Three-Dimensional Tunnel Reconstruction Using Photogrammetry and Laser Scanning

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Abstract. Automatic dense high-resolution tunnel surface reconstruction using photogrammetric methods has been realized by the Dibit tunnel measurement system for almost a decade. We report on the current state of the system from the computer vision point of view.

The tunnel surface is measured by a laser scanner or stereo photogrammetry. Sensor orientation is accomplished by geodetic means. Laser scan points and stereoscopic reconstructions are projected to a regular grid on the design surface, which contains both radial deviations from the design and image texture represented by digital images. Methods for refinement and increase of accuracy include the usage of an additional distance sensor for each stereo image set, texture based fusion between laser scan and camera image, 3d textured point cloud alignment, and automatic image stitching.

The data flow of the main system components from data acquisition to the derivation of quality measures and digital maps of the tunnel surface is shown. With the example of crack detection new exploitation potential for tunnel documentation & inspection is demonstrated.

Keywords: Tunnel Reconstruction, Tunnel Inspection, Photogrammetry, Terrestrial Laser Scanning

1 Introduction

Close range photogrammetry and laser scanner are widely used for surveying and quality control in construction and mining. The photogrammetric measurement of linear edifices (tunnels, roads, channels) has been a well established application area of digital vision metrology within the last 10 years. Several systems for tunnel surveying are on the market with different approaches and sensor configurations, most of them using laser scanners in frame scan [1], [5] or line scan mode [3]. For geologic excavation documentation the high spatial and radiometric resolution of digital stereo images has been well established [6]. Most promising, however, is the combination of laser scanning and high-resolution digital images [7], [8]. The Dibit system [2], which is described in the following, currently offers different sensor options, depending on the type of application:

- For excavation, a stereo photogrammetry system provides high flexibility in terms of acquisition time.
- Dense surface profiles are covered by frame laser scanning.

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- Fusion between laser scans and digital camera images performs best for high-resolution surface inspection.
- The ability to add arbitrary digital images without precise geodetic orientation into existing surface reconstructions gives additional flexibility for quality monitoring.

All sensor modes work on the same data model, the means to present the results is independent on data acquisition. Figure 1 gives a coarse overview on the major processing components of the system.
Section 2 presents the specific geometric model for tunnels. The different data acquisition modes are sketched in Section 3. Section 4 summarizes the main computer vision processing components. Some examples for data exploitation are listed in Section 5. The paper concludes with comments on current and future developments.

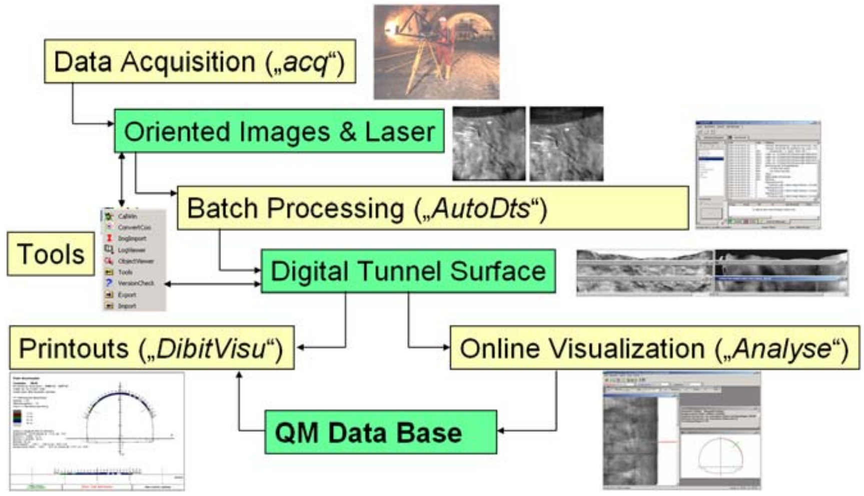

Figure 1: Major components of tunnel reconstruction system Dibit

2 Tunnel Model

The definition of the tunnel model follows well established principles of the engineering community. The tunnel axis horizontal component contains line, circular arc and clothoid segments. Vertical elements are line and parabola segments. Perpendicular to the axis, the tunnel profile is composed of line and circular arc segments. Different profiles with different offsets to the axis (along to the axis-perpendicular plane) and tilt angles may be defined in sequence, even with smooth transitions between them.
Figure 2 illustrates how this model is utilized to form an image-based representation of the tunnel surface: A non-orthogonal co-ordinate system is defined by

- Chainage along the axis
- Arc length along the nominal profile (starting with the roof)
- Radial deviation from the nominal profile.

A regular grid on Chainage and Arc length is used as image co-ordinate system for the surface representation. Two image data sets are then needed to describe each discrete 3d point on the tunnel surface:

- Ortho image, which contains grey levels or RGB values projected to the nominal grid
- Digital Tunnel Surface image, which contains the radial deviations to the nominal surface on each grid point.

This data model allows efficient access to the tunnel reconstruction results in the form of digital images. It includes the description of the tunnel face using a vertical plane located at a certain chainage.

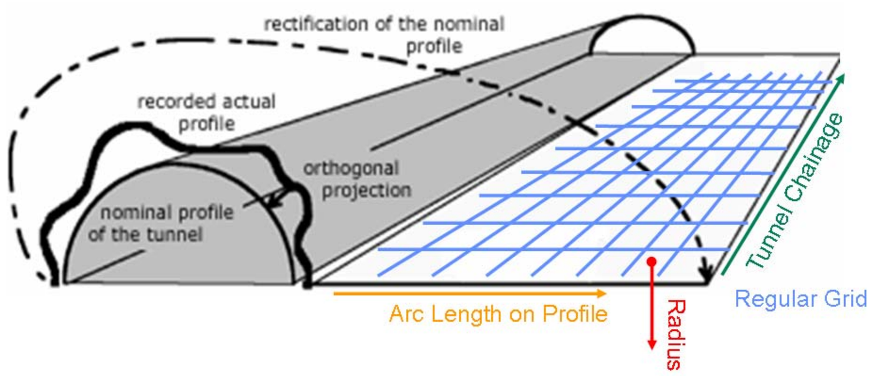

Figure 2: Surface unwrapping for image-based tunnel surface representation

3 Data Acquisition

3.1 Stereo Photogrammetry Mode

Stereo photogrammetry data recording can be performed by non-(geodesy/photogrammetry) expert users such as personnel available during the advance process. The recording equipment mainly consists of a tripod stand, field computer and a sturdy carbon fiber frame with two CCD cameras and three surveying targets attached to it (Figure 3, left). The surveying targets are needed for the geodetic determination of the position and pointing of the two cameras. They are localized either by a motorized theodolite (with stored co-ordinates, height and orientation), which is at the same time used as motor laser for the advance control, or freely stationed by the operator. It is automatically controlled via radio modems from the recording device. During theodolite measurement the cameras simultaneously record a pair of images of the tunnel surface. Image orientation is calculated from the targets positions, and their known co-ordinates in the image co-ordinate systems of the cameras. To compensate for mechanical distortions of the acquisition hardware each stereo pair is additionally calibrated using a laser distance measurement whose footprint is automatically localized on the images. The acquisition process results in two globally oriented digital images.

3.2 Laser Scan Mode

In the current system, laser data acquisition is done using a Riegl LMS Z-360i laser scanner [4] and manually distributed 3d targets for mutual orientation between adjacent scans. Similar to the stereo photogrammetry mode, during laser scanning the 3d targets are measured by a theodolite controlled via radio link by the scanning PC. This allows fully automatic laser scanner orientation [12] and on-line user feedback about the orientation success.

For high resolution texture data acquisition, within tunnels the use of line-scan cameras for high resolution texture and/or to facilitate mutual orientation is not easily applicable due to poor illumination conditions. Therefore high-resolution frame cameras using flash-light are used. Image acquisition and preliminary image orientation in the current set-up can be done in two modes:

1. A camera is fixed on the sensor head and, together with the sensor, moves around the main sensor axis (Figure 3, middle). In this case mutual orientation between sensor axis and camera can be determined in the lab. Proper synchronization between camera exposure and laser scanner is required to determine the correct laser scanner angle during exposure.
2. Scanner and camera data are acquired seperately, an odometer on the mobile platform enables rough knowledge about the camera poses within the reference tunnel co-ordinate system (Figure 3, right).

In Option 2 the odometer has an accuracy of several tens of cm including a rough initialization using well known positions within the tunnel. The position with respect to the tunnel axis (elevation & horizontal offset) has the same order of accuracy. The camera viewing angles are only known within a range of +/- 3 degrees, due to changing tilt of the vehicle. Option 1 does not lead to perfectly aligned texture results either, since the interior orientation of consumer camera optics is not stable enough when used in various rotational states. Moreover the mounting between laser scanner and camera is frequently separated, which prevents a repeatable system calibration.

Therefore both acquisition modes require a refinement of laser – to – camera orientation. This is accomplished by matching between the laser reflectivity texture and the digital image [11].

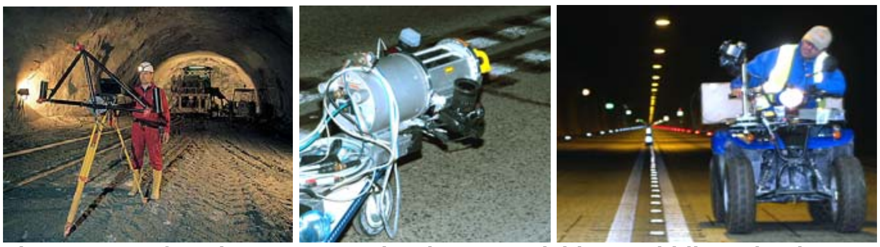

Figure 3: Left: Photogrammetric data acquisition. Middle: Simultaneous Laser-Scanner and image data acquisition. Right: Image acquisition to update texture information of existing tunnel surface reconstructions

4 Data Processing

Data acquisition provides either oriented stereo images, oriented laser scan point clouds, or both. The first part of the data processing chain therefore differs depending on the data source:

- For the case of stereo images, stereo matching takes place [9], [10], followed by a projection of the disparities onto the discrete tunnel model [13].
- In case of laser scans the 3d co-ordinates and laser reflectivity values are projected to the discrete tunnel model [14], optionally together with the registered images [11].

Therefore, for each sensor data set the 3d reconstruction result is a high resolution textured tunnel model segment represented as regular grid. The grid contains on the one hand the deviations to the design model ("digital surface model image"), on the other hand the camera (and/or laser reflectivity) image texture projected on the design model ("ortho image"). The following steps can be done directly on these images:

To refine the sensor orientations, mutual matching between adjacent reconstructions is used for a global geometry – based adjustment [15]. Finally the texture mosaic is further refined by an automatic global non-linear stitching process.

5 Data Exploitation

5.1 Visualization & Plotting

Data visualization takes place either in interactive mode (Module *Analyse*, see Figure 4), or in the form of customer – defined plots. *Analyse* offers the ability to display the colour ortho image in full resolution, real time display of profiles at arbitrary locations, co-ordinates, distances in various modes, and a large set of customer – defined statistical values such as volumes (within regions of interest, interpolated and/or extrapolated). Different construction phases (raw excavation, shotcrete, inner lining etc.) can be visualized and overlaid simultaneously, which allows a high- resolution registered comparison between them. To focus on specific regions of interest or omit obsolete surface parts interactive masking is possible.

Plotting is realized making use of a commercial visualization suite [16] which handles the layout, colouring and annotation for profile plots and virtually infinite texture plots, optionally overlaid with false colouring, iso-lines for radial deviations from the design profile, or generic objects from a data base (see Section 5.2).

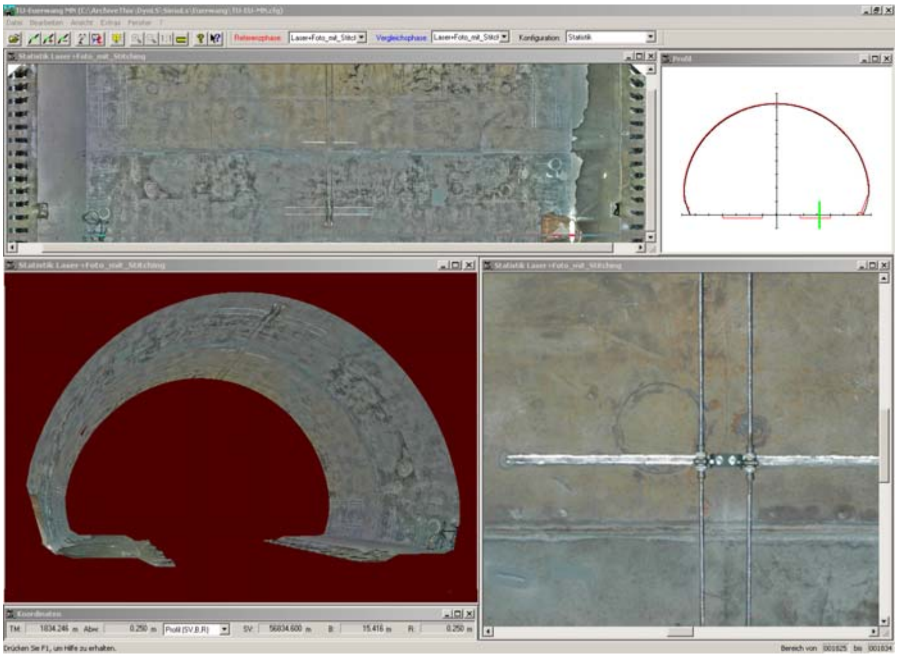

Figure 4: *Analyse* Module, used for interactive tunnel surface visualization. Clockwise from top left: Overview (RGB ortho overlay) of 10 m chainage, profile display, enlarged texture part with 4mm resolution, rendered 3d plot

5.2 Crack Monitoring

Tunnel surface observation and inspection are necessary for the tunnel maintenance and security. Therefore, besides the standard evolved data utilization such as profile control, volume measurements, deviation mapping or geological recordings, the system provides a flexible object data base (Tunnel Information System - TIS) that enables a 3d localization of objects within the tunnel. It supports the recognition and detection of changes and artefacts in the surface that might degrade and deteriorate the concrete layer and allow water intrusion, destabilize the static framework and may cause harmful loss of material. Cracks are such artefacts that indicate mechanical instabilities and leaks in the tunnel surface. The continuous monitoring of cracks is therefore an important source of information about the quality and safety conditions in tunnels. Initiated by user-given estimations of crack start and end point, crack following takes place on the basis of local line fitting and exhaustive search in both directions of the crack [17]. Several restrictions, rules and optimization criteria to find the correct crack trajectory are taken into account. The operational implementation polygonizes the extracted cracks and feeds them into the TIS (Figure 5). The method is applicable to various types of background texture as expected in the tunnel environment.

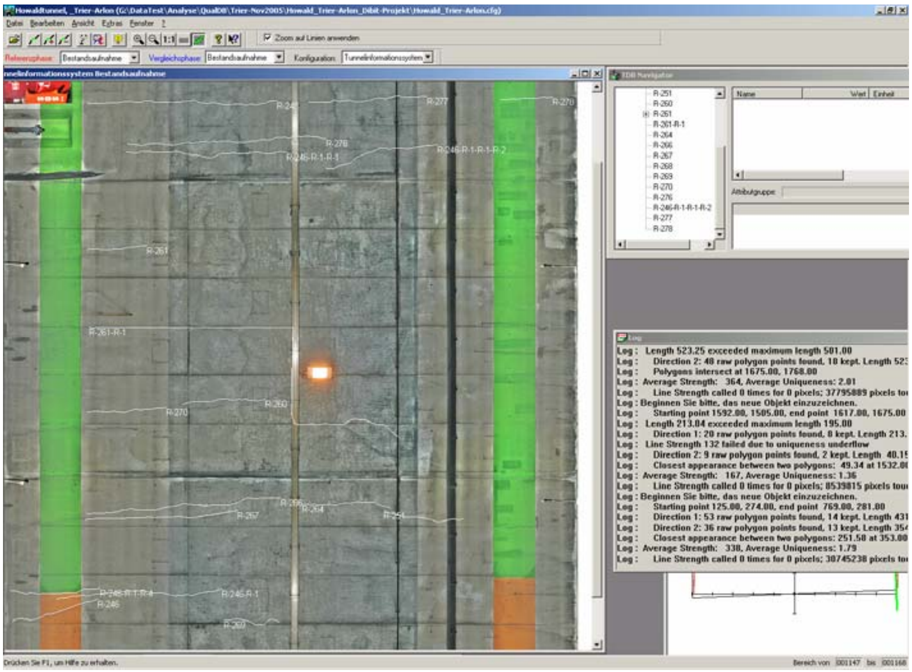

Figure 5: Crack Tracing session in *Analyse*

6 Conclusions and Outlook

The Dibit tunnel scanner is a multi-sensor measurement system for the documentation, inspection and quality monitoring of tunnel advances and underground constructions. The geometric tunnel model allows the employment of a regular grid as tunnel surface representation, which is used to project point clouds from measurements either obtained by stereo imagery, laser scans, or a combination of both. The fully automatic data processing chain provides a high – resolution surface model necessary for various kinds of documentation products such as profile and texture plots, statistical evaluations, and a data base used for defect and infrastructure documentation.

Ongoing developments include the integration of new sensor types, thus adding flexibility in terms of acquisition speed, accuracy, resolution and cost. One key challenge is the large amount of data to cover the tunnel surface with a resolution in the range down to 1 mm, and in high radiometric and temporal resolution. In addition, further real-time visualization options, the interactive access to objects, planning facilities, automatic tunnel model generation, as well as new methods of quality assurance of the measurement process itself are current topics of research.

Acknowledgements

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