euspen's 21st International Conference &
Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

ACVISION: A six-degree-of-freedom measuring system combining autocollimation and photogrammetric principles

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Abstract

The six-degree-of-freedom error measurement for the motion accuracy of large mechatronics remains a challenge nowadays. Thus, this paper presents a novel six-degree-of-freedom measurement concept combining the photogrammetric spatial resection method with the autocollimation technique, the so-called ACVISION system. The presented non-contact measurement system tackles the limitations related to the space resection techniques when estimating the extrinsic calibration parameters of a camera due to the high correlation between the orientation and translation parameters, by measuring the pitch (θ) and yaw (Ψ) angles with autocollimation. In this way, the space resection algorithm is fed by the known pitch (θ) and yaw (Ψ) angles to solve the remaining four-degree-of-freedom parameters (translation along the X-axis (TX), translation along the Y-axis (TY), translation along the Z-axis (TZ) and the roll angle (Φ)) so they are estimated with higher accuracy and lower correlation among them. The ACVISION includes a calibrated artefact attached to the tracking object which combines a planar mirror for the autocollimation measurement, and a grid of reference points for the space resection measurement. Finally, the article presents the ACVISION prototype including a description of the system characterization exercise and validating testing employing a laser tracker system as a reference measurement system.

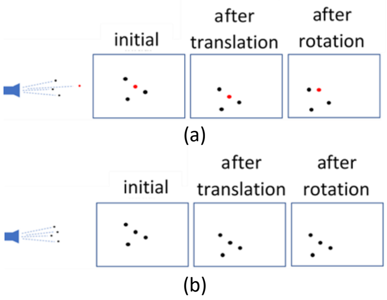
6 DOF tracking system, Non-contact measuring system, photogrammetric spatial resection, autocollimation, large mechatronics

1. Introduction

Currently, as explained by Schmitt et al. there are different options for the non-contact spatial tracking of objects, such as laser tracker, iGPS and photogrammetry technologies [1]. Within those technologies, photogrammetry, which is based on the extraction of three-dimensional information from two-dimensional images, is lately very much in demand by industrial metrology application. Typically, photogrammetry uses the space resection method to obtain the extrinsic calibration parameters of the camera from a single image or multiple ones. Thus, the spatial position and orientation of a camera are determined based on the central projection principle and the modelling of the optical distortion, caused by lens form errors and assembly deviations [2]. The space resection method is also used in photogrammetry to identify simultaneously the intrinsic camera parameters.

However, as explained by Luhmann et al., this method presents some accuracy limitations when estimating the external calibration parameters of the camera [3]. These limitations arise from the high correlation between the orientation and translation parameters of the camera. With a suitable configuration of the a) camera position, b) the object size, and c) the reference system location, the achievable accuracy shall be better than 1:10.000 of the measuring volume. Nevertheless, the accuracy results related to translation along the Z-axis (TZ) and the pitch (θ) and yaw (Ψ) rotations (see Figure 2) are limited if the space resection algorithm is not constrained.

To introduce the challenge regarding the correlation of parameters when solving the 6 DOF photogrammetric space resection method. Figure 1 highlights conceptually the correlation effect. Figure 1 (a) shows a low correlation scenario where a suitable target distribution allows creating a different image pattern after the camera translation and rotation. However, Figure 1 (b) depicts a high correlation scenario where a poor target distribution overlaps the image pattern preventing an accurate distinction of the parameters under research.



(a)
(b)

Figure 1. Photogrammetric target distribution with a different correlation between translation and rotation of a camera: (a) low correlation, and (b) high correlation. Image: TEKNIKER.

To tackle this limitation, the ACVISION system combines the photogrammetric space resection technique with the autocollimation measuring principle [4], so the achievable accuracy of the space resection method is significantly improved.

Thus, the proposed ACVISION suggests a) an autocollimator for the absolute pitch (θ) and yaw (Ψ) angles estimation of a specular surface and b) a constrained space resection photogrammetry by using the autocollimation-based orientation angles to fed and restrict the space resection algorithm. Hence, the remaining four-degree-of-freedom (DOF) parameters (XYZ translation (TX-TY-TZ) and roll angle (Φ)) are estimated with higher accuracy and lower correlation among them by improving the 6 DOF space resection traditional approach.

This work presents the complete ACVISION product development cycle, from the very initial simulation of the novel 6 DOF measurement concept to the prototype performance characterisation tests. Currently, the ACVISION system is a patent-pending product [5].

2. Methodology

Aiming to demonstrate the feasibility of the suggested measurement concept, an initial simulation process is run within Matlab® software with a self-developed ACVISION model, the so-called digital twin of the system. Here, a Monte-Carlo simulation approach is employed to determine the measurement uncertainty of the suggested measurement approach. Thus, the JCGM 101:2008 [6]describes practical guidance on the application of Monte Carlo simulation for the estimation of uncertainty in measurement. It involves the error propagation of the distributions regarding the 6 DOF parameters by using the ACVISION error model. As a result, the expanded uncertainty for every DOF is assessed.

Once the measurement concept is validated in simulation, the next step is to construct the prototype with all the necessary equipment to have a functional measurement system to test the prototype and characterise its performance.

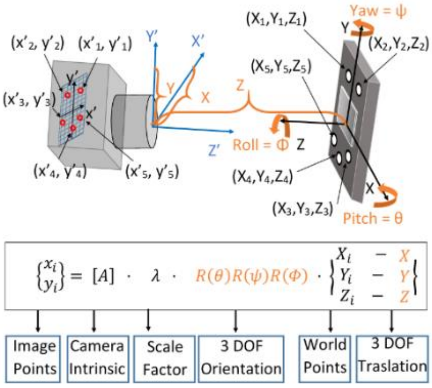
Every step through the product development cycle is explained in detail in the following points.

2.1. Simulation process

This section gives an overview of the methodology employed during the initial simulation stage.

Once the potential correlation effect is exposed, the photogrammetric space resection method is simulated considering the collinearity equations and the central projection model theory. At this point, a pin-hole camera model is considered to represent the camera behaviour and to obtain the 6 DOF camera poses (see Figure 2).

For the simulation, the Monte-Carlo approach is employed considering a virtual measurement scenario of 5 m between the camera and the tracking object. Here, several input variables are introduced, such as the image noise and the camera intrinsic parameters estimation errors, considering a normal error distribution for them. Moreover, two different scenarios are suggested during the simulation: a) a 6 DOF exercise is performed, with no restriction on the pitch (θ) and yaw (Ψ) rotation parameters (traditional space resection method), and b) a 4 DOF exercise is executed by considering that those rotation parameters are input known values. On this second approach, a low-correlation measurement scenario is envisaged which should allow improving the achievable measurement uncertainty, which in turn could validate the ACVISION measurement.



$$\begin{Bmatrix} x_i \\ y_i \end{Bmatrix} = [A] \cdot \lambda \cdot R(\theta)R(\psi)R(\Phi) \cdot \begin{Bmatrix} X_i & - & X \\ Y_i & - & Y \\ Z_i & - & Z \end{Bmatrix}$$

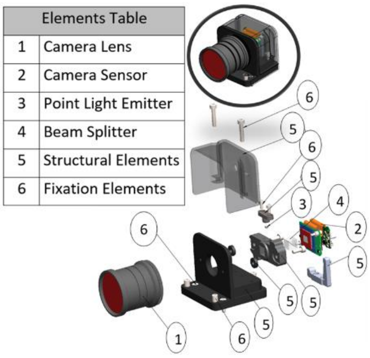
Figure 2. Scheme with the 3D object projection to the 2D image data by the collinearity equations. Image by: TEKNIKER.

Once that the simulation is performed, a sensitivity analysis during the minimization problem is performed by minimizing the distance among observed and reprojected points in the image plane, which correspondence is previously determined. Thus, the correlation effect of the parameters of interest is characterized.

2.2. Integration and materialization of the concept

The second section explains the integration exercise between photogrammetry and autocollimation technologies to materialize the ACVISION single device.

The prototype is conceived by using a single industrial camera in conjunction with an industrial lens. As shown in Figure 3, the prototype includes an in-camera embedded led light source and a beam-splitter to realize the on-board autocollimation system. To work in autocollimation mode, the led is switched on and the camera lens focus distance is set to infinity to ensure the light collimation. The device could also be conceived in such a manner that a single industrial camera and a 2D autocollimator are mounted on the same support performing an individual operation of each technology and a common data processing.



Elements Table	
1	Camera Lens
2	Camera Sensor
3	Point Light Emitter
4	Beam Splitter
5	Structural Elements
6	Fixation Elements

Figure 3. The prototype materialization includes optical components to enable photogrammetry and autocollimation in a single device. Image by: TEKNIKER.

In addition to the sensor, a singular artefact is also needed to realize the object tracking. The artefact comprises a) a specular surface (mirror) for the autocollimation measurement, and b) a set of "N" reference points, wherein each reference point is known and defined by a Xi, Yi, Zi position within a coordinate system defined on the artefact (see Figure 4). The relationship between this coordinate system and the specular surface is well-known (calibrated), which allows merging the information coming from both types of measurement technologies.

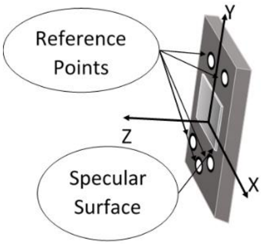


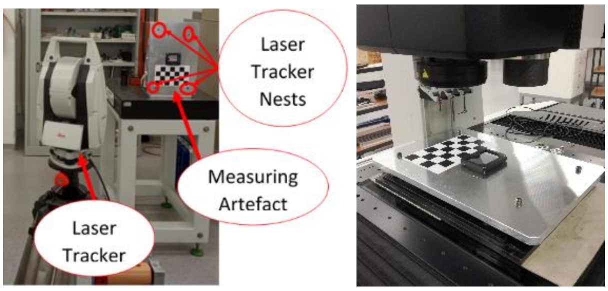
Figure 4. Singular artefact employed on the ACVISION system. Image: TEKNIKER.

2.3. Experimental tests

This section describes the characterization work related to the ACVISION validation.

Some preliminary experimental measurements are performed by using laser tracker technology as a reference framework. For this purpose, four specific nests are conceived on the measuring artefact to define a common reference system between the laser-tracker performed measurements and the ACVISION measurements (see Figure 5 a). Four laser tracker reflectors are placed on these nests, one reflector per nest. The measurement of these fiducial points enables a best-fit alignment between the laser tracker technology and the ACVISION system, considering that the artefact is previously calibrated on a hybrid (contact and vision-based) coordinate measuring machine (CMM) U= ± 3μm (see Figure 5 b).

During the experimental test campaign, the measurement sequence is divided into 4 artefact arbitrary positions (manual movements/adjustments). Thus, the artefact is placed at a variable distance to the sensor and taking the first position as reference the 6 DOF relative transformation is calculated between the next 3 artefact positions.


a)

b)

Figure 5. Experimental test campaign execution using an AT402 laser tracker. Image: TEKNIKER.

2.4. Measurement sequence

This section explains the ACVISION system´s measurement sequence.

1st. Autocollimator-based measurement of the pitch (θ) and yaw (Ψ) rotation parameters by measuring the specular mirror on the artefact (see Figure 6). The two rotation parameters are calculated by identifying the centre of the returned collimated beam in the camera sensor $(\delta x'$ and $\delta y')$,. Thus, the autocollimator formula is applied where the focal distance of the camera (f) is introduced (see 1 and 2).

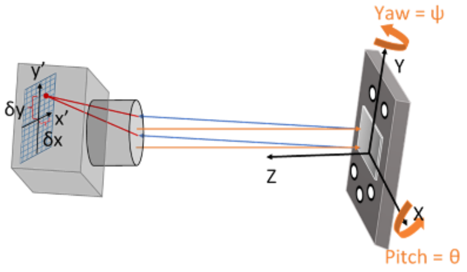


Figure 6. Device autocollimation based measurement scheme. Image: TEKNIKER.

$$\boldsymbol{\theta} = \frac{\boldsymbol{\delta x'}}{\mathbf{2} \cdot \boldsymbol{f}} \qquad (1)$$

$$\boldsymbol{\psi} = \frac{\boldsymbol{\delta y'}}{\mathbf{2} \cdot \boldsymbol{f}} \qquad (2)$$

2nd. Photogrammetry-based measurement: Measuring and identification of the image points corresponding to the set of "N" reference points placed on the artefact by the camera vision (see Figure 7). Here, the previously measured pitch (θ) and yaw (Ψ) rotation parameters are introduced into the space resection algorithm so a 4 DOF identification exercise is performed. Thus, the remaining 4 DOF are obtained (XYZ translation (TX-TY-TZ) and roll angle (Φ)) and the 6 DOF measurement is guaranteed.

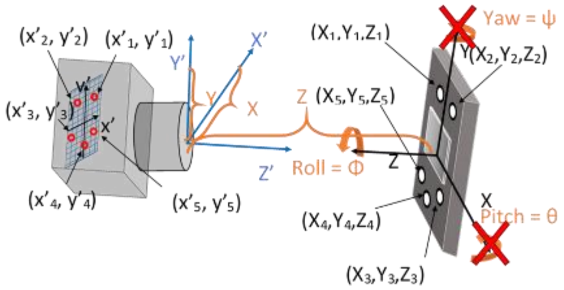


Figure 7. 4 DOF space resection photogrammetry measurements scheme. Image: TEKNIKER.

3rd. Mathematical optimization: A minimization problem is performed (see 3) to reduce the difference between the observed image points (x'i and y'i) and the estimated image points (x'Ei and y'Ei) [7]. The estimated image points (x'Ei and y'Ei) are obtained by the collinearity equation and using a pinhole camera model for the projection of the 3D reference points. In such a modified algorithm, the pitch (θ) and yaw (Ψ) rotation parameters are introduced as known values.

$$\sum_{i=1}^{N}\left(\begin{Bmatrix}x'_i\\ y'_i\end{Bmatrix}-\begin{Bmatrix}x'_{Ei}\\ y'_{Ei}\end{Bmatrix}\right)^2=\mathbf{0} \qquad (3)$$

4th. Offline characterization: Before performing the prototype validation, the ACVISION offline characterization is done. Here, the two measurement technologies are characterized separately. On one side, the camera is characterized so the camera intrinsic parameters and the camera lens distortion are identified. On the other side, the autocollimator is characterized by high accuracy angle generator.

3. Results

3.1. Simulation results

The output of the simulation testing is analyzed in detail by a sensitivity analysis where the correlation among the 6 DOF pose parameters is established. Figure 8 shows the correlation matrix. It highlights that the translation along X-axis (Tx) is highly correlated with the rotation around Y-axis (Ry). Similarly, the translation along Y-axis (Ty) is highly correlated with the rotation around X-axis (Rx).

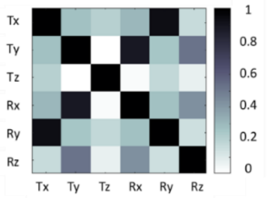


Figure 8. Correlation matrix for the photogrammetry space resection method (translations: Tx, Ty, Tz / rotations: Rx, Ry, Rz). Image: TEKNIKER.

Next, the Monte-Carlo simulation approach is employed to determine the measurement uncertainty of the suggested ACVISION system. Figure 9 (a) breaks down the 6 DOF uncertainty estimation with no restriction on the pitch (θ) and yaw (Ψ) rotation parameters, and Figure 9 (b) does the same considering that the pitch (θ) and yaw (Ψ) rotation parameters are previously known after the offline calibration [8]. Those rotation parameters have a measurement uncertainty of ± 15 arc-sec for a level of confidence of 95%, which is within 2σ standard deviation for a normal distribution (k = 2).

Results show an improvement from the 6 DOF to 4 DOF measurement simulation in an order of magnitude. Based on the obtained results, the ACVISION product development continued to the concept of physical implementation (prototype).

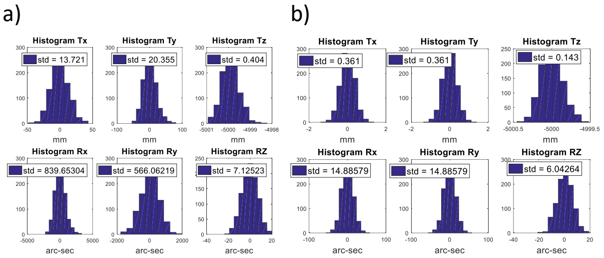


Figure 9. The 6 DOF uncertainty estimation simulation exercise: a) No restrictions and b) with restrictions. Image: TEKNIKER.

3.1. Integration and experiment Results

Finally, the ACVISION prototype is developed. Figure 10 (a) shows the integration of the photogrammetry and autocollimation techniques in a single envelope. Figure 10 (b) shows the singular artefact development for object tracking. Here, the ACVISION coordinate system is constructed using the planar chessboard pattern as a reference. The Laser Tracker coordinate system is also depicted above the artefact.

Figure 10. The ACVISION prototype realization; a) Photogrammetry and autocollimation in a single camera device, b) special artefact for the object tracking. Image: TEKNIKER.

Figure 11 shows the experimental setup for the test campaign. Here, the ACVISION system is placed 5 m far (Figure 11 a) from the artefact (according to the simulation parametrization) while the laser tracker as a reference measurement is positioned just 1 m far from the artefact to guarantee a low measurement uncertainty (simulated with measured data U (k=2) =30 µm). The experimental setup is complemented with an industrial camera to validate and compare the coherency of the results obtained with the ACVISION system (Figure 11 b).

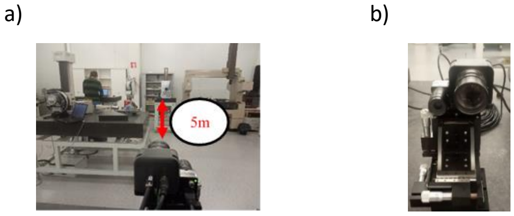


Figure 11. ACVISION experimental setup; a) Laboratory-type scenario, and b) industrial camera and the ACVISION system. Image: TEKNIKER.

As previously described, the measurement sequence during the experimental test campaign is divided into four artefact positions. Thus, the artefact is placed at a variable distance to the sensor and taking the first position as reference the 6 DOF relative transformation is calculated between artefact positions, comparing those results to what obtained with laser tracker technology.

Table 1 and Table 2 show translations and rotations respectively. They describe the 6 DOF parameter results and their estimated uncertainty (U (k=2)) between the artefact positions measured by the laser tracker using the Spatial Analyzer® software. Here, the translation motion is in the range of tens of mm and the rotation is in the range of one-tenth of degrees. Note that the relative displacement between artefact positions is manual. Therefore, these movements are not controlled but are within the prototype measuring range.

Table 1 The 3 DOF translation parameters and corresponding uncertainty values considered as the reference for testing.

Tx (mm)	U_{Tx} (µm)	Ty (mm)	U_{Ty} (µm)	Tz (mm)	U_{Tz} (µm)
-14.088	15.783	0.018	12.960	3.891	28.578
0.098	15.965	0.067	12.919	3.521	27.411
-0.053	16.020	0.066	12.191	3.558	27.207

Table 2 The 3 DOF rotation parameters and corresponding uncertainty values considered as the reference for testing.

Rx (Deg)	U_{Rx} (arcsec)	Ry (Deg)	U_{Ry} (arcsec)	Rz (Deg)	U_{Rz} (arcsec)
-0.0015	17.930	0.3177	33.189	0.0009	12.495
-0.0004	19.573	0.225	34.1858	-0.0003	12.516
-0.0005	18.373	0.0504	32.957	0.0024	12.623

Once that 6 DOF parameters between artefact positions are known, the ACVISION measured parameters are compared to the reference values. Table 3 presents the results. Those results are in the range of one-tenth of mm for the translation parameters and tens of arcsec for the rotation parameters. Experimental results are coherent with the simulated results and they are also coherent with results obtained with the additional industrial camera.

Table 3 The 6 DOF parameter differences between the ACVISION prototype and the laser tracker measurements with constraints.

Tx (mm)	Ty (mm)	Tz (mm)	Rx (arcsec)	Ry (arcsec)	Rz (arcsec)
-0,170	-0,049	1,233	-1,790	-546,660	16,850
-0,115	-0,121	0,142	-14,814	-379,582	13,064
-0,002	-0,009	0,023	15,155	291,955	-14,197

4. Conclusions

This article presents the complete ACVISION product development cycle, from the very initial simulation of the novel 6 DOF measurement concept to the prototype performance characterisation tests. Even though the obtained experimental results are good enough to validate the prototype functionality, some limitations are observed during the test campaign: a) a high measurement uncertainty on the camera intrinsic parameter estimation, and b) Artefact manual movements shall introduce errors during the system characterization. In this way, the next steps are focused on performing additional tests to conclude the ACVISION prototype validation in such a way that the current prototype limitations shall be corrected.

In the near future, the scalability of the ACVISION system from the laboratory conditions to the shopfloor shall also be assessed to deploy a robust solution for the 6 DOF error measurement in large mechatronics challenges, such as rigid body stability monitoring, structure monitoring, linear stages characterization, large machine tools TCP real-time monitoring, etc...

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