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Measurement of bullet impact conditions using automated in-flight photography system

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ABSTRACT

Knowledge of impact conditions is critical to evaluating the terminal impact performance of a projectile. For a small caliber bullet, in-flight velocity has been precisely measured for decades using detection screens, but accurately quantifying the orientation of the bullet on a target has been more challenging. This report introduces the Automated Small-Arms Photogrammetry (ASAP) analysis method used to measure, model, and predict the orientation of a small caliber bullet before reaching an impact surface. ASAP uses advanced hardware developed by Sydor Technologies to record a series of infrared digital photographs. Individual images (four orthogonal pairs) are processed using computer vision algorithms to quantify the orientation of the projectile and re-project its precise position and orientation into a three-dimensional muzzle-fixed coordinate system. An epicyclic motion model is fit to the measured data, and the epicyclic motion is extrapolated to the target location. Analysis results are fairly immediate and may be reviewed during testing. Prove-out demonstrations have shown that the impact-angle prediction capability is less than six hundredths of a degree for the 5.56 mm ball round tested. Keywords: Yaw, Terminal ballistics, Exterior ballistics, Test & evaluation, Computer vision, Image processing, Angle of attack

1. Introduction

Upon impact with a target, a projectile's terminal ballistic performance is highly dependent on numerous factors including: impact velocity, bullet orientation, bullet construction, target composition, target orientation, and test geometry. The orientation of the target is easily controlled, since the target is usually stationary when testing small caliber ammunition (engraving diameter smaller than 20 mm). Bullet velocity has been measured using light-detection screens for decades which have well-established accuracies within 1 ft/s. The orientation of the bullet, however, is a more challenging piece of information to accurately quantify.

There are two important aspects of impact orientation that must be clarified. The first is the angle of obliquity, which is the angular difference between the normal vector of the target surface and the velocity vector of the incoming projectile [1]. For most penetrator-type projectiles, penetration performance improves as the angle of obliquity approaches zero. During testing, the angle of obliquity can be controlled by orienting the target surface to be normal to the bullet trajectory at the impact location.

The other aspect of impact orientation to be considered is the angle of attack (AoA). The AoA is the angular difference between the projectile's velocity vector and its longitudinal axis, also known as pointing direction. During flight, the longitudinal axis of an axially-symmetric spin-stabilized projectile rotates around its velocity vector in a profile known as epicyclic motion. This will be discussed in detail later in this report [2]. When evaluating a projectile's impact effects on a target, the AoA is of particular importance because lower AoA values lead to improved penetration performance [3].

The next section of this report describes conventional methods used to measure the in-flight orientation of projectiles. The following section introduces the Automated Small-Arms Photogrammetry (ASAP) analysis method, offering an overview of the calibration procedure, computer-vision image-analysis algorithms, three-dimensional re-projection, and the process used to fit measurements to an epicyclic motion model. The following section includes sample data collected during a recent firing test. Section 4 includes a series of studies performed to evaluate the accuracy of

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the ASAP method. The final section contains the conclusions of this study.

2. Background

There are several conventional methods in use for measuring the orientation of a small-caliber bullet in flight. Yaw cards [4], which are made from plastic, paper, or cardboard-like materials are placed at various locations along a trajectory. The shape of the hole made in the card after the bullet passes through is then compared to a template to estimate the orientation angle at that location. These estimates are very crude in precision, especially for small-caliber projectiles. The setup and post-processing of yaw cards is often exhaustive as well, as new cards are usually needed for each shot. In some situations it may not be possible to place yaw cards at the point of the impact, because damage from spalled components may affect the shape of the hole.

Another common approach involves the use of “pitch and yaw” high speed video cameras [Ref. [3]]. To do this, camera systems are placed at the target location to record images of the bullet before impact. The setup of these systems along with illuminating bulbs can be exhaustive. Following a test, the results are usually analyzed by an operator clicking on various points on the projectile. This type of analysis has been found to require days, (it not weeks) of data reduction, and even with proper calibration is difficult to verify in terms of accuracy. Because of spalling at impact, these expensive camera systems must be shielded using thick bullet-proof glass which can hinder results and further complicate setup. Sometimes, pseudo-automated image analysis software can be used to reduce the reliance on manual selection of key points [5].

More sophisticated methods of orientation measurement include shadowgraphs and radiographs. These images are generated by short duration pulses of light or x-rays which are similar to photographs. These images are collected between shots, digitized, and then processed relative to a template or background fiducial to develop orientation and position histories at each station. The accuracies of these systems have been reported to be within 0.14° at a given station relative to a fiducial wire, resulting in target impact accuracies between 0.24° and 0.41° [6]. Some spark ranges have even better accuracies upon target impact because they may have upwards of 30 shadowgraph stations. The time required for analysis, however, can be significant because of manual data collection and digitization.

Large ammunition, such as artillery and mortar projectiles, may have on-board instrumentation to measure orientation with inertial sensors or solar light detecting yawsondes [7]. These systems, although accurate, are expensive and usually single-use. Such systems are much too large for use with small caliber ammunition as discussed in Ref. [5].

Finally, the Automated Launch Video Analysis (ALVA) method was developed to process high resolution moving field-of-view (FOV) videos of large caliber projectiles. This system relies on computer-vision techniques to analyze videos from orthogonal views at launch. In each video frame, the projectile shape is identified with sub-pixel accuracy. When the data is combined, the initial orientation history of a projectile can be measured. The accuracy of the ALVA system has been shown to be roughly 0.1° [8]. ALVA was originally designed to determine the first maximum yaw of artillery rounds, but has since been expanded to efficiently determine spin-rate, aerodynamic coefficients, stability metrics, and in-flight shape transformations [9,10].

3. Automated Small-Arms Photogrammetry (ASAP) analysis

In 2014 engineers at Picatinny Arsenal purchased a sophisticated timing system complete with illumination hardware from Sydor Technologies [11]. The assembled structure of the Sydor system, which will be referred to as the “gantry,” uses light-detection pulses from a velocity screen (located uprange of the gantry) to sequentially trigger infrared strobes as a bullet travels downrange. During these brief strobes, camera systems (Allied Vision model Prosilica GC 1380) record high resolution grayscale images of the bullet in flight. There are four stations in the current gantry system, each of which has two strobes that illuminate the FOV for two orthogonal cameras. Currently there are 4 stations (each 470 mm) apart yielding eight images (four orthogonal pairs) per shot. Illustrations and a photograph of the gantry system are shown in Fig. 1.

Sample images from some of the various ammunition types tested to date are shown in Fig. 2. Note the clarity of the high resolution images (1360 × 1032 pixels), which even show flaws in the bullet casings (caused during the engraving process during launch). The resolution, contrast, and focal length of the camera systems are more than sufficient to accurately measure orientation as will be discussed later in this report.

At the beginning of each ammunition test, the gantry is wheeled into the firing range and aligned with the line-of-fire (LOF) using jack-stands located on the bottom of the gantry system. Once in position, the system is locked in place, and a calibration procedure is conducted before rounds can be fired.

3.1. Calibration procedure overview

The purpose of the calibration procedure is to develop the critical transforms for each camera system that relate the pixel coordinates to the range coordinate system ($\mathbb{R}3$). This begins with surveying the muzzle of the gun, the target, and various extrema points on the gantry system to determine their locations in $\mathbb{R}3$. This allows the position of each camera to be determined (relationships to surveyed gantry extrema points are known a-priori).

Similarly, a calibration bar is positioned in the gantry and its extrema points are surveyed. The calibration bar contains a

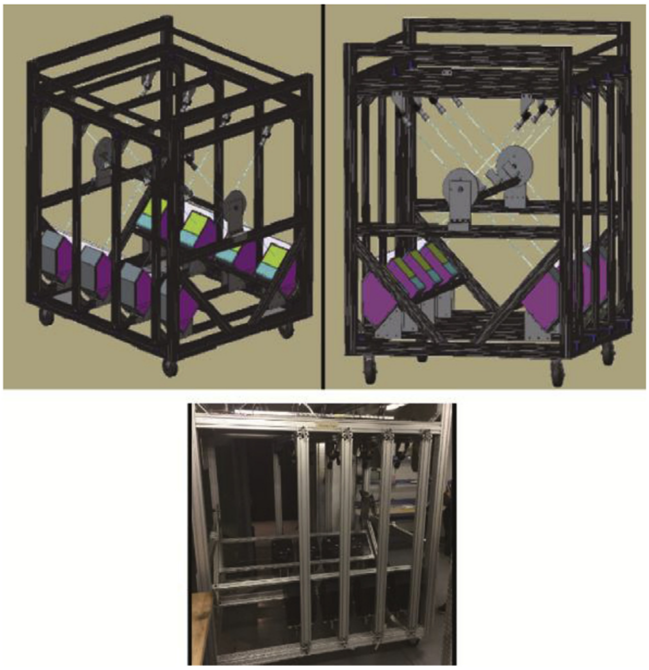

Fig. 1. Sydor gantry system at Picatinny Arsenal.

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