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AD-E404 546

Technical Report ARMET-TR-22025

**LOW-COST INDEPENDENT ORIENTATION MEASUREMENT FOR
FIXED POSITION INFRARED CAMERA**

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April 2024



U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
COMMAND ARMAMENTS CENTER

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REPORT DOCUMENTATION PAGE

1. REPORT DATE April 2024		2. REPORT TYPE Final		3. DATES COVERED	
				START DATE March 1, 2020	END DATE April 30, 2021
4. TITLE AND SUBTITLE Low-cost Independent Orientation Measurement for Fixed Position Infrared Camera					
5a. CONTRACT NUMBER Not available		5b. GRANT NUMBER Not available		5c. PROGRAM ELEMENT NUMBER 622624	
5d. PROJECT NUMBER H1A00		5e. TASK NUMBER Not available		5f. WORK UNIT NUMBER Not available	
6. AUTHOR(S) Steven Manole, Ryan Decker, Arhum Mirza, and Benjamin Abruzzo					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army DEVCOM AC, METC Armaments Engineering Analysis & Manufacturing Directorate (FCDD-ACM-AA) Picatinny Arsenal, NJ 07806-5000				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army DEVCOM AC, ESIC Knowledge & Process Management Office (FCDD-ACE-K) Picatinny Arsenal, NJ 07806-5000			10. SPONSOR/MONITOR'S ACRONYM(S)		11. SPONSOR/MONITOR'S REPORT NUMBER(S) Technical Report ARMET-TR-22025
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The use of photogrammetry and computer vision to determine the position of objects in a camera's field of view requires knowledge of the camera's position and orientation. Many techniques to obtain camera orientation currently exist, but they rely on several points in the camera's field of view. A study was performed to investigate if a low-cost external measurement device such as a digital level could be used to make sufficiently accurate measurements of the camera's roll orientation. It required the inclusion of an adapter plate to fit the level securely onto the camera's exterior surface. Several experiments were conducted to determine the accuracy required for the roll angle measurement with this setup. By measuring the roll angle with a standard deviation (SD) of 0.012 to 0.020 deg, it was discovered that the affordable digital level was as accurate as (if not better than) expensive computational algorithms that measured roll angle with a SD of 0.034 deg.					
15. SUBJECT TERMS Computer vision Image processing Infrared Camera orientation Digital level					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR		17
19a. NAME OF RESPONSIBLE PERSON Steven Manole			19b. PHONE NUMBER (Include area code) (973) 724-2744		

Standard Form 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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ACKNOWLEDGMENTS

The authors would like to express their gratitude to the In-House Laboratory Independent Research (ILIR) panel at the U.S. Army Combat Capabilities Development Command Armaments Center, Picatinny Arsenal, NJ, for their support in conducting this research.

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INTRODUCTION

Images captured from cameras (including infrared cameras) can be used for purposes of high-precision measurement. Such measurements are performed using photogrammetric techniques that depend on knowledge of the intrinsic and extrinsic parameters of the camera. For the field of ballistics, this includes measuring the orientation and position of a projectile in flight (ref. 1). There are several complications that exist when performing these types of measurements, especially when a high degree of precision is required. One of the challenges is measuring the extrinsic parameters of position and orientation of the camera itself. The measurement of the projectile can only be as accurate as the camera (ref. 2).

Ideally, the camera location should be identified at the focal point when using a pinhole camera model. Since the focal point often exists inside the camera system, it cannot be measured directly. Several methods exist for independent measurement of the focal point (ref. 3). It is also important to incorporate the intrinsic parameters of the camera and lens system to minimize any errors in photographic measurements.

The focus of this study is the roll orientation of the camera specifically. It is possible to determine the camera extrinsic parameters by triangulation techniques or using multiple known reference points in the field of view (ref. 4). It is also essential to have a direct measurement of the extrinsic parameters if only one point in the field of view is known. This point is tactically relevant for armament systems, as only a single point might be identified within the field of view (most likely the target location). During experimental testing, the geometry of the test range may limit how far apart reference points can be placed in the field of view. This requires a secondary method of measuring roll angle. Assuming a camera is leveled in the roll direction with a known position, the pitch and yaw can be computed using a single reference point (that is identified in both the image and world coordinate systems). This is also true if the camera roll orientation is known (after adjusting for this rotation).

The purpose of this study is to understand the accuracy required by a low-cost digital level in measuring a camera's roll angle. Commercial camera systems do not typically include internal orientation measurements. The camera systems that do include that feature are not highly accurate. The use of an external measurement system is necessary. The majority of the engineering effort goes into the internal components of the camera systems. The body is not usually precision-machined flat and level. In this case, an adapter plate must be used to provide a flat and secure reference surface relative to the camera system. The loss in accuracy caused by this adapter and user inconsistencies in placing the level must be considered when understanding the roll angle precision measured by a system as a whole. The inclusion of a level or inclinometer was first adapted in other high-precision pose measurement systems as an essential element (ref. 5).

METHODS

Several steps are required to determine the orientation of a system when using a digital level. First, the coordinate system of the level must be aligned with the coordinate system of the camera. A level is capable of angular measurements in two axes perpendicular to the gravity vector of the Earth. These axes must be aligned to transform the level measurements to define a camera's orientation. The proposed method incorporates a level platform that rests on top of the camera and conforms to the surface contours.

The level platform shown in figure 1 was custom-built according to the detailed three-dimensional (3D) geometry of the camera provided by the vendor (Telops, Quebec City, Canada). The top surface of the camera is a complex contoured surface that is not easy to index. This is compounded by some inconsistencies between the provided model and the physical cameras used in the tests. Careful measurements were required to ensure a secure fit.

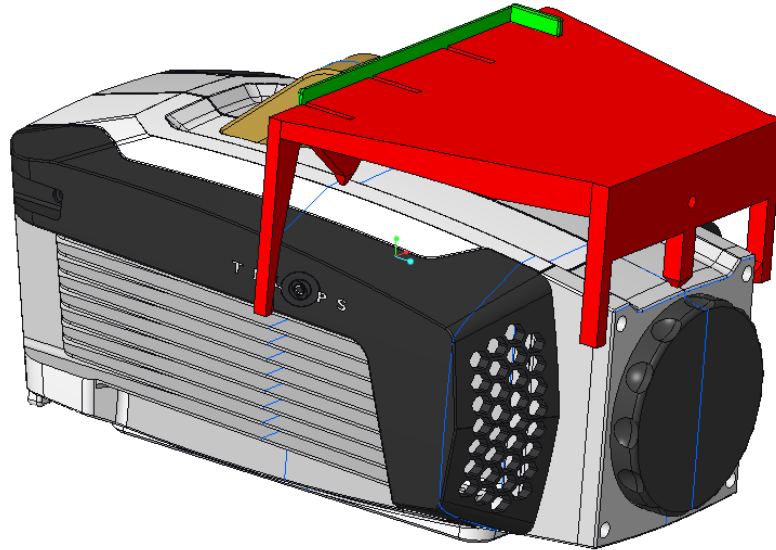


Figure 1
Solid model of camera with level platform

The level platform rises over the handle of the camera, only contacting it on the front surface. It is used as a stop in the downrange direction. Since the handle in the solid model does not match the actual hardware, a bolt was added to adjust the position of the level platform after it was set permanently. Seven points of contact in total were designed between the camera body and the level platform. Three tapered legs contacted the top surface of the camera with two legs pointing toward the camera contact on each side. These features ensured consistent placement of the level platform.

To enable consistent placement of the level on the platform, several stops were designed and assembled into a separate part. This allowed the level platform (a 3D printed part) to be oriented with the top surface on the print bed, making it as flat as possible. All parts were printed as polylactic acid (PLA) with a fused deposition modeling (FDM) printer. Changes in system geometry due to variations in temperature were assumed to be negligible.

The underside of the platform included features for aligning itself with the camera (one axis is parallel to the camera axis). There are also features on top of the platform that aligned one measurement axis of the level to the same camera axis. The tolerances for these features dictated how accurately the coordinate systems were aligned.

The errors caused by misalignment are described in this section. The measured roll and pitch are defined as ϕ' , θ' . The angular misalignment with the plane of the sensor in the image Y-axis (downward) direction is defined as α in equations 1 to 4.

$$\phi' = \phi \cos \alpha - \theta \sin \alpha \quad (1)$$

$$\theta' = \phi \sin \alpha + \theta \cos \alpha \quad (2)$$

$$\epsilon_{\phi} = \phi' - \phi \approx \theta \sin \alpha \quad (3)$$

$$\epsilon_{\theta} = \theta' - \theta \approx \phi \sin \alpha \quad (4)$$

If the calibration is performed while the camera is non level, the errors will be relative to the angle at which the camera is calibrated (ref. 2). Alignment errors in the other two rotational directions were not considered, as they will be corrected by calibration.

Next, the camera must be aligned with the gravity vector. This would be trivial if the camera was manufactured with a flat top parallel to the camera axis. The alignment would be dependent on the flatness-tolerance stack-up of the level and platform. Since the camera top surface is curved, there is no reference datum to align the level platform. The level platform contains features that can fix its alignment, but not in any known position about the camera axis or the horizontal axis of the sensor. To account for this, the level platform must first be calibrated independently to establish the offsets. Once the offsets have been computed, they are expected to remain valid for that combination of camera, platform, and level. The offsets would need to be computed for each new configuration. Figures 2 and 3 show photographs of the final design with the level system in place.



Figure 2
Digital level on platform side view



Figure 3
Digital level on platform top view

The candidate level, Digi-Pas model DWL-1500XY, has a nominal accuracy of 0.002 deg for angles less than 0.5 deg and 0.004 deg for angles up to 2.5 deg, at which point the measurement is saturated (ref. 6). This instrument costs approximately \$400. This cost is considerably lower than the cost of a total station with comparable accuracy by several thousand dollars. State-of-the-art Telops M100HD high-resolution infrared cameras were used for this study (ref. 7). The conclusions that were reached are relevant across all electro-optic/infrared (EO/IR) cameras depending on the body of the camera rather than the sensor type. The camera selected was dictated by availability of the cameras, as well as the calibration setup. A Topcon GM-52 total station was used to determine the precise location of each reference point (light bulbs), as well as the camera. The position of the camera was determined by using a four-eared gimbal that fits around the camera lens. The center of all four points is considered the focal point, which is precisely located, as long as three of the four ears can be surveyed.

The first experiment was conducted to verify the stated accuracy of the level. This was performed by placing a level on a flat table. The following procedure was used for experiment 1.

- Place the level on top of the table
- Take the level measurement
- Remove the level and repeat the procedure

The second experiment was conducted to determine the effect of the level platform on the level's accuracy. This was performed by repeating the first experiment and including the level platform as part of the stack. The following procedure was used for experiment 2.

- Place the camera on top of the table.
- Place the level platform on top of the camera.
- Take the level measurement.
- Remove the level and level platform. Then repeat the procedure.

Finally, an experiment was conducted to test the level measurement against a roll angle measurement which was calculated from the image and reference points. The experiment was repeated for three camera positions to understand whether the measurement is affected by various degrees of unlevelness. The calibration poles that were used are the same as those used in a spatial calibration scheme (ref. 2). Each pole contains a set of five halogen light bulbs spread out over 16 ft.

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The original intent was to use only two reference points within the field of view to calculate the roll angle. While it was possible to calculate the angle using the two points in the image, the results were inconsistent. More reference points were required to measure roll accurately from the camera image. A third point significantly improved algorithm performance based on the mean reprojection error (MRE), with more points yielding additional benefits. This relationship was not quantified because it was not the focus of the study, but it guided the setup of the next experiment. The final experiment 3 made use of the full array of reference points to produce the most accurate roll angles possible. The following procedure was used for experiment 3.

- Set up the full 5x5 calibration reference point (light bulb) array with the entire array within the field of view of the 100 and 200-mm cameras (ref. 2)
- Set up the 100 and 200-mm cameras at the appropriate distances to fill the field of view with the reference point array. Position the cameras with the gimbals attached but not secured to the table
- Survey all relevant light bulbs within the field of view
- Repeat the following steps 10 times for each camera by varying the camera position each time
 - Turn on the reference points (light bulbs)
 - Record 200 frames of video over Gigabit Ethernet at 20 Hz
 - Survey the four stickers on the camera gimbal
 - Place the level on the camera and take the level measurement in both axes
- Repeat the survey of all relevant light bulbs within the field of view

RESULTS

When reading the results in the following tables in this report, consider that the roll angle is measured across the length of the level and the pitch angle is measured across the width. The direction corresponds to the side that the level indicated as “high.” Consider that a roll from the right is negative and a roll from the left is positive if the roll axis is pointing away from the observer. Similarly, a pitch up is positive and a pitch down is negative if the pitch axis is pointing to the right of the observer.

While experiment 1 was expected to yield results similar to the stated accuracy of the level, there were several factors that were most likely different from the environment in which the level was calibrated. The first factor was that the table was not perfectly flat. This meant that the level could rock from side to side slightly. The second factor was that every effort was made to align the level with the edges of the table, but the position of the level varied slightly each time. The third factor was that high-precision measurements may have been affected by noise factors such as people walking near the table. The results from experiment 1 are shown in table 1. The results from experiment 2 are shown in table 2.

Table 1
Experiment 1 results

Trial	Roll angle (deg)	Roll direction	Pitch angle (deg)	Pitch direction
1	1.920	Right	0.940	Up
2	1.930	Right	0.892	Up
3	1.928	Right	0.884	Up
4	1.944	Right	0.892	Up
5	1.931	Right	0.884	Up
Standard deviation (SD)	0.0086		0.0236	
Manufacturer specification	0.004		0.004	

Table 2
Experiment 2 results

Trial	Roll angle (deg)	Roll direction	Pitch angle (deg)	Pitch direction
1	0.812	Right	2.452	Down
2	0.800	Right	2.461	Down
3	0.801	Right	2.452	Down
4	0.819	Right	2.422	Down
5	0.792	Right	2.440	Down
SD	0.0107		0.0151	
Manufacturer specification	0.004		0.004	

As shown in table 3, the results from experiment 3 follow the same convention for the roll and pitch direction used throughout this report. The MATLAB code was used to compute the roll and pitch angles of the relationship between world and image reference point locations (ref. 8). The “Roll Difference” (δ_ϕ) and “Pitch Difference” (δ_θ) columns in table 3 represent the difference between the MATLAB code (ϕ, θ) and level ($\phi_{level}, \theta_{level}$) measurements, as shown in equations 5 and 6.

$$\phi = \phi_{level} - \delta_\phi \quad (5)$$

$$\theta = \theta_{level} - \delta_\theta \quad (6)$$

The data in these columns represent the offset for each camera that is subtracted from the level measurement to obtain the roll and pitch angles. The SDs of the offsets for the level platform are computed in the two rows at the bottom of table 3. The metrics that are used to understand the accuracy of the MATLAB measurements are in the columns representing the SDs for the roll and pitch angles (across 200 frames of video), as well as the MRE in pixels. Since the roll and pitch are changed for each run, the accuracy of the system is based on the SD of the computed differences.

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Table 3
Experiment 3 results*

Camera lens (mm)	Run number	Roll angle	Direction (+L)	Pitch angle	Direction (+U)	Roll difference (δ_ϕ)	Pitch difference (δ_θ)	MATLAB SD roll	MATLAB SD pitch	MRE pixels (px)
200	1	0.705	R	0.214	U	-0.018	-0.601	0.049	0.004	0.29
200	2	1.149	R	0.004	D	0.027	-0.662	0.026	0.002	0.28
200	3	1.182	R	0.009	U	0.028	-0.633	0.022	0.002	0.27
200	4	0.106	R	0.349	U	---**	---**	---**	---**	4.22
200	5	0.935	R	0.164	U	0.021	-0.652	0.020	0.003	0.29
200	6	0.711	R	0.013	U	0.031	-0.608	0.024	0.002	0.28
200	7	0.904	R	0.147	U	0.052	-0.645	0.038	0.003	0.40
200	8	0.119	R	0.465	U	0.026	-0.617	0.021	0.003	0.29
200	9	0.241	R	0.393	U	0.044	-0.603	0.036	0.004	0.41
200	10	0.299	R	0.41	U	0.045	-0.634	0.034	0.003	0.37
100	1	0.826	R	1.372	U	-0.277	-0.862	0.031	0.002	0.22
100	2	0.1	R	1.605	U	-0.282	-0.869	0.034	0.003	0.25
100	3	0.164	L	1.721	U	-0.279	-0.840	0.036	0.003	0.26
100	4	0.181	R	1.987	U	-0.283	-0.853	0.040	0.003	0.29
100	5	0.15	R	1.274	U	-0.261	-0.852	0.030	0.002	0.26
100	6	0.324	L	1.441	U	-0.260	-0.836	0.052	0.004	0.47
100	7	0.837	L	1.633	U	-0.252	-0.802	0.057	0.004	0.49
100	8	0.055	L	1.682	U	-0.284	-0.841	0.035	0.003	0.28
100	9	0.312	R	1.334	U	-0.284	-0.862	0.031	0.003	0.32
100	10	0.817	L	1.747	U	-0.281	-0.800	0.035	0.004	0.32
Average								0.034	0.003	0.51
200-mm SD						0.020	0.024			
100-mm SD						0.012	0.024			

* - All measurements are in degrees unless defined differently.

** - The roll angle measurement code for camera run number 4 at 200 mm did not produce an acceptable solution. The data was omitted because the measurement could not be used due to very high MRE.

DISCUSSION

As shown in table 1, the SD for roll angle is a little more than double the stated accuracy of 0.004 deg, while the SD for pitch angle is an order of magnitude greater. Since the width of the level is quite a bit narrower than the length, it is possible that some of the difference between the two accuracy values could be due to higher sensitivity to placement. While not matching the nominal accuracy, these values are still very low and fall within the acceptable range for a high-precision system (ref. 2).

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As shown in table 2, the pitch angle is once again less accurate than the roll angle. However, an interesting result is that the pitch angle was actually more accurate on the level platform than on a table. This lends credence to the theory that placement of the level (which is more controlled due to the boss on the level platform) has a significant effect on the repeatability of the measurement. The SD for roll angle of 0.0107 deg on the level platform can be compared to that of 0.0086 deg on the table. This represents an increase of 24.4% in relative terms. Considering that the difference of 0.0021 deg in absolute terms is comparable to the nominal level accuracy of 0.002 deg, a strong case can be made that the level platform does not have a meaningful effect on the accuracy of the level.

As shown in table 3, the SDs of 0.012 and 0.020 deg for the roll angle are comparable to that of 0.011 deg when not placed on a camera. This positive result demonstrated that the level platform did not lose accuracy when it was placed on the camera nor when the camera was moved into a new position. The SD of the MATLAB roll computations at 0.034 deg was actually greater than the level platform at 0.020 deg. This meant that the accuracy of the platform might be better than what was reported. Based on the results in experiment 2, the difference was not expected to be large. Overall, the final values computed for the accuracy of the level platform were only five to six times that of the stated manufacturer's specification at worst. In addition, it was comparable to what was obtained using a high-precision survey combined with a rigorous computer vision calculation, which is a much more expensive and time-consuming process.

CONCLUSIONS

Based on the experimental results that were observed, the low-cost digital level is a more than sufficient substitute for measuring roll or pitch angle using multiple image reference points. Furthermore, the precision of the digital level exceeded that of the computer image alignment process while taking only seconds to provide measurements. The downside of using a digital level is that the level platform and camera must be calibrated together to determine the fixed offset bias. Long-term studies of how this offset may change over time with various temperatures have not been performed. Multiple calibrations may be required. However, the digital level is not affected by changes in distortion or focal length, which may present stronger inaccuracies than a change in the level platform over time. Overall, the digital level has been determined to provide an excellent measure of roll and pitch angle after it has been calibrated for the offsets.

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