Active IR System for Projectile Detection and Tracking

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***Abstract*—Reliable detection and tracking of high-speed projectiles is crucial in providing modern battlefield protection or to be used as a forensic tool. Subsonic projectiles fired from silenced weapons are difficult to detect, whereas reliable tracking of the projectile trajectory is hard to accomplish. Contemporary radar based counter-battery systems showed to be valuable in detection of incoming artillery fire, but are unable to provide detection at close ranges. In this paper, an active IR system is proposed that aims to detect and track incoming projectiles at close ranges. Proposed system is able to reconstruct projectile's trajectory in space, predict impact location and estimate direction of projectile origin. Active detector system is based on a pair of high-speed cameras in stereo-configuration synced with computer and IR illuminator that emits coded IR light bursts. Innovative IR light coding enables automated detection and tracking of a nearby projectile and elimination of false positive alarms caused by distant objects.**

***Index Terms*—gunshot detection system, infrared imaging, object recognition, reconstruction algorithms, stereo image processing.**

I. Introduction

It is very challenging for researchers to detect incoming subsonic ammunition or projectiles fired from silenced weapons. Acoustic techniques employ sensors, or array of sensors that detects shockwaves of supersonic projectiles passing through the air, allowing the system to calculate the coordinates and/or trajectory of the shot [1-7]. However, if shots are travelling at subsonic speeds, they are difficult to detect by acoustic sensors. Although the projectile is travelling at subsonic speed, some acoustic-based techniques rely on muzzle blast detection that measures pressure traveling at the speed of sound in all directions to deployed sensors [8].

Other techniques based on optical or optical-electrical sensors (Infra-Red technology) have been proposed, allowing the system a visual detection of muzzle flash [9]. Unfortunately, most of present day weapons are employed with bullet/projectile (flash) suppression techniques which make the muzzle blast hard to detect by both IR (Infra-Red), as well as acoustic detection systems. On the other hand, some IR detection techniques employ detection and tracking of hot projectile trajectories [10-13]. These passive optical systems detect IR radiation from a bullet/projectile that becomes hot due to aerodynamic heat produced by traveling at supersonic speeds. Unfortunately, it can be very challenging to track cold loaded ammunition that travels at subsonic speeds and does not develop aerodynamic heat [14]. Other researchers propose multi-sensor radar platform for projectile detection and localization [15-17], which include deployed counter battery radar-based systems that can detect and track projectiles up to 24 km range and with accuracy up to 1% of range [18].

We present a system that detects and tracks cold loaded projectiles traveling at subsonic velocities at close range that cannot be detected by passive systems or by naked eye. We introduce innovative coding of IR light that enables simple, reliable and automated detection of projectile trajectory in a range of IR illuminator. High speed cameras in stereo configuration allow us to detect projectile direction, origin and trajectory and simultaneously estimate impact location with high accuracy.

II. Proposed Design

We present the development of a prototype for an active projectile detection that operates in near IR spectrum. The proposed system detects and tracks projectile location in space enabling full reconstruction of projectile trajectory, estimating the location of impact and incoming direction with high accuracy. Due to their high speeds, projectiles can only be visible in camera image if they are illuminated by a high-intensity illuminator. Although IR light emitted by illuminator is not visible by naked eye, most CCD and CMOS cameras are sensitive in near-IR spectrum [19]. Cameras are additionally modified to capture only in near-IR spectrum by means of optical filtering. Since IR reflector is continuously illuminating, projectile that travels in front of the camera will be visible in the image as a blurred line. Those lines represent all locations of the projectile during particular time frame (projectile trajectory trail). We propose stereo camera configuration, meaning that projectile trajectory is visible in both left and right camera image.

The proposed system aims to detect projectiles traveling at subsonic velocities (100 - 300 m/s), so cameras must be fast enough to capture projectile trail in a single frame. In scenario where 100 fps (frames per second) camera is used, simple calculations show that projectile traveling at 100 m/s displaces 1 m during one time frame (or 3 m if projectile is traveling at 300 m/s), and must be captured by both cameras. To effectively detect higher velocity projectiles, more advanced cameras should be used, such as "Basler acA640-750um" industrial cameras that can operate at more than 750 fps. As relatively small projectiles are used, their small surface and surface reflective ratio (even when

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illuminated with a powerful IR illuminator) make them hardly visible, thus forcing implementation of advanced image processing algorithms for object detection.

To minimize false positive alarms, illuminator light must be synchronized with both cameras. In one frame, the space in front of the camera is actively illuminated, whereas in the following the illuminator is turned off. By repeating this process, a set of actively illuminated and non-illuminated frames is obtained. Using this modification, only nearby objects are intensified in camera image by illuminator, whereas further objects (behind illuminator's effective range) are not intensified. This allows us to improve detection effectiveness by eliminating false positive alarms caused by objects far behind the system's effective detection range.

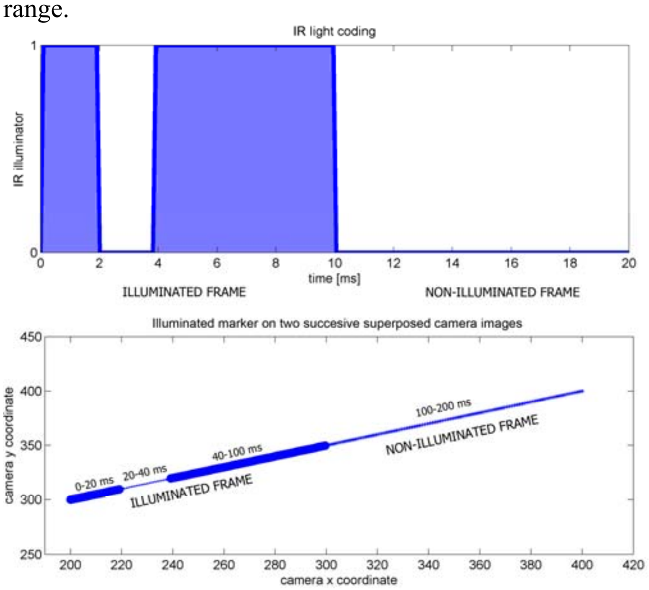

Figure 1. Proposed light-sequences produced by IR illuminator (top) and illuminated projectile trajectory as seen in camera image (bottom)

Another modification of light sequence is also proposed: the area in front of the camera is actively illuminated for 20% of the frame's total time, followed by 20% of time not being illuminated, and finally, by actively illuminating the remaining 60% of the time. This illumination sequence is presented in Fig. 1 top. The proposed modification allows simpler implementation of projectile direction estimator. It additionally removes false positive alarms by considering only two lines in serial (continuous) configuration, where one line is relatively longer and / or ticker than the other. Simulation of projectile illuminated by proposed sequence and captured by single camera is presented at Fig. 1 bottom.

III. Measurement Setup

The proposed active IR projectile detection system includes both hardware and software components. The main hardware component is a pair of Basler 602fc high speed digital cameras, capable of feeding the computer with a video of 656 x 491 pixels resolution at a rate of 100 Hz. Fujinon 12.5 mm HF12.5HA-1B lenses were attached to the cameras, effectively covering area with 4 m in width, 3 m in height and 8 m in depth, over which IR filter lens (940 nm) is installed. Cameras are connected to the computer using a high-speed fire-wire interface, driven by Intel Core i5-3450 processor, with 8 GB of RAM and 64 GB SSD drive for storing the camera's video feed. Besides obvious image capturing task, computer is also responsible for executing the algorithm that detects, tracks and calculates trajectory of projectiles from camera images. Hardware components and measurement setup is depicted in Fig. 2. Image acquisition and image processing, together with 3D reconstruction algorithms are executed in Matlab 2016b software package with installed image acquisition, image processing and camera calibration toolbox. Another important hardware component of the system is an IR reflector (illuminator) made from five 3 W SMD IR LEDs operating at 940 nm wavelength, which are used to illuminate nearby objects. Both cameras, together with the IR illuminator, are hardware synced and controlled by ATmega 2560 microcontroller. IR illuminator is powered by external power source over TIP142 MSOFET power transistors, which are digitally controlled by the same microcontroller, allowing fast switching of IR illuminator up to 10 MHz. Both cameras and reflector are placed on a metallic construction and mounted on camera tripod and raised to effective height of 150 cm. Whole detection system weighs less than 2 kg and is 15 x 40 x 10 cm in size (excluding the tripod and computer).

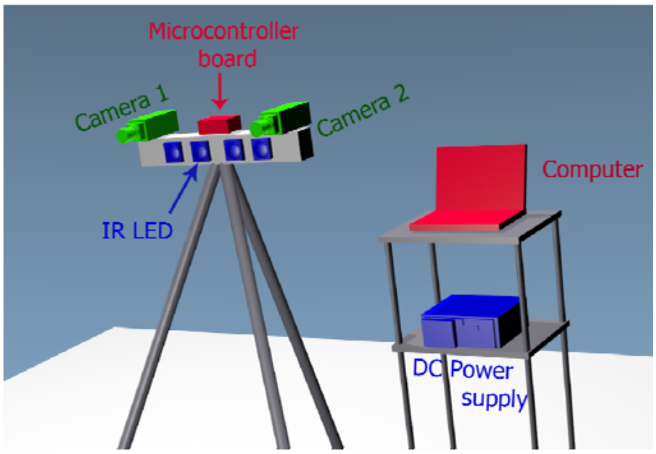

Figure 2. Components of the active IR projectile detection system

As a projectile launcher, handgun that uses compressed CO_2 as a propellant was chosen to be ideal. It is relatively safe to use and launches non-lethal pellets ammunition. For the trials of a proposed system, Walter CP99 produced by Umarex was used. It has a rifled 4.5 mm inner barrel with 8.5 cm (3.3") length, and can launch pellets of various types with maximum velocity of 360 fps (~110 m/s) propelled by the expanding CO_2 from a 12 g canisters. RWS Sportline 4.5 flat-top pellets with a mass of 0.45 g were used as ammunition, which allowed the maximum projectile velocity at short ranges. Next, we introduce projectile trajectory detection in 2D images based on computer vision.

IV. Projectile Trajectory Detection

First step towards successful projectile trajectory detection is to extract parts of the image that appear to be in motion. Unlike the following stages, where detection is performed solely on actively illuminated frames, at this point both non-illuminated and actively illuminated frames are analyzed. Current background estimate used for motion detection is built iteratively for each frame using the current frame and the previous background estimate. More specifically, background estimate is calculated using Eqs. (1)-(2), as introduced in [20]:

$$B_0 = I_0 \tag{1}$$

$$B_{n+1}[k,l] = \begin{cases} \alpha B_n[k,l] + (1-\alpha) I_n[k,l] \\ B_n[k,l] \end{cases} \tag{2}$$

where $I_n[k,l]$ represents an intensity of a pixel with coordinates (k,l) in the n^{th} non-illuminated frame, and $B_n[k,l]$ is an intensity of a pixel in a background estimate. The actual motion detection is given in Eqs. (3)-(4):

$$T_{n+1}[k,l] = \begin{cases} \alpha T_n[k,l] + (1-\alpha)(5 \cdot |X_n[k,l] - B_n[k,l]|) \\ T_n[k,l] \end{cases} \tag{3}$$

$$|X_n[k,l] - B_n[k,l]| > T_n(x) \tag{4}$$

where $X_n[k,l]$ represents an intensity of a pixel in n^{th} frame (which can be either actively illuminated or non-illuminated frame), $T_n[k,l]$ represents a threshold value, and α a parameter from interval $[0,1]$ that defines how fast the new information supplants old observations. Please note that in Eqs. (2)-(3) the upper parts of the equation represent a result if the current pixel is considered stationary, whereas lower parts represent the result if the current pixel is considered moving (i.e., Eq. (4) is satisfied).

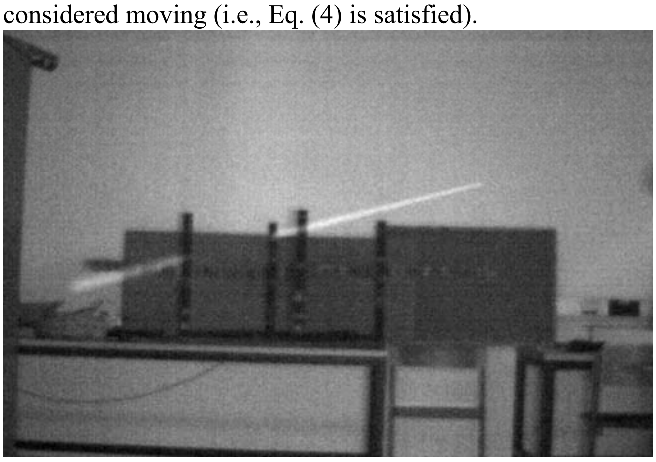

Figure 3. An example of an actively illuminated frame that contains a projectile trajectory trail of a projectile traveling at a subsonic speed

Projectile trajectory trail can only be visible in actively illuminated frames. However, obtained background estimate is used to detect motion in both non-illuminated and actively illuminated frames, simultaneously. This gives us the opportunity to detect and eliminate false positives that are a consequence of movement in the background scene. Therefore, image regions detected as moving regions only in actively illuminated frames are further processed as candidate regions.

Fig. 3 shows an example of projectile trajectory trail captured by one of the cameras, whereas Fig. 4 shows the result of the motion detection algorithm. As seen from both figures, the actual trajectory is divided into two parts (longer and shorter one) that define the direction of the projectile. However, as seen in Fig. 4, not only the trajectory is detected as candidate region, therefore, additional processing is required to successfully distinguish actual projectile from false positives.

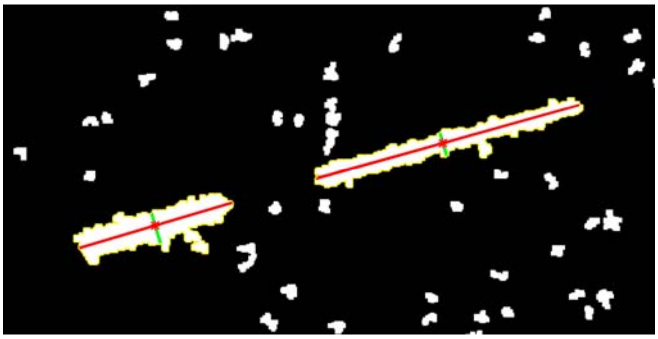

Figure 4. Line segments defining the width and height of candidate regions

First, all candidate regions smaller than some threshold T_{size} are discarded as false positives to eliminate noise in the image. For all remaining candidate regions, a line segment with following characteristics must be found: it goes through the centroid (the center of mass of the candidate region) and connects two boundary points that are farthest from each other. The length of this line segment is defined as the width of the candidate region W_c. The centroid of the candidate region is defined as $M_c(k,l)$. The height H_c of the candidate region is the length of the line segment perpendicular to the width and going through the centroid M_c (as seen in Fig. 5).

All candidate regions that do not satisfy Eq. (5) are discarded as false positives:

$$\frac{W_c}{T_{aspect}} > H_c \tag{5}$$

where T_{aspect} represents a user defined threshold that guarantees that the width of the candidate region is larger than its height.

Furthermore, since the projectile was illuminated when the image was taken, it is expected that the average pixel intensity of pixels contained in that candidate region should be higher than some user defined threshold T_{color}.

Additional processing is required in the case when more than one candidate region satisfied all the aforementioned conditions. The remaining candidate regions are mutually examined to check whether they satisfy the following "*mutual characteristics*":

1. *Line segments that define the width of two candidate regions must lay on the same line, or very close to it,*
2. *the width of one candidate region must be significantly smaller than the width of the second candidate region,*
3. *the width of the gap between two candidate regions must be smaller or equal to the width of the smaller candidate region.*

One more confirmation is required before the final decision is made. Since the system uses stereo camera system, it is expected that projectile trajectory trail is

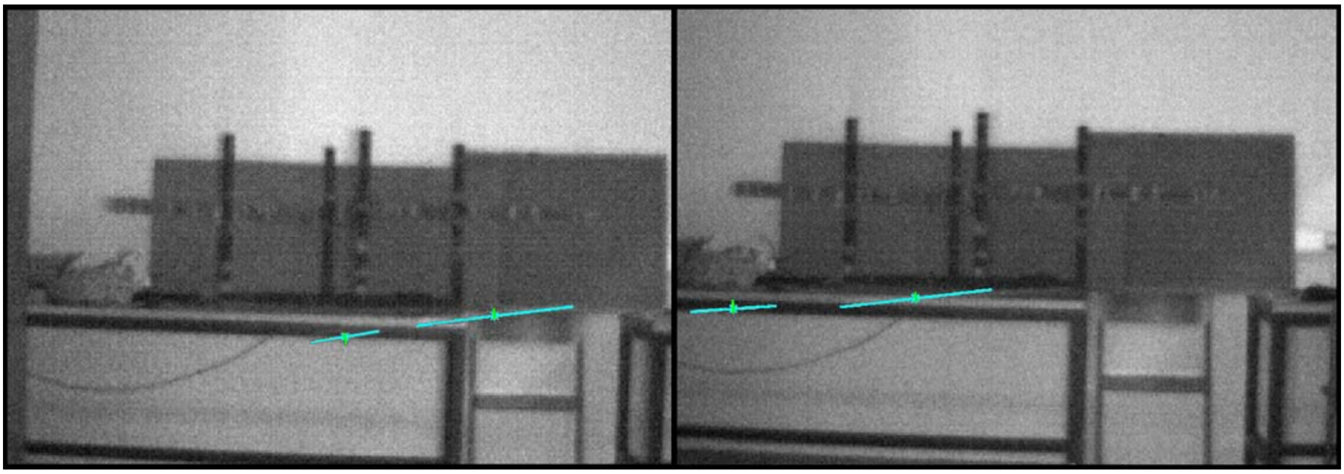

Figure 5. An example of a successful projectile trajectory detection (images from both left and right camera)

successfully detected in both left and right camera image. The overview of the whole detection process is given in Algorithm 1:

Algorithm 1 Projectile trajectory detection

1) Motion detection – extract candidate regions that appear to be in motion (only) in actively illuminated frames.
2) Eliminate small regions.
3) The width of the region must be significantly larger than its height.
4) Eliminate regions based on chromatic characteristics.
5) Detect a pair of candidate regions that satisfies "mutual characteristics", as described above.
6) A pair of regions must be detected in both stereo images.

If all the conditions are met, the final line that represents the projectile trajectory can be found. It is the line that best fits the two previously described line segments. One example of a successful detection of projectile trajectory in both images from the stereo system is given in Fig. 5.

V. Trajectory Reconstruction

As can be observed in Fig. 6., two lines (detected in previous section) represent projectile trajectory in 2D space. In this section, we will show how to estimate 3D line equation that represents projectile trajectory in 3D space. When two distinct cameras (noted as Camera 1 and Camera 2) perceive a scene from two different perspectives, any 3D object from a scene is transformed to a 2D object on each camera's image (camera frame). This conversion from 3D to 2D is referred to as a perspective projection and is described by the pinhole camera model [21]. Camera calibration, which is an essential requirement of any 3D reconstruction process, is responsible to determine of the mapping relationship between image points and corresponding point in space. By performing the calibration, two camera matrices are obtained, P_D and P_L respectively, following the procedure described in section III. Position of a 3D point labeled as X in Fig. 6 (endpoint of projectile trajectory) is derived using Eqs. (6)-(7), where X_D and X_L are coordinates in camera's frame; τ is a triangulation function and H is linear transformation that transforms $X_D = HX_L$ [21].

$$X = \tau(X_D, X_L, P_D, P_L) \tag{6}$$

$$\tau = H^{-1}\tau(X_L, X_D, P_D H^{-1}, P_L H^{-1}) \tag{7}$$

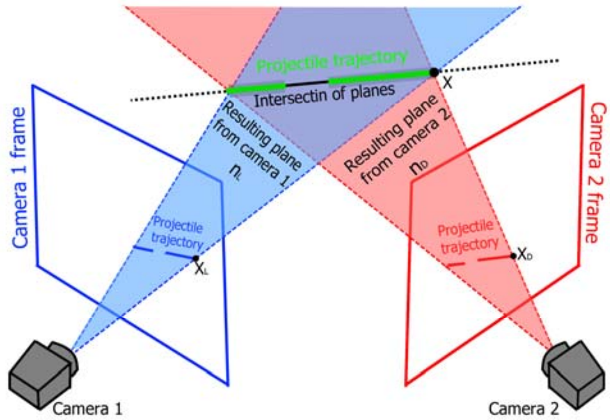

Figure 6. Camera geometry and transformation of 3D point X in two 2D points X_L and X_D on each camera's frame

The original idea was to utilize already existing algorithms for location reconstruction in 3D [21-23], satisfying the minimal requirement that calculate 3D line equation using only two points in 3D. However, relatively small deviation in detection of line boundaries from camera image (in terms of just few pixels), can result in significant 3D reconstruction error. Therefore, alternative approach was proposed, where complete line detected by the system and containing multiple points serves as an input. By implementing this alternative approach, the system is made more robust and eliminates need for pairing the exact same points from two images, which would require utilization of advanced image feature detection algorithms.

When projecting a 3D line to each camera's frame a 2D line(s) can be observed. That 2D line can be reprojected back from camera frame to 3D space with infinite number of lines, all originating from corresponding camera's center. Those infinite set of lines are forming a 3D plane depicted as shaded areas on Fig. 6. If not parallel, planes intersect in a single line, which is in fact line that describes wanted spatial trajectory of a projectile. By following the Eq. (8), when two planes are described by normal vectors $\vec{n}_L$ and $\vec{n}_D$ (as can be seen in Fig. 6), their cross product gives a line vector l

that is contained in both planes:

$$l = \vec{n}_D \times \vec{n}_L \tag{8}$$

Implementation of this simple algorithm results with line equation in 3D space, which is used for predicting location of projectile impact and estimation of projectile origin.

VI. Measurements

Measurement process is divided into two stages: preparation and accuracy trials. In preparation stage measurement system is placed in ideal position which is followed by system calibration process. Repetition of system calibration must be repeated if any relation between cameras (distance or orientation) change. However, by hard-fixing the cameras on metallic construction, only initial calibration is required allowing system to be designed as a portable device.

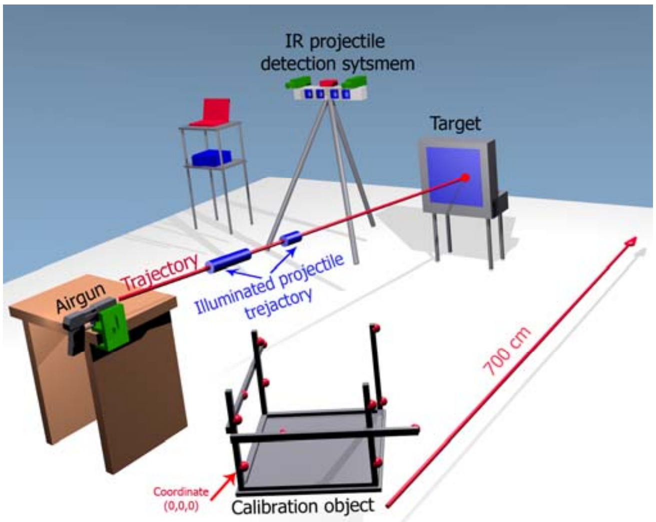

Figure 7. Measurement setup with calibration object (used in the initial stage) and airgun and target (used in a second stage).

The large metallic object (illustrated on the bottom of Fig. 7), with a size of 160 x 90 x 60 cm with 12 IR LED markers embedded at known locations was used for the camera calibration. Markers' locations were measured with submillimeter precision caliper (FESTA 300/0.02). Ideally, the light rays coming from the scene should pass through the optical center linearly, but in practice, complex lens systems introduce distortion to optical paths and the resulting image. Camera intrinsic calibration is achieved by capturing images of printed chess-board pattern from multiple views by following the procedure proposed by Tsai [24]. After removing the distortion, physical camera calibration was performed and camera's extrinsic and intrinsic parameters were calculated. Intrinsic parameters encompass focal length, image format, and principal point, whereas extrinsic parameters describe the relationship between the cameras and coordinate system, crucial for mapping 3D points into the 2D images and vice versa [21]. Calibration of the proposed system was performed by using the MATLAB calibration toolbox developed by Bouguet [25]. The origin of the coordinate system is the first marker on the calibration object, labeled as a Coordinate (0,0,0) on Fig. 7. In the initial stage, coordinate system is fixed to the displaced calibration object, but for the sake of simplicity and simpler analysis of measured data it can be moved (transformed) to a key point located on a detector system and set a coordinate system origin coordinate. The outputs of extrinsic calibration process are the camera's matrices P_D and P_L, respectively, which hold rotational and translation information of the cameras within a chosen coordinate system.

After initial stage is completed and camera matrices are obtained, actual system accuracy trials were executed. Airgun was fixed to a heavy laboratory table by a mechanical vice at known position, and was aimed to the center of a target object. Active IR detector system was activated and continuously recording video feed. Launching was performed manually by pressing the handgun trigger, after which recording was stopped and position of projectile impact to object was manually measured by the caliper. Both target object and handgun were displaced at different, but known location before next measurement was executed. This process was repeated for a total of 20 times.

VII. Results and Discussion

All 20 trials showed to be successful in detection and estimation of projectile's spatial trajectory. Resolution and accuracy of camera-based system is directly related to objects size in camera's image, which is consequently related to distance from the object to a camera. It is presumed that estimation of impact location on target object (in our trials placed ~1 m from the IR detector) is more accurate than estimation of projectile origin which is usually located more distant from the detector. The results of the trials in controlled laboratory conditions are presented in Table I. Mean error showed to be of 2.45 cm with standard deviation of 1.54 cm for impact location estimation and 2,9 cm described as RMSE (Root Mean Square Error) in target's plane. It is unwise to analyze origin location, as launcher can be anywhere on trajectory line, but for the sake of easier comparison, depth location of launcher (distance) is presumed. In this case estimation of projectile origin is accurate with mean error of 6.87 cm. As mentioned before, location of projectile origin (location of marksman) is usually far behind IR detector range, resulting with decreased accuracy at longer distances. Alternative approach to present our results is by using minutes of angle (MOA), measure which is not affected by range and is commonly used in firearm industry to indicate accuracy of firearms at fixed range. In terms of MOA our system is estimating launcher direction with accuracy of 33.7 which is not far inferior when compared to modern counter-battery radars with MOA in range of 13-30 [18].

TABLE I. System Accuracy in Controlled Laboratory Conditions

Description	Statistical parameter	Value
Location of impact	Mean	2.4852 cm
	STD	1.5440 cm
	RMSE	2.9053 cm
Location of projectile origin	Mean	6.8707 cm
	STD	5.3139 cm
	RMSE	8.5690 cm
	MOA	33.7

Although our system offers adequate accuracy in laboratory conditions, some future improvements must be considered in order to develop more effective system usable in real scenarios. First improvement would be introduction of a subpixel detection algorithm of projectile trajectory from camera image [24]. This would result in more accurate line detection instead of currently implemented algorithm that inputs discrete pixels for all calculations. Advancement would be achieved by improving the hardware, and replacing the current camera with more sensitive and faster generation of industrial grade camera. Introduction of faster, more sensible and greater resolution camera would achieve that single projectile can be tracked in multiple frames at longer distances and with higher accuracy.

VIII. CONCLUSION

Objective of this paper was to design, develop, and validate the prototype for a subsonic projectile detection and estimation of projectile's trajectory. The novelty of the proposed system lies in its design which uses cost-effective IR LED illuminator and fast industrial cameras, as opposed to similar approaches that use passive IR, acoustic or radio waves approach. The system is aimed to be simple and small, what is achieved by embedding a pair of cameras in stereovision configuration which are synced with the IR illuminator. Innovative IR light sequences enable detection of projectiles in its effective range, which enables computer vision algorithm to detect projectile trajectory and simultaneously ignore objects in the background and far behind illuminator effective range. All 20 trials were successful, projectile was detected by both cameras and its trajectory was reconstructed with high accuracy. Impact location to nearby target can be estimated with 2.48 cm accuracy for projectiles traveling at 100 m/s, whereas origin of projectile can be traced with 34 MOA. The work presented in this paper is mainly focused on proving the effectiveness of a proposed principle.

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