Sun Tracker Robotic Arm Optical Distance Measurement Evaluation at Different Positions Using Six Sigma Tools

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Abstract—This paper presents an optical distance evaluation solution, for a sun tracker robotic arm, with the help of Six Sigma. With the help of statistical tools any measurement system can be evaluated and a measurement system analysis (MSA) can be easily made. Like every measurement system, optical distance measurement can have errors. Six Sigma tools can evaluate the measurement system and can give useful data about its accuracy. Sometimes measurement system evaluation is done twice. First, initial tests are done, after some fine tuning and error correction is performed, and finally a repeated test is done, to show that the measurement errors were corrected.

Index Terms—cameras, databases, distance measurement, data processing, stereo vision.

I. INTRODUCTION

THIS paper presents an evaluation tool of an optical distance measurement system. Optical distance measurement can have errors, apparently larger than traditional systems [1, 2]. Using the Six Sigma (6σ) tools, we can ensure that optical distance measurement is accurate, having high precision at smaller and bigger distances too [18].

In today's industrialized world, robots are the key elements which makes possible to build products in big volume and with a high-quality standard to cover the needs of today's consumer world [3, 4, 14, 15]. Robots need to measure distances to know their position in space and the distance to the manipulated object [5]. They must use optical distance measurement methods to ensure flexibility [6]. Optical distance measurement with the usage of stereo cameras [16] is one of the most common ways to achieve high precision distance measurement for industrial robots [7].

Measurement system analysis (MSA) is often performed to ensure that the system behaves as desired [10]. First, a pre-test is done, where the measurement system errors are measured [11]. After, some corrections are made, and is checked if the changes really reduced the measurement errors [12].

II. PROBLEM FORMULATION

In the laboratory we had access to an educational/industrial robotic arm (Fig. 1), which we needed to program to track the sun [18]. The demand was to know its position in space and the distance to the manipulated object to implement automated software which can control it to move autonomously [18]. The optical distance measurement was the best solution to obtain the position of the key parts of the robotic arm in space [8]. We evaluated the optical distance measurement against the distances measured with laser. The optical distance measurement had some errors. We had to measure somehow if these errors are acceptable, if some corrections are needed, or if we need to use another distance measurement method [9].
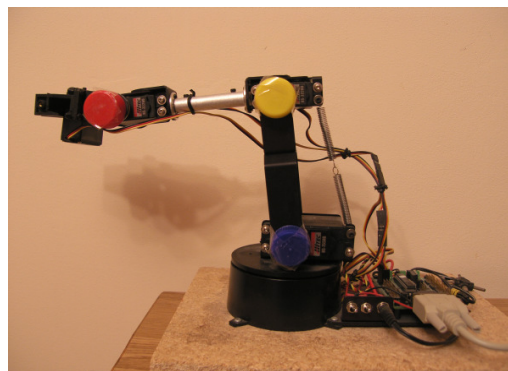

Fig. 1. The normal probability plot, for the actual real distance and the distance computed, by the system using the cameras.

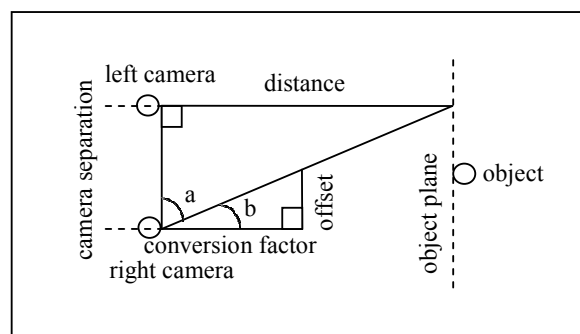On Fig. 2 there can be seen the optical distance measurement method with two cameras (stereo cameras).

Fig. 2. Distance computation using two video cameras (stereo cameras).

The camera separation and initial distance from the base of the robotic arm is measured previously with laser. These values are hardcoded in the automated distance measurement software, made by the authors, in C++ programming language, for the robotic arm. The automated distance measurement system can compute the distances to each colored bottle cap (blue, yellow and red) at the robotic arm's joints. The colored bottle caps are recognized using color filtering.

On the *0x* and *0y* axes the distance can be computed easily based on a 2D coordinate system based on the pixels from one camera. To compute the distance on the *0z* axis (in 3D) the following formulas were used.

On equation (1) can be seen the tangent of the *a* and *b* angles.

$$\begin{cases} tg(a) = \dfrac{distance}{camera\ separation} \\ tg(b) = \dfrac{offset}{conversion\ factor} \end{cases} \qquad (1)$$

The initial offset can be computed from the *x* coordinates of the left and right camera, as shown on equation (2).

$$initial\ offset = |x_{i_R} - x_{i_L}| \qquad (2)$$

The conversion factor can be computed as shown on equation (3).

$$conversion\ factor = \frac{initial\ offset \times initial\ distance}{camera\ separation} \qquad (3)$$

The final offset can be computed from the *x* coordinates of the left and right camera, as shown on equation (4).

$$final\ offset = |x_{f_R} - x_{f_L}| \qquad (4)$$

The final distance can be computed as shown on equation (5).

$$final\ distance = \frac{converison\ factor \times camera\ separation}{final\ offset} \qquad (5)$$

The novelty of the paper is measuring movement distances for a robotic arm's gripper, during movement (dynamically), with the usage of two cameras (stereo cameras) in real-time.

To have a robotic arm which can move freely, to execute any given task, as it was programmed previously (statically), the optical distance measurement must be very precise. To test the robustness of the optical distance measurement, the system must be tested as any industrial process. The best way to test this is to create a measurement system analysis (MSA) using Six Sigma tools.

III. PROBLEM SOLUTION

The optical distance measurement method was tested using Six Sigma tools [17]. Six Sigma represents a set of methods and tools which are used to improve the process. Six Sigma methods try to improve the quality of a process by finding and

eliminating the root causes of defects. It uses a set of quality management tools, mainly statistical tools. The Six Sigma tools were implemented using graphs in Minitab statistical software [18].

These tools can show if the measurements are accurate enough and if some fine tuning is needed [13].

As shown on Table I., the system was tested with measurements at different distances. The range of values used for the measurements is between 100 mm and 3000 mm, with 100 mm step. The real values, measured by laser, and the distance measured and computed by the system with the cameras are very close. There are two cameras, they are placed near each other, and the distance is computed with stereo triangulation. We computed also an error delta, the difference between the actual distance value and the value measured by the camera system. The low sample size is not a problem for the Six Sigma tools, because it can be used always normal probability plot instead of histograms.

TABLE I
DISTANCE MEASUREMENT USING CAMERAS AT DIFFERENT DISTANCES [MM]
AND THE MEASUREMENT ERROR DELTA [MM]

Real Distance [mm]	Computed Distance [mm]	Error Delta [mm]
100	99	1
200	202	-2
300	303	-3
400	395	5
500	502	-2
600	598	2
700	699	1
800	797	3
900	904	-4
1000	1005	-5
1100	1101	-1
1200	1204	-4
1300	1298	2
1400	1402	-2
1500	1494	6
1600	1599	1
1700	1701	-1
1800	1802	-2
1900	1905	-5
2000	2005	-5
2100	2105	-5
2200	2202	-2
2300	2302	-2
2400	2404	-4
2500	2496	4
2600	2598	2
2700	2697	3
2800	2796	4
2900	2902	-2
3000	3006	-6

IV. EVALUATION

In Fig. 3 we present a normal probability plot with a 95% confidence interval of the two measurements, the real distance and the measured distance with the camera system. Please note that these graphs overlap almost perfectly, so the measured distance, does not differ very much from the actual distance. The Anderson-Darling (AD)value is 0.321, and the p-value (the p-value or probability value is the probability for a specific statistical model, when the null hypothesis is true) is

0.514, so it is higher than α = 0.05 (the significance level α is the probability of making the wrong decision, when the null hypothesis is true), so the null hypothesis is not rejected; thus, we can say that the measured distance values do not differ too much from each other.
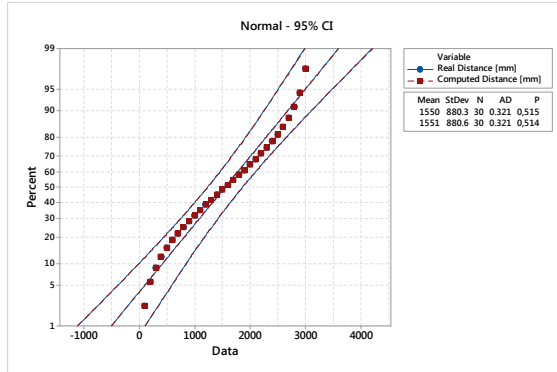

Fig. 3. The normal probability plot, for the actual real distance and the distance computed, by the system using the cameras.

In Fig. 4 we see the normal probability plot for absolute error delta with a confidence interval of 95%. The mean for the absolute error delta is 3.033 mm. The standard deviation is 1.586 mm. The AD value is 1.261, and the value is p <0.005, which is lower than 0.05, so the null hypothesis is rejected. This means that the absolute error delta values differ from each other, which could be expected, because for absolute error delta is a computed value, not a measured one. Each value is transformed to a positive error, all errors are added and stacked, and all errors are over 0, even if the computed distance is higher or lower than the real distance. The mean of the absolute error has the value just over 3 mm.
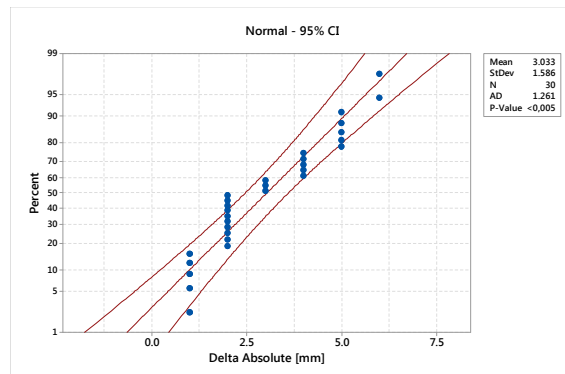

Fig. 4. The normal probability plot created for the absolute error delta.

In Fig. 5 we can see the fitted line plot, which is a method of the regression analysis. The computed distance is presented as a function of the actual real distance. The values are obtained first from the actual real distance values and then from the computed distance values. The standard deviation of these values is 3.42693 mm. The R-Square (R-Sq) and R-Square adjusted (R-Sq (adj)) values are 100%, which shows that the responses can be perfectly predicted by knowing the input values. This means that if we know the actual real distance, we can obtain the distance computed by the

algorithm using video cameras. For regression analysis we obtained an empirical formula presented in the graph and shown in equation (6).

$$\text{computed distance } [mm] = 0.246 + \text{real distance } [mm]$$
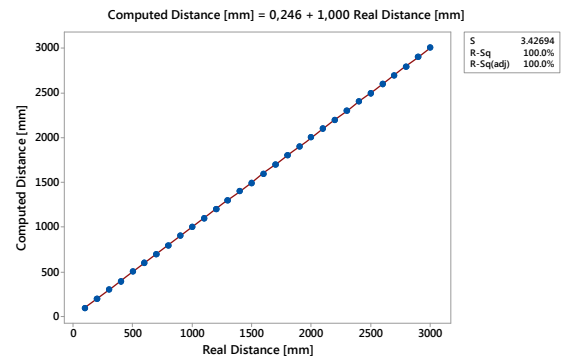$$\text{or} \qquad\qquad (6)$$
$$Y = 0.246 + X$$

Fig. 5. Regression analysis, for actual real distance and the distance computed, by the system using cameras.

In Fig. 6 we show a more detailed analysis of regression, where, versus graphs are observed, indicating that there are no problems with the regression model, because the values are spread randomly above and below 0. Also, on the graph we can see a red dot, representing a high residual value, at the (-6, 1500) coordinate. This means that for the measurement of 1500 mm, the largest error delta is 6 mm.
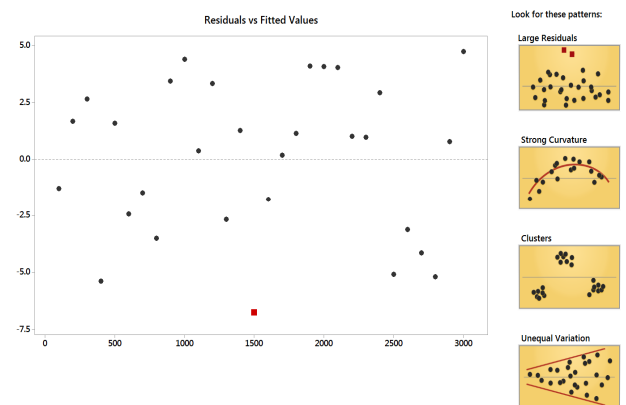

Fig. 6. The graph of residuals versus fitted values, for the actual real distance and the distance computed, by the system using cameras.

In Fig. 7 we show the residual values obtained after the fitted line plot. We can see that the AD value is 0.549, and the p-value is 0.145, this is higher than α = 0.05, the null hypothesis is not rejected. Thus, we can say that the residual values do not differ too much from each other. The histogram does not look like a Gaussian distribution, but for such a small number of values it cannot be expected a better result. The versus graphs (versus fits and versus order) show a large distribution of the values, which is normal and expected.
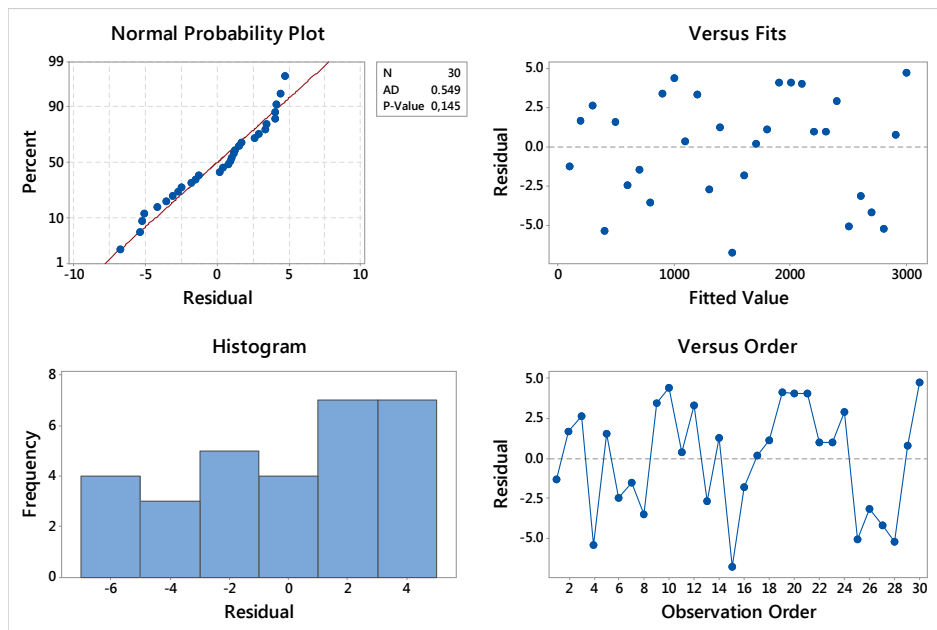
Fig. 7. Analysis of the residual values, for the distance computed, by the system using cameras.

In Fig. 8 we continue the regression analysis between the actual real distance and the distance computed by the algorithm for measuring distances using cameras. For each input value x (actual real distance) there is a prediction of y (the computed distance) using a prediction interval of 95% for $\alpha = 0.05$.
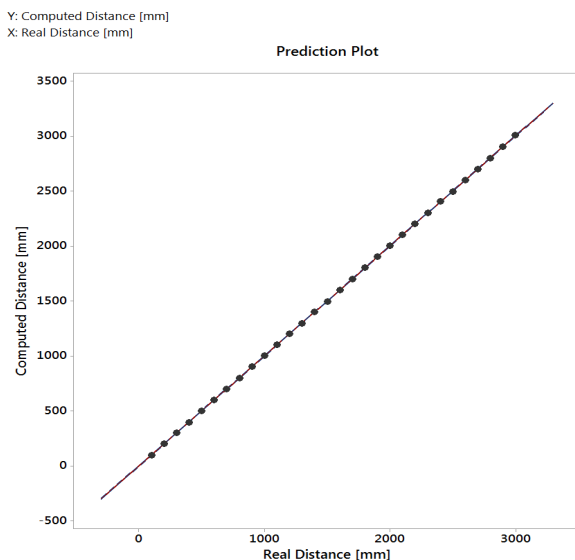

Fig. 8. The prediction plot, for the actual real distance and the distance computed, by the system using cameras.

In Fig. 9 we continue again the regression analysis, highlighting certain important values. We can see the R-Square (R-Sq) value adjusted to 100%, which shows that the output values (computed distance) can be predicted 100% from the input values (actual real distance). The residual standard deviation is 3.427 mm in the linear model and in the

alternative quadratic model is 3.468 mm; these values are very good and there were expected. On the graph we can observe the empirical formula obtained by the regression analysis and the highest residual value of 6 mm when measuring the distance of 1500 mm.
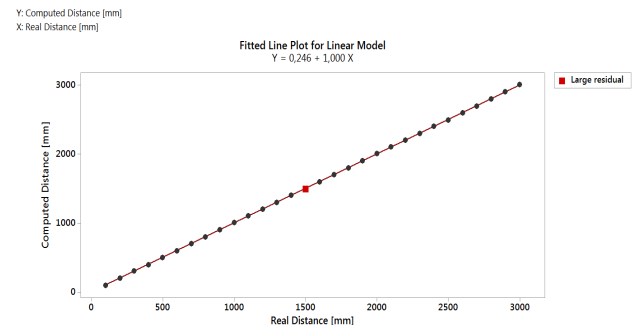

Fig. 9. The fitted line plot for linear model, for the actual real distance and the distance computed, by the system using cameras.

In Fig. 10 we present the summary report of the regression analysis. We can see that p <0.001, which is lower than $\alpha = 0.05$, so the null hypothesis is rejected: This means that the measured values differ enough from each other, to form a mathematical relationship between the computed distance (Y) and the actual real distance (X). The model variation, the R-Square (R-Sq) is 100%, therefore the output values (computed distance) can be predicted 100% from the input values (actual real distance), in other words the variation of the model is very small or non-existent, or the computed values with the camera system are very close to the actual real values measured with laser. There is a perfect correlation between the computed distance (Y) and the actual real distance (X) using the empirical equation obtained by the regression analysis.
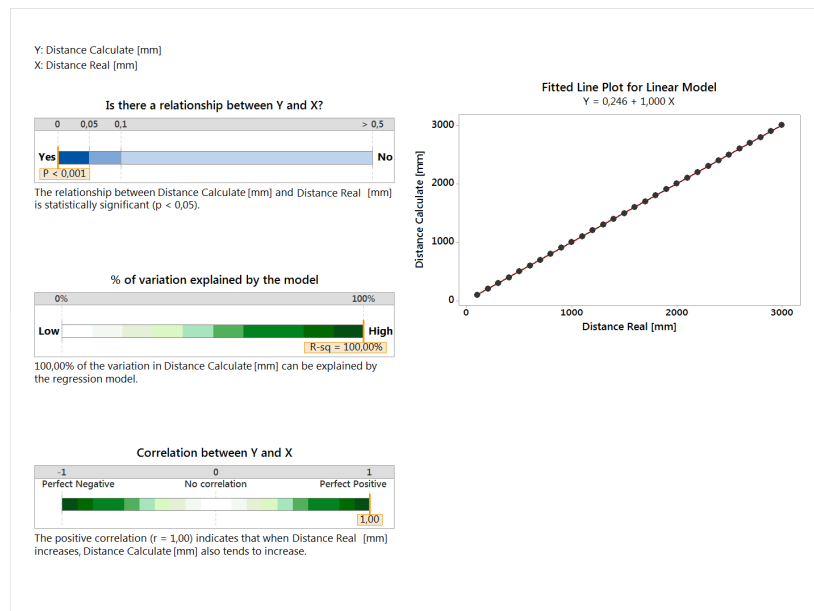
Fig. 10. Summary report of the regression analysis, for the actual real distance and the distance computed, by the system using cameras.

In Fig. 11 we show the capability analysis for 30 error deltas. The individual value and moving range (I-MR) charts are within limits. The histogram has somehow a Gaussian tendency but for a histogram, 30 values are not enough (better use normal probability plot). On the histogram we observe that there are no values where the error delta is 0, which means there is no measurement without error, but the errors are not too high. On the normal probability plot, the AD value is 0.643 and the p-value is 0.084, so this is higher than $\alpha = 0.05$, so the null hypothesis is not rejected. This means that the error deltas do not differ too much between each other. The most important values are at the conclusions: the standard deviation is 2.965 mm for the subgroup and 3.38 mm for all the measurements. The process capability index for subgroup: C_{pk} = 1.38, over 4σ (where C_{pk} = 1.33), which is a very good result in a system of this kind. The performance for subgroup: C_p = 1.46, the performance overall the data: P_p = 1.28 and the process capability index overall the data: P_{pk} = 1.21, all values are very close 4σ, which is a very good result for a system running under normal conditions. For parts per million (PPM), or the reported error to one million measurements is 20.21 for the subgroup and 171.11 for all the measurements, these values are also very good.
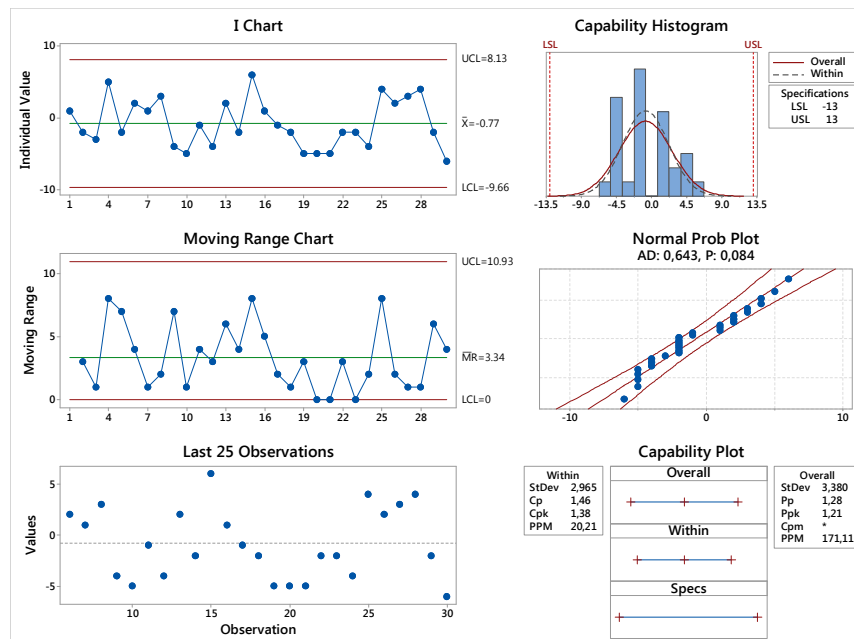

Fig. 11. The process capability analysis made for the error delta.

In Fig. 12 we continue the capability analysis for the error delta. We can see the individual value and moving range (I-MR) charts which are in limits. The normality (Anderson-Darling) test is passed with the p-value of 0.084, which is greater than α = 0.05, so the null hypothesis is not rejected. Thus, we can say that the error delta values do not differ too much between each other.
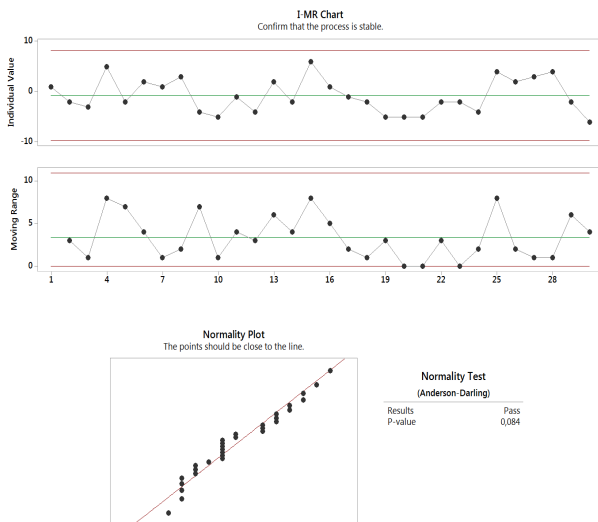

Fig. 12.   The I-MR (individual value - moving range) analysis and the normality test made for the error delta.

In Fig. 13 we observe the fluctuation of the error delta, measured in mm, as a function of the actual real distance, measured with laser in m. We can see a tendency of fluctuation of higher values, for the small distances, under 1 m, a tendency of fluctuation of proportional values, for the average distances, between 1 m and 2 m, and a tendency of fluctuation of lower values, for the higher distances, between 2 m and 3 m. This was expected, as this chart represents proportionality, so after this graph it can be said that the error deltas are mostly constant throughout all the distance ranges. This graph is a qualitative rather than a quantitative one; it shows the errors as the measurement distance is increased.
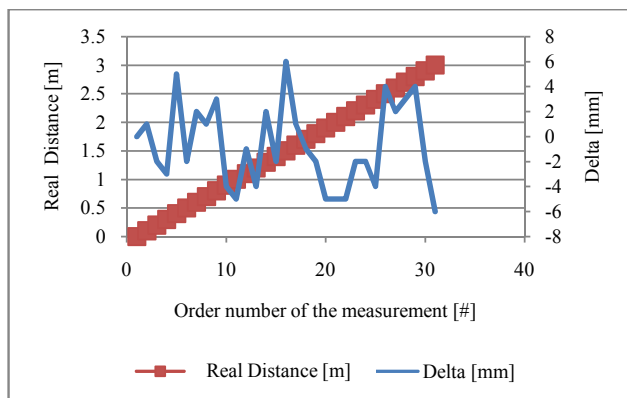

Fig. 13. Graphic representation of the actual real distance [m] and the error of measurement (error delta) [mm] on the same graph.

V.   CONCLUSION

As it was seen an optical distance measurement system, with stereo cameras, used for a sun tracker robotic arm, was evaluated using Six Sigma tools.

The Six Sigma tools materialized by the graphs in Minitab showed that the optical distance measurement with video cameras is accurate enough and there is no need for fine tuning or replacing with other distance measurement method. This means that the measurement system analysis (MSA) has good results, 4σ accuracy which for real processes is very good (6σ is the theoretically ideal process, not existent in real life). Knowing that the MSA had good results we can say that the industrial robots can precisely detect their position in space and the distance to the manipulated object just by using optical distance measurement using video cameras.

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