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A Practical Ballistic Yaw Sensor

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It is widely recognized that angled or yawed projectile impacts on armour can affect the perceived performance due to changes in projectile's interactions with the armour-. Furthermore, spurious results and greater uncertainty in armour performance can result from variations in yaw angles if not accounted for. While many ballistic test standards limit the allowable incident angle, its measurement has long been accomplished with yaw cards despite having poor precision and possible effect on trajectory. This paper describes the development of a non-contact ballistic yaw sensor for small calibre ammunition and fragment simulating projectiles that meets the requirements of ballistic standards while providing much greater precision and ease of use over that of yaw cards. The use of computer vision methods combined with LED lighting has resulted in a system that is quick and simple to use. The setup, operation, data analysis and accuracy are described with examples of its use.

INTRODUCTION

It is widely recognized that angled projectile impacts on armour systems can affect the perceived performance due to the different interactions between the armour materials and projectiles. Increased incident angles between the projectile and strike face generally result in an overestimation of the armour performance but it has also been shown that the performance of some armour-projectile combinations can also be reduced at small angles [1, 2]. The importance of projectile incident angle in wound ballistics is also widely recognized as it can greatly affect the wound tract, mode of projectile damage and rate of energy transfer affecting wound severity outcome. While the intended incident angle between the projectile and target (i.e. obliquity angle) can be controlled, precession and nutation of the projectile about the velocity vector, i.e. yaw angle, Figure 1, can result in unintended angled impacts. As a result, requirements for reducing the variation in the incident angle for small calibre ammunition and fragment simulating projectiles can be found in many ballistic performance standards requiring the angle between the projectile and target to be below a threshold, typically 3° or 5° (e.g. NIJ 0101.06, MIL-STD 662F, AEP-55 Vol.1, STANAG 2920).

The measurement of the incident angle has long been accomplished with yaw cards placed in close proximity to the strike face. While yaw cards are readily accessible, they

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are known to have poor precision and require effort to analyze each card. Furthermore, yaw cards may affect the trajectory and yaw of projectiles, especially for small calibre ammunition in aeroballistics studies where several yaw cards may be used [3]. Requirements for greater precision in yaw measurement have led to the use of non-contact methods including the capture of orthogonal views of the projectile in flight with radiographic systems [4, 5], with shadowgraphs [6], the use of a single camera and mirrors to simplify image capture [7, 2], and single or video image capture systems using front or rear illumination systems [8, 9]. The setup, calibration and operation of some systems, however, can be complex and time-consuming resulting in low test rates and high costs thereby inhibiting their widespread use.

This paper describes the development and application of a Ballistic Yaw Sensor (BYS) for small calibre ammunition and fragment simulating projectiles that meet the requirements of ballistic performance standards while providing much greater precision and ease of use over that of yaw cards. The use of computer vision methods combined with backlit LED lighting has resulted in a system that is not only simple to use but offers greater accuracy and repeatability. The setup, operation, data analysis and calibration methods are described along with its application across a wide range of test conditions including ammunition and fragment simulating projectiles.

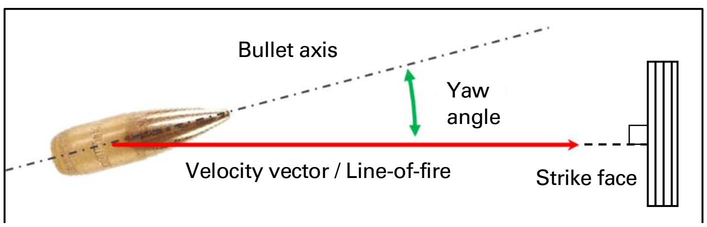


Figure 1: Illustration of yaw and incident angles of a bullet for an orthogonal strike.

BALLISTIC YAW SENSOR REQUIREMENTS

Yaw Angle Measurement

The primary motivation for developing a ballistic yaw sensor is to obtain precise estimates of the yaw angle relative to the strike face of the target. The allowable degree of yaw deviation for armour performance assessment is typically 3° or 5° depending on the projectile type or performance standard (*e.g.* NIJ 0101.06, MIL-STD 662F, AEP-55 Vol.1, STANAG 2920). With yaw angle measurement accuracy requirements of ±0.5° to ±1° specified in the standards (or none at all), it is recognized that these are minimum requirements and any yaw measurement system would need to provide better precision and accuracy.

Current yaw measurement methods with yaw cards rely on the residual hole diameter being elongated if the projectile is angled. The degree of precision required to measure the elongation is dependent on the projectile's profile, length and diameter. Analysis of some small calibre ammunition with varying yaw angles shows that a 5% change in hole elongation, or less, must be resolved to establish whether the 3° yaw angle threshold has been exceeded, Figure 2. This requires a measurement resolution better than 0.1-0.4 mm (0.005-0.015 in) which is challenging given that some projectiles form irregular holes with spring back and tearing of the hole edges. In contrast, photographic and radiographic based yaw measurement systems have been used to collect images of the projectile's side profile with far better accuracies. The literature has reported incident angle accuracies of ±0.06° to ±0.2° [10, 8] for image-based methods and ±0.2° for radiographic system [5]. It can also be noted that any errors in initial setup, calibration and measurement anomalies will decrease accuracy in the form of systematic or random errors. For these reasons, the basis of the Ballistic Yaw Sensor (BYS) was chosen to leverage the advantages of photographic systems.

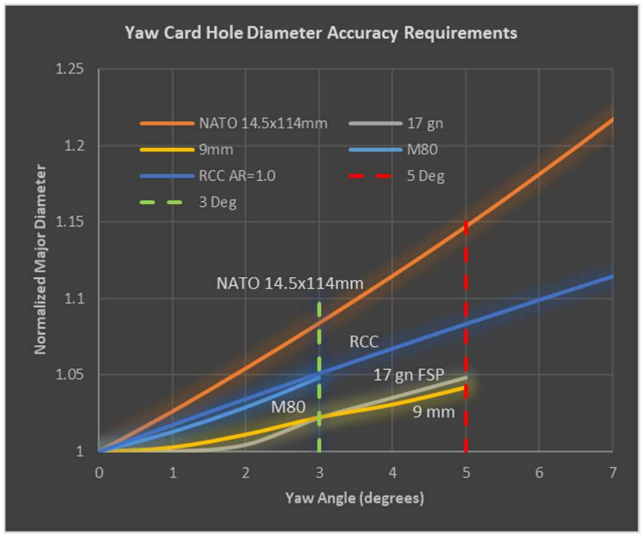


Figure 2: Estimation of yard card major hole diameters for various projectile yaw angles.

BALLISTIC YAW SENSOR DESIGN AND OPERATION

Operational Requirements

The operational requirements for a yaw measurement system are numerous and depend on the experiment/test objectives, environment, measurement requirements and level of technical input. The BYS is intended to be used in research, government or commercial test ranges requiring high rate yaw measurement for each test shot to comply with civilian and military armour performance test standards. While yaw cards are traditionally used in this context, improved accuracy, minimal analysis time and minimal operator input was sought for development of the BYS.

Operationally, the setup and verification effort of the BYS system should be minimal allowing for quick changes to the range configuration. Armour strike-face access between shots, if required, should not be impeded. Furthermore, most test ranges include chronographs (e.g. IR, radar), cameras and lighting systems, and interference with these should be minimized.

The operating test conditions of the BYS need to encompass very small projectiles (e.g. 2 grain RCC) up to 0.5 calibre ammunition at speeds up to 1500 m/s (5000 ft/s) to satisfy most soft/hard armour performance test standards for personal protection and light armoured vehicles. Archiving of all data and raw images along with time stamps completes the test requirements.

Configuration

The BYS enclosure contains a single CMOS imaging camera providing high quality images having high resolution and dynamic range, Figure 3. A mirror system creates two orthogonal views of the projectile with the line-of-fire being colinear with the visual planes. Backlighting of the projectile was selected to create a shadowgraph type of image but without being sensitive to dark/light banding that typically occurs from light being refracted by the shock waves. This provides a more uniform background for subsequent image analysis. A pulsed LED lighting system is used to provide extremely high backlight levels allowing for very short exposure times (500 ns). Triggering of the light system is provided by an integrated custom high-speed IR light screen having high spatial resolution along with automatic threshold setting to accommodate different or fluctuating ambient light conditions. An external trigger output is also provided for synchronization with external instrumentation or cameras. The BYS system is capable of operating from 150-1500 m/s (1000-5000 ft/s) with projectiles as small as a 2 grain RCC and as large as 50 caliber ammunition and 207 grain FSPs.

Practical operation of the BYS, critical for ensuring its widespread use under a variety of conditions, must consider the complete usage cycle from initial setup to system alignment and verification all the way to its use and access to the strike face working area.

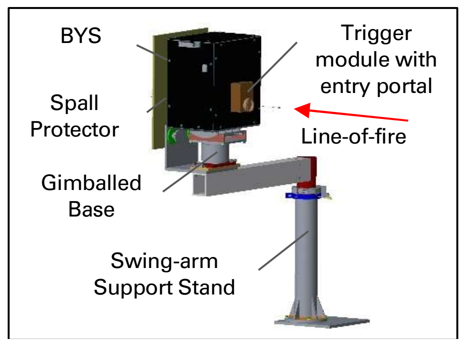


Figure 3: The Ballistic Yaw Sensor (BYS) camera and software (left) positioned on a gimballed based and swing-arm stand (right).

The small footprint of the BYS allows the unit to remain portable for placement on a benchtop, tripod or support base. A gimballed base with micro-screws permits alignment adjustability for pitch, yaw, lateral and vertical translation. Additionally, with pinhole caps at the entry/exit portals and use of an in-bore laser, alignment with the line-of-fire can be made to be better than ±0.3°. A swing-arm support base can also be provided, Figure 3 (right side), for repeatable repositioning of the BYS after initial alignment has been performed. When the BYS is swung towards the side, full access is provided to the strike face for repositioning of the armour, measuring back-face signature or for inspection purposes.

The BYS permits yaw angles to be measured as close as 150 mm (6 in) to the target but some offset between the exit port and strike face is recommended. Protection of the BYS is required for armour systems susceptible to spall or from projectile erosion and subsequent ejecta. An optional spall plate support bracket is provided for protection and a similar bracket can be provided at the entry side for protection from errant projectiles, sabots or pusher plates. Routine removal of debris entering the BYS can be performed through an access panel, and in the case of damage, replacement of the mirrors can be accomplished quickly.

The size of the entry portal was intended to be small to limit entry of unintended objects into the camera housing. To ensure uninterrupted entry of the main projectile, the entry portal diameter of 50 mm (2 in) was confirmed experimentally with the measurement of dispersion of common small calibre ammunition, FSPs and RCCs. The greatest dispersion radius observed was 16 mm (0.63 in) for the 4 grain RCC based on the outermost surface of the projectile with added variance of 3 standard deviations. The results are specific to Biokinetics' ballistics range (e.g. 5 m muzzle to target distance) but should be representative of other setups.

SYSTEM ACCURACY ASSESSMENTS

Any image based ballistic yaw measurment system will have to consider potential error sources from; a) misalignment of the bullet velcoity vector with respect to the line-of-fire; b) initial misalignment between the line-of-fire and the strike face; c) misalignment of the measurement system (e.g. camera, mirrors) relative to the line-of-fire; d) misalignment of the camera image plane with respect to the line-of-sight; e) optical disortions of the camera lens; f) image parallax errors; g) yaw angle errors due to the projectile being out-of-plane, and; g) poor image quality due to exposure, camera resolution, motion blurr, vibrations and reflections on the projectile.

While not directly controlled by the BYS, initial misalignment of the bullet velocity vector with the line-of-fire may introduce biases in the yaw estimates. Standard procedures are used employing an in-bore laser and witness card placed close to the strike face location to confirm shot placement. When combined with a mirror placed on the strike face, reflection of the laser back to the muzzle ensures that orthogonality is achieved. The errors associated with this step are estimated to be fractions of a degree given the long distance between the muzzle and target but, nonetheless, add to overall system accuracy.

Specific to the BYS, are the physical alignment of the internal mirrors with the camera to ensure that orthogonal views are obtained and accurate yaw estimates made. This is accomplished with a calibrated rod inserted between the entry and exit portals coincident with the intended line-of-fire. The mirrors and camera are adjusted until orthogonality and alignment are confirmed by observation of the rod. Further numerical corrections of the field of view are then conducted to account for optical distortions including barrelling, skewness and perspective. Another calibrated planar grid image is used for this purpose, viewable in both orthogonal views. Verification of the corrected views is then made with another rod containing a yawed right circle cylinder (RCC) placed in the centre of the image. This rod acts as a gauge for establishing accuracy of the BYS system and is surveyed to a high degree of accuracy (±0.001°) by an external certified metrology lab traceable to national standards. In this manner, compliance with quality management practices are satisfied. The gauge rod can also be used by the technician for system verification before and after any test series to confirm system calibration.

In addition to optically based errors, yaw estimation errors can occur for non-ideal location of the projectile with respect to the imaging system designed with the underlying assumptions of orthogonality. Consider Figure 4 which depicts the BYS configuration comprising two mirrors and a camera to capture the location of the projectile. The dark lines represent the trajectory of light from the projectile to the mirror and reflected to the camera. The blue lines represent the mirrors, the red circle the BYS portal and the camera image plane is on the far right. In this ideal configuration, the projectile passes through the optimal flight path with the projected views being orthogonal to each other.

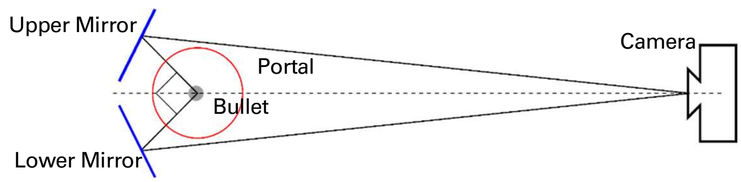


Figure 4. Schematic of BYS configuration.

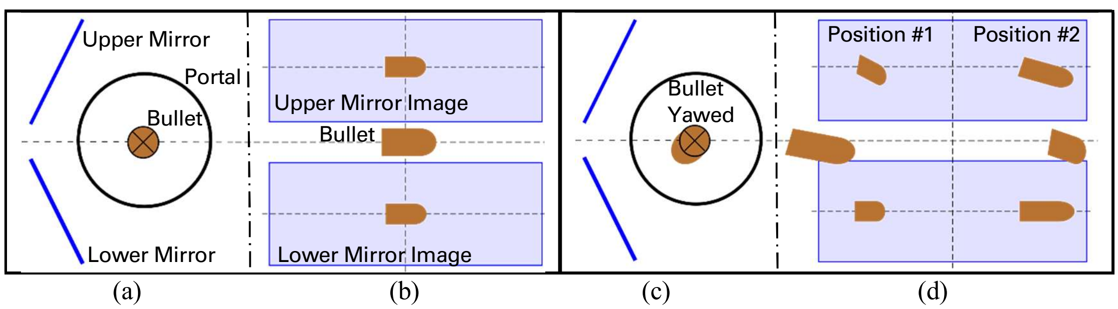
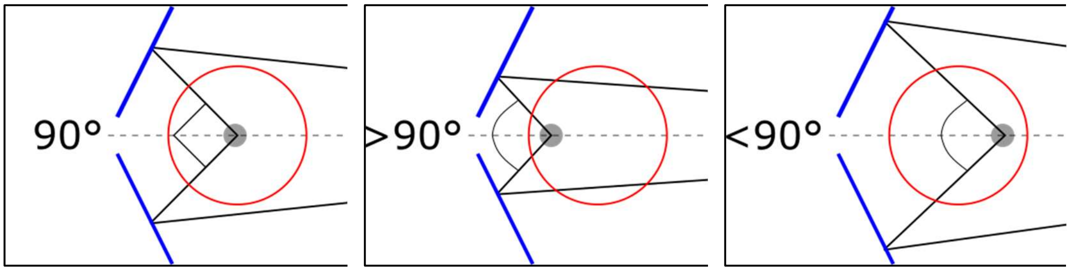


Figure 5. Schematic view of projectile and mirrors; (a) through the portal of the BYS; (b) from the camera; (c) portal view of a yawed bullet, and; (d) view of bullet at two possible positions along its trajectory.

Figure 5 (a) depicts an end view as seen through the BYS portal with the projectile passing through its centre with corresponding views from each mirror in Figure 5 (b) viewed from the camera and being centred with the focal centre. Changes to the location of the projectile with respect to the image frame, for example from flight trajectory or velocity variations, will also change the position and orientation of the two reflections from their ideal position resulting in inaccurate yaw estimates. Study of the relationship between actual and perceived bullet location revealed two geometric sources of error; 1) non-orthogonality, and; 2) parallax.

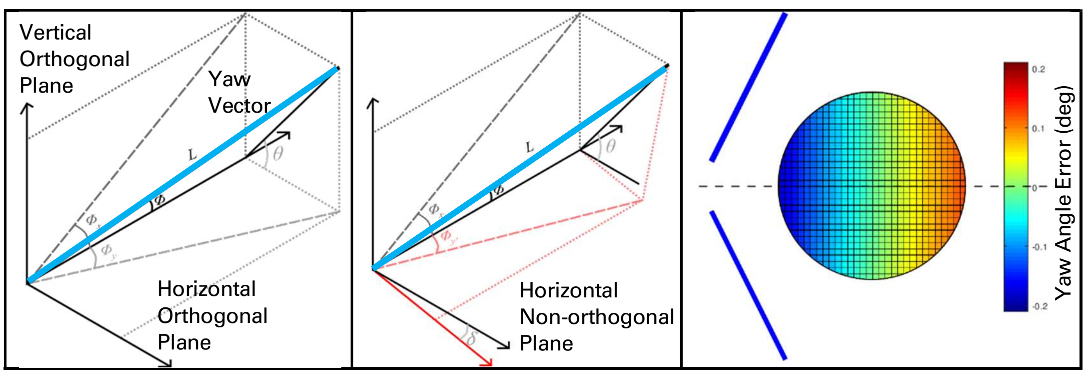
In the ideal case having the bullet coincident with the centre of the image plane, the BYS system results in two orthogonal views, Figure 6 (a). Examples of two non-ideal trajectories, shown in Figure 6 (b) and (c), illustrate that non-orthogonal views will result requiring corrections for accurate yaw estimates.



(a) (b) (c)

Figure 6. Projectile trajectories with included angles between views of; (a) 90°; (b) >90°, and; (c) <90°.

The equations used to compute complex yaw angle were based on the schematic in Figure 7 (a); however, the equation for non-orthogonal projections was derived using a modified version shown in Figure 7 (b). Based on the specific geometry of the BYS, it was determined that the maximum expected deviation from orthogonality is 6.5° and can result in a perceived yaw error of ±0.2°. The error distribution for all trajectories across the entry portal is shown in Figure 7 (c).



(a) (b) (c)

Figure 7. Schematics of a projectile yawed in 3D space with projections onto; (a) two orthogonal planes; (b) non-orthogonal planes, and: (c) error in perceived yaw for all bullet locations in the viewing portal.

The second geometric source of error is caused by parallax effects, where longitudinal changes in the relative positioning of the projectile in the field of view affect the perceived yaw angle. Figure 5 (c) shows an end view of the yawed bullet in the entry portal of the BYS. Additionally, the bullet is shown at two different places on the horizontal centreline of Figure 5 (d), both having the exact same orientation but resulting in a different perceived shape of the projectile and yaw angle.

The contribution of parallax error was quantified and is depicted in Figure 8 for the case shown above where the combined yaw is at the 3-degree threshold (3° yaw away from the camera to maximize potential error). Note that only displacements along the image plane were considered (e.g. no displacements towards or away from the camera were included).

The error contributions from parallax were found to be similar to that for non-orthogonality (<0.2°), however, after correcting for non-orthogonality, the parallax errors are small (<0.04°). While it is reasonable to assume that the parallax error source would be greater than that for non-orthogonality, projectile yaw angles equal to or less than the threshold of 3° do not result in a large contribution from parallax. Therefore, no correction was required in the context of the BYS operating environment. An accurate estimate of the projectile velocity will further reduce the measurement error as projectiles centred laterally in Figure 8 have lower magnitude geometric error (e.g. below 0.02°).

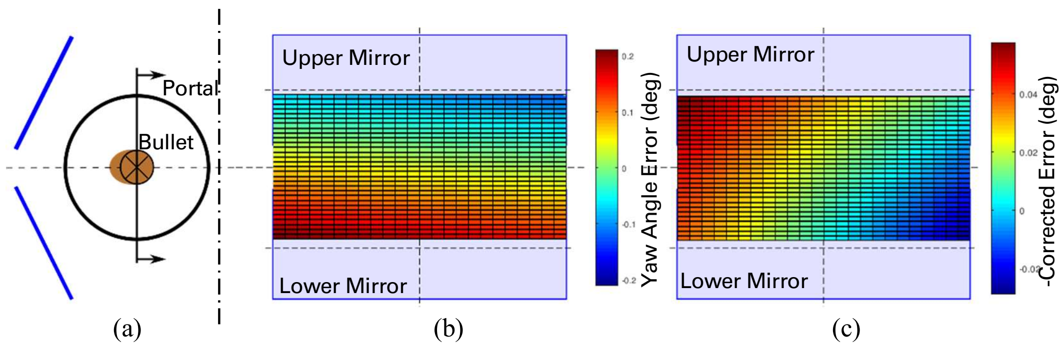


Figure 8. Parallax error distribution based on the location of the projectile in the image plane. (b) before and (c) after non-orthogonality correction.

Verification of the BYS accuracy was demonstrated with the gauge rod placed at ten different positions by axially rotating the rod in increments of 36°. Ten samples were collected in each position and the mean and three standard deviations (3σ) determined for each yaw estimation method. A maximum error of the mean was ±0.12° with 3σ of 0.34° for the principle axis method and an error of ±0.09° and a 3σ of 0.18° for the edge detection method, Figure 9 (left) and Figure 9 (right), respectively.

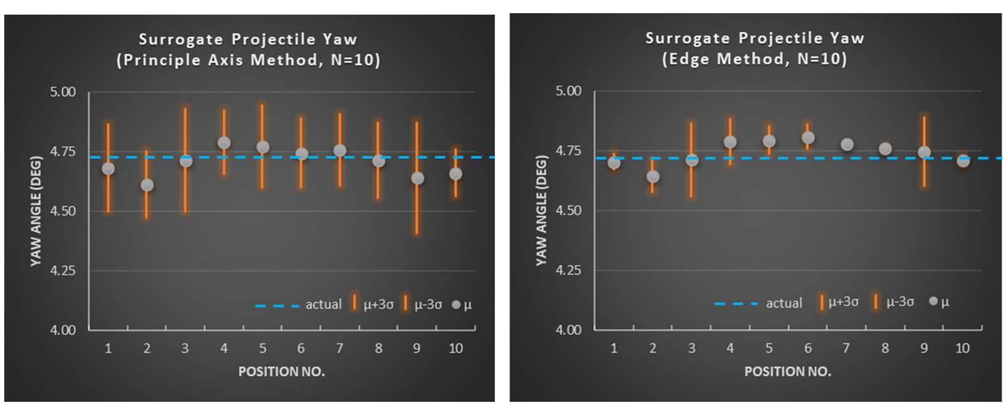
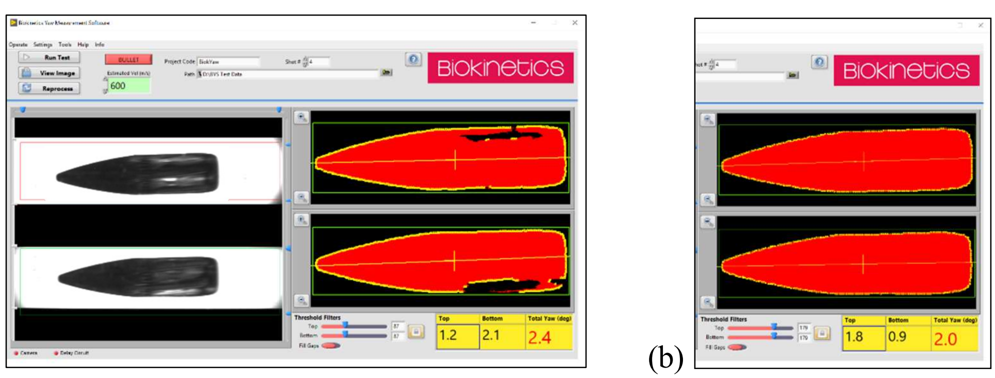


Figure 9: Yaw assessments for the surrogate projectile at different rotational positions.

Operation and Image Analysis

Operation of the BYS first involves initial alignment of the unit with the established line-of-fire. This is carried out with the in-bore laser and pinhole end caps on the BYS. Adjustments are made with the gimballed base and alignment is normally achieved within 10-15 minutes. The endcaps are then removed and the system is ready for operation. The software is then opened followed by insertion of the gauge rod to verify system calibration. The system is then armed and manually triggered for image capture. The gauge rod image and yaw angle are instantly displayed and automatically stored. The gauge rod is removed and subsequent projectile tests only require the projectile speed to be entered and the system armed.

The yaw analysis software is based on sophisticated computer vision algorithms that primarily serve to extract the key geometric characteristics of the projectile for yaw estimation. Two methods have been implemented to address symmetrical and non symmetrical projectiles; 1) the principle axis method which extracts the line of symmetry for fully symmetrical projectiles (e.g. bullets), and; 2) the edge detection method which uses the upper and lower sidewalls of a projectile to determine the yaw angle for non-symmetrical projectiles having parallel sidewalls (e.g. FSP, RCC). The software also contains several features to increase the robustness of image extraction to deal with uneven backlighting, dust and debris speckles and surface reflections/shadows on the projectile. Sample orthogonal images for the principle axis method are shown in Figure 10 (a) with magnification of the raw image and the extracted image on the right in red. The image in Figure 10 (b) illustrates the effect of adjusting the image processing parameters on improving the quality of the extracted image and yaw estimates. Once the correct processing parameters are chosen for a given setup, no further adjustments are required. The software also allows archived raw images of the projectile to be reprocessed at a later date. Other features of the software include system calibration and verification functions with image capture of the gauge rod and archiving of all related files. All data files can be easily imported into other analysis packages such as Excel® and MatLab®. A software feature to process external high-speed video data of front or rear illuminated projectiles is also being developed to leverage the analysis capabilities of the BYS software.



(a) (b)

Figure 10: Captured bullet images and yaw angle estimates with; (a) minimal image correction; (b) optimal image correction.

SUMMARY

A practical ballistic yaw sensor was described having the ability to rapidly measure yaw angle with a high degree of accuracy that overcomes many of the limitations widely recognized with yaw cards. Time savings of 40% were seen with the BYS in comparison with yaw cards during a test series while removing uncertainties associated with their interpretation and adding traceability to certifying bodies for compliance with quality management practices. Automatic archiving of image, estimates and configuration files maintains test data integrity and the ability to audit the data at a later time.

Particular importance was placed on the practical operation of the sensor to ensure that it is simple and quick to use including setup, system verification and testing while providing access to the armour sample with an optional support stand. Spall protection of the unit is required, as with all instrumentation placed in close proximity to the test sample, and features have been included for ease of maintenance. The system can also be used to characterize the yaw cycle of a particular ammunition so that the BYS can be used upstream to reduce exposure to spall while providing some certainty of the yaw angle at the strike face.

The current BYS is suitable for testing small caliber projectiles from a 2 grain RCC up to 0.5 caliber ammunition or 207 grain FSP at speeds of 150-1500 m/s (1000-5000 ft/s). Yaw estimates with an accuracy of ±0.5° can be achieved for use with armour systems of all types including soft and hard types found in law enforcement and combat clothing as well as for vehicles and wound ballistics studies.

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