THE RESULT PRESENTATION OF THE DEVELOPMENT OF LASER AND OPTIC ROTATING SCANNER LORS AND INTRODUCTION OF PUBLIC LIBRARY OF CLASSES AND FUNCTIONS SPATFIG

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Abstract: The actual information about the development of the 3D laser scanning system LORS (Laser and Optic Rotating Scanner) are presented in the first part of the paper. The system LORS was developed within the scope of the grant GA ČR 103/02/0357 „Modern Optoelectronic Methods of Measuring Surfaces’ Topography“.

LORS was designed for scanning of small objects at the first stage. It consists of four basic parts. There is a calibrated digital camera, the laser module, which forms a laser plane, a rotating platform and a calibration cage. The rotating platform has a constant angular velocity. The laser plane crosses a measured object and creates a laser mark. The 3D point is created by intersection of the laser mark and an optic line which is defined by corrected image coordinates of the laser mark and by direct linear transformation (DLT) parameters. The DLT parameters are computed from 20 known points on calibration cage. The theoretical and software solution of 3D point computation was solved and tested. It is possible to add a real colour to each computed point.

The calibration model for accuracy assessing of LORS was suggested and created. It consists of six identical spheres. These spheres are fixed on duralumin poles. The tests for reliable determination of spatial accuracy were made and results are presented in the paper.

The public (GNU GPL) library of classes and functions SPATFIG (Spatial Figure) is presented in the second part of the paper. The library is developed in the frame of my Ph.D. thesis at the present. The main function of SPATFIG is fitting of primitives in 3D space (2D primitives: straight line, plane, circle; 3D: sphere, cone, cylinder ...) in accordance with the least square method (LSM). There are solved estimations of mean square errors of adjusted variables and their covariant matrix and there are considered the covariant matrix of measuring.

There are showed the reasons for developing the library, there is presented the actual state of art and there is described the principal of the solution.
1. LASER AND OPTIC ROTATING SCANNER LORS

Assoc. Prof. Jiří Pospíšil (K154, FCE, CTU) has obtained grant GA ČR 103/02/0357 „Modern Optoelectronic Methods of Measuring Surfaces’ Topography“ for years 2002-04. One of the main goals of this project was developing of the system for a mass contact-less collection of 3D data at an affordable price. The main result of this grant is the presented 3D laser scanning system LORS (Laser and Optic Rotating Scanner).

1.1. Theoretical solution of the system LORS

1.1.1. Short overview

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 (Fig. 1).

![Figure 1: Model of the system LORS](image)

A 3D point is defined by intersection of the laser plane and an optic line. The determined laser plane crosses a measured object and creates a laser mark which is recorded by the digital camera. The optic line is determined from corrected image coordinates of the laser mark and from the direct linear transformation (DLT) parameters. 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.

Each section (image) is independently transformed to the model coordinate system (rotating system).

There can be add a real colour to each computed point. The colours are scanned during the next rotation of rotating platform. There have to be sufficient lights during the colour scanning and the laser module have to be switched off.

1.1.2. Mathematical solution

The laser plane is defined by an equation:

\[ A \cdot X + B \cdot Y + C \cdot Z + D = 0, \]  

\[ (I) \]
with constraint:
\[ A^2 + B^2 + C^2 - 1 = 0. \]  
(2)

The DLT parameters are computed from identical points on calibration cage. The DLT equations are:
\[
\begin{align*}
\frac{x'}{L_4} &= \frac{a}{c}, \\
y' &= \frac{b}{c},
\end{align*}
\]
(3)
where \( L_1..L_{11} \) are DLT coefficients and \( x', y' \) are image coordinates of point \( X, Y, Z \).

The DLT is supplemented with correction of camera objective radial distortion:
\[
X' = \frac{a}{c} - R' \left( x' - x_0 \right), \quad y' = \frac{b}{c} - R' \left( y' - y_0 \right),
\]
(4)
where \( x_0', y_0' \) are image coordinates of the main image point and \( k_0, k_1, k_2 \) are coefficients of polynomial which describe objective radial distortion.

From equations (1) and (4) can be easily computed 3D coordinates of any point (there are three linear equations and three unknown coordinates).

The last step of computation is a spatial transformation. The rotating platform is defined by a rotation axis point \( X_{CR} \), the rotation plane normal vector \( v_R \) \((v_{RA}, v_{RB}, v_{RC})\) and the time of one rotation (period) \( T \). The spatial transformation is defined by formula:
\[
X = S + R \cdot X',
\]
(5)
where \( X \) is point in global coordinate system, \( S \) is movement, \( R \) is rotation matrix and \( X' \) is point in local (rotating) coordinate system. In our situation we can rewrite formula (5):
\[
\begin{align*}
X &= X_{CR} + R \cdot X' \\
X' &= R^T \cdot (X - X_{CR})',
\end{align*}
\]
(6)
where:
\[
R = R_Z(\alpha_1) \cdot R_{\phi}(\alpha_2) \cdot R_Z(\alpha_3),
\]
(7)
\[
R_{\phi}(\alpha) = \begin{bmatrix}
\cos \alpha & -\sin \alpha & 0 \\
\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1
\end{bmatrix},
\]
(8)
\[
\alpha_1 = \arccos \left( \frac{v_{RA}}{\sqrt{v_{RA}^2 + v_{RB}^2}} \right), \quad \alpha_2 = \arccos(v_{RC}), \quad \alpha_3 = 2\pi \left( 1 - \frac{t}{T} \right),
\]
(9)
and \( t \) is the time when the picture is taken.
1.2. Practical determination of LORS configuration

The configuration of the whole system LORS (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 \((d = 0.3\text{m})\) was computed \((\sigma_d = 0.08\text{mm})\) by accuracy analysis.

The laser plane is determined by least square method (LSM) from 10 points (for more information see [2]). These points are visible on the calibration cage (see Fig. 2).

![Figure 2: Reality and model of the calibration cage and the calibration model](image)

The position of the rotating platform is determined from one point. This point is measured in a few positions (5-10) during one rotation. It is possible to adjust a rotation axis point \(X_{CR}\) and the rotation plane normal vector \(v_R\) by LSM from various positions of the point.

The period \(T\) is determined from digital camera pictures. The determination is based on the moment when a specific point (pin peak) crosses the laser plane.

1.3. Hardware solution of the system LORS

The system is composed of four hardware components (see Fig. 1). There was made a lot of hardware and software innovations during development of LORS (see [1],[3] and [4]).

1.3.1. Digital camera

Two digital cameras are used at the system LORS at present.

The first is the digital camera Lumenera LU120 with the physical resolution 1280x1024/16 fps, with a progressive scan mode, with a direct connection by USB 2.0 port and recording without compression.

The second tested camera is the standard commercial digital camcorder Panasonic NV-GS120EG. The physical resolution is 720x576/25 fps. This camera doesn’t support a progressive scan mode. It is possible to get comparable results to camera Lumenera if a special treatment of recorded data is used (the conversion from video format PAL to the
format of video recorded with progressive scanning camera was solved by using programs AviSynth and VirtualDub).

Any other digital camera with possibility of extracting progressive bitmap image sequence is possible to use with LORS.

1.3.2. Laser module

A laser module forms a laser plane. The Laser module DPGL-3005L-45 (power 5mW, wavelength 532nm) which makes directly the laser plane is used at present. The width of the laser plane is approximately three millimetre. That’s why a precise iron diaphragm was made and put in front of the laser module. The resulting laser plane width is approximately one millimetre what is in accordance with the size of camera pixel.

1.3.3. Rotating platform

The rotating platform has a constant angular velocity (in accordance with required accuracy). The platform has been change recently. The new one has more stable axle which was taken from theodolite vertical axle. The angular velocity is also much more stable regardless of a loading. The rotation period is 42.20 s.

1.3.4. Calibration cage

The calibration cage is a new component of the system LORS. It contains 20 identical points. It is made of metal pipes and its size is approximately 0.5x0.5x0.5 meter (Fig. 2). It is used for determination of the DLT parameters.

Rotating platform, calibration cage, calibration model and iron diaphragm were precisely and skilfully made by Mr. J. Janota who is an our department technician.

1.4. Software solution of the system LORS

1.4.1. Self developed programs

The whole system consists of several programs which provide computing of all necessary configurations parameters, automatic scanning of image coordinates and finally computing of the 3D coordinates of the points on a scanned object.

The first program provides computing of all configurations parameters (parameters of the laser plane and of the rotating platform). The library of classes “SPATFIG” (made by B. Koska) is used for adjusting of these parameters. The issue is closely described in the second part of the paper.

The second configuration program is “DLT” (M. Štroner). This program compute the DLT parameters for the digital camera from identical points on the calibration cage.

The next component is the program “POWOK” (M. Štroner) which provide treating images from the digital camera. It consists of two modules. The module “Základní vyhodnocení” (basic evaluation) provides automatic scanning of the image coordinates of the pixels which correspond with a preset RGB filter (the coordinates of the laser mark). The module “Podrobné vyhodnocení” (detailed evaluation) provides the automatic line evaluation of filtered out pixels in accordance with a selected criterion (the elimination of a multivalent laser mark, computing of the column width and the column average of the laser mark).

The following program is “DLTR2XYZ” (M. Štroner). This program computes the 3D coordinates for each point in global coordinate system from the DLT parameters, plane parameters and image coordinates of the laser mark.
The last component is the program “TRANSFORM” (B. Koska). This program transforms 3D coordinates from global coordinates system to local (rotating) system. This program uses parameters of rotating platform (a rotation axis point $X_{CR}$, the rotation plane normal vector $v_R$ and rotation period $T$).

The program “COLORADO” (M. Štroner) can be used for additional extracting of a real point colours. The input to this program is a binary file with image coordinates of the laser mark and a file with names of corresponding colour images. The output is a file with colours. The colours can be added to corresponding 3D point during spatial transformation with program “TRANSFORM_WITH_COLOR” (B. Koska).

1.4.2. Processing software

The professional software for treatment of a point cloud 3Dipsos (made by Mensi) has been bought within the scope of the mentioned grant GA ČR Grant No. 103/02/0357. This software provides complete treatment of any point cloud and is also used for the 3D scanner CALLIDUS which is also hold by the Faculty of Civil Engineering.

The software Geomagic Studio 7 was also used for processing of some made experiments. This software seems to be more suitable for irregular surfaces (triangular mesh).

1.5. Testing of the system LORS with the camera Panasonic NV-GS120EG

The calibration model for accuracy assessing of the system LORSM was suggested and created. It consists of six identical spheres. These spheres are fixed on duralumin poles (see Fig. 2). For determination of calibration model configuration was again used spatial forward intersection from angles.

The most suitable method for determining of reached spatial accuracy seems to be using of 3D Helmert transformation [5] (using the sphere centres of the calibration model) and assessing distance differences between spheres. The same method was used for the verifying of the calibration model itself (from two independent measuring). The standard deviation (a posteriori) of Helmert transformation is $\sigma_0=0.05\text{mm}$ and the scale coefficient is 1.00021. The maximum distance differences between spheres is 0.12mm and average is 0.05mm. The results are in accordance with accuracy analysis which is mentioned above.

The accuracy of the whole system LORS was tested by measuring of calibration model. The created point cloud was fitted with spheres with fixed radius by library SPATFIG. The error standard deviation (a posteriori) of Helmert transformation is $\sigma_0=0.21\text{mm}$ (standard deviation of distance between points is 0.36 mm) and the scale coefficient is 1.0012. For distance differences assessing see the table below:

<table>
<thead>
<tr>
<th>Distance between. points</th>
<th>Difference [mm]</th>
<th>Distance betw. points</th>
<th>Difference [mm]</th>
<th>Distance betw. points</th>
<th>Difference [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>-0.24</td>
<td>1-2</td>
<td>0.24</td>
<td>6-1</td>
<td>-0.02</td>
</tr>
<tr>
<td>2-3</td>
<td>-0.53</td>
<td>1-3</td>
<td>0.49</td>
<td>6-2</td>
<td>0.24</td>
</tr>
<tr>
<td>3-4</td>
<td>0.17</td>
<td>1-4</td>
<td>0.44</td>
<td>6-3</td>
<td>-0.35</td>
</tr>
<tr>
<td>4-5</td>
<td>-0.34</td>
<td>1-5</td>
<td>0.53</td>
<td>6-4</td>
<td>0.13</td>
</tr>
<tr>
<td>5-6</td>
<td>0.02</td>
<td>1-6</td>
<td>-0.02</td>
<td>6-5</td>
<td>-0.02</td>
</tr>
<tr>
<td>Average of abs. differen.</td>
<td>0.26</td>
<td></td>
<td>0.34</td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>Average differences</td>
<td>-0.18</td>
<td></td>
<td>0.34</td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1: The testing of the system LORS
The result of made experiment is in accordance with our expectations. The accuracy of modelled figures seems to be between 0.2 and 0.5 mm (it means standard deviations in coordinates axes directions).

The accuracy of one point is probably lower and depends on more factors. One factor is the real size of digital camera pixel. In case of camera Panasonic NV-GS120EG is pixel size approximately 1.2x1.2 mm (from distance one meter). It means that maximal error produced by camera should be 0.6mm. Another error is produced by the width of the laser plane. The actual laser plane width is approximately 1mm. It is in correspondence with pixel size. Some more error are produced by various factors like the configuration of the whole system LORS (should be lower than 0.1mm), the stability of rotation platform angular velocity and rotation axle, flatness of the laser plane and other factors. The present system LORS isn’t able to scan any detail smaller than 0.5 mm.

1.6. Made experiments

A several experiments with LORS have been done to verify the functionality of whole system, to get some more experience and to discover weak points of the system.

![Figure 3: Reality and model of a stone](image)

![Figure 4: Reality, point cloud, mesh and model of a home slippers](image)
1.7. Future development of the system LORS

The first suggested extension of LORS is acquiring of high quality digital camera. This extension depends on existing funds and offered products. The quality of digital camera (physical resolution and frame rate) is a limiting factor of the accuracy and resolution (or object size) at present. The accuracy and resolution of LORS are nearly directly proportional to the digital camera resolution (up to the 0.1mm what is approximately accuracy of the whole configuration). The suitable camera would be e.g. VDS CCD-11000 (progressive scan 4024x2680/3fps).

The next extension would be the diaphragm with changeable aperture (for laser plane width correction). The most suitable width of the laser plane is the same as the real size of the pixel on a scanned object is.

Another possibility for scanning more detail object with the present hardware is using of denser calibration field. The necessary number of identical point for DLT with distortion correction is seven. The higher number of point assures more reliable results. If we put the camera a half distance closer to a scanned object the real size of pixel on a object will be the half size of the original one (also a maximal scanned object is proportionally smaller). For this case it is necessary to have a denser field of calibration point and camera with sufficient range of focus depth.

The scanning of larger objects (human size) by reconfiguration of the present hardware is also planned.

1.8. Summary

The original system for 3D scanning of small objects (at present is max. size 0.5x0.5x0.5m) has been suggested and realized. The practical experiments have confirmed the functionality of the system LORS and allowed to estimate its real accuracy. The standard deviation a posteriori of 3D Helmert transformation of accurate sphere model is $\sigma_0 = 0.21$mm.

We suggest to continue in development of the system LORS in the future.

2. INTRODUCTION OF PUBLIC LIBRARY OF CLASSES AND FUNCTIONS SPATFIG

We had to solve a few primitive fitting cases during the development of LORS (specifically fitting of plane and circle). When we got the first real results (point cloud) we needed some tool for processing of the data. That’s why the first version of SPATFIG was developed [6]. It contained only a few the most useful primitives with various constraints (plane, sphere, 3D line and 2D circle). The available commercial processing software has a few disadvantages. It doesn’t consider the covariant matrix of measuring, doesn’t make accuracy analyses and a computing algorithm is unknown. That’s why the new more sophisticated version of SPATFIG is being developed at present.

2.1. Introduction

There are two main reasons for a high activity in the field of fitting of curves and surfaces in space during last few years. The present state of computer power enables to use a new more robustness and more accurate computing methods. Developed algorithms are very widely use (besides in land surveying also in astronomy, computer aided drug design, particles physics, robotics etc. - for more details see [7]).
The 3D data processing software tools usually use for model fitting an algorithm based on the least-square method (LSM). The algorithm minimizes the square sum of some predefined error-of-fit. The best estimation of model parameters is acquired by using the shortest distance. The shortest distance fitting is called geometrical fitting, Euclidean fitting or orthogonal distance fitting (ODF) in literature. ODF is position independent. The analytical and computational difficulties in using ODF led to use of some approximate determination of shortest distance in the past.

2.2. Dividing of fitting algorithms

The fitting algorithms are presented and compared in [8]. The basic dividing of the algorithms depends on the function which is minimized. If we consider an implicit form of 3D surface for example:

\[ F(a, X) = 0, \]  

(10)

where \( a \) is a vector of surface parameters and \( X^T = (X,Y,Z) \). The number of point is \( m \).

- Algebraic fitting is easy to implement and it has much lower computation cost. It minimizes the function:

\[ \min_a \sum_{i=1}^{m} F^2(a, X_i). \]  

(11)

- Normalized algebraic fitting (Taubin’s fitting) is first order approximation of ODF:

\[ \min_a \sum_{i=1}^{m} \left( \frac{F(a, X_i)}{\|\nabla F(a, X_i)\|} \right)^2. \]  

(12)

- ODF. It has the best results in all categories according to [8] except computational cost:

\[ \min_{a, i} \sum_{i=1}^{m} \|X_i - X_i'\|^2. \]  

(13)

where \( X_i' \) is the nearest point on the surface \( F \) to the point \( X_i \).

The ODF algorithms are divided into two groups. There are coordinate-based algorithms (CBA) (13) and distance-based algorithms (DBA) which minimizes the sum of distances \( d_i \). The CBA are more general because each coordinate \( X_i, Y_i, Z_i \) can be individually weighted.

2.3. State of the art

There are noticed various ODF algorithms in the literature [7]. All of them have some limitation. The goals for a new ODF algorithm are:

- Fitting of general implicit and parametric features defined in 2D/3D space
- Estimation of the model parameters in terms of form, position, and rotation parameters
- Robust and rapid convergence
- Low computing cost and memory space usage
- Low implementation cost for a new model feature
In [7] are also presented and tested three new ODF algorithms. The algorithm II and III seems to be suitable for implementation in SPATFIG.

In the literature [9] are also classified and compared the actual ODF algorithms and the algorithm II and III have a good rating especially in curve fitting in 3D.

2.4. **ODF in the field of civil engineering**

For the processing of 3D data in the field of civil engineering is necessary to implement only a some of geometrical primitives (GP). The good base for the list of GP can be the catalogue from the professional processing software 3DIpsos (GP is called constructed entities in the 3DIpsos manual).

2.5. **Summary**

The information about the public library of classes and functions SPATFIG is presented in the paper. The main function of SPATFIG is fitting of geometrical primitives in 3D space in accordance with the least square method (LSM). There are showed the reasons for developing the library, there is presented the actual state of art and there is described the principal of the solution.

The latest information from the development of the library SPATFIG will be presented at the conference.

**References:**


