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Multimedia Firearms Training System

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Abstract**—**The goal of the article is to present a novel Multimedia Firearms Training System. The system was developed in order to compensate for major problems of existing shooting training systems. The designed and implemented solution can be characterized by five major advantages: algorithm for automatic geometric calibration, algorithm of photometric recalibration, firearms hit point detection using thermal imaging camera, IR laser spot tracking algorithm for after action review analysis, and implementation of ballistics equations. The combination of the abovementioned advantages in a single multimedia firearms training system creates a comprehensive solution for detecting and tracking of the target point usable for shooting training systems and improving intervention tactics of uniformed services. The introduced algorithms of geometric and photometric recalibration allow the use of economically viable commercially available projectors for systems that require long and intensive use without most of the negative impacts on color mapping of existing multi-projector multimedia shooting range systems. The article presents the results of the developed algorithms and their application in real training systems.

Keywords**—**Firearms shot detection, geometric recalibration, photometric recalibration, IR tracking algorithm, thermography, ballistics.

I. INTRODUCTION

THERE is a need for training systems allowing their users to train in operational activities at a relatively low operating cost, and without endangering personal health and the lives of others. One of the solutions used in industry practice are training simulators, which are used for ground and air vehicles. Simulation systems commonly use virtual reality in order to reduce operating costs and enable training scenarios that would be difficult or impossible to implement in the real-life training. However, the use of virtual reality is associated with making some simplifications related to the representation of the actual training in virtual world. One of the areas in which any simplification can carry the risk of acquiring erroneous practice is shooting and training muscle memory in carrying out operational activities. This article presents the development of a multimedia shooting range solution allowing for the use of the advantages of virtual reality while using real firearms. The proposed multimedia shooting detection system has five major advantages: firearm hit detection using thermal imaging camera, IR laser point tracking algorithm for analysis purposes, implementation of ballistics equations and algorithms of geometric and photometric recalibration).

II. OVERVIEW OF EXISTING SOLUTIONS

Typically, shooting training is conducted at shooting galleries or at indoor or outdoor shooting ranges with the use of firearms and metal or paper shooting targets. Training of this type can only be conducted in specially protected areas due to the potential dangers that could result in personal injury or loss of life. This results in limited access and skills training, as well as higher costs of operating the solution. For training purposes, shooting targets are usually simple images printed on paper, and therefore it is difficult to perform realistic training of tactics of intervention using real officer's equipment.

Solutions are available in the market, which use virtual technology to significantly reduce the aforementioned problems. Most of those systems require a costly certification process, and therefore, these solutions are characterized by a closed construction that prevents their development and general use, covert implementation of algorithms and the use of often outdated equipment due to the long development cycle of these systems.

Solutions using virtual technology can be divided into two groups: Fully virtual and using firearms. Fully virtual systems use only laser replica firearms to interact with the virtual world. Systems from the second group use vision systems capable of detecting a hit from real firearms, and thus, interact with the virtual world. In this article, we consider only the second group due to the high level of realism.

Based on our review of the existing and applied solutions, there are two main solutions for the detection of hits with the use of firearms: The Digital Police Combat System (DPCS) from SST GmbH [1] and the system offered by LaserShot for the needs of uniformed services [2]. The DPCS system uses a multi-projector system to project an image of virtual reality on the plane of the screen and the system of illuminators and cameras in order to detect the bullet holes resulting from shots into the plane of the screen with a firearm. Lack of implementation of the algorithm of photometric recalibration forces the manufacturer to use projectors with lower image presentation parameters and at significantly increased cost due to the longer stable lifetime of a projector's lamp. The DPCS uses a system of illuminators and cameras in order to detect hits. The system requires a special construction of the screen and makes it impossible to display the image directly on the ricochets muffler, which greatly complicates the structure and increases the cost of the solution, resulting in difficulty in its common usage. Because of the closed construction of the system and the use of simple video scenarios, it is difficult to determine whether the system implements the ballistics equations allowing conducting training for longer distances than 50 m.

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Fig. 1 The system architecture enables modular use of the system (A) a single track, (B) multiple tracks simultaneously

The system offered by LaserShot for the armed forces consists of a thermal imaging camera with a screen made of special material and calibrated with a projector. Detection of hits in the plane of the screen is done using computer analysis of the video stream from the thermal imaging camera and the use of a special screen with known thermal properties. A specially calibrated algorithm allows to threshold the known signature of heat generated by the bullet hitting the screen, and thus detects the x, y coordinates of the strike point in the screen's coordinate system.

As in the case of DPCS, due to the closed construction of the system and the use of simple video scenarios instead of a 3D virtual world, it is difficult to determine whether the system implements the ballistics equations allowing conducting training for longer distances than 50m.

It is worth noting that in versions of the systems offered by both DPCS and LaserShot that use multiple screens, despite the use of expensive projectors they fail to provide a seamless connection between the images projected on individual screens, which significantly reduces the realism of the training and distracts the participants.

III. SYSTEM ARCHITECTURE

After analysis of the existing solutions, we have identified the following needs and problems to be resolved:

1. Creation of a robust physics engine that implements the ballistic equations and takes into account not only the influence of gravity, but also other important factors such as wind, air resistance, gyroscopic drift etc.;
2. Developing an algorithm that allows photometric recalibration in order to create a high quality system without using projectors with high life-time, but often outdated output parameters;
3. Developing an algorithm that allows automatic recalibration of geometric parameters in order to compensate for screen imperfections etc.;
4. Enabling the detection of hits directly on the muffler ricocheting instead of the specially developed screen;
5. Implementation of the algorithm of geometric and photometric calibration through the screen in the multi-projector system will be characterized by the so-called seamless connection;
6. Implementation in the system capabilities of continuously tracking the target point in order to collect more advanced statistics than is currently available, in order to allow the possibility of carrying out an exhaustive review after a performed action.

The developed system consists of the following hardware components: a projection module comprising two high quality video projectors, computer responsible for the implementation of the algorithms, computer responsible for generating the virtual reality, and the module comprising multimodal system: FIR, IR and visible light cameras.

The main goal of the system is the modular design that allows configuration of shooting detection on both a single track, and the construction of multi-lane systems (Fig. 1).

A. Geometric Calibration

The application of a simulation system that maps actual situations can be used in training operations at a low cost and without endangering life. The basis of the operation of the multi-projector systems is to ensure the consistency of the visualization, the geometric and photometric calibration of the projectors in done in such a way that any human observer cannot determine a distinct line between one projector and another. If such requirements are met, the participants of the training course experience such system as more effective and realistic.

During creation of an image projection system using multiple projectors there are a number of challenges with regard to establishing the correct geometric alignment of the projectors and the photometric calibration so that the resulting image is consistent in terms of geometry, color and luminance [3]-[5]. For this purpose, the geometric and photometric calibrations are performed. Calibration ensures consistency of the geometric visualization composed of images from multiple projectors on the projection screen in terms of geometric means, e.g. the behavior of straight lines along the entire visualization [3], [4], [23].

Let us define the starting image as an image generated by a virtual reality engine in the computer screen coordinates. Transforming the starting image in such a way that its projection on the screen is in line with the earlier designed place during the geometrical calibration. For that purpose, finding such a transformation is needed. The operator of the system can determine such a transformation manually by changing the geometry of the starting image, generated by the virtual reality engine. This can be done by changing the positions of the corners of the image and observing the changes of the geometry of the projected image on the screen at the same time. This procedure could be also done automatically using vision information from the camera [5]. Feedback from the camera, in the form of the image, could deliver information about quality of the calibration. Based in those data, the necessary changes of the geometry of the image could be computed.

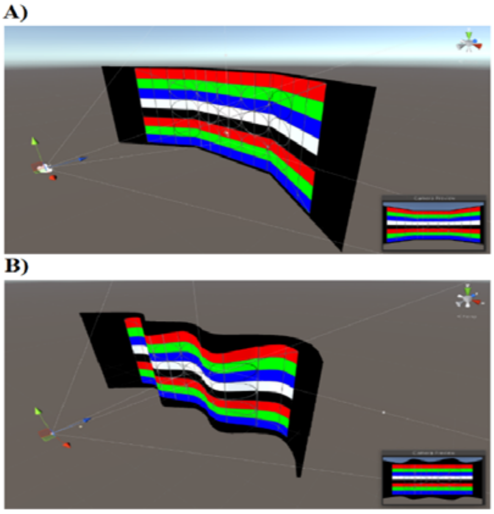

Fig. 2 Screen of the projection consisting of a few plains (a) and screen of an irregular shape (b)

Depending on the type of the screen of the projection we can distinguish two kinds of shapes of the screen. The first kind is a screen made from one or more planar surfaces, and the second is a screen of an irregular, unknown shape (Fig. 2). In case of the calibration for the first type of screen, it is possible to use linear transformations e.g. homography. In the second case the mapping pixel to pixel is needed.

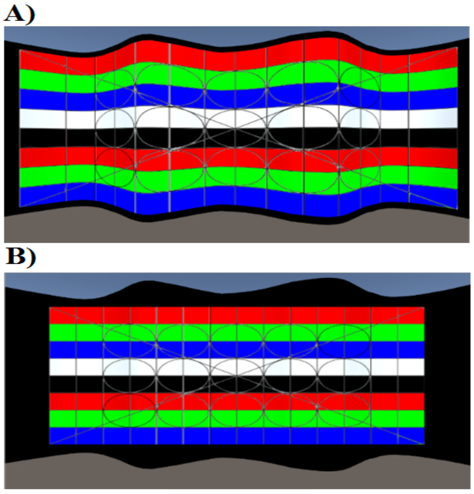

Fig. 3 Two methods for geometrical calibration using irregular shaped screens. First, it is "sticking" of projection to the shape of the screen like wallpaper is mounted to a wall (a), second it is a calibration of the projection relative to the chosen position of the observer in the space so that shape of the projection comparatively is kept (b)

When we are dealing with screens of irregular shape, we can distinguish two approaches to the geometric calibration (Fig. 3).

The first one assumes that visualization is rigidly "glued" to the projection screen; this approach can be compared to wallpaper on the screen. The second approach is to calibrate the projection system to the desired position of the observer in the space in such a way that the image is seen correctly from that location.

Photometric calibration provides continuity of brightness levels in the visualization. In this paper, the authors present a calibration method to calibrate any number of DLP projectors on the screen comprising of any number of planes. Based on tests, the authors have distinguished factors distorting the output visualization, such as offset color black, brighter areas receipt of images from adjacent projectors and developed methods that allow for a uniform visualization.

Having detailed information about how the vertices of the output image (texture) are converted to the output image of the projector it is possible to map the entire texture from one quadrangle into another [5]. The aim of the methods is to find bilinear equations opposite to the following:

$$X = a_0 + a_1U + a_2V + a_3UV \tag{1}$$

$$Y = b_0 + b_1U + b_2V + b_3U \tag{2}$$

After transformations, we obtain equations for the coordinates *U* and *V*:

$$U = (X - a_0 - a_2V)(a_1 + a_3V) \tag{3}$$

$$V = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{4}$$

The geometric calibration challenge is a seamless connection of adjacent projected images [6]. For this purpose, the blending of images of the joints, described by transfer function whose argument is the distance from the edge of the pixel image, is used. The output value of the pixel is its actual value multiplied by the value of the function.

$$f(x) = \begin{cases} 0.5\,(2x)^p & for\ \ 0\ \le x\ \le 0.5 \\ 1 - 0.5\,\big(2(1-x)\big)^p & for\ \ 0.5\ \le x\ \le 1 \end{cases} \tag{5}$$

The curvature of the function is controlled by the parameter p, where blending is linear with p = 1, the growth of p will increase the degree of curvature of the blending. In the case of image projection systems, applying only the function f is insufficient. It is necessary to take into account of the gamma function that informs how the pixel values are mapped to the brightness of the device. The value of gamma *G* is in the range 1.8 to 2.2 [6]. Blending after taking into account the gamma is as:

$$f(x) = \begin{cases} f(x)^{\frac{1}{G}} & for\ \ 0\ \le x\ \le 0.5 \\ f(1-x)^{\frac{1}{G}} & for\ \ 0.5\ \le x\ \le 1 \end{cases} \tag{6}$$

The results of these functions are presented in the test chapter of the article.

B. Ballistic Engine

Marksmanship Training Systems includes simulation of the bullet trajectory, to make it more realistic. Movement of the projectile and forces acting on the bullet is the subject of exterior ballistics that is well described in scientific literature [7], [8]. Based on that, a mathematical model was created. It describes the movement of the bullet as close as possible to reality. These following effects influence the trajectory of a bullet [7]:

- Gravity force – causes a bullet to fall.
- Air resistance – causes a bullet to decelerate.
- Wind – causes a bullet to change flight direction.
- Coriolis effect – additional forces acting on a bullet, as it moves relative to a rotating frame of reference.
- Gyroscopic drift – drift caused by rotation of the bullet.
- Magnus effect and Poisson effect – additional forces acting on a bullet caused by the circular movement of a bullet in the atmosphere.

Atmosphere parameters such as air temperature, air density, air pressure also impact on all effects that are caused by bullet movement in atmosphere. These effects are: air resistance, wind, Magnus effect, and Poisson effect. However, gyroscopic drift, Magnus effect and Poisson effect do not have a significant impact on the bullet trajectory, and Poisson effect cannot even be described by mathematical equations. Therefore, not every effect is considered in the mathematical model of a bullet trajectory was used for the simulation. To simulate projectile movement, the mathematical model takes into account: Gravity force, air resistance, wind, Coriolis effect and the changing parameters of atmosphere. These effects have significant impact on bullet trajectory.

To simulate bullet trajectory, specific bullet parameters are required including its weight, caliber, ballistic coefficient and drag model [8]. A ballistic coefficient is a bullet's parameter that describes its ability to overcome air resistance during flight. Drag model is a function that describes a relationship between bullet velocity and drag coefficient. Combining ballistic coefficient and drag model allows the computation of drag force acting on a projectile. These parameters are often found in ballistic tables provided by ammunition manufacturers.

C. IR Laser Point Tracking

Modern tracking algorithms are focused on complicated objects, which can be described with complex methods. Object tracking survey [9] lists four common visual features: color, edges, optical flow and texture. These features are used to build models, create templates and probability densities functions in order to find representation of object. Novel trackers can define and learn about the object not only by initialization, but online as well [10]. However, tracking a simple laser dot, which is seemingly immutable in real-time even in an environment close to a laboratory simulation becomes difficult task.

The basic reason for the problems is the fast laser movement. Because of its small dimensions and rapid dynamics, it is often observed that it can move multiple diameters between two consequent frames. What is more, rapid movements create a blurred and darker dot, which means that none of features listed above are preserved. The size of the dot during movement can become be observed by the camera as many times larger than static dot. Once an area of the dot is too big, information about the relevant position of the laser is lost and cannot be calculated from just a single frame. Last but not least is the problem is of real–time processing in high resolution video streams. This is n important task, because it can increase the quality of the tracking. The ability to process frames with high frequency allows usage of a faster camera and thus reducing the dot's blurring effect.

We have selected few trackers to compare with our algorithm. The first of them, the FragTrack [11] algorithm divides a tracked object to set of fragmented images, where each fragment is represented and identified by histogram. The second algorithm called VTD [12] is based on two steps – the first is defining the object's observation and movement model. Usage of this data can make the tracker robust to simultaneous changes of movement and shape. In the second step, tracking is divided into group of elements, where each one traces a single, different type of object change. In order to combine the results of the elements, it uses the Interactive Markov Chain Monte Carlo (IMCMC) method. The Locally Orderless Tracking (LOT) [13] method is based on the combination of the image space and object appearance, which allows the tracking of targets that are deformed. This method adapts its operation to the form of the object that is being tracked. If the object is a solid body, then the value of the arrangement coefficient is close to zero and can be used in methods based on spatial alignment such as pattern matching. Otherwise, when the shape of the object is changing, the LOT method cannot take advantage of spatial fit and works by matching the histogram.

Our algorithm, RLPT, is a feature based tracker. In order to determine whenever the processed object of interest of the tracker is the laser's dot or noise, we use two features: color and area of the dot. Both must match predefined, parameterized thresholds. The tracking processing for every frame works in two different modes: the regional or global search of a point. In regional mode, the search is performed only within parameterized boundaries around the previous laser's position e.g. within a 50x50 pixels bounding box around the last known laser's position. In the case of rapid dot movement it starts to estimate position of the laser using the point's velocity and contour. If a regional search fails or the position of any laser in a previous frame is unknown, a global search is conducted. It scans the whole frame for a point, which can be possibly related to the laser. The algorithm returns to the found position of the laser as a centroid value of the found laser's dot. If the algorithm did not find the laser, it returns the information that the laser was not found. The details of the algorithm are presented in article [14].

D. Photometric and Geometric Recalibration

The first stage of recalibration for color is the detection of light the area of each projector relative to the screen. This is done by displaying a green image for each projector, which is then thresholded in order to detect an area of the projector (Fig. 4). It is assumed that before the camera is calibrated [20].

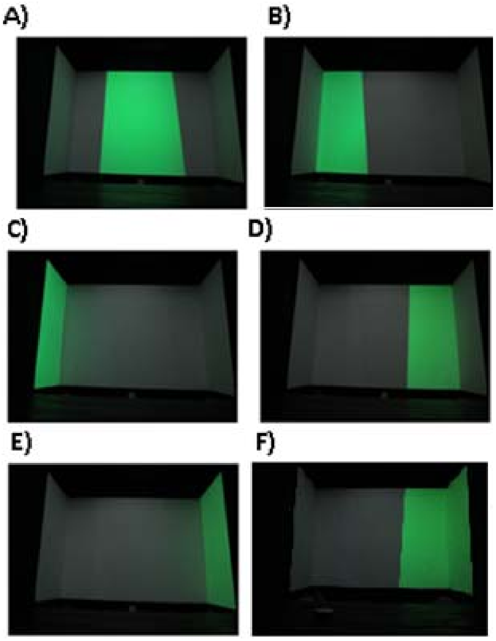

Fig. 4 Steps of an algorithm of automatic detection of an area of each projector in the multi-projector system

The screen detection presented in Fig. 4 is sufficient for a flat screen surface; however, in reality, most screens are not perfectly straight; thus, note the imperfections near the center of the screen (Fig. 5 (A)). Therefore, it is required to determine the shape of the screen. One of the possible methods to determine the shape of the screen is to visualize horizontal and vertical stripes (Fig. 5 (B)) and detect their intersections. In order to compensate for its imperfections, it is necessary not only to detect intersections of the displayed lines, but also to detect points at the border of a previously thresholded screen area per projector (Fig 5 (C)). Following on from these steps, it is possible to automatically compute the homographies required to compensate for projection screen imperfections.

The photometric color recalibration algorithm for a multi-projector system proceeds in the following steps:

1. Automatically detect the screen and compensate for its imperfections.
2. Determination of the transfer function projectors and their reversal [16].
3. Balancing the white point for each projector individually [15], the effect of actions are gains for the different channels that are common to all the pixels of the projector.
4. Transforming gamut for each pixel [15], the result is a map where the pixel belonging to the common parts reduces the brightness.
5. Filtration using morphological opening, the structuring element has a square shape with a side length equal to 10% of the root of the sum of pixels of the histogram multiplied by the width of the histogram.
6. Reducing the brightness of each pixel [15], [16], resulting in two maps - gains and redeployment of black.
7. Smoothing brightness for each pixel [15], the result is another map of gains.

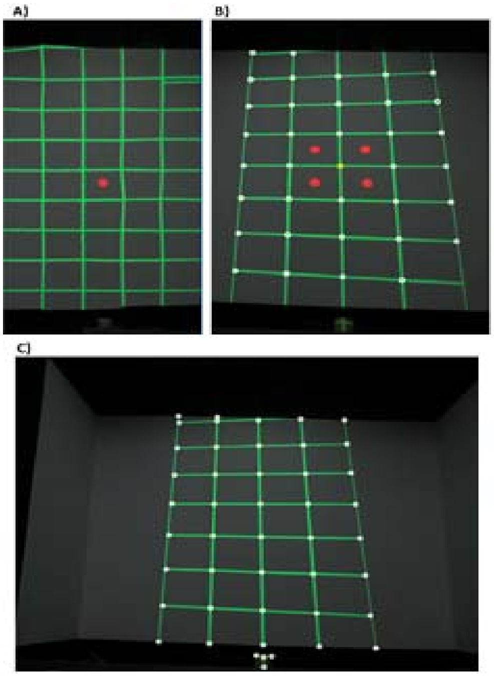

Fig. 5 (A) Screen imperfections visualization using horizontal and vertical straight lines in virtual reality, (B) detection of lines intersections, (C) detection of line's endpoints

IV. TESTS AND RESULTS

The developed algorithms were implemented in software and tested quantitatively and qualitatively. Selected results are shown below. Tests were performed both in simulation and in reality conditions. Tests were present at all stages of the calibration to verify the correctness of the implementation of the methods and the evaluation results. Simulation tests were performed in simulation engine, which enables the deployment of virtual projectors and a virtual projection screen, built by the user and in MATLAB. These allowed for the preliminary examination of the accuracy of the methods used. The tests were performed on the prepared actual image projection system consisting of three DLP projectors and the screen, which is made up of three perpendicular walls (Fig. 6).

A. Photometric Recalibration

The effects of the selected steps of photometric recalibration algorithm are illustrated in Fig. 7.

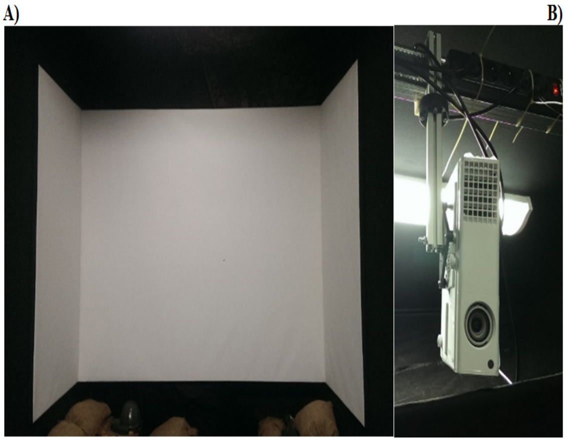

Fig. 6 The tested system of image projection. Screen (A) and (B) one of 3 DLP projectors

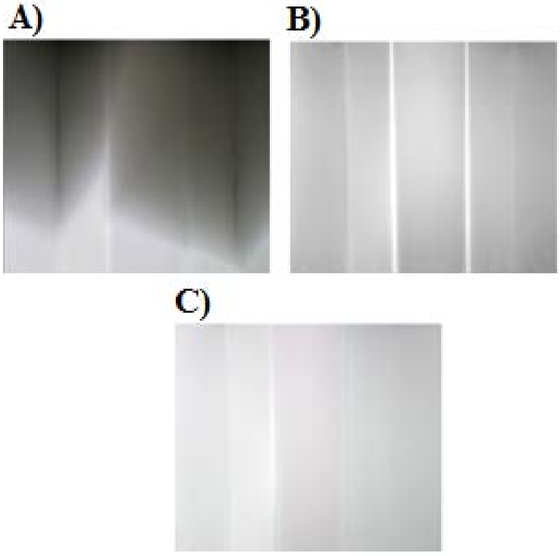

Fig. 7 The result of the selected steps of photometric recalibration algorithm. (A) the result of step 3, (B) the result of step 4, (C) the result of step 6

The results of the implementation of all the steps of the proposed algorithm are shown in Fig. 8.

B. Hit Point Detection

The developed and implemented hit detection algorithm using the video analysis of a stream from a thermal imaging camera which was based on the authors' experience with the friends-foe recognition systems [19], [22], underwent extensive testing in quantitative and qualitative terms. The input data for the algorithm is a video stream from a thermal imaging camera (Fig. 9). The 3D visualization of the first and last frame of the sample sequence recorded during the filming of five test shots is shown in Fig. 10.

During the testing, it was found to be experimentally possible to detect the bullet’s hits in the firearm ricochets muffler:

- In different places of the plane of the screen,
- In the same place of the plane of the screen,
- Single shots,
- Series (up to 600 rounds per minute),
- Detection of shots from handguns,
- Detection of shots from rifles,
- Detection of ASG shots using BB above 2g.

The result of the implemented algorithm is illustrated in Fig. 11.

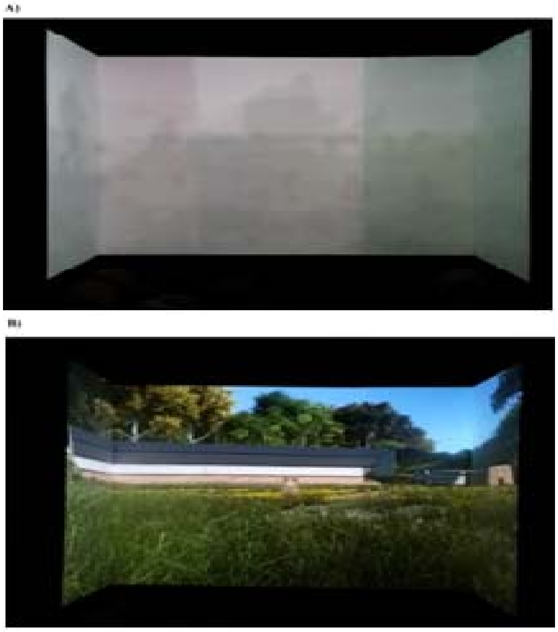

Fig. 8 The result of implemented photometric recalibration algorithm (A) Before use, (B) after use

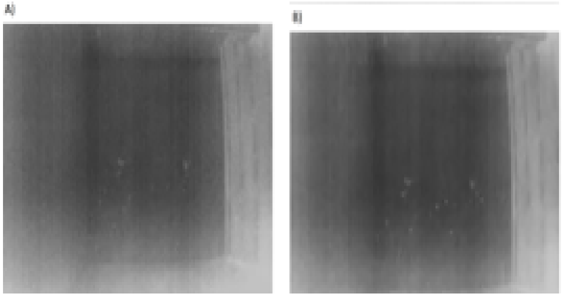

Fig. 9 The first and last frame of the sample sequence recorded using a thermal imaging camera while five shots were fired. (a) first, (b) last

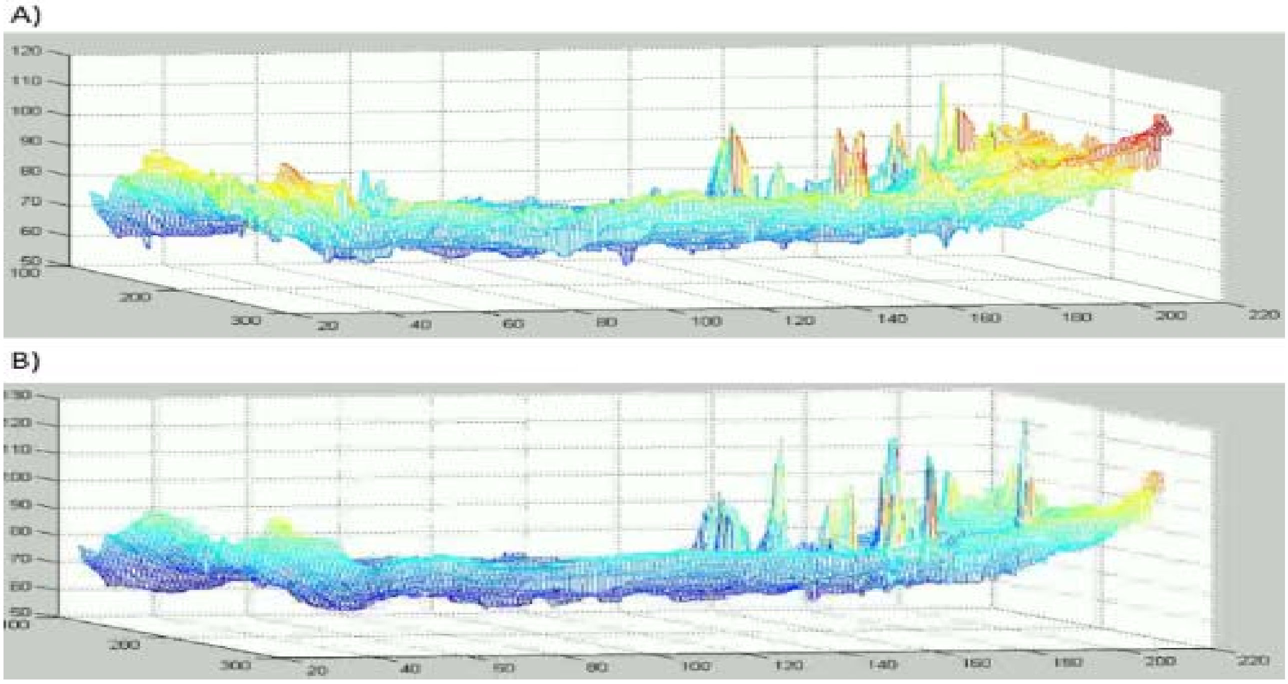

Fig. 10 3D visualization of the first and last frame of the sample sequence recorded using a thermal imaging camera while five shots were fired. a) first, b) last

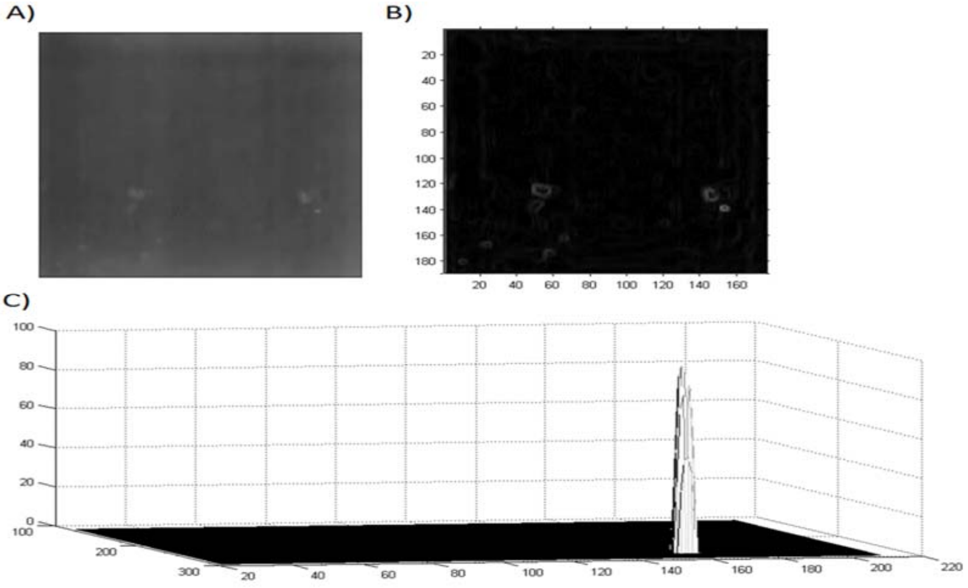

Fig. 11 3D The results of implemented algorithm of a gun’s bullet hit into firearms ricochets muffler. a) before processing, b) after processing using the dynamic model of the background, c) 3D visualization of the frame sequence with detected hit point

C. Laser Point Tracking

The test data for the IR laser point tracking includes three recordings, which are named: Easy, Medium and Hard. Each of them contains two moving laser dots. In the Easy test the lasers’ dots move slowly and never blur. In the Medium test the lasers move at an average speed and blur occasionally, while in the Hard test they move dynamically and are blurred through the majority of the record and finally disappear for a few frames: Figs. 12-15. The database of reference positions and areas for each frame has been carried out manually, and thus, it can be used for analysis of the algorithm.

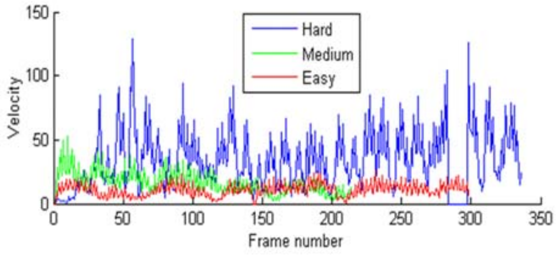

Fig. 12 Comparison of velocity of the dot in particular tests

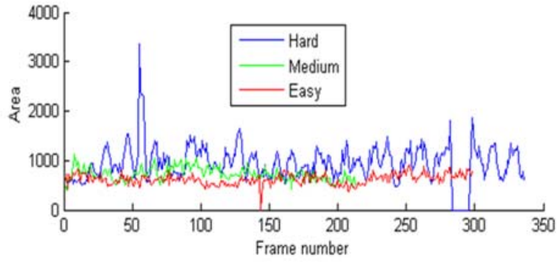

Fig. 13 Comparison of the area of the dot in particular test

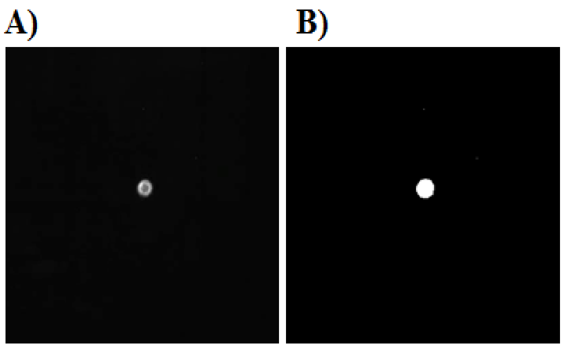

Fig. 14 Comparison of the static dot (A) and its thresholded bitmask (B)

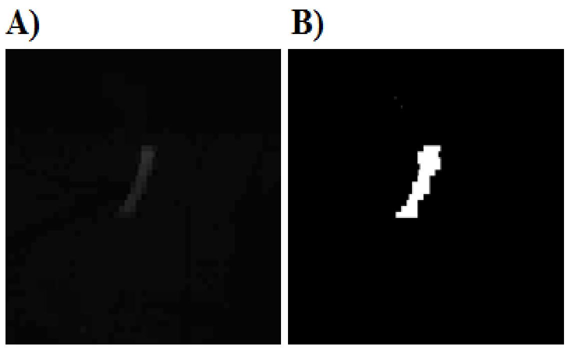

Fig. 15 Comparison of the blurred dot (A) and its threshold bitmask (B)

The proposed Laser Point Tracker (LPT) was tested on the three test records described earlier. The results were compared with those of three other trackers: LOT, FragTrack and VTD. Tests were run on default parameters on implementations published by their authors.

Quality factor q was calculated as:

$$q = \begin{cases} 2\dfrac{(A \cap B)}{(A+B)}; A > 0, B > 0 \\ 0; A = 0, B > 0 \\ 1; A = 0, B = 0 \end{cases} \qquad (7)$$

where A is the dot area in the reference data, B is the dot area returned by the tracker. Quality factor q represents the normalized value of common area of dot A and B. Values vary from 0 to 1. Area value is equal to 0, when no dot was found in a frame.

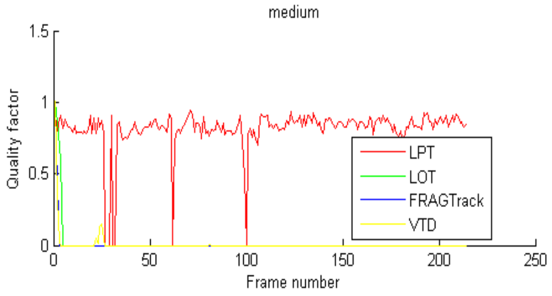

Fig. 16 Quality factor for different trackers over time for Medium sequence

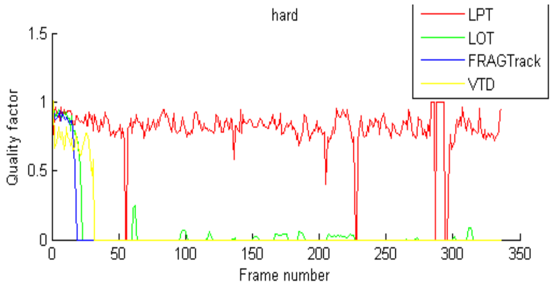

Fig. 17 Quality factor for different trackers over time for Hard sequence

The proposed algorithm LPT is able to a track laser's point almost constantly, regardless of the sequence (Figs. 16 and 17), and even if it loses the laser point for a few frames, it is able to find it again, which is a huge advantage over other trackers. The Hard test sequence contains a video recording of the high speed dynamic movement of the laser's dot and in consequence its severe blurring. Regardless the difficult conditions for object trackers, the methods LOT and VTD managed to successfully track the laser's dot at the beginning of the Hard sequence. However, once observed by the camera, the laser's dot started to become blurry (in the Medium test) and both object trackers lost the object. Unfortunately a static laser's dot was not complicated enough to be properly recognized by FragTrack.

D. Ballistic Engine

For testing purposes, we ran a simulation for three different bullets:

- Parabellum 9x19mm,
- Winchester .308,

- BMG .50.

The simulation results were compared to ballistic chart data provided by the ammunition producers. The initial conditions for the simulation were set to match the sight calibration from the ballistic charts. Sight calibration is the act of adjusting firearm sight to hit the center of a target at a fixed distance.

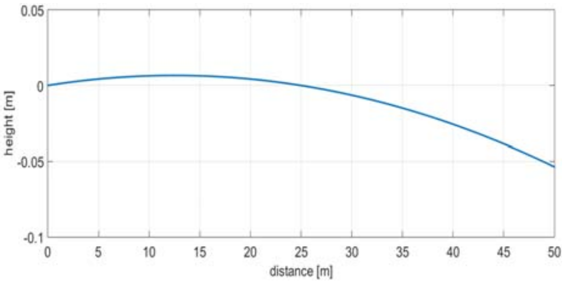

Fig. 18 Results of simulation for Parabellum 9x19mm at a distance of 50 meters. Sight was calibrated for 25m

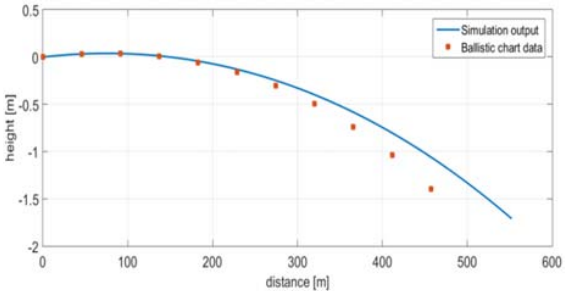

Fig. 19 Results of simulation for Winchester .308 bullets compared to ballistic chart data

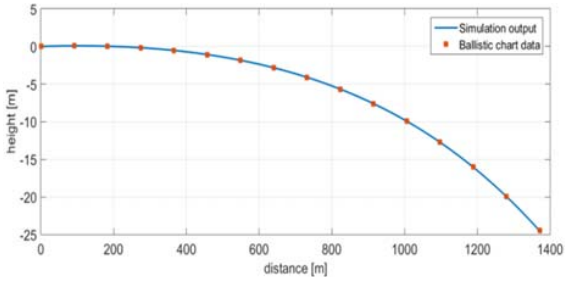

Fig. 20 Results of simulation for BMG .50 bullets compared to ballistic chart data

Results of the simulations are shown on Figs. 18-20. The results show that the outcomes of the simulations are very close to the ballistic charts data. This leads to the conclusion that the used mathematic model of projectile movement appropriately describes the bullet's true trajectory.

V. SUMMARY AND CONCLUSIONS

The results of the study confirm the possibility of the practical application of these algorithms to solve the current problems occurring in the industry. Implemented algorithms of geometric and photometric recalibration allow a significant reduction of the negative impacts of the use of projectors such as changes in color and light intensity due to the lamp used. The complexity of the presented solution is a new quality among existing training shooting systems, which in most cases have been developed over a decade ago and continue to benefit from the technology developed back then. The presented algorithm of a gun's bullet hit detection using thermal imaging was able to successfully detect shots and allowed for detection of both single shots and a series of up to 600 rounds per minute. The acquired results meet the expectations for the shooting training requirements for the majority of the uniformed services. The results of the implementation of external ballistics equations in the simulations engine were compared with actual shooting tests and ballistic tables [7]. The level of compliance at distances exceeding 400m allows the use of a developed computational engine to simulate marksman training. In summary, the concept, development and results of the multimedia shooting detection system are promising and allow for practical application in real-life training systems, e.g. for uniformed services shooting training. It is worth noting that the use of virtual training systems positively affects the motivation to exercise and the acquired in the simulator skills are possible to use in real life [17], [18], [21] (Fig. 21).

Fig. 21 The real life application of the described concept of multimedia shooting detection system for shooting training system

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