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Technical Report ARMET-TR-18033

ACCURATE THREE-DIMENSIONAL ORIENTATION MEASUREMENT USING DIGITAL IMAGES OR VIDEO

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14. ABSTRACT

This report discusses an approach to measuring orientation vectors and angles from video or photographs. It builds on an earlier technical report that describes a simple and straightforward means of calibrating a camera's field of view (see technical report ARMET-TR-18031 or DTIC Submission AD1083571). The methods described in the report provide measurements made with extremely high accuracy in both the two-dimensional and three-dimensional spaces. This approach corrects large-scale distortions and provides precision that is orders of magnitude beyond current capabilities from simplistic approaches such as measuring an angle using the inverse tangent of two pixel locations.

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CONTENTS

FIGURES

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INTRODUCTION

The accurate measurement of angles or orientation vectors from photographs or videos is difficult without corrections for aberrations, camera misalignment, and image skew. Image skew, in particular, is a commonly overlooked effect. Measurements are often made with the assumption that pixels are square. In reality, they are commonly skewed several percent even when using the best camera and lens equipment available. Image skew causes one direction of an image to appear stretched compared to another direction and therefore causes significant errors to the measurement of angles or orientations. This report provides simple methods to significantly improve the accuracy of angle measurements in both the two-dimensional (2D) and three-dimensional (3D) spaces.

CONVENTIONAL ANGLE MEASUREMENT TECHNIQUES

There are numerous applications when knowledge of orientation information is important. In military weapons testing in particular, there are two cases when angle measurements are commonly made. The first case involves measuring the motion or trajectory path of an object moving through the air in a video. To do this, any point on an object (such as the nose) is usually tracked in subsequent video frames and then its motion history (in pixel coordinates) is determined by examining the history of tracked points. This is problematic because the nose of the projectile often wobbles or “cones” around its velocity vector (also known as epicyclic motion). Using the nose instead of the center of gravity (CG) of an object results in a motion path that is not representative of the object’s true motion.

The second case involves taking a common measurement from photographs or videos about the orientation angle of an object such as a projectile's body, wing, or canard. Figure 1 shows an engineer measuring a bullet’s orientation with a protractor held up to a computer monitor. This is obviously an absurd way to measure the orientation angle, but conventional approaches are not much better. A more realistic approach is to select the pixel corresponding to the right side (or nose) of the object and the left side (or base) of the object and then calculate the apparent pitch angle using equation 1. Note that the ΔY term is negative because the pixel coordinate for Y usually increases as it moves down the image.

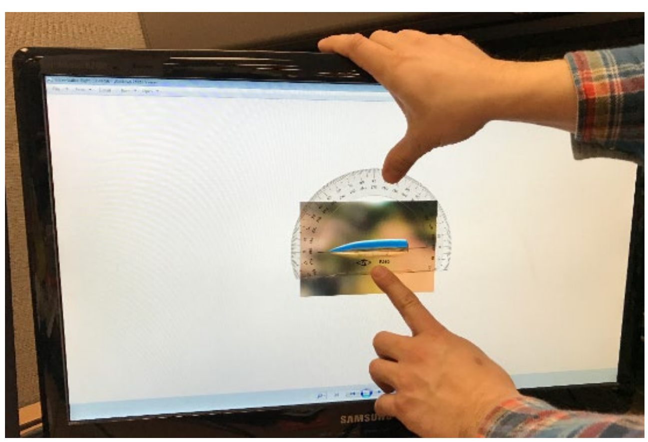

Figure 1
Improper orientation measurement

$$\theta = \tan^{-1}\left(\frac{-\Delta Y}{\Delta X}\right) \tag{1}$$

Unfortunately, this approach is still problematic for several reasons. The apparent pitch angle is only relative to the horizontal axis of the digital image, as shown in figure 2. In addition, the horizontal direction of the image often does not match the desired line of reference such as the horizon line. Therefore, the apparent pitch angle measured in a 2D image may have little significance in 3D space. More importantly, the true pitch angle for a projectile in flight is measured relative to the velocity vector of the object's trajectory, not an arbitrary horizontal direction. Even worse, when the observed angle is correctly measured relative to a known horizontal reference, the precision of this method (without considering the effects of distortions) may still be highly inaccurate due to the image resolution. As an example of this highly inaccurate method, if the points used to determine the orientation are only 12 pixels apart, the best case precision is only about 5 deg.

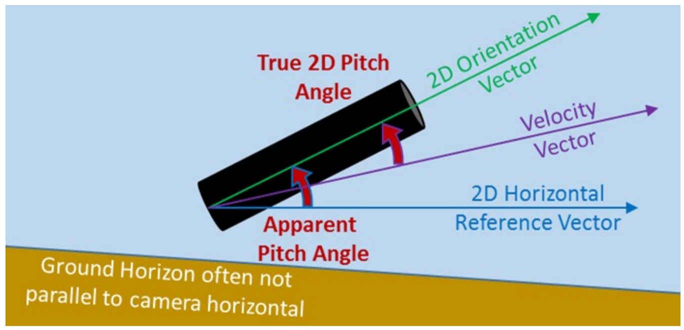

Figure 2
Measurement relative to image horizontal

FIELD OF VIEW CALIBRATION AND TWO-DIMENSIONAL ANGLE MEASUREMENTS

An effective method to accurately transform pixel coordinates into 3D coordinates is discussed in reference 1. This method places surveyed reference points on a calibration plane in the field of view. It allows any pair of X and Y pixel coordinates to be projected onto the 2D calibration plane with 3D units in the East, North, and Up directions if using Universal Transverse Mercator (UTM) coordinates. There are several benefits to this approach. The affine transform corrects some large-scale lens aberrations and image skew distortions. This leads to much more accurate results, especially for measuring angles. Figure 3 shows the calibration plane projection process.

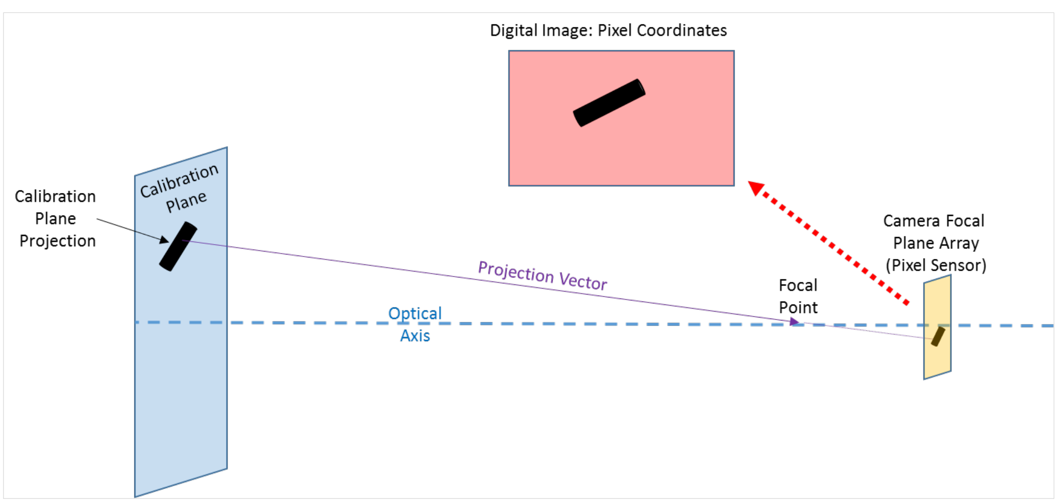

Figure 3
Calibration plane projection process

This approach works very well when the motion of interest occurs only in one plane and it requires only one camera system for making accurate angle measurements in 3D coordinates. An example of this approach may be the case of monitoring a shape's pitch angle in a wind tunnel where the pitching motion of the object is constrained to one plane. Another example is monitoring the recoil angle of a mortar tube when it is being fired. If mounted correctly, the mortar tube will move predominantly in the plane defined by the firing azimuth and the up direction. This assumes that there is no significant movement in cross-range direction (toward or away from the camera).

Computer vision methods that segment the shape of an object work nicely with this approach and allow the orientation of the object (in image coordinates) to be measured with sub-pixel accuracy. To do this, all of the pixels corresponding to the shape must be identified. This can be done using the computer vision segmentation methods described in references 2 and 3. Once segmented, the pixel coordinates for the segmented shape's pixels must be listed in two columns. The first column represents the X coordinate and the second column represents the Y coordinate for each pixel in the shape. The average X and Y ($\bar{X}$ and $\bar{Y}$) coordinates of the shape's pixels are then subtracted from each row of pixel coordinates. Then, the 2-by-2 covariance matrix is calculated allowing the eigenvector for the largest eigenvalue of that matrix to be computed. Using equation 1, the orientation angle (θ) is calculated by substituting ΔY with the second value of the eigenvector and ΔX with the first value of the eigenvector.

This method is significantly more accurate than antiquated template-fitting techniques that may be computationally expensive and require an elaborate shape template. Shape segmentation based orientation estimates are also more accurate because they analyze the distribution of thousands of data points, unlike the outlines used in template-matching approaches. Pseudo-code for this algorithm can be found in reference 4.

Once the orientation vector is found in the 2D pixel coordinates, it must be projected onto the 2D calibration plane in 3D using the following steps. First, project the center of the shape ($\bar{X}$ and $\bar{Y}$) onto the calibration plane as described in reference 1. Then determine a "heading point" (in pixel coordinates) near the center point along the orientation axis that was previously computed. For example, use a distance of one pixel, as shown in equations 2 and 3.

$$X_{Heading\ Point} = \bar{X} + cos(\theta) \tag{2}$$

$$Y_{Heading\ Point} = \bar{Y} - sin(\theta) \tag{3}$$

In the final step, project the "heading point" onto the calibration plane. Find the 3D orientation vector by subtracting the two projected points. Projecting a "heading point" near the first projected point minimizes the effects of local aberrations and has virtually the same transverse projection errors as the initial projected point. This greatly reduces transverse projection errors.

OBJECT ORIENTATION MEASUREMENT USING TWO CAMERAS

When an object's orientation is not constrained to a predetermined plane, a second camera is required. Both cameras must have their fields of view calibrated as discussed in reference 1. Ideally, the cameras should provide two perpendicular views of the 3D zone of interest. These camera views do not need to be perfectly perpendicular, but precise measurements become more diluted as the angle between the optical axes of the two cameras approach each other. As a rule of thumb, camera views should be as close to 90 deg as possible and not less than 45 deg or more than 135 deg apart.

The views from each camera should first be analyzed separately. The orientation vectors calculated using each view must then be projected onto the calibration plane for each camera, as described in the previous section. Assuming a pin-hole camera model is used, a 3D plane exists that contains the focal point of the camera and the projected vector on the calibration plane. Figure 4 shows this 3D plane with a camera focal point and calibration vector where the vector represents a bullet's axis.

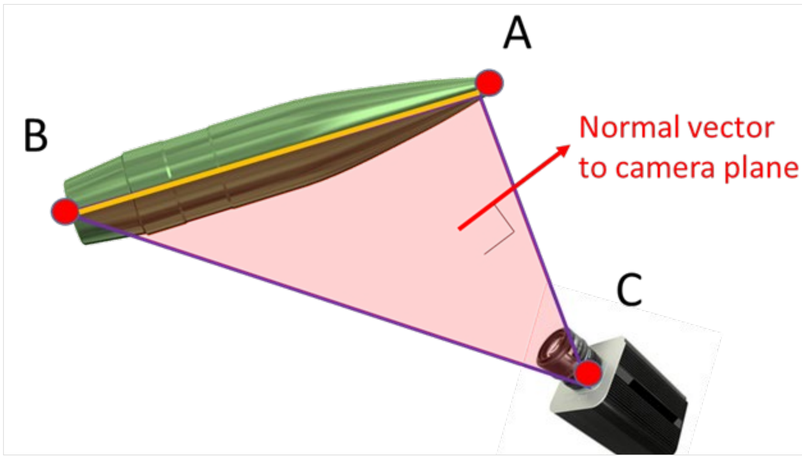

Figure 4
3D plane camera focal point and vector AB

The next step is to calculate the normal vector of that plane. As shown in figure 4, vector AB on the calibration plane goes from the bullet's nose to the bullet's base. Another vector must be created that contains the camera's focal point C. The normal vector of the plane is then perpendicular to both AB and AC (or BC). It can be found by computing the cross product of AB and AC (or BC).

Perform the same process with the other camera. This will result in a normal vector for the plane containing the camera and the projected vectors in each camera's calibration plane. The 3D orientation of the object in space can be calculated as the intersection of those two planes, as shown in figure 5. The 3D orientation of the intersection line is perpendicular to the normal vectors of both camera planes. The intersection vector can be calculated by taking the cross product of the normal vector for each camera plane.

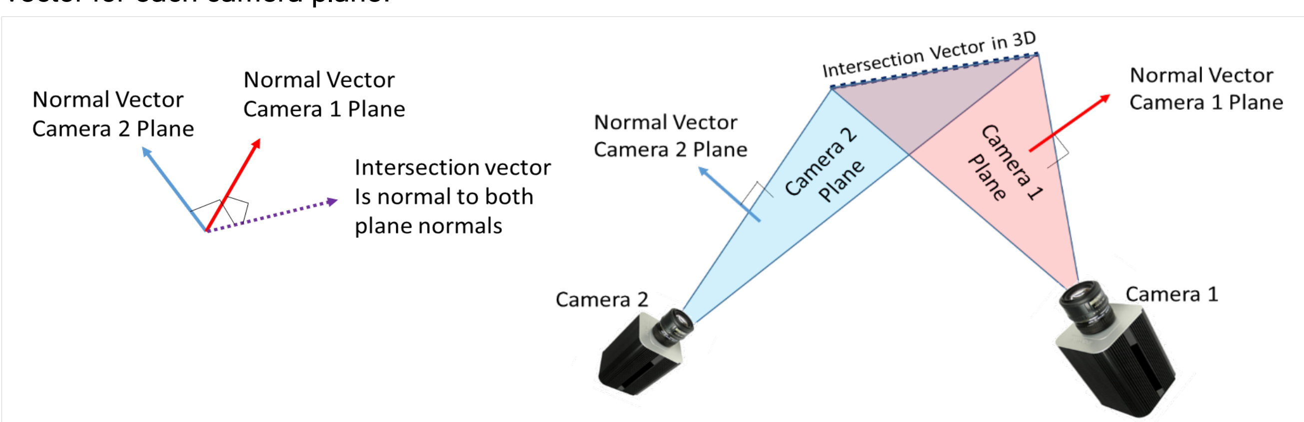

Figure 5
Intersection of two planes forms a vector that is normal to the normal vector of both camera planes

If only the orientation vector is needed, then the work is completed. Otherwise, the 3D orientation vector can further be broken down into angular components such as Euler angles. To measure the pitch and yaw of a bullet, the orientation vector must be subtracted from the bullet's trajectory vector. The actual 3D intersection of any points on the object (such as the CG or nose) can be found using the approach described in reference 1.

For the most accurate results, do not use the extrema points of the shape (such as the bullet's nose and base). Project any one point (such as the bullet's base, nose, or CG) onto the calibration plane. The orientation vector on the calibration plane must be constructed using a "heading point" as described in the previous section. This approach has been demonstrated to make angle measurements of bullet shaped objects in 3D with accuracies better than 0.1 deg when compared to other sources of orientation truth. Furthermore, this approach has also been used to measure 3D angular disturbances in angles with amplitudes smaller than 0.02 deg (ref. 5), indicating that the method has an extremely fine precision when compared to other methods such as yaw cards.

CONCLUSIONS

The approach described in this report provides a straightforward means of making accurate angle/orientation measurements in both two dimensions and three dimensions. Having a calibrated field of view greatly reduces the effects of image skew, camera alignment, and some lens distortions. When used with computer vision techniques, orientation measurements can be made with sub-pixel accuracy, which are orders of magnitude more accurate than crude estimates made using only a few pixel points. Due to simplicity, accuracy, and other advantages of this approach, it is recommended that this process be used to gather accurate angle measurements for a multitude of military weapon testing applications.

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