EVALUATION OF A PHOTOGRAMMETRIC SYSTEM EMPLOYED IN THE CLOSED LOOP CONTROL OF ROBOTS PERFORMING DRILLING AND FASTENING OF AERONAUTICAL STRUCTURAL ASSEMBLY

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Abstract. The automation of structural assemblies in the aeronautical industry needs a high level of accuracy and repeatability. Robots are employed in the entire joining process and, more specifically, in the riveting of the various fuselage sections. In order to measure the correct positioning of the robots during the riveting process, a large volume metrology system is needed. This paper evaluates a photogrammetry system with an accuracy level greater than a hundred micrometers. It presents an experiment which verifies this accuracy by comparing its results to the readings of a coordinate measuring machine. Then, a repeatability test is carried out to evaluate whether the system outputs the same distance measurements between two points. It is shown that the errors increase as the measured object moves away from the sensors. However, the observed results are always within the expected range. The analysis of the experiments shows that a photogrammetric metrology system is adequate for the automation of aeronautical assemblies, both for measurements and for the positioning correction in closed loop applications.

Keywords: photogrammetry system, metrology, fuselage assembly.

1. INTRODUCTION

The increasing employment of robots in industrial manufacture is evident in the international scenario. In order to reduce problems generated by systematic human error, increase speed and reduce production costs, it is essential to implement automation solutions in manufacturing processes (Kleebaur, 2005).

The use of robots in the riveting process of the various sections of the fuselage is essential to increase production rates. An industrial robot such as the Kuka[TM] KR210, shown in Fig. 1, could be employed for this function as DeVlieg *et al* (2002) do with the Kuka 350. However, its repeatability is 0.12 mm, according to Kuka (2009), thus not accurate enough for such application.

Figure 1. Kuka[TM] KR210 Robot

To ensure proper positioning of the tool, it is necessary to use a coordinate measuring equipment for large volumes.

Figure 2 presents the K-Series from Nikon, a photogrammetry equipment which, according to its manufacturer, suits the needs of aircraft assembly. The equipment works with a 17m³ working volume. Metris (2009) says that the

minimum working distance is 1.6 meters and the maximum is 6.0 meters. The manufacturer's datasheet specifies the accuracy varying according to the distance from the camera to the object and is divided into three zones, as shown in Tab. 1.

Table 1. K-Series system nominal accuracy

	Distance from camera	Accuracy error
Zone 1	1.5 to 3.0 meters	$60\mu m + 10\mu m/m$
Zone 2	3.0 to 5.0 meters	$70\mu m + 25\mu m/m$
Zone 3	5.0 to 6.0 meters	$140\mu m + 25\mu m/m$

The measurement system is equipped with three linear CCD cameras. Each camera has a specific arrangement of its pixels' direction. The cameras capture infrared signals, emitted by proprietary LEDs. All LEDs are connected to a controller, and so is the camera. The controller synchronizes the LEDs with the camera, making each LED flash at a time, in a pre-defined sequence. Thus, the K-Series system can identify each LED attached to a body, the robot in this case, and calculate the position in space of each point individually, using a triangulation method, also shown in Fig. 2.
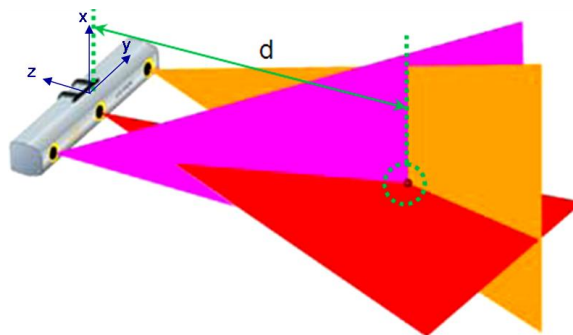

Figure 2. K-Series photogrammetry system

To check the accuracy of the K-Series, a series of experiments were done in conjunction with a coordinated measuring machine (CMM) Mitutoyo CrystaC 7106 presented in Fig. 3.

The Mitutoyo machine has an accuracy of (1.9 + 3 L/1000) micrometers where L is the distance between two points (Mitutoyo, 2009). In this paper, the experiment was carried out with a displacement of 100mm, resulting in a calibrated accuracy of 2.2 micrometers. This value is much lower than that specified for the K-Series, meeting the needs of the experiment described below.

Figure 3. Mitutoyo CrystaC 7106 Coordinate Measuring Machine

2. ACCURACY AND REPEATABILITY VERIFICATION OF THE K-SERIES SYSTEM

The following experiment was carried out to determine the K-Series' accuracy and repeatability in a temperature and humidity controlled environment. Temperature is set to 20±2°C and humidity to 50±5%.

2.1. Setup of the experiment

The experiment consists of moving the Mitutoyo's arm and measuring its position with the K-Series. Three K-Series' infrared LEDs are fixed on the CMM's arm in order to emit signals that give the location in space for the photogrammetry equipment, as shown in Fig. 4.
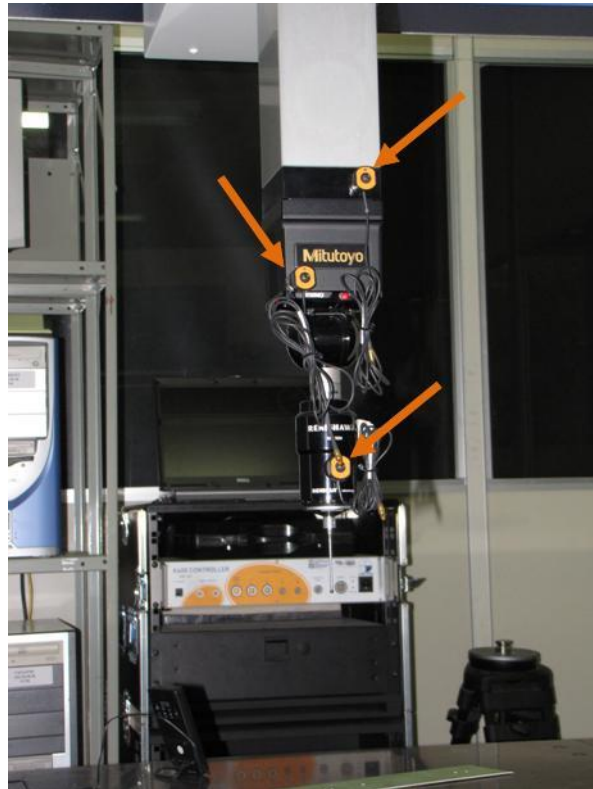

Figure 4. K-Series LEDs attached to the Mitutoyo CMM

The second step to setup the experiment is to define the K-Series' coordinate system. For this, the Mitutoyo's measuring arm is manually commanded to move to its origin point which is measured by the optical equipment. Then, the machine is commanded to move only in its X-axis and the K-Series collects the new position. With the K-Series proprietary software Geoloc, a line is created from these two sampled points, defining the X-axis' direction and orientation for the photogrammetry system. Similarly, the Mitutoyo machine is commanded into a Y-axis only movement and the Nikon equipment reads the new position and defines the Y-axis for its coordinate system. The K-Series' Z axis is created mathematically in Geoloc, from the previous two defined axes.

2.2. Procedure of the experiment

With the K-Series coordinate system defined, the experiment itself is started by moving the machine arm in different positions and measuring them using the optical system, as described below.

According to Fig. 5, the machine from Mitutoyo reaches thirteen specific points and the K-Series equipment measures each position. The first point (P0) is the origin of the coordinate system for both equipments. The Mitutoyo's arm is commanded to that point and K-Series measures it. Then, it moves 100mm on the X-axis, reaching P1=(100,0,0), and the photogrammetry system measures this position. After that, the Mitutoyo returns to the origin (P2=P0) and K-Series reads its position. Similarly, it reaches the points P3=(0,100,0) and P5=(0,0,100). Finally, it performs the same motion in the opposite orientation and returns to the origin. For each of the thirteen points, the K-Series system measures the Mitutoyo's arm position and the results are exported to a text file to be analyzed.
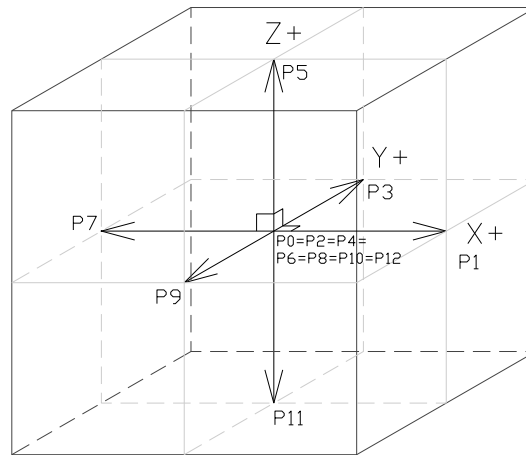
Figure 5. CMM moving points

The experiment is comprised of thirteen points (P0, P1, P2 ... P12) and is performed with two replications. The number of samples is thus 26 points. For each of the points, the positional error is calculated according to Eq. 1, where the MEAS and NOM indexes correspond to the measured and the nominal coordinates, respectively.

$$\Delta R = \sqrt{(x_{MEAS} - x_{NOM})^2 + (y_{MEAS} - y_{NOM})^2 + (z_{MEAS} - z_{NOM})^2} \tag{1}$$

All of the points are analyzed to obtain the accuracy and precision of the K-Series system. After this analysis, the called "origin points" sampled (P0, P2, P4 ... P12) are analyzed to assess the repeatability of the photogrammetry system at the first zone.

This experiment is based on the European Standard EN ISO 9283 (ISO, 1998), but instead of evaluating the robot (in this case, the Mitutoyo's arm), the present work qualifies the measuring equipment, i.e. the K-Series, considering the arm as the reference. The points used to evaluate the equipment are not on the corners of the cube, but on its faces, as it is proposed by Villani *et al.* (2010).

The Villani *et al.* (2010) work evaluates the Kuka KR-210 robot using the K-Series as a reference measuring machine. The present work, however, qualifies the earlier experiments by evaluating the K-Series using the same method but with the Mitutoyo machine as the reference.

2.2. Results of the experiment

Figure 6 shows the resulting errors from the measured points with the K-Series. Observe that the errors are accentuated in the offset points of the origin, since it adds the random error with the K-Series coordinate system's creation error.
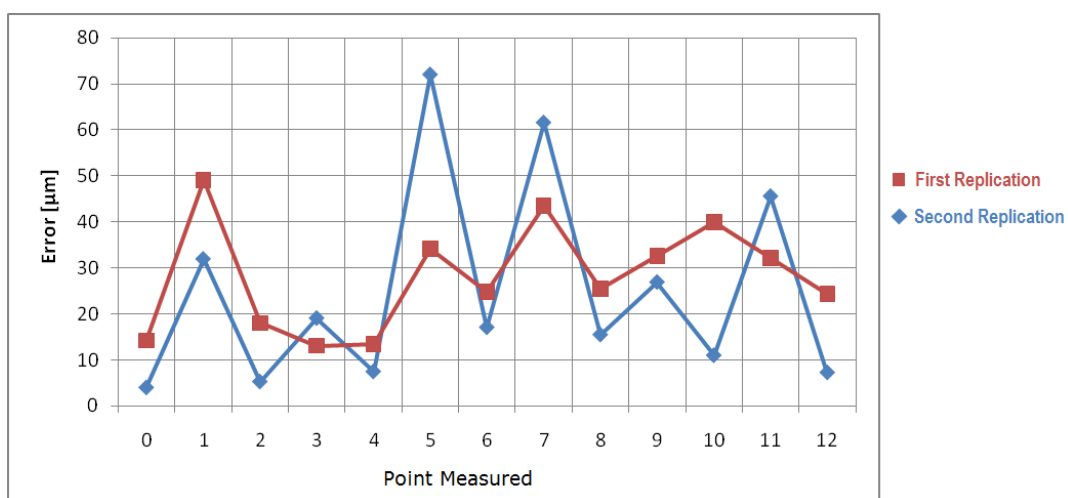
Figure 6. K-Series' measurements error

The average error found for n=26 samples is 26.5μm with a standard deviation of 17.4μm. The maximum error was 71.9μm at (0,0,100), within the second replication of the experiment. As it can be seen, the maximum error is reached in the displacement of the Z-axis, which is expected considering that the errors in this direction (Z) sums error definitions from the X-axis and Y-axis, in the process of creating the coordinate system.

Even considering the worst measured error, it can be concluded that the K-Series system operates within the manufacturer's specification, which guarantees a maximum error of 76μm in the best working condition (zone 1, the shortest distance from the camera, 1.6 meters).

Analyzing the points measured at the origin of the created coordinate system, it's visible in Fig. 7 the great repeatability of the system on the first zone of measurement.
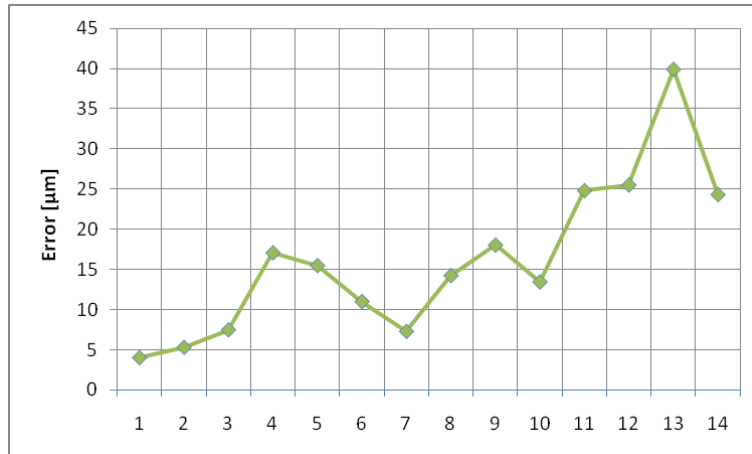

Figure 7. K-Series' repeatability error

In this case, an average error of 16.3μm and standard deviation of 9.8μm is obtained. The maximum error was 39.9μm.

Finally, the angular error of the measurements is analyzed.

Similar to the position vector, the rotation vector is also comprised of three components. Figure 8 represents the rotations A, B and C about axes X, Y and Z, respectively.

The expression that defines the rotation vector is similar to those defining the position vector. The error in rotation, therefore, is obtained by an expression very close to the positioning error, as shown in Eq. 2.

$$\Delta A = \sqrt{\left(\theta_{MEAS} - \theta_{NOM}\right)^2 + \left(\phi_{MEAS} - \phi_{NOM}\right)^2 + \left(\varphi_{MEAS} - \varphi_{NOM}\right)^2} \tag{2}$$

All measured points are hit with the same orientation of the arm, i.e. 0° rotation in the three Cartesian axes. Thus, the θ_{NOM}, ϕ_{NOM} and φ_{NOM} angle ratings are 0°.
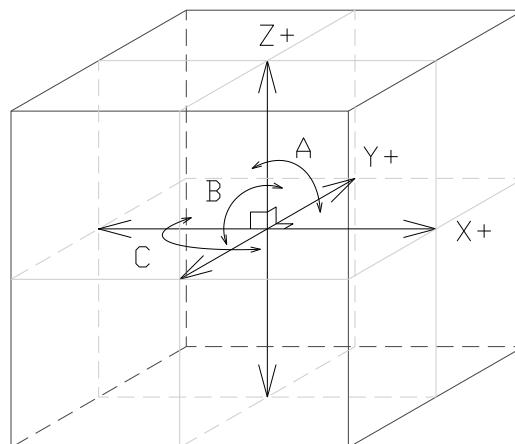

Figure 8. Effect of rotation on the coordinate axes

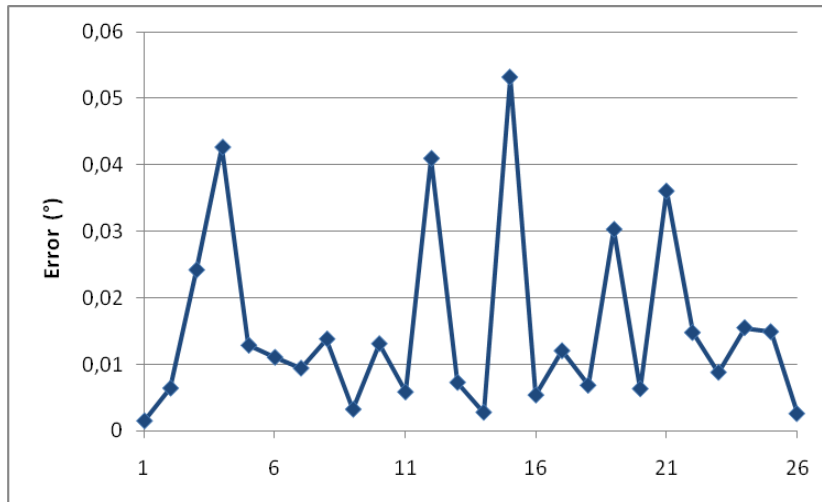Figure 9 shows the modules of the errors of orientation measured by photogrammetry equipment:

Figure 9. K-Series orientation error

The greatest error in the orientation measurements equals 0.053°, with an average of 0.014° and a standard deviation of 0.013°. It is apparent that the accuracy of the system is suitable for measuring robot orientation as well as the tools' orientation in the aeronautical assembly industry.

3. VERIFICATION OF REPEATABILITY VARYING K-SERIES' MEASURING ZONES

In order to specifically check the repeatability of the K-Series in its three measuring zones, another experiment was conducted in a larger environment, but without temperature and humidity control (as a typical application).

3.1 Setup and procedure

The experiment consists on attaching three individual and independent LEDs in a metallic body, according to Fig. 10, then measuring the separation between them. It is noteworthy that these measurements cannot be assessed in accuracy, only repeatability, because the nominal values can't be measured physically by another instrument for comparison, i.e. the LEDs individual plastic housings are not accurate.
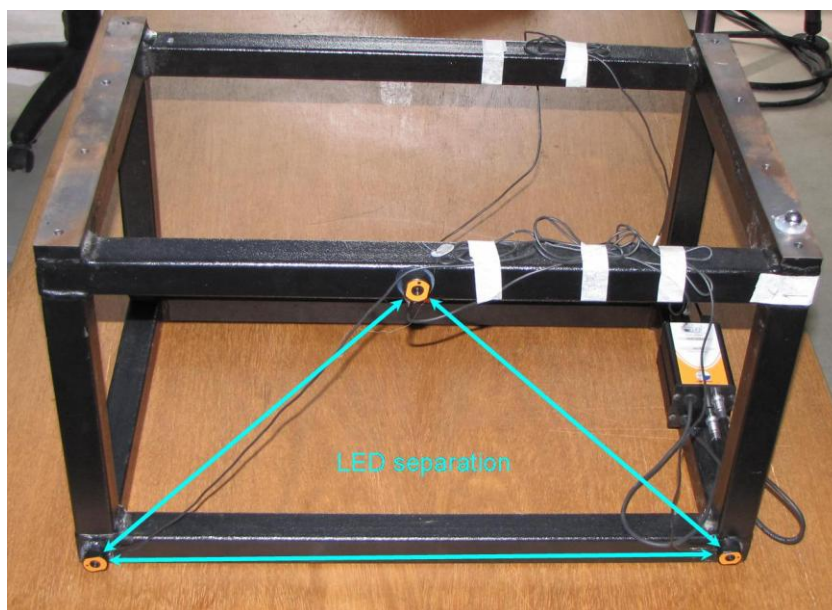

Figure 10. Body with three individual LEDs attached

With the body placed at a distance from the camera, the measurements of each of the three LEDs are repeated ten times with 1-second interval between each measurement, resulting in 30 point readings. Then the body is moved to a new position and the measurements are performed similarly. The body is positioned in 16 different locations in order to analyze the distance-from-camera influence on the measurements.

3.2. Results of the experiment

In this experiment, <u>separation</u> concerns about the separation distance from one LED to another, while <u>distance</u> means the distance from the measured point to the photogrammetry camera. Now, it can be defined the nominal distance ($D_{[pos]}$|[pos]=1 to 16) as the mean distance of the three LEDs (z_1, z_2, z_3) in its ten replications in relation to the camera at one of the 16 positions, according to Eq. 3. Note that the camera's z-axis is perpendicular to the camera and decreases out of his front, as sawn in Fig. 3.

$$D_{[pos]} = \left\{ \sum_{rep=1}^{10} \left[(z_{1,[pos]} + z_{2,[pos]} + z_{3,[pos]})/3 \right] \right\}/10 \tag{3}$$

The separation between two LEDs ($s_{[i,i,pos,rep]}$|[i,j]=[1,2];[1,3];[2,3] and rep=1 to 10) is the separation measured from one LED (i) to a second one (j) in a specific position and replication, expressed in Eq. 4.

$$s_{[i,j,pos,rep]} = \sqrt{(x_{i,pos,rep} - x_{j,pos,rep})^2 + (y_{i,pos,rep} - y_{j,pos,rep})^2 + (z_{i,pos,rep} - z_{j,pos,rep})^2} \tag{4}$$

The nominal separation ($S_{[i,i]}$|[i,j]=[1,2];[1,3];[2,3]) is the average separation between two LEDs (i and j) calculated for each position and replication, according to Eq. 5.

$$S_{[i,j]} = \sum_{rep=1}^{10} \left[\left(\sum_{pos=1}^{16} s_{i,j,pos,rep} \right)/16 \right]/10 \tag{5}$$

The error of each separation measurement ($e_{[i,j,pos,rep]}$) is obtained through Eq. 6.

$$e_{[i,j,pos,rep]} = s_{[i,j,pos,rep]} - S_{[i,j]} \tag{6}$$

The graph in Fig. 11 represents the separation error for each pair of LEDs, at 16 positions of the body with its 10 replications at each position ($e_{[i,i,pos,rep]}$), showing that the variance of the errors increase with an increased distance from the camera ($D_{[pos]}$), but in the worst case (65um error, at 5,619mm from the camera), the result is within what is specified by the manufacturer.
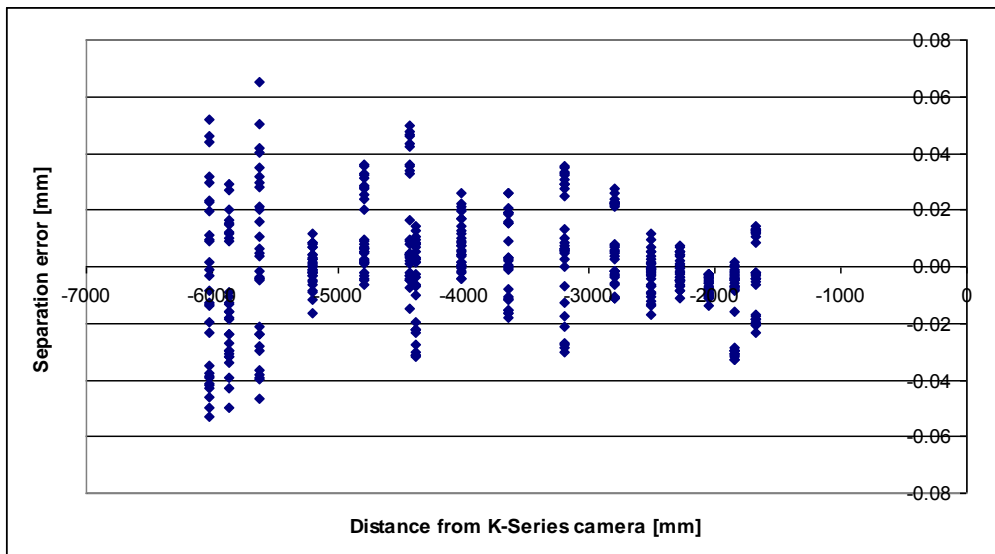

Figure 11. Separation error ($e_{[i,j,pos]}$) vs. Distance ($D_{[pos]}$)

4. CONCLUSION

The experiment conducted with the coordinate measuring machine as an auxiliary metrology system evaluates the accuracy and repeatability of an optical measuring machine. Its analysis states that the photogrammetry equipment meets the manufacturer's specifications and can be used to measure the positioning of conventional robots in applications requiring high accuracy and repeatability level as the aeronautical industry.

The ability to measure the orientation of a robotic arm with the K-Series photogrammetry system is also suitable for the aeronautical industry and other applications requiring high accuracy and repeatability in orientation such as drilling and fastening.

One of the experiments was conducted in a laboratory under controlled temperature ($20\pm2°C$) and humidity ($50\pm5\%$) to ensure the accuracy of the CMM from Mitutoyo. The photogrammetry equipment, however, has temperature sensors and the system is capable of correcting measurement errors when the temperature ranges from about $5°C$, common in industrial environments. When there is a wider variation in temperature, the system warns that extrapolation and requests a new referencing procedure using a proprietary standard bar and its procedures.

The main precaution to observe is when defining the K-Series coordinate system. The poor definition of the primary and secondary axes (in this work, the X-axis and Y-axis, respectively) can cause large errors, especially on the third axis, created mathematically, thus accumulating those two errors.

A second experiment took place in a not controlled environment to broaden the working space. The results show the high repeatability level of the photogrammetry system even at the longest visible distance from the camera, making the K-Series suitable for the measurement in large volumes, such as aeronautical applications.

Future work will include the redefinition of the K-Series coordinate system and watching the influence in the results. The variation of work volume must also be in focus for the next studies, as well as experiments with nominal angular displacement. Another factor that may influence the accuracy of the K-Series system is the amount of infrared sensors used. This study used only three sensors, but a greater number of those tends to increase the system's accuracy.

5. ACKNOWLEDGEMENTS

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