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TERRESTRIAL LASER SCANNING FOR DEFORMATION ANALYSIS

Research Team

Maria Tsakiri, *Lecturer, NTUA, Greece*

Artemis Valani, *PhD Student, NTUA, Greece*

1. INTRODUCTION

In this project, new algorithms and methods that assess and exploit the metric accuracy of a commercial laser scanner were developed, with a view to create a system that can be used for deformation monitoring applications.

The project involved several experiments in order to assess the repeatability of the measurements obtained by a laser scanner. Considering that the use of targets is the only way to accurately register point clouds acquired from different positions of the scanner to a common reference system, several algorithms for the automated and precise determination of the centre of a target were developed. These algorithms were tested and the results were compared both to those of other methods, mentioned in the literature, and to those that are produced by commercial software. The results have confirmed the reliability and accuracy of the proposed methods. Furthermore, in order to increase the degree of automation and the robustness of the original algorithms several improvements have been made and additional algorithms were created so as to automatically detect numerous targets from a single scan and, more importantly, to automatically match targets that appear in scans acquired from different positions. Finally, the algorithms and methods developed were implemented to detect motion caused by deformation in controlled conditions.

2. REPEATABILITY EVALUATION

Measurement repeatability is a very important property for a laser scanner system. In order to evaluate this property for a commercial laser scanner (Cyrax 2500), a number of experiments were conducted. The results of two typical experiments are summarized in Table 1. The first involved scanning four targets mounted on four pillars of the internal EDM calibration baseline of NTUA. The second involved the scanning of five targets placed on a wall. For both cases, nine scans of each target were collected and for each scan, the mean X, Y and Z values were calculated. Also, in order to evaluate the repeatability of the reflectivity, its mean value and standard deviation were calculated. The radiometric centre of each target (i.e. the weighted mean X, Y and Z values, using the reflectivity as a weight) was also calculated. Using the derived mean values, their standard deviation was calculated for each one of the targets. These calculations, though fairly simple, provide an efficient way to evaluate the repeatability. The low standard deviation in both cases indicates that the repeatability of the scans is very high. These are described in detail in Valanis & Tsakiri [5].

Table 1: Results for repeatability check for the baseline targets and the targets on the wall

	Standard deviation of mean position (m)			Standard deviation of position of radiometric centre (m)			
targets	X	Y	Z	Xrad	Yrad	Zrad	Rmean
Baseline	1.54E-04	1.13E-04	2.28E-04	1.90E-04	2.17E-04	2.67E-04	2.20E+00
Wall	2.51E-05	1.18E-04	5.77E-05	3.41E-05	7.32E-05	9.02E-05	2.29E-01

3. ALGORITHM PRESENTATION

A procedure that is critical for the registration (i.e. the process of referencing all data into a common coordinate system) of point clouds acquired from different positions of the scanner, is the identification of the centre of the special retroreflective targets that are used. Although not very well documented, the issue of automatic target identification has been previously addressed in Gordon et al.[1] and Lichti et al.[2]. In [2] three different methods are described. The first one defines the centre of the target as the position with the maximum radiance. The second defines the centre by the mean position of the radiometric centre of the 4 strongest returns. The third algorithm defines the centre of the target as the radiometric centre of all returns. These algorithms will be referred to henceforth as maxrad, maxrad4 and radcent respectively. In the experiments described below, these algorithms were applied and the results are compared to those of the new-develloped algorithms. In particular, several new algorithms have been developed. The “fuzzypos” and “fuzzyposfine” algorithms are based on the fuzzy classification of the points of a point-cloud based on their reflectivity. The “gridrad” and “delrad” algorithms utilise gridding and delaunay surface modelling techniques so as to obtain a model of the target and define its centre using the radcent algorithm. Finally the “fuzzygridrad” and “fuzzydelrad” algorithms are based on the same idea but use the “fuzzypos” algorithm instead. All of the above are described in detail in Valanis & Tsakiri [3].

The original algorithms, "fuzzypos" and "fuzzyposfine" were proved to be very stable and produced results of higher accuracy compared to those of other algorithms mentioned in the literature or those of proprietary software. However, experimenting has shown that in some cases (such as those depicted in Figure 1) the algorithms, in their original versions, are not always able to detect the target and isolate it from its background solely based on the results of the fuzzy classification. Therefore, several improvements have been made [3]. For the "fuzzypos" algorithm, a process that yields a refined solution was added so that it can produce accurate results when the reflective area of the target is classified into the correct class, such as in Figure 1a.

In even more difficult cases, such as the one presented in Figure 1b, where the reflective area of the target is assigned to the wrong class, another course of action has to be taken and therefore, the "fuzzyposfine" algorithm has also been improved. First, instead of applying the original "fuzzypos" algorithm, the improved one is applied, and a process that verifies the existence of a target was added. If the existence of a target is confirmed, its centre is defined by the original algorithm. If not, a reflectance map of all of the original data, such as the one in Figure 1b, is presented to the user who must depict the approximate position of the centre of the target if there is one.

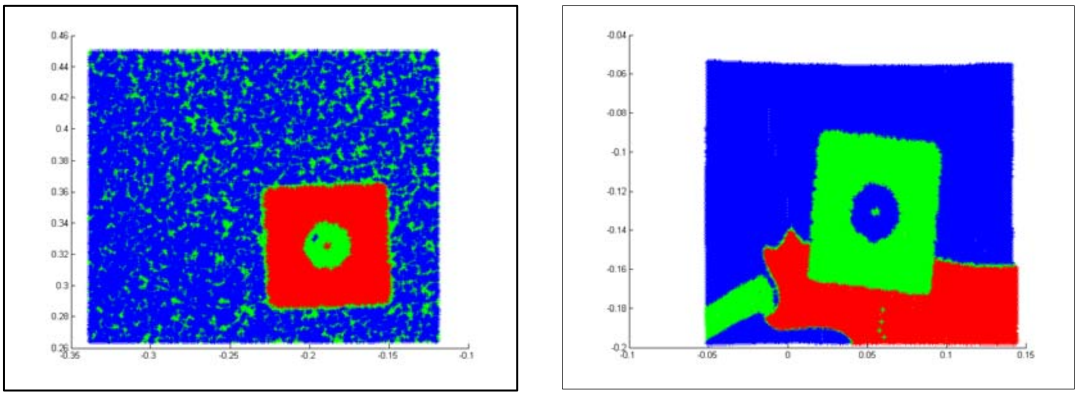

Figure 1: Cases of unexpected fuzzy classification results. a) The reflective area of the target is assigned to the correct class (presented in red). b) The reflective area of the target is assigned to the wrong class (presented in green).

The experiments that are presented in the following sections indicate that the new "fuzzypos" and "fuzzyposfine" algorithms yield better results than those produced by proprietary software.

Apart from the above, some more algorithms that increase the degree of automation were developed. The first algorithm "Autotarg", given a scan that comprises many targets, identifies them, calculates the positions of their centres using the original "fuzzyposfine" algorithm and yields a list with the results. If there are targets that could not be detected, the new algorithm can be used so as to define their centres too and add them to the list. The second algorithm, "Targmatch", given two lists that comprise the positions of targets that were acquired from two different positions of the scanner, matches the targets that are appear in both lists and determines the parameters of a rigid body transformation between the two systems so that the data can be referred to a common coordinate system. The method used for the determination of the parameters of the transformation is the least squares method. Finally, another algorithm for the registration of point clouds without the use of targets is currently being developed. The main idea is to detect planes within the point clouds and by matching their dual points determine the parameters of the transformation between the two reference systems. A detailed description of this method and a presentation of the results of the experiments will be available in Valanis & Tsakiri [4].

4. EXPERIMENTS AND RESULTS

Several experiments were conducted to evaluate the performance of the original algorithms and compare it with the performance of the algorithms mentioned in the literature. In particular, two series of experiments were designed and conducted. The first series, involved scanning several targets that were mounted on the pillars of the EDM internal calibration baseline at NTUA. Multiple scans of the targets were obtained from two positions. The second series involved the scanning of five targets that were mounted on a wall. The scanning in this case was carried out from various distances and angles. The data collected for both cases were subdued to processing in order to evaluate both the internal and external accuracy of the results produced by the aforementioned algorithms. In Table 3 the results of those experiments are summarised. Both the internal and external accuracy evaluation results indicate that in all cases the algorithms "fuzzypos" and "fuzzyposfine" exhibit the best performance. In particular, the "fuzzyposfine" algorithms yields the best results in all cases, with a mean absolute error ranged from 0.4mm to 0.7mm for all combinations of scanning distances and angles.

Table 3: Accuracy evaluation results

	DATA	Mean Absolute Error (mm)			
		Baseline targets		Targets on the wall	
		Int.	Ext	Int.	Ex.
METHOD	radcent	0.9	2.1	4.3	5.1
	maxrad	13.2	8.3	12.6	19.8
	maxrad4	14.0	6.3	9.2	12.9
	fuzzypos	0.6	1.3	0.2	0.9
	fuzzyposfine	0.4	0.9	0.1	0.5
	gridrad	0.9	1.6	4.7	5.6
	delrad	1.0	1.4	3.7	4.2
	fuzzygridrad	0.7	1.3	1.6	2.1
	fuzzydelrad	1.3	1.3	1.3	1.9

Having estimated the repeatability of the raw measurements, the accuracy in the estimation of the centre of a target by the original algorithms, and taking into consideration that the improved versions of the algorithms can in some cases attain even higher accuracies, an extended experiment for deformation detection was designed. For this experiment, ten targets were used. Half of them were stationary whereas the remaining targets were placed on a deforming object. All of the targets were acquired twice from two positions and for three epochs. For the first epoch, the scanner was placed approximately 4m far form the targets. For the second and third epoch, the scanner was placed at a distance of 10m. The deformation of the object took place right after the second and before the third epoch. For each epoch and for each target, apart from the two scans that were acquired at a resolution of 1mm, a fine scan (collected by the scanner when the user requests the determination of the centre of a target) of each target and the position of the centre as calculated by the proprietary software were also acquired. The first step was to estimate the internal accuracy of the system (the term "system" shall be used henceforth to describe the scanner used coupled with the proposed algorithms). In order to do that, two experiments were carried out. For the first experiment, data of the same type acquired for the stationary targets during the second and third epoch (where the position of the scanner remained the same) were used. For the first, the second and the fine scans, the position of the centre of each target was determined by the new "fuzzyposfine" algorithm, and these points were used to calculate the transformation between the two epochs for each case and the respective standard error. The transformation and the standard error were also calculated using the cyrax centres of the targets for comparison. For the second experiment, the first and the second scans of each epoch were used. The results are summarised in Table 4. As these indicate, the internal accuracy of the system is very high ranging between 0.1mm – 0.2 mm. It is also seen that the results of the fuzzyposfine algorithm for the finescan data (0.07mm) are better than those attained by using the cyrax centres (0.11mm).

Table 4: Results of the internal accuracy evaluation process

	Epoch 2- Epoch 3				Epoch 1	Epoch 2	Epoch 3
Type of data	scan 1	scan 2	Fine-scan	Cyrax centre	scan 1-scan2	scan 1-scan2	scan 1-scan2
standard error (mm)	0.12	0.17	0.07	0.11	0.12	0.11	0.07

Following the same process, the next step was to evaluate the external accuracy of the system. For this purpose, data of the same type acquired during different epochs and from different positions of the scanner were used. The results are presented in Table 5.

Table 5: Results of the external accuracy evaluation process

	scan 1	scan 2	Fine-scan	Cyrax centre
Epochs 1&2 standard error (mm)	0.19	0.23	0.18	0.24
Epochs 1&3 standard error (mm)	0.17	0.25	0.17	0.25

The external accuracy of the system is very high, and the results yielded by the finescans compared to those produced by the cyrax centres confirm that the "fuzzyposfine" algorithm can attain higher accuracies.

The experiments described above have indicated that the system is able to detect deformations of approximately ±0.5mm. In the following, the data analysis performed for the detection of deformation is described. In Table 6 the deformation components calculated between epochs 1 &3 and 2 &3 are presented.

Table 6: Results of deformation detection using epochs 1 & 3, and 2&3. Deformation components derived using the first scans and the second scans expressed in all cases in CS1

	Epochs 1 & 3			Epochs 2 & 3		
	Deformation components for 1st scans σ_{d1}= ±0.00024 m, c.i$_1$= ±0.00047 m			Deformation components for 1st scans σ_{d1}= ±0.00017 m, c.i$_1$= ±0.00033 m (95%)		
Targ.	ΔX1 (m)	ΔY1 (m)	ΔZ1 (m)	ΔX1 (m)	ΔY1 (m)	ΔZ1 (m)
1	0.00358 *	0.01182 *	0.00860 *	0.00325 *	0.01150 *	0.00958 *
2	0.00268 *	0.00761 *	0.02006 *	0.00228 *	0.00728 *	0.02086 *
3	0.00204 *	0.00315 *	0.02276 *	0.00178 *	0.00282 *	0.02382 *
4	0.00105 *	-0.00008	0.02274 *	0.00082 *	-0.00034 *	0.02302 *
5	-0.00053 *	-0.00315 *	0.01813 *	-0.00059 *	-0.00326 *	0.01806 *
	Deformation components for 2nd scans σ_{d2}= ±0.00035 m, c.i$_2$= ±0.00069 m			Deformation components for 2nd scans σ_{d2}= ±0.00024 m, c.i$_2$= ±0.00047 m		
Targ.	ΔX2 (m)	ΔY2 (m)	ΔZ2 (m)	ΔX2 (m)	ΔY2 (m)	ΔZ2 (m)
1	0.00338 *	0.01209 *	0.00807 *	0.00328 *	0.01180 *	0.00920 *
2	0.00245 *	0.00772 *	0.02001 *	0.00234 *	0.00740 *	0.02069 *
3	0.00194 *	0.00334 *	0.02298 *	0.00196 *	0.00302 *	0.02402 *
4	0.00091 *	-0.00010	0.02305 *	0.00106 *	-0.00034 *	0.02330 *
5	-0.00069	-0.00289 *	0.01871 *	-0.00051 *	-0.00331 *	0.01874 *

The first step of an analysis for deformation detection is to express all data in a single reference system. Therefore, as reference coordinate system the system defined by the scanner during the first scan of the first epoch was used and shall be referred to as CS1. In all cases, using the stationary targets the parameters of the transformation of each system to CS1 and the respective error were calculated. The positions of the moving targets were expressed in CS1 and for each case the accuracy in the position of all targets was considered to be the standard error $\pm\sigma_o$ of the respective transformation. The components of the deformation at each target were calculated by subtracting the original from the transformed position. The accuracy of each deformation component was considered to be $\sigma_d = \pm\sqrt{2}\sigma_o$. Furthermore, assuming a level of confidence of 95%, the respective confidence interval was calculated to be $\sigma_i = \pm 1.96\sigma_d$. The results of Table 6, were produced using epochs 1&3 and 2&3. For both cases, all of the calculations were performed using the first and the second scans. As indicated by the results, deformations of approximately ±0.5mm can be detected with a probability of 95%. In [3] the process for the deformation detection is described in more detail, along with a process that evaluates the internal accuracy of the algorithms, which is found to be 10^{-7}-10^{-10}m.

6. CONCLUSIONS AND FUTURE WORK

This paper has presented an evaluated process for the analysis of deformations using terrestrial laser scanner data. New accurate algorithms for the detection of the centre of retroreflective targets have been presented. These algorithms exhibit a remarkably high internal accuracy of 10^{-7}- 10^{-10}m and it has been found that their application with data collected by a commercial laser scanner permits the detection of deformations of about ± 0.5mm.

Future work will involve experiments of larger scale and application of the proposed algorithms and methods so as to evaluate the accuracies that can be attained with other commercial laser scanners.

7. REFERENCES

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