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Bullet trajectory reconstruction – Methods, accuracy and precision

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ABSTRACT

Based on the spatial relation between a primary and secondary bullet defect or on the shape and dimensions of the primary bullet defect, a bullet's trajectory prior to impact can be estimated for a shooting scene reconstruction. The accuracy and precision of the estimated trajectories will vary depending on variables such as, the applied method of reconstruction, the (true) angle of incidence, the properties of the target material and the properties of the bullet upon impact. This study focused on the accuracy and precision of estimated bullet trajectories when different variants of the probing method, ellipse method, and lead-in method are applied on bullet defects resulting from shots at various angles of incidence on drywall, MDF and sheet metal. The results show that in most situations the best performance (accuracy and precision) is seen when the probing method is applied. Only for the lowest angles of incidence the performance was better when either the ellipse or lead-in method was applied. The data provided in this paper can be used to select the appropriate method(s) for reconstruction and to correct for systematic errors (accuracy) and to provide a value of the precision, by means of a confidence interval of the specific measurement.

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1. Introduction

Shooting scene reconstructions often include measurements to estimate a bullet's trajectory to provide information about the direction from where the shot was fired. These estimations are based on the spatial relation between a primary and secondary, tertiary, etc., bullet defect or on the shape and dimensions of the primary bullet defect. When estimating the bullet trajectory this trajectory has an angle of incidence that can be resolved into two angles: the vertical angle (i.e. elevation angle, side view angle) and the horizontal angle (i.e. azimuth angle, top view angle, lateral angle) [1–4]. For practical reasons the estimated bullet trajectory can be regarded as a straight line when the shooting distance is relatively short (up until distances of 9–18 m [2] or even 30 m [5]) for shots fired by common handguns and rifles. The actual distance up to which a bullet trajectory might be regarded as a straight line depends on the flight time, which results from the shooting distance and from the characteristics of the used firearm–ammunition combination such as muzzle velocity and the bullet's drag coefficient.

For each estimated trajectory it is important to report both the accuracy and the precision of the measurements. In common use, accuracy describes how close a measured value or the mean of several measured values are to the actual (true) value of the measurand and is thus associated with systematic errors. Precision describes how close the measured values of the same measurand are to each other and is thus associated with random errors [6]. An optimal method has both a high accuracy and a high precision. The accuracy and precision of an estimated bullet trajectory when applying a given method might be influenced by: (1) the (true) angle of incidence (the angle between the bullet's trajectory and the target surface prior to impact), (2) the properties of the target material and (3) properties of the bullet upon impact, such as its mass, velocity, design, stability and spin [1,7]. These variables combined will affect the shape and dimensions of a primary bullet defect, but will also influence the degree of deflection of the bullet from its original trajectory due to interaction with the target material. The deflection of bullets, when perforating target material, increases if the interaction energy fraction that does not result in either bullet or target deformation increases. The interaction energy results from the interaction force and the interaction path and is proportional to the interaction time. Therefore the deflection of bullets when perforating target materials generally increases when: (1) the angle of incidence decreases [8,9], (2) the density or thickness of the target material increases [8] and (3) the mass of the bullet decreases [8,9].

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In literature, three main approaches have been described to estimate bullet trajectories based on one or multiple bullet defects: (1) describing the bullet's trajectory between consecutive bullet defects, (2) using the dimensions of the elliptical shape of a primary bullet defect to calculate the angle of incidence by trigonometry and (3) using the 3-dimensional shape of the lead-in portion of a bullet defect.

1.1. Bullet trajectory between consecutive bullet defects

The spatial relation between a primary and a secondary bullet defect or between an entrance and exit hole in thicker target materials from one fired bullet can be used to measure the trajectory between those two defects (Fig. 1). This trajectory can be used to estimate the trajectory of the bullet prior to impact, before possible deflection of the bullet has occurred by perforating the target material. The accuracy of the measured trajectory will be highest when the interaction time of the bullet with the primary target material has been short and therefore the resulting bullet deviation small. To measure the trajectory between two consecutive bullet defects different materials can be used, such as: probes (trajectory rods), lasers and strings [2–5,10–13]. When using these measurements to estimate the bullet's trajectory the precision depends on the distance between two consecutive bullet defects [3] and the thickness of the target material when only using the entrance and exit hole [2], the smaller the distance or the thinner the target material, the less precise the measurements will be. In the remainder of this paper this method will be referred to in short as the 'probing method'.

1.2. Dimensions of the elliptical shape of a primary bullet defect

The shape of a primary bullet defect resulting from a stable bullet can be used to estimate the direction where the bullet came from and the angle of incidence of the bullet prior to impact. Bullet defects resulting from bullets fired orthogonal to a target material will result in more or less circular bullet defects. When the angle of incidence decreases the shape of the bullet defect will elongate and become elliptical [4,14]. The dimensions (width and length) of the elliptical shape can be used to calculate the angle of incidence of a bullet using trigonometry [2,4,5,14–16] as was originally proposed for impacted blood droplets [17] based on the work of Balthazard [18]:

$$\text{Angle of incidence}\,(\alpha) = \sin^{-1}(\text{width}/\text{length})$$

The dimensions of a primary bullet defect can be measured by using callipers [15,16,19], fitting an ellipse around the lead-in portion of the defect using a computer graphics programme [15] or by overlaying templates of various ellipses [19]. Bullet defects from especially the lower angles of incidence are often not truly elliptical in shape. When this is the case the half-length of the bullet defect (measured from the widest point of the bullet defect) can be measured and multiplied by two to get an estimation of the total ellipse length [16] (Fig. 2). This procedure can also be applied to the lead-in portion of ricochet marks.

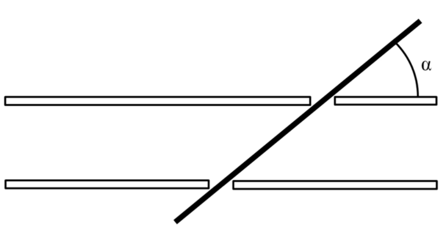

Fig. 1. Schematic representation of the probing method where in this example the angle of incidence (α) is measured by using the spatial relation between two consecutive bullet defects.

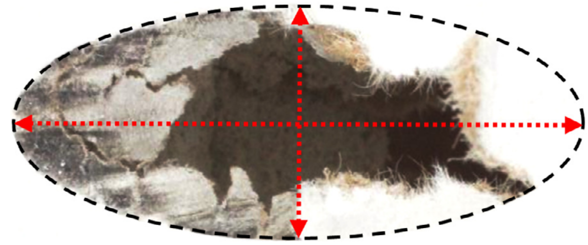

Fig. 2. Example of the ellipse method where the width (vertical) and length (horizontal) are measured. The widest point of the bullet defect is selected as the half-length of the ellipse.

In addition to bullet defects being almost undistinguishable at angles of incidence between 70° and 90° [19], the sine function is really sensitive to minor measurement errors when the angle of incidence is high, which might result in large errors in trajectory calculations [14]. Several studies have argued that this method can only be used up to angles of incidence of approximately 60°–70° [14,16,19], where precision seemed to decrease with increasing angles of incidence [16]. In the remainder of this paper this method will be referred to in short as the 'ellipse method'.

1.3. Lead-in portion of a primary bullet defect

The lead-in portion of a primary bullet defect from a stable bullet can be used to estimate the angle of incidence of the bullet prior to impact. The lead-in mark is the result from the initial contact of a bullet with a target material [2,3], where the bullet has created an elliptical indentation in the target material. The position of the lead-in mark can be used to establish the direction where the bullet came from and the depth component of the mark can be used to estimate the angle of incidence. Aligning a probe with the lead-in portion of a primary bullet defect provides an estimation of the angle of incidence [1] (Fig. 3). When applying this method, only the first part (some mm) of the lead-in portion of a primary bullet defect should be used, because of possible secondary effects after that first part, such as deformation, deflection and structure disruption of the target material. This procedure can also be applied to the lead-in portion of ricochet marks. In the remainder of this paper this method will be referred to in short as the 'lead-in method'.

1.4. Scope of the study

To be able to report the accuracy and the precision of an estimated bullet trajectory prior to impact, both the systematic and random errors of the measurement should be known. This study will focus on both the accuracy and precision of the three described methods when reconstructing bullet trajectories from bullet defects on different types of target material for different angles of incidence. The results can be used to select the most appropriate method(s) for a specific bullet trajectory estimation, to adjust for possible systematic errors (accuracy) and to provide a

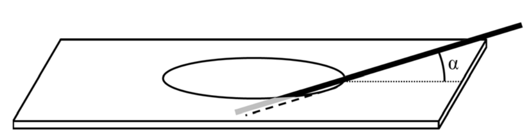

Fig. 3. Schematic representation of the lead-in method, where in this example the angle of incidence (α) is estimated by aligning a probe with the lead-in portion (thick dotted line) of a primary bullet defect.

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