Innovations in the Development of Laser and Optic Rotating Scanner LORS

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Key words: laser scanning, accuracy analysis, calibration

SUMMARY

The paper presents information about the significantly innovated version of the laser and optical rotation LORS scanner and about the new system LORS2, which arose by changes in configuration of the original system.

LORS started to be developed in 2002 within a grant project on the basis of in its time original concept. One of demands on the system was a lower price than for the commercial scanning systems. The basic system components of the original version stayed preserved. It is a digital camera, a laser plane and a rotating platform. The measured object is placed on the rotating platform through which a vertically orientated laser plane goes. A suitably placed digital camera reads trail position. On the basis of knowledge of geometric parameters of all system components and of trail image coordinates it is possible to calculate 3D point coordinates on the object surface.

A digital reflex camera Canon E350D with high resolution 8 MPixels, fast USB 2 connection and with possibility of developing the own operating software with the aid of the original Remote Control Software Development Kit (RC-SDK) is used in the new version. An exact step motor operated from a control card, which is connected to the computer by a serial port, is newly used for drive of the rotating platform. A worm gearing with gear ration 60:1 is used for making possible smaller steps. The both new components enable fully automatic work of the LORS system.

Software solution was simplified on two modules LORS – Processing and LORS – Scanning. Calibration system and theoretical solution remained preserved. Accuracy of the innovated system was tested and the results are presented.

A new system conception called LORS2 was designed, realized and tested. The identical hardware equipment as for the LORS system was used. In this version, a rotating platform and a digital camera are placed on the ends of the fixed meter base. A laser module is fixed onto the rotating platform. The system is designed for scanning in distance approximately two meters from the base. A solution arranged in such a way has several advantages in comparison with the original system. It is possible to scan objects of sizes up to 1.6 x 2.2 x 1.4 meter (width, height, depth), it is possible to obtain a quality colour information for all calculated 3D coordinates from one photograph and it is possible to use a simpler difference detection method of laser trail.

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1. INTRODUCTION

The laser scanning systems (LSS) consist of software and hardware as most today's systems. Both these LSS components are very complicated and expensive and have been developing very fast recently. Before we obtained the Leica HDS 3000 scanning system and the Cyclone software for our workplace this year, it had been very complicated to obtain and process suitable data. That is why software for processing point clouds (Koska, 2005) and also the 3D scanner called Laser and Optic Rotating Scanner LORS (Koska, 2004, 2005) have been developed in our workplace.

LORS started to be developed in 2002 within a grant project on the basis of in its time original concept. One of the basic demands on the system was a lower price in comparison with commercial products.

The basic system components of the new version stayed preserved. It is a digital camera, a laser plain and a rotating platform. The measured object is placed on the rotating platform through which a vertically orientated laser plane goes. A suitably placed digital camera reads trail position. On the basis of knowledge of geometric parameters of all system components and trail image coordinates it is possible to calculate 3D point coordinates on the object surface. In the original version it was an imperfect system for scanning small objects. The problem was especially hardware equipment, for example the digital cameras had either low resolution or very slow speed of taking pictures series. The other system components were not technologically advanced either. As development went on, much progress in accuracy, automation rate and other LORS system parameters was achieved. Development of LORS system is closed by finishing the last version.

The LORS2 system arose by change in component configuration of the original system. The new system has several advantages in comparison with the original system. It is possible to scan objects of size 1.6 x 2.2 x 1.4 meter (width, height, depth), it is possible to obtain a quality colour information for all calculated 3D coordinates from one picture and it is possible to use a simpler difference detection method of laser trail.

2. THE SYSTEM LORS

2.1 Theoretical solution of the system LORS

Theoretical solution has not been changed since the previous version (Koska, 2005) and therefore it will be summarized only briefly.

The system is composed of four components. There is a digital camera, the laser module, which forms a laser plane, a rotating platform and a calibration cage (see Figure 1).

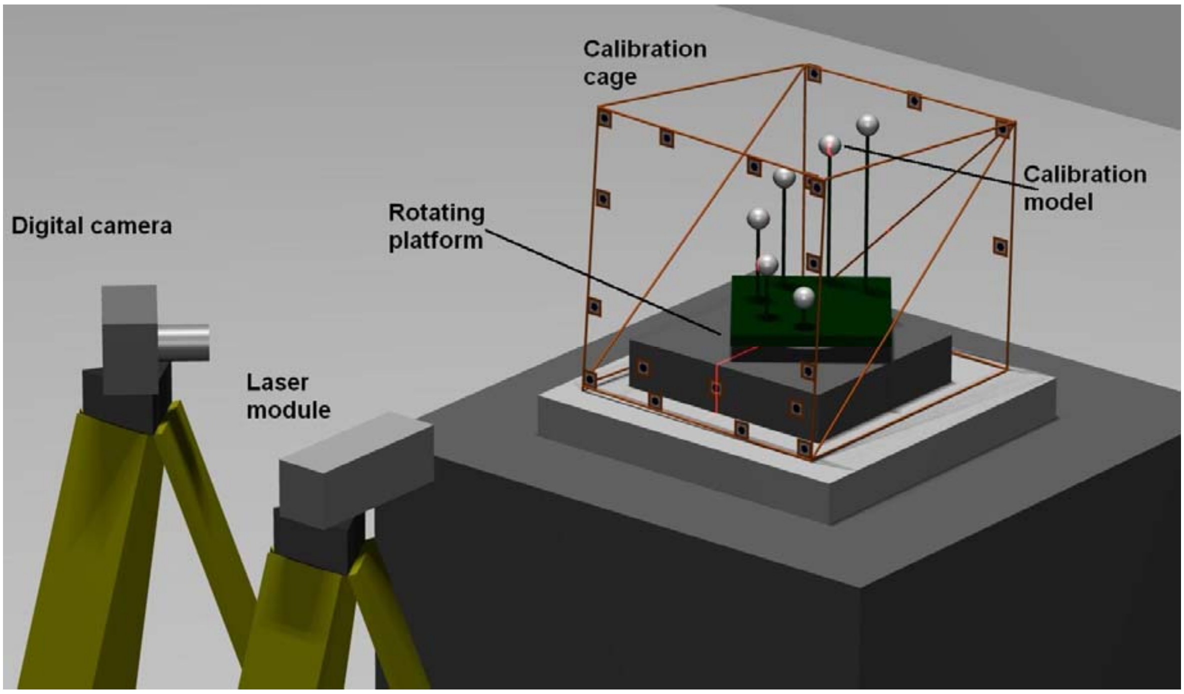

Figure 1 – Model of the system LORS

A 3D point is defined by intersection of the laser plane and an optic line. The determined laser plane crosses the measured object and creates a laser trail which is recorded by the digital camera. The optic line is determined from corrected image coordinates of the laser trail and from the parameters of the direct linear transformation (DLT) with correction of camera objective radial distortion. The DLT parameters are computed from known points on calibration cage. The digital camera elements of inner and outer orientation can be computed from the DLT parameters.

The rotating platform is automatically turned after each image was taken. Each section (image) is independently transformed to the model coordinate system (rotating system).
There can be added a real colour to each computed point. The colours are scanned during the next rotation of rotating platform with the laser switched off.

2.2 Practical Determination of LORS Configuration

Practical determination of geometric parameters of the single LORS system components was the same as for the previous version (Koska, 2005) and therefore it will be summarized only briefly.

The configuration of the whole LORS system (laser plane, calibration cage, rotating platform) was determined by spatial forward intersection from angles with using of the total station Topcon GPT 2006 (standard deviation of direction is 0.0020gon).
The standard deviation estimation of intersection point and of two points distance (d = 0.3m) was computed (σ_d = 0.08mm) by accuracy analysis.

2.3 Hardware Solution of the System LORS

2.3.1 Rotating Platform

A significant change in comparison with the previous version is change in drive and operating the rotating platform. The rotating platform has been up to now always driven by an engine with constant angular velocity and turning angle was derived from rotating platform movement time. Rotating platform movement time was determined for the whole periods from position of a sign on rotating platform read by the digital camera.

The stepper motor Microcon SX23-1012 with the control card CD30M (chip M1486B) was newly acquired. Basic step of the motor is 1.8 degree and step accuracy is 0.1 degree. The controller is connected with the computer by a serial port and is operated by asci commands. The TOS Znojmo MRTK30A worm gearing with gear ratio 60:1 was acquired for reduction of step length and for raising accuracy. Free travel approximately 0.5 degree was found out after delivery and mounting the worm gearing. Its influence was removed with one-sided inroad of the rotating platform into the required position.

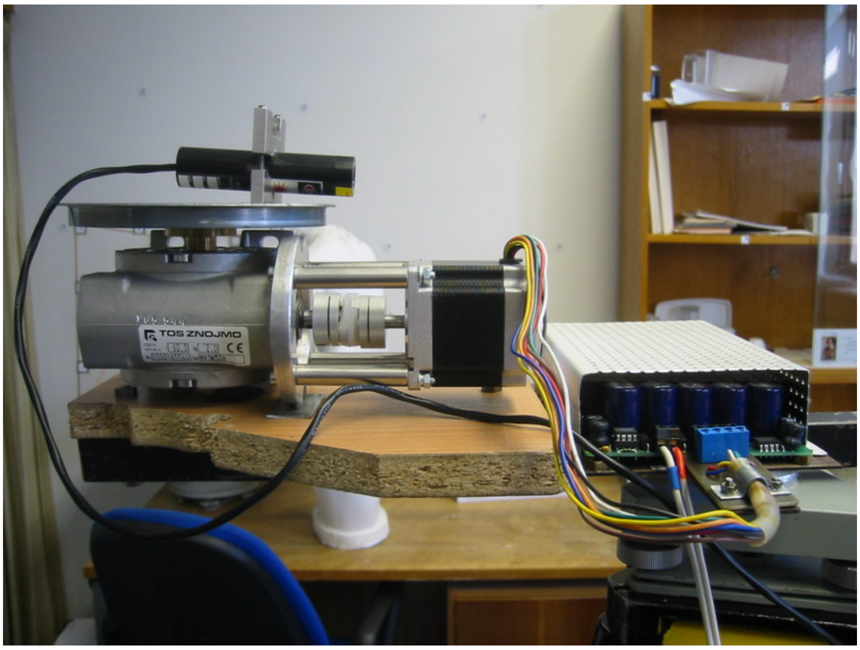

Figure 2 – New solution of the rotating platform

Very exact and automatic operating of position of the rotating platform was enabled like this.

Price of the whole equipment (stepper motor, controller, worm gearing, power source, elastic coupling) was approximately 450 EUR.

2.3.2 The Digital Camera

Other significant innovation of the LORS system was change in the digital camera. A standard digital reflex camera Canon E350D with physical sensor resolution 8 Mpixel (3456 x 2304) was bought. Other camera parameters are connection with USB 2 port and possibility of developing the own operating software by the aid of original Remote Control Software Development Kit (RC-SDK). Photography speed during operating the camera from the computer is approximately one frame per second including transmission of a picture into the computer.

Significant characteristics of the camera are possibility of full manual operating (shutter speed and f-number) and using objectives with mechanical switching on manual focus. All operating elements can be set by software from the computer.
The standard objective Sigma 18–50 mm F3.5–5.6 DC in extreme wide-range position is being currently used. An important objective parameter is focus depth, which can be calculated from hyper-focal distance *h*:

$$h = \frac{f^2}{n \cdot d}, \tag{1}$$

where f is focal length, n is f-number and d is maximum accepted non-sharpness on the sensor (for example pixels distance).
For calculation of front ff and back bf focus edge, the following formula can be used:

$$ff = \frac{h \cdot s}{h + s - f}, \quad bf = \frac{h \cdot s}{h - s + f} \tag{2}$$

where s is on focus distance.
Parameters of the given objective are for values f = 18 mm, n = 8 a d = 0.0063 mm stated in the following table:

Focused on dist. [m]	Front focus edge [m]	Back focus edge [m]	Focus Field [m]
0.2	0.19	0.21	0.01
0.4	0.38	0.43	0.05
0.6	0.55	0.66	0.11
0.8	0.71	0.91	0.20
1	0.87	1.18	0.32
1.5	1.22	1.95	0.74
2	1.53	2.90	1.37
3	2.04	5.63	3.58
4	2.46	10.63	8.16
5	2.81	22.75	19.94
6	3.10	95.03	91.93
7	3.34	-74.88	-78.23

tab. 1 – Parameters of used objective

Negative numbers means that back focus edge is in the infinity.
Price of the stated camera in the set with an objective is approximately 800 EUR.

2.3.3 The Laser Plane

Laser module stayed preserved from the previous version. It is the laser module DPGL-3005L-45 (power 5mW, wave length 532nm) that makes directly the laser plane. The width of the laser plane is approximately 2 millimetres. That is why a precise iron diaphragm was made and put in front of the laser module. The resulting laser plane width is approximately one millimetre.
The approximate price of the laser module is 600 EUR. The red light laser module are significantly cheaper and can be also used in the system.

2.4 Software Solution of the System

Software solution of the LORS system was simplified and reduced on two basic modules LORS – Scanning a LORS – Processing.

2.4.1 Configuration Determination

System configuration is determined by means of geometric parameters of its single components (laser module – parameters of plane equation, rotating platform – parameters of circle in 3D, camera –DLT parameters). The SPATFIG library (Koska, 2005) was used for calculation of geometric parameters of laser module and rotating platform. The ALLTRAN library (Koska, 2006) was used for calculation of DLT parameters.

2.4.2 Scanning

A simple program called LORS – Scanning, which operates both digital camera and stepper motor of the rotating platform, is used. Only picture saving location, rotation range and rotation step are set.

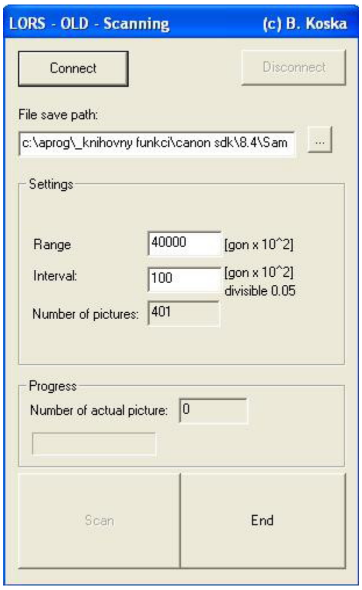

Figure 3 – Program LORS Scanning

2.4.3 Processing

The program called LORS – Processing (see Figure 4) is now used for evaluation. The program enables to carry out all necessary operations for obtaining the final 3D coordinates. Set of photographs is open first. Then detection parameters of the RGB filter (R: 0 – 255, G: 190 – 255 a B: 0 – 255 is usually sufficient for a green laser) and range of the filtered area are set. Then detection on all pictures (approximate speed two fps) is carried out. Setting of configuration parameters of the calculation follows. This is carried out by recording files with DLT parameters, with transformation parameters (of the rotating platform) and with laser plane parameters. Angle step of the rotating platform between the single photographs is set. The last step of the procedure is selection of a file for saving the final 3D coordinates and switching on the calculation.

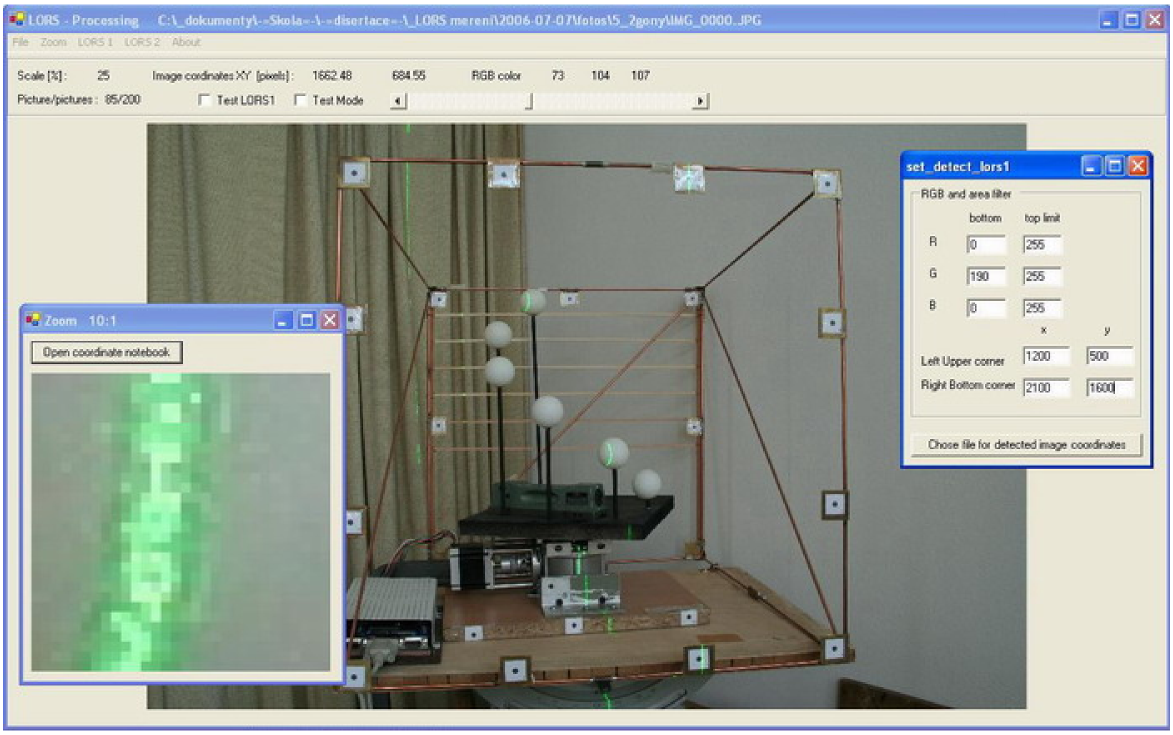

Figure 4 – The program LORS – Processing

2.5 Accuracy Testing

Accuracy of the whole system was determined by measuring the calibration model with the LORS system and by its comparison with its precise coordinates by identity transformation in space (ALLTRAN – identity_3d).
The same calibration model as during testing the previous versions (six spheres placed in space see the Figure 4) was used. Position of sphere centres was exactly determined by spatial forward intersection from angles. Accuracy of reference measurement of the calibration model was estimated by two independent measurement and comparison of identity transformation in space. Standard deviation a posteriori of this transformation was 0.05 mm and is defined in the following way:

$$\sigma_0 = \sqrt{\frac{\sum_{1}^{r1}\left(v_x^2 + v_y^2 + v_z^2\right)}{r_1 + \frac{q-p}{3}}}, \tag{3}$$

where v_x, v_y and v_z are residuals, r_1 is number of points, q is number of additional conditions (for this transformation 9) and p is the number of unknowns (for this transformation 15). This standard deviation a posteriori also represents standard deviation of the distances between the original and the transformed points.
The model was also measured twice by the system LORS and it was compared with reference coordinates with identity transformation in space. Standard deviations of these transformations are 0.14 mm and 0.21 mm.

On the basis of these results it is possible to review overall accuracy of the system LORS even if it is necessary to realize that it is not accuracy of one point but accuracy of a sphere modelled from several hundred points.

3. THE SYSTEM LORS2

As it has been mentioned in introduction, the LORS2 system was created by reconfiguration of the original system LORS. The new solution has several advantages in comparison with the original system. It is possible to scan objects of significantly larger sizes up to 1.6 x 2.2 x 1.4 meter (width, height, depth), it is possible to obtain quality colour information for all calculated 3D coordinates from one picture and it is possible to use simpler differential detection method of laser trail.

The system is built by solid meter base. A rotating platform with fasten laser module is fixed to one end of the base. A digital camera is placed on the other end. The system is designed for scanning in distance two meters from the base and therefore the camera is slightly turned towards the middle of the base (see Figure 5).

Figure 5 –The system LORS2

3.1 Theoretical Solution of the System LORS2

Principle of the system is similar as it was with the original system. The base is again a laser plane with known parameters and a digital camera with known parameters of inner and outer orientation (DLT parameters). After reading image coordinates of the laser trail it is possible to calculate 3D coordinates of the individual points.

3.1.1 Calibration of the System

It is necessary to determine parameters of all system components in one coordinate system *XYZ*.

Determining components of inner and outer orientation of camera was carried out by measurement of the calibration field (20 points) with the size of camera field of view in distance of two meters. The calculation was carried out by the modified DLT method in the ALLTRAN library.

Rotating platform parameters are a rotating platform turning axis vector $\boldsymbol{n}_{\boldsymbol{RP}}$ and a point on the axis $\boldsymbol{X}_{\boldsymbol{CR}}$. These elements were determined from one point measurement on the rotating platform in its several positions (seven points). The points were fitted with a circle in 3D in the library SPATFIG.

The last component is a laser plane. It was measured in one position of the rotating platform with ten points and fitted with plane equation.
All stated measurements were carried out by spatial forward intersection from angles.

3.1.2 Mathematical Solution

Calculation method of 3D coordinates from image coordinates of laser plane trail, DLT parameters and plane equation parameters has been described in a detailed way in the paper (Koska, 2005) and therefore it will not be stated here.
A new element of the LORS2 system is calculation of plane equation in arbitrary turning of the rotating platform. As it has been stated in the previous paragraph, the plane is measured in one position of the rotating platform. The task is to determine the equation of the plane in arbitrary position of the rotating platform.
Parameters of equation plane A, *B, C* and *D* are calculated from the measurement. The laser plane is defined by an equation:

$$A \cdot X + B \cdot Y + C \cdot Z + D = 0\,, \tag{4}$$

with constraint:

$$A^2 + B^2 + C^2 - 1 = 0\,. \tag{5}$$

Three points in this plane in the *XYZ* system are suitably calculated. Nevertheless, these points have to be known also in the *xyz* coordinate system. That is why their transformation was carried out. The basic relation of space transformation is:

$$\boldsymbol{X}_i = \boldsymbol{X}_{\boldsymbol{CR}} + \boldsymbol{R} \cdot \boldsymbol{x}_i\,, \tag{6}$$

where $\boldsymbol{X}_i$ is a point in global coordinate system *XYZ*, $\boldsymbol{X}_{\boldsymbol{CR}}$ is shift, $\boldsymbol{R}$ is rotation matrix and $\boldsymbol{x}_i$ is point in local (rotating) coordinate system *xyz*. In our situation we can rewrite formula (6):

$$\boldsymbol{x}_{0i} = \boldsymbol{R}^{\boldsymbol{T}} \cdot (\boldsymbol{X}_{0i} - \boldsymbol{X}_{\boldsymbol{CR}})\,, \tag{7}$$

where:

$$\boldsymbol{R} = \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_1) \cdot \boldsymbol{R}_{\boldsymbol{Y'}}(\alpha_2) \cdot \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_3)\,, \tag{8}$$

$$\boldsymbol{R}_{Z'}(\alpha_1) = \begin{pmatrix} \cos\alpha_1 & -\sin\alpha_1 & 0 \\ \sin\alpha_1 & \cos\alpha_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \boldsymbol{R}_{Y'}(\alpha_2) = \begin{pmatrix} \cos\alpha_2 & 0 & \sin\alpha_2 \\ 0 & 1 & 0 \\ -\sin\alpha_2 & 0 & \cos\alpha_2 \end{pmatrix}, \boldsymbol{R}_{Z'}(\alpha_3) = \begin{pmatrix} \cos\alpha_3 & -\sin\alpha_3 & 0 \\ \sin\alpha_3 & \cos\alpha_3 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{9}$$

$$\alpha_1 = \arccos\left(\frac{\boldsymbol{n}_{\boldsymbol{RPx}}}{\sqrt{\boldsymbol{n}_{\boldsymbol{RPx}}{}^2 + \boldsymbol{n}_{\boldsymbol{RPy}}{}^2}}\right), \alpha_2 = \arccos(\boldsymbol{n}_{\boldsymbol{RPz}})\,, \tag{10}$$

where $\boldsymbol{n}_{\boldsymbol{RP}}$ is rotating platform turning axis vector, angle α_3 is current direction of rotating platform, which is zero in the moment of measuring the plane, and index *0* for $\boldsymbol{X}_{0i}$ and $\boldsymbol{x}_{0i}$ means just zero α_3.
The final transformation of three points in a plane has this form:

$$\boldsymbol{x}_i = \boldsymbol{R}_{\boldsymbol{Y'}}^{\boldsymbol{T}}(\alpha_2)\cdot \boldsymbol{R}_{\boldsymbol{Z'}}^{\boldsymbol{T}}(\alpha_1)\cdot(\boldsymbol{X}_{0i}-\boldsymbol{X}_{\boldsymbol{CR}}) . \quad (11)$$

If the laser plane is turned by a non-zero α_3, the final transformation of points into the *XYZ* system is defined like this:

$$\boldsymbol{X}_{i\alpha_3} = \boldsymbol{X}_{\boldsymbol{CR}} + \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_1)\cdot \boldsymbol{R}_{\boldsymbol{Y'}}(\alpha_2)\cdot \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_3)\cdot \boldsymbol{x}_{0i} . \quad (12)$$

If we connect both transformations, we will obtain the final relation in the form:

$$\boldsymbol{X}_{i\alpha_3} = \boldsymbol{X}_{\boldsymbol{CR}} + \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_1)\cdot \boldsymbol{R}_{\boldsymbol{Y'}}(\alpha_2)\cdot \boldsymbol{R}_{\boldsymbol{Z'}}(\alpha_3)\cdot \boldsymbol{R}_{\boldsymbol{Y'}}^{\boldsymbol{T}}(\alpha_2)\cdot \boldsymbol{R}_{\boldsymbol{Z'}}^{\boldsymbol{T}}(\alpha_1)\cdot(\boldsymbol{X}_{0i}-\boldsymbol{X}_{\boldsymbol{CR}}) . \quad (13)$$

Now it is already possible to obtain a laser plane equation in any given position of the rotating platform by fitting the plane equation throw three transformed points for example according to the relation (Rektorys, 1995):

$$\begin{vmatrix} x-x_1 & y-y_1 & z-z_1 \\ x_2-x_1 & y_2-y_1 & z_2-z_1 \\ x_3-x_1 & y_3-y_1 & z_3-z_1 \end{vmatrix} = 0 , \quad (14)$$

and thus

$$A = (y_2-y_1)\cdot(z_3-z_1)-(y_3-y_1)\cdot(z_2-z_1) , \quad (15)$$

$$B = -\left[(x_2-x_1)\cdot(z_3-z_1)-(x_3-x_1)\cdot(z_2-z_1)\right] , \quad (16)$$

$$C = (x_2-x_1)\cdot(y_3-y_1)-(x_3-x_1)\cdot(y_2-y_1) , \quad (17)$$

$$D = -x_1\cdot A - y_1\cdot B - z_1\cdot C . \quad (18)$$

3.2 Hardware Solution of the System

It is identical to the solution of the original LORS system, which is described above in a detailed way.

3.3 Software Solution of the System

The software solution was again simplified on two basic modules LORS2 – Scanning and LORS – Processing.

The LORS2 – Scanning program is a simple program that operates a digital camera and the stepper motor of rotating platform. Only right and left scanning edge and rotating platform step size in gons are set. Before driving the scanner into the scanning area, a reference picture is taken and then the system carries out measurement automatically.
For the purposes of the LORS2 system, the LORS – Processing program was extended by a differential filter method that is more sensitive in comparison with the RGB filter. For both methods of laser trail detection, the program was added by export of colours in the RGB scheme from relevant pixels of the reference picture.

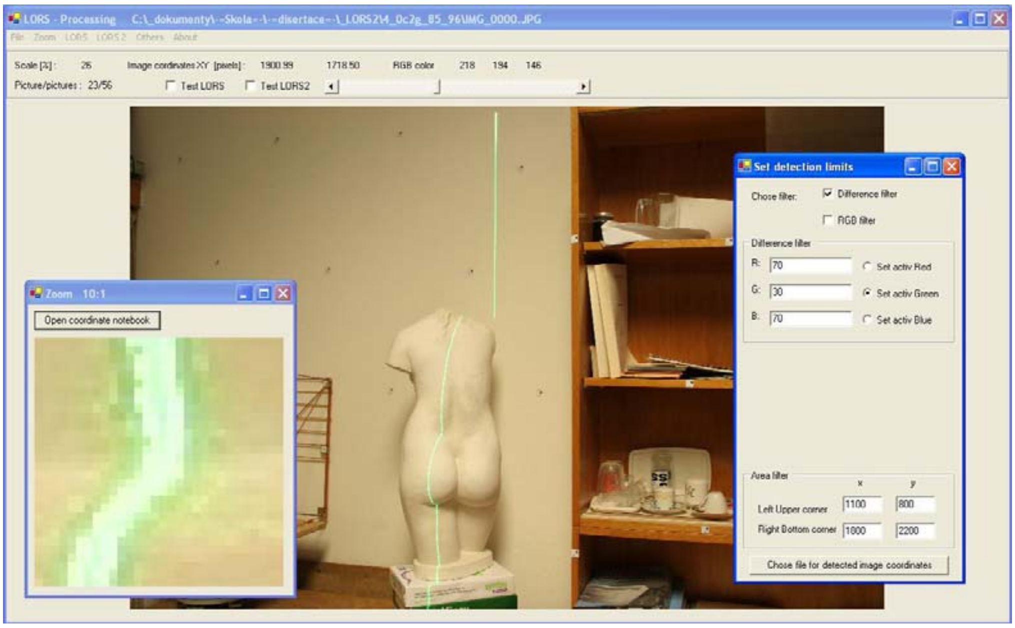

Figure 6 – LORS – Processing working environment

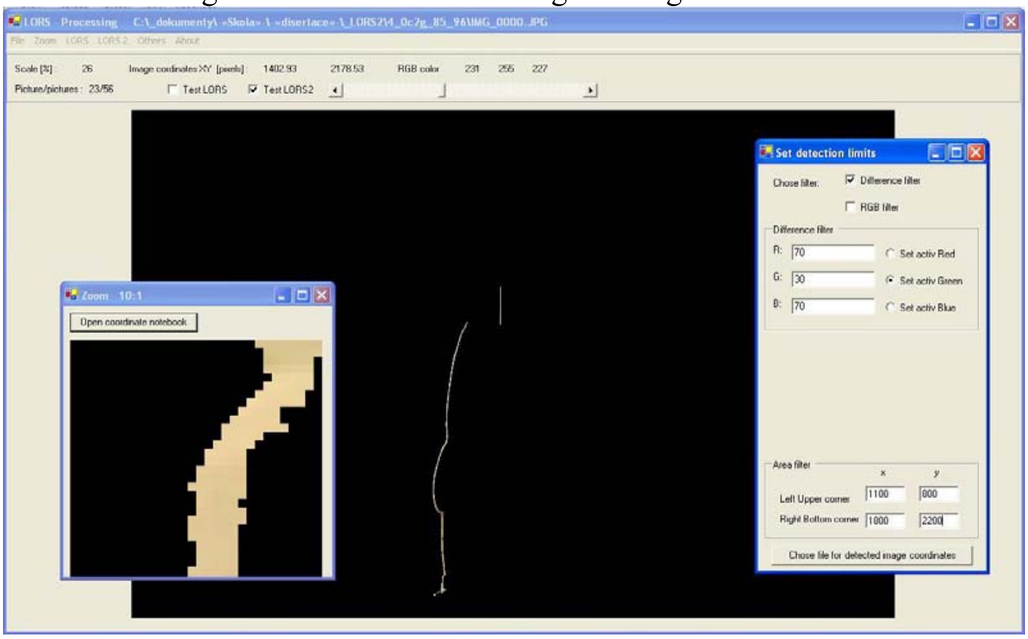

Figure 7 – Detection by the differential filter method

3.4 Some made Experiments

A several experiments have been done to verify the functionality of whole system, to get some more experience and to discover weak points of the system.
The one meter height women sculpture was scanned from a few positions. After registration an overall model was created.

Figure 8 – Pictures and model of women sculpture

The next figures show the system ability to scan an object real colour.

Figure 9 – Photo, point cloud and point cloud detail of Topcon GPT 2006

3.5 Accuracy Testing

Accuracy testing of the new system LORS2 was carried out. At first, a local accuracy test with using a small calibration model (used also for the original system) was carried out (see

Figure 4). This model was measured in rough raster (rotating platform step 0.2 gon means six mm in two meter distance). Spheres were modelled from the measured cloud (one sphere from approximately 150 points) and their centres were compared with the precise coordinates by identity transformation in space. Standard deviation a posterior of this transformation (3) was 0.4 mm.

A calibration field with spherical targets for testing of the system overall accuracy was created. The dimension of the field was approximately 1 x 1 x 0.4 meter (width, height, depth). The same method for evaluating of the results was used as with previous model. The standard deviation a posteriori of the transformation was one millimeter for sphere modeled without known radius and 0.9 millimeter for sphere modeled with known radius.

4. CONCLUSION

An innovated version of the LORS scanning system is introduced in the paper. The most significant change is the digital camera Canon E350D with high physical resolution and a rotating platform driven by an precise stepper motor. This innovation enabled full automation of scanning proces. Measuring and evaluation programs were simplified on two modules LORS – Scanning a LORS – Processing. Accuracy testing on the basis of comparison with calibration model was carried out for the new system. Standard deviation a posterior of the identical transformation is 0.14 mm in the first and 0.2 mm in the second test. These values indicate the accuracy of the overall system.

In the second part of the paper a new system LORS2 is introduced. The system was created by reconfiguration of the original system and it has several advantages in comparison with it. It is possible to scan objects of significantly larger sizes up to 1.6 x 2.2 x 1.4 meters (width, height, depth), it is possible to obtain quality colour information for all calculated 3D points from one picture and it is possible to use a simpler differential filter method of laser trail detection. The program LORS2 – Scanning was created for measuring. The original LORS – Processing program was extended by differential filter method and for both methods of laser trail detection, the program was added by export of colour in the RGB scheme from relevant pixels of the reference picture.

Several tests were carried out with the new system. Standard deviation a posterior of identity transformation in the test with original calibration model was 0.4 mm. When the larger calibration field was used the reached standard deviation a posteriori was approximately one millimeter.

The novel 3D scanning system for human size objects LORS2 was suggested, realized and tested. The overall accuracy of the point measured with the system is approximately one millimeter. The important advantage of the system is affordable price.

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BIOGRAPHICAL NOTES

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30 years of research practice, chairman of branch of the Czech Association of Geodesists and Cartographers, authorised expert in electronics with specialisation in optoelectronic measurement systems, optical quantum generators (lasers) and receptors of their radiation. In the years 2006 to 2008 is a solver of grant project of GA ČR 103/06/0094 "Processing and the Analysis of the Products of the Mass 3D Data Collection realized by Terrestrial Scanning Systems". He is intensively interested in 3D scanning since year 2000.

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