1	True Negatives *(TN)* 11

***Source*: compiled by the authors**

Quantitative indicators of classification: error of the first kind F_1=0.08; error of the second kind F_2=0.15; probability of error-free classification P_0=0.77. The results are given in Table 6 show a significant increase in the accuracy of classifying the state of the barrel when analyzing all the physical fields that occur during an artillery shot.

Analysis of the results are given in Table. 6 show a significant increase in the accuracy of classifying the state of an artillery barrel when considering all physical fields from the acoustic fields of ballistic and muzzle waves and video recording of the muzzle burst dynamics that occur during an artillery shot. The data obtained open up broad prospects for the introduction of real-time passive diagnostic systems to increase the efficiency of field artillery.

CONCLUSIONS

A full-scale experiment on video recording of the muzzle ejection of powder gases accompanying a gun shot with high-speed video cameras in the visible and infrared ranges with different viewing angles showed significant differences in the dynamics of muzzle ejection development when firing from defect-free and worn barrels. This gave grounds for the development of a classifier for the state of the barrel according to the level of its wear based on the video recording of the muzzle ejection. A technique for analyzing synchronized video streams has been developed. Based on the analysis, informative signs were established that distinguish muzzle ejection from defect-free and worn barrels. This made it possible to develop a binary classifier based on the least squares support vector machine. To assess the quality of classification, it is proposed, in addition to classification errors of the first and second kind, to evaluate the integral indicator of quality – the probability of error-free classification. It has been established that for the obtained experimental sample, the classification errors based on the analysis of video recordings of the dynamics of muzzle blast development are: error of the first kind F_1=0.33; error of the second kind F_2=0.15, probability of error-free classification P_0=0.52. The concept of a universal stem state classifier is proposed. The concept assumes a classification based on the video recording of the muzzle ejection and the acoustic fields of the shot – ballistic and muzzle waves. It is shown that in this case the probability of error-free classification increases to 0.77.

As a direction for further research, one should indicate the continuation of experimental studies in the presented direction in order to refine the results on large statistical samples. Another direction for further research is to reduce the sets of informative features by highlighting the most significant ones. This will lead to a reduction in the cost of computational time for training the classifier, which is now quite significant.

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Розробка універсального бінарного класифікатора стану артилерійських стволів за фізичними полями пострілів

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АНОТАЦІЯ

Артилерійський постріл супроводжується викидом зі стволу продуктів згоряння порохових газів. Запропоновано використовувати дульний викид для класифікації рівня зносу стволу в процесі стрільби. Проведено натурний експеримент зі швидкісною відеореєстрацією у видимому та інфрачервоному діапазонах динаміки розвитку дульного викиду при стрільбі гармат з бездефектним та зношеним стволом. Дульний викид при пострілі з гармати великого калібру складається з трьох просторових областей: фронтальної та двох бічних, пов'язаних із викидом порохових газів через отвори компенсаторів. Області дульного викиду реєструвалися у бічному та вертикальному ракурсах. Розроблено методику аналізу трьох синхронізованих відеопотоків. Методика дозволила досить повно дослідити процеси динаміки розвитку дульного викиду у бездефектному та зношеному стволах. Вибрано інформативні ознаки, різні для динаміки дульного викиду з бездефектного та зношеного стволів. Це дозволило побудувати бінарний класифікатор стану стволів за рівнем зносу на підставі методу опорних векторів з найменшими квадратами. На відміну від класичного SVM класифікатора це дозволило скоротити час розрахунків і зменшити необхідний розмір навчальної вибірки. Для оцінки якості класифікації запропоновано розраховувати не лише помилки першого і другого роду, а й інтегральний показник – ймовірність безпомилкової класифікації. На підставі результатів польового експерименту показано перспективність застосування відеореєстрації динаміки розвитку дульного викиду для класифікації стволыв за рівнем зносу. Для підвищення достовірності класифікації запропоновано концепцію універсального бінарного класифікатора, який використовує для діагностики стану стволу як відеореєстрацію дульного викиду, так і акустичні поля пострілу – балістичну та дульну хвилі. На підставі експериментальних даних показано, що застосування для бінарної SVM класифікації всіх фізичних полів, що супроводжують артилерійський постріл, дозволяє отримати високе значення ймовірності безпомилкової класифікації. Запропонована концепція діагностики зносу стволів не супроводжується додатковими випромінюваннями, заснована на реєстрації фізичних полів, що виникають при пострілі, і може здійснюватися безпосередньо на вогневій позиції при стрільбі гармати.

Ключові слова: знос стволу; дульний викид; швидкісна відеозйомка; універсальний класифікатор; якість класифікації

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