Generation of 3D City Models with Linear Array CCD-Sensors

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ABSTRACT: Linear Array CCD-Scanners are nowadays a prime technology for space and aerial image sensing. In this paper we report about the development of new algorithms and the related software for the precision processing of this kind of data. Specifically we address the issue of 3D city modeling. We combine the semi-automated object extraction method of CyberCity Modeler with the new sensor models of CCD-Linear Array Cameras. In our examples we use images from TLS (Three-Line-Scanner) and SI-200 (Starimager-200), both from Starlabo Inc., and IKONOS, Spaceimaging. Of course, this approach can also be applied to other sensors of similar type. We have interfaced TLS, SI-200 and IKONOS data with CyberCity Modeler functionality and have produced several data sets over Yokohama and Ginza, Tokyo, Japan and Izmir, Turkey. We will report briefly about the current status of TLS and SI-200 functionality (the system is still under development) and we will describe the related generation of city models. We show high-resolution photo-textured models of Yokohama, including buildings and objects like street lamps, roads, waterways, parking lots, bridges and trees and Ginza and a lower resolution model of Izmir. The combination of two modern technologies from sensing and processing opens interesting perspectives for future applications in 3D virtual environment generation.

1. Introduction

The development of new high-resolution aerial cameras is currently an important issue in photogrammetric system and in algorithmic research. In particular Three-Line Scanner technology, with its new sensor model and quasi real-time capabilities, provides a challenge for algorithmic redesign. Geometric and radiometric conditions vary significantly from traditional photographic single frame based systems. This opens the possibility to reconsider and improve many photogrammetric processing components, like image enhancement, multi-channel color processing, rectification, triangulation, ortho-image generation, DTM generation and object extraction in general. We will focus here on the generation of high-resolution 3D city models.

Our group is currently involved in the design and development of the application software for the TLS system and the second-generation STARIMAGER SI-200 systems (both manufactured by Starlabo Corporation, Tokyo; see also Murai, Matsumoto, 2000 and Murai, 2000). This includes user interface, manual measurement system, image enhancement, rectification, ortho-image generation, triangulation, point positioning, and DTM generation. We have reported about these activities on several occasions (Gruen, Zhang, 2001, 2002a, 2002b; Gruen et al., 2003).

Another new sensor of interest is IKONOS. It was proposed for city modeling as well. We have published a first related study (Fraser et al., 2001), comparing 3D city models of the campus of the University of Melbourne, Australia, extracted from aerial images and IKONOS.

In this paper, we deal with the derivation of 3D city models by applying CyberCity Modeler technology to TLS, SI-200 and IKONOS imagery. First we will briefly report about the current status of the system in terms of hardware and software. Then we will outline the particular advantages that come with Three-Line-Scanner technology with respect to object extraction, including city modeling. In chapter 5 we show the results of four pilot projects over the cities of Yokohama and Tokyo (Ginza), both Japan, and Izmir, Turkey, which were performed in cooperation with STARLABO Corporation, Tokyo and CyberCity AG, Bellikon.

2. The TLS and SI-200 Systems

2.1 Hardware status

The TLS (Three-Line-Scanner) system is an aerial multi-spectral digital sensor system, developed by STARLABO Corporation, Tokyo (Murai, Matsumoto, 2000; Murai, 2001; Chen et al., 2001). It utilizes the Three-Line-Scanner principle to capture digital image triplets in along-strip mode. It has panchromatic sensors of forward, nadir and backward direction, and also has multi-spectral sensors of RGB. The imaging system contains three times three parallel one-dimensional CCD focal plane arrays, with 10 200 pixels of 7µm each (Figure 1). The TLS system produces seamless high-resolution images with usually 5 - 10 cm footprint on the ground with three viewing directions (forward, nadir and backward). There are two configurations for image acquisition. The first configuration ensures the stereo imaging capability, in which the three CCD arrays working in the green channels are read out with stereo angles of about 21 degrees. The second configuration uses the RGB CCD arrays in nadir direction to deliver color imagery.

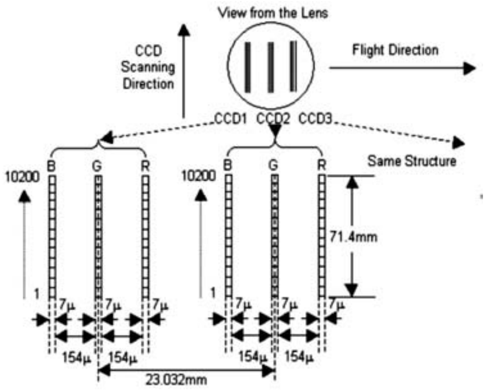

Figure 1: TLS CCD sensor configuration

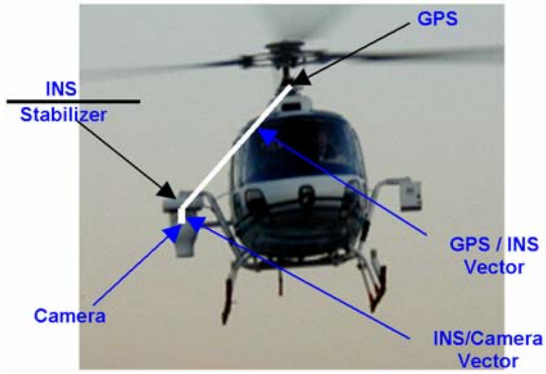

Figure 2: System configuration of the TLS system

STARLABO is currently developing a new generation camera system, called SI-200 (STARIMAGER-200). This comes with an improved lens system and with 10 CCD arrays on the focal plane (3 × 3 work in RGB mode, 1 CCD array works in infrared mode). Each CCD array consists of 14 404 pixels at 5µm size. For the detailed sensor and imaging parameters see Table 1.

Table 1: TLS and SI-200 sensor parameters

	TLS	SI-200
Focal length	60.0 mm	65.0 mm
Number of pixels per array	10200	14404
Pixel size	7 µm	5 µm
Stereo CCD arrays	3	3
Multi-spectral CCD lines	3 RGB	3 RGB + 1 Infrared
Stereo view angle	21°	21°/30° *
Field of view	61.5°	68.0°
Scan line frequency	500 HZ	500 HZ

* forward-nadir / nadir-backward stereo view angle

In order to get highly precise attitude and positional data over long flight lines a combination of a high local accuracy INS with the high global accuracy GPS is exploited. An advanced stabilizer is used to keep the camera pointing vertically to the ground in order to get high quality raw level images and outputs attitude data at 500 Hz. A Trimble MS750 serves as Rover GPS and collects L1/L2 kinematic data at 5 Hz and another Trimble MS750 serves as Base GPS on the ground. The rover GPS is installed on the top of the aircraft and the INS and the TLS camera are firmly attached together. Figure 2 shows the configuration of the TLS components.

2.2. Application software development

The application software is developed by our group at the Institute of Geodesy and Photogrammetry, ETH Zurich. The outline of the TLS/SI-200 data processing is shown in Figure 3. The processing modules include:

+ User interface and measurement system

The user interface allows the display, manipulation and measurement of images. It includes the mono and stereoscopic measurement modules in manual and semi-automated mode. It employs large-size image roaming techniques to display the TLS forward, nadir, and backward (plus other channels if possible) view direction images simultaneously. The stereoscopic measurement module, together with a STARLABO developed plug-in module "SIPES.dll" for attributation, is responsible for manual measurement / collection of the objects such as roads, buildings and others.

+ Triangulation

This module consists of two stages. At the first stage, the directly measured GPS/INS data are taken as input and the exterior orientation elements for each scan-line are calculated / interpolated at the time of image

capturing. The output of this procedure is called "raw orientation data". The raw orientation parameters are already of fairly good quality and may be used in some applications right away, e.g. in small-scale mapping.
For high accuracy applications however we recommend a previous triangulation. The related software is a modified bundle adjustment called TLS-LAB. We have developed a special TLS camera model and offer three different trajectory models (DGR… Direct Georeferencing Model; PPM… Piecewise Polynomial Model and LIM… Lagrange Interpolation Model). For more details and results of several accuracy tests see (Gruen, Zhang, 2001, 2002a). The self-calibration technique is currently implemented. The accuracy of the orientation data is improved by simultaneous bundle adjustment with the exterior orientation parameters from the pre-processing stage.
We also have developed new methods for automated tie point measurement. Tie points in multi-strip / cross-strip configuration, with different image scales and image directions can be measured through a least squares matching approach.

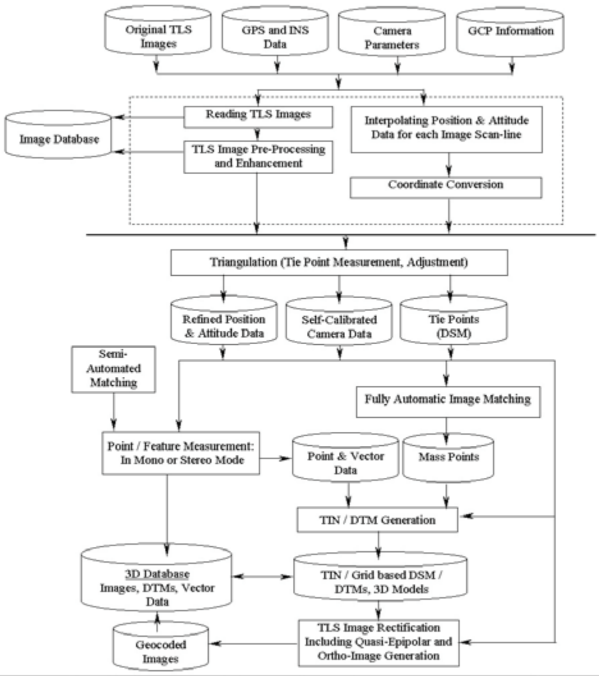

Figure 3: Outline of the TLS data processing chain

+ Image Rectification
Here the raw level image data is transformed into quasi-epipolar form in order to reduce the large y-parallaxes caused by high frequency variations of the parameters of exterior orientation. This is absolutely necessary for smooth stereo viewing and also recommended for image matching. Rectification comes in two modes. The coarse version just uses the orientation elements as given (or already derived from triangulation) and projects the raw images onto a pre-defined horizontal object plane. The refined version uses an existing DTM (of whatever quality) in replacement of the object plane. This latter method reduces the remaining y-parallaxes substantially.

+ DTM generation
We have devised and implemented a new matching strategy for the automatic generation of Digital Surface Models, from which Digital Terrain Models may be derived. This strategy consists of a number of matching components (cross-correlation, least squares matching, multi-image matching, geometrical constraints, multi-patch matching with continuity constraints, etc.), which are combined in particular ways in order to respond to divers image contents (e.g. feature points, textureless areas, etc.). The matching module can extract large numbers of mass point by using multi-images. Even in non-texture image areas reasonable matching results can be achieved by enforcing the local smoothness constraints. For more details on matching see (Gruen, Zhang, 2002b; Zhang, Gruen, 2003).

+ Ortho-image generation
This is a special solution for fast derivation of ortho-images given the TLS-geometry and images.

3. IKONOS
IKONOS is well-know sensor, described in the meanwhile in a great number of publications (e.g. Dial, Gene, 2001; Fraser, et al., 2001). The images are commercially available and give sometimes spectacular views on areas and objects, which are otherwise hard to get (www.spaceimaging.com). Since IKONOS is of the Linear Array scanner type the software developed for TLS/SI-200 can also be used (with some minor modifications) for IKONOS. IKONOS is occasionally proposed for 3D city modeling. In an earlier study we have compared such city models with those derived from aerial images (Fraser et al., 2001) and have diagnosed a serious loss of detail and thus valuable information.
Considering the fact that IKONOS resolution may suffice for some users we will integrate IKONOS processing in this paper as well.

4. CyberCity Modeler and TLS/SI-200 Data Interface

4.1 CyberCity Modeler

CyberCity Modeler (CCM) represents a methodology for semi-automated object extraction and modeling of built-up environments from images of satellite, aerial and terrestrial platforms. It is generic in the sense that it allows to model not only buildings, but all objects of interest which can be represented as polyhedral model, which includes DTM, roads, waterways, parking lots, bridges, trees and so forth (even ships have been modeled). As such it produces 3D city models efficiently, with a high degree of flexibility with respect to metric accuracy, modeling resolution (level of detail), type of objects and processing speed. The basic algorithm and related projects have been previously reported in (Gruen, Wang, 1998).
In a parallel effort and as a pilot project, a spatial information system (CC-SIS, CyberCity Spatial Information System) has been developed which, based on a relational database (ORACLE), includes both 3D functionality and image raster data integration on database level and as such represents a fully hybrid system (Wang, Gruen, 2000).
In the meantime, CCM became a commercial software product, marketed by the ETHZ spin-off company CyberCity AG (www.cybercity.ethz.ch). There is a steadily increasing interest in 3D city models, with the current major customers being city planning and surveying offices, industrial facilities (chemical and car industry) and telecom companies. With the different types of customers comes a great variability in project specifications. Here it turned out to be of advantage that CCM was set up from the very beginning as a technique with high degree of flexibility. In spite of that, some additions to and extension of the original functionality had to be developed in order to fulfill specific requests (Gruen, Wang, 2001). One of the latest additions is the derivation of 3D city models from image data of Linear Array CCD cameras.

4.2 CyberCity Modeler and TLS/SI-200

There are mainly two advantages in using TLS/SI-200 imagery to derive a 3D city model. Firstly, very high-resolution seamless image data (3-10 cm ground resolution) can be obtained by installing the system on a helicopter. All the detailed information on the ground can be viewed and measured. Several multi-spectral channels (RGB, Infrared) are available simultaneously. Secondly, unlike with the traditional frame-based photography, the three-line geometry is characterized by nearly parallel projection in the flight direction and perspective projection perpendicular to it (so-called line-perspective projection). In the TLS/SI-200 system, a stabilizer is used to absorb the high frequency positional and attitude variations of the camera during the flight in order to get high quality raw-level images. Furthermore, the stabilizer always keeps the camera pointing nearly vertically to the ground. This results in minimal occlusions in the nadir view images. In addition, the image information of the building's façades are recorded in shortened form in the forward and backward view images, (Figure 4).

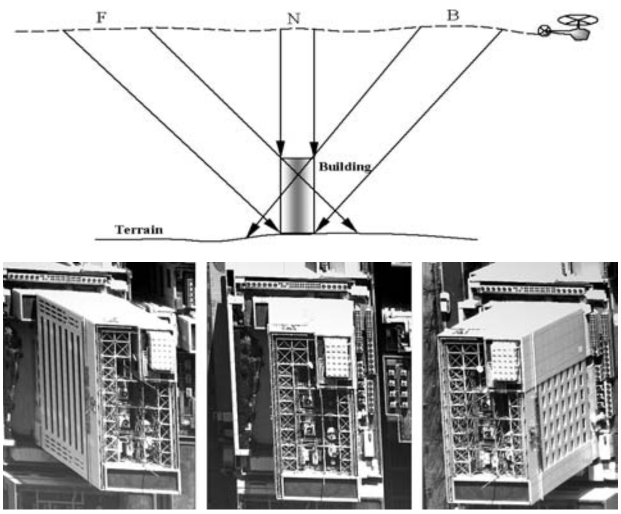

Figure 4: Forward, nadir and backward view images

Since the input data of CC-Modeler is just point clouds, it does not matter which sensor model is used to construct the 3D vector model. The measurement procedure must follow the regulation of CC-Modeler, such that it can process TLS/SI-200 data directly.
With the TLS/SI-200 stereoscopic measurement software the buildings, roads and other kinds of man-made objects can be measured manually or semi-automatically.
However, the sensor model must be identified if the full 3D model with texture mapping is required. In this case, the necessary modification of CC-Modeler is to extend the sensor model from the normal frame perspective projection to the line-perspective projection of the TLS/SI-200 system. The software "CC-TLSAutotext" does the texture mapping with TLS/SI-200 images as the original data source (see Figure 5).
In "CC-TLSAutotext", the procedure of texture mapping is to project the 3D polygon to the TLS images (forward, nadir and backward view) and take the image patch that has the best resolution. The best resolution is equivalent to the largest related image patch size. However, considering the possible occlusions between 3D objects, the best texture may not be contained in the patch with the best resolution. It could be the one with the highest amount of completeness or could be an image mosaic with texture patches that are from different TLS

images. Therefore, an occlusion checking procedure has to be involved. In case of occlusions the user has three options: (a) Paste partial patches from different images together, (b) use terrestrial images captured on the ground and (c) randomly take artificial textures. In case of full occlusions the procedure will use the artificial texture or manual texturing. The workflow of the texture mapping is described in the Figure 5.

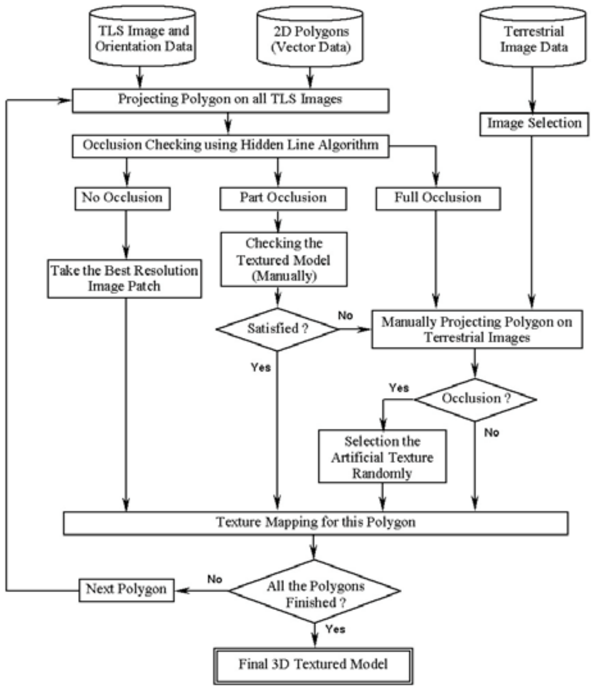

Figure 5: The workflow of the texture mapping with TLS images (CC-TLSAutotext)

5. Examples

We report here about several test projects, using different kind of Linear Array sensor imagery, with the purpose of demonstrating the feasibility of our procedures:

(a) Yokohama city, two selected sub-areas; TLS imagery
(b) Ginza, Tokyo; SI-200 imagery
(c) Izmir, Turkey; IKONOS imagery

5.1 Yokohama city

The first project includes a small area in downtown Yokohama, Japan (Area 1 in Figure 6). All the buildings, the detailed infrastructures, main roads, and some trees were measured and a 3D model was constructed. Figure 11 shows the 3D hybrid model, rendered with Cosmo Player.

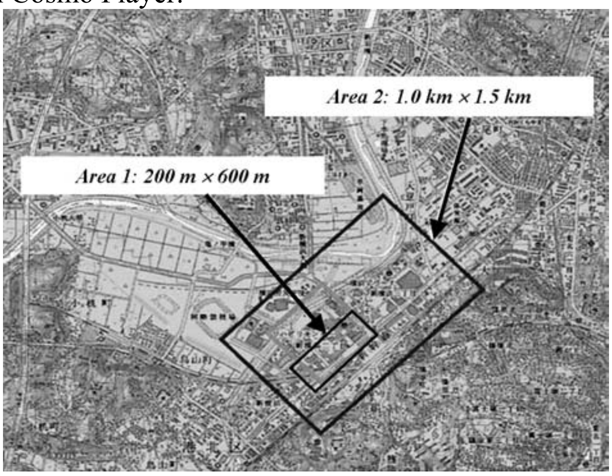

Figure 6: Experimental area of Yokohama

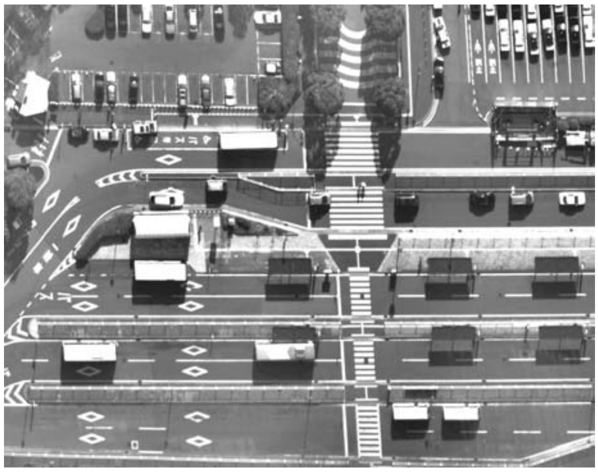

Figure 8: Enlarged area of TLS image

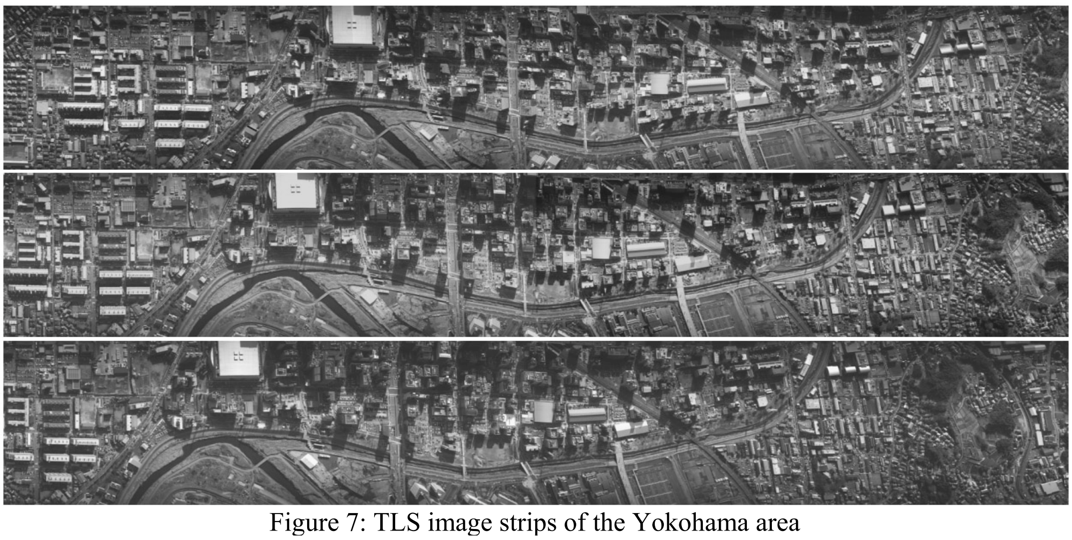

Figure 7: TLS image strips of the Yokohama area

The second project represents a larger area of about 1.5 km^2, with a boulevard in front of the Shin-Yokohama Station (Area 2 in Figure 6). The whole model includes 2482 houses, 26 bridges, 20 road segments, 1 river, 129 trees, 8 electric power lines, 170 street lights. Figure 7 shows the three overlapping TLS image strips with 6.5cm ground resolution (Figures 4 and 8). For texture mapping purposes about 100 terrestrial still video photos of some high buildings were used.

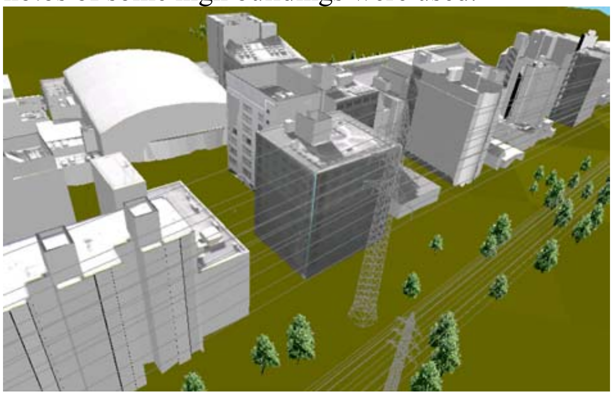

Figure 9a: View on the reconstructed 3D model (rendered with Cosmo Player)

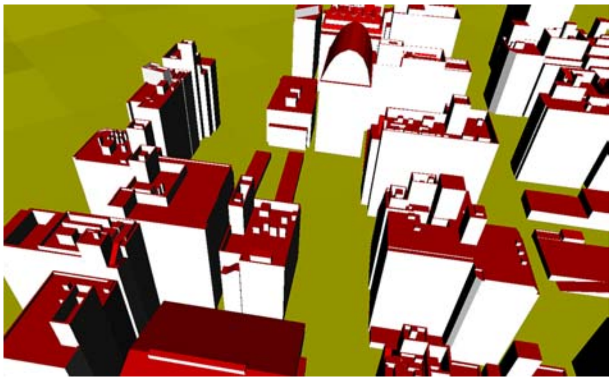

Figure 9b: Detailed roof structures of the 3D model (rendered with Cosmo Player)

After the triangulation procedure with several ground control points, a DTM was automatically generated with the TLS image matching module "TLS-IMS", and a 0.25 m resolution ortho-image was generated with the TLS image rectification module "TLS-IRS".
We use the stereoscopic measurement module "TLS-SMS" as the measurement platform to measure the point clouds, following the regulation of CC-Modeler. The integration of CC-Modeler and TLS-SMS is crucial for the 3D model generation. After measuring all the objects, CC-modeler is employed to construct the 3D model. Figures 9a and 9b show views on the reconstruction results. The level of detail in reconstruction can be checked by the roof structures of Figure 9b.
Finally, the texture mapping procedure for all measured objects is done with CC-Modeler's extended module "CC-TLSAutotext". In this procedure, the ortho-image mosaic is mapped onto the DTM, and the high-resolution image patches are mapped onto the 3D objects such as houses, bridges and roads. The workflow is shown in Figure 10. Figure 12 and 13 show the hybrid 3D textured models. In these models, a background static image with sky and clouds is also rendered in order to achieve a more realistic effect.

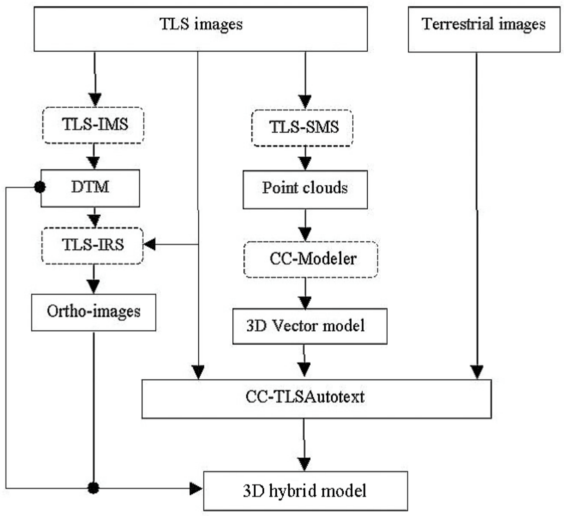

Figure 10: Work flow of the hybrid model generation with TLS image data
TLS-IMS: TLS Image Matching Software Module
TLS-IRS: TLS Image Rectification Software Module
TLS-SMS: TLS Stereo Measurement Software Module

5.2 Ginza, Tokyo

This project uses SI-200 image data and is to create a 3D model with the texture mapping along the main street of downtown Ginza, Tokyo. The area of the Ginza project is about 2.0 km^2 with about 600 houses and 15 road segments. The 3D vector model was extracted from aerial laser-scan data. The texture mapping for roofs and walls is done automatically by "CC-TLSAutotext", using only aerial image data. This explains the somehow blurred impression of façade texture. Figure 14 shows an example of the 3D model.

5.3 Izmir, Turkey

The imagery comprised a stereopair of epipolar-resampled IKONOS Geo panchromatic images with the following parameters:

Acquisition Date/Time: 2002-Jan-16, 9:06 GMT
Sun Angle Azimuth: 160.04 degrees
Sun Angle Elevation: 28.24 degrees
Terrain elevation variation: 0 – 350 meters

The area to be modeled is of $7x7\ km^2$ extension and covered by 7 GCPs, which were measured from 1:1000 digital maps. With the help of these GCPs and a simple translation (bias removal), an absolute accuracy of 1.2 m in planimetry and height could be achieved with the full set of 60 RPCs per image. After the orientation of the stereopair, a modified version of our matching software TLS-IMS was used to generate a DTM and another package for the subsequent orthoimage. About 440 buildings were measured and structured with CC-Modeler. Figure 15 shows a section of one of the IKONOS images. Figure 16 shows a view onto the textured 3D model.

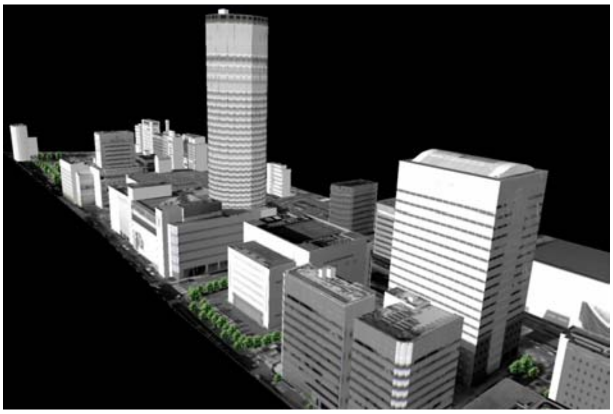

Figure 11: Textured 3D model of a small area in downtown Yokohama (rendered with Cosmo Player)

Figure 12: 3D textured model of the Yokohama project (rendered with CyberCity Browser)

Figure 13: An overview of the whole textured 3D model of the Yokohama project (rendered with CyberCity Browser)

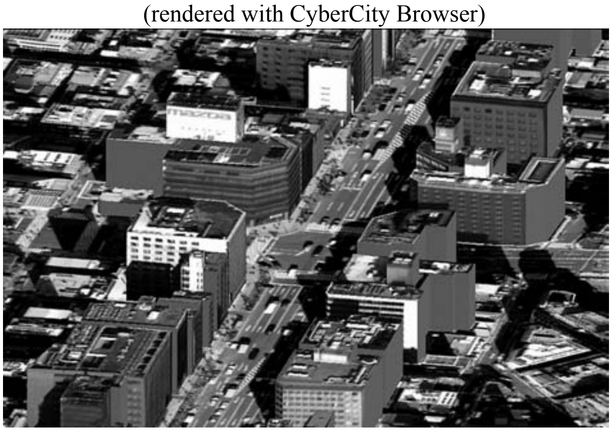

Figure 14: Textured 3D model of Ginza, Tokyo (rendered with CyberCity Browser)

Figure 15: A section of the IKONOS Izmir image

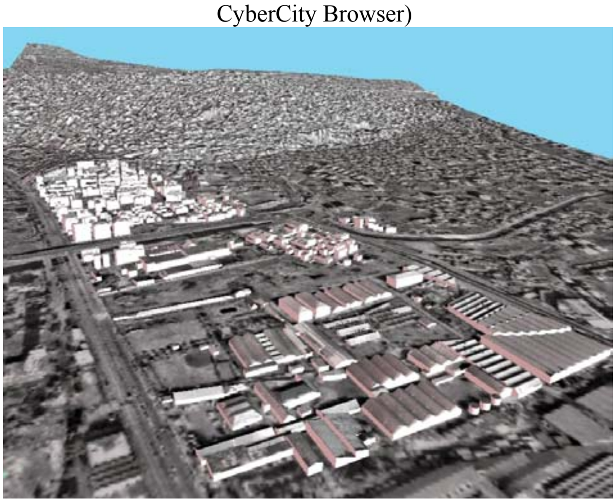

Figure 16: View onto the textured 3D model of Izmir

6. Conclusions

The status of the hardware and application software of the Three-Line-Scanner (TLS) and the new STARIMAGER SI-200 systems, both developed by STARLABO Corporation, Tokyo has been described briefly. We have outlined the advantages that lie in the use of Three-Line-Scanner and other Linear Array scanner data for general object extraction and for city modeling in particular. With the pilot projects

Yokohama, Ginza and Izmir we have demonstrated the successful integration of Linear Array CCD- image data and CyberCity Modeler.

The geometric resolution of the models depends of course primarily on the resolution of the source images. Any really high-resolution city model requires aerial imagery. Satellite images, even of highres type, produce 3D models which, due to lack of resolution, are not of interest any more for European cities.

High quality texture mapping is an expensive procedure, if it cannot fully be automated. While with Three-Line-Scanner imagery we are in a better position for automated texture mapping from aerial platforms than with conventional single frame imagery, we still have to cope with full and semi-occlusions, texture shortening and other problems, such that the quality of those results may not satisfy all users.

Acknowledgement

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