# STARIMAGER – A NEW AIRBORNE THREE-LINE SCANNER FOR LARGE-SCALE APPLICATIONS

Koichi TSUNO*, Armin GRUEN and Li ZHANG**, Shunji MURAI**, Ryosuke SHIBASAKI***,
* STARLABO Corporation, 1-20-1, Sanshin Bldg., Shibuya, Shibuya-ku, Tokyo 150-0002, JAPAN
tsuno-koichi@sei.co.jp
** Institute of Geodesy and Photogrammetry, ETH-Hoenggerberg, CH-8093 Zurich, SWITZERLAND
agruen@geod.baug.ethz.ch, zhangl@geod.baug.ethz.ch
*** University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, JAPAN
shmurai@nifty.com, shiba@skl.iis.u-tokyo.ac.jp

**Commission I, WG 6**

**KEY WORDS:** Airborne Three-Line-Scanner, Stabilizer, GPS/IMU, Digital Photogrammetry, Aerial Triangulation, DSM Generation, Object Extraction

**ABSTRACT:**

STARIMAGER is a helicopter-borne high resolution Three-Line Scanner (TLS) imaging system developed by STARLABO Corporation, Tokyo, Japan, jointly with the University of Tokyo and the Institute of Geodesy and Photogrammetry (IGP), ETH Zurich for large scale applications, especially for line-shaped ground object recording (such as roads, rivers, railways), and remote sensing applications. As other airborne and space-borne linear array imaging sensors, STARIMAGER is equipped with GPS/IMU to record the exterior orientation parameters of each obtained image line per forward, nadir and backward views during the flight. Since a high-performance stabilizer is used, which absorbs the vibrations of the aircraft and stabilizes the camera's axis within a pixel, the resulting original images have very little waving and blurring, leading to fewer problems for post-processing. A feature of particular interest is that STARIMAGER can currently read out 10 channels simultaneously, so besides providing stereo capabilities it can also be used in multi-spectral modes. The TLS principle brings line perspective images with very little distortion in the flight direction, thus we get less occlusions especially in city and mountainous areas. It can generate seamless and high-quality ortho-images, which have already true ortho-image characteristics in flight direction. This paper focuses on the system hardware configuration and data pre-processing of the STARIMAGER, including the camera system, the stabilizer, GPS/IMU, data controlling and recording units. In addition we will report about the status of the application software development. Given the new sensor geometry a number of new features can be used in the processing algorithms, which are up to now not available on Digital Stations dealing with single frame images. This software includes a modern GUI with image handling and measuring in mono, stereo and multi-image modes. Furthermore we will address the following functions: image orientation and forward intersection, triangulation procedures with three different trajectory models, image rectification using different levels of approximation of object surfaces (plane, DSM), automated DSM generation, ortho-image generation, mono-plotting, 3D city model generation (geometric and textural parts), and support of feature and object extraction in manual and semi-automatic mode. We will also briely address a variety of applications, featuring the TLS principle in already existing and new application fields.

## 1. INTRODUCTION



Figure 1. STARIMAGER of STARLABO Corp., Tokyo

Line sensor systems are already widely used on satellite platforms, now they are also entering the scene as aerial systems. In comparison to matrix array CCD sensor systems the linear array CCD principle offers some distinct advantages which have caused a number of camera manufacturers to use this principle for their new digital aerial cameras. One of the key advantages lies in the fact that a very large image format, as it is required in the traditional aerial photogrammetric practice, can more easily be generated (Murai, Matsumoto, 1994). This paper explains the system configuration, hardware and software features and various applications of a state-of-the-art helicopter-borne three-line scanner (TLS) system, STARIMAGER, developed by STARLABO Corporation, Tokyo, Japan (see Figure 1).

## 2. STARIMAGER

### 2.1 Principle and features

The TLS camera is equipped with a stabilizer and mounted together on the arm outside a helicopter. This stabilizer absorbs the vibrations of the helicopter movement and produces images

with much less jitter caused by an uncompensated platform movement. As shown in Figure 2, four CCD line sensor packages are placed parallel to each other onto the focal plane of the camera system. Three packages serve as forward, nadir and backward looking sensors. Each of those packages consists of 3 lines, generating R (Red), G (Green) and B (Blue) images to be combined into a color image. In addition, there is another CCD line sensor package for a near infra-red (NIR) image between the backward looking and the nadir looking packages. Each line sensor can produce a high-resolution, two-dimensional image in during the helicopter flight, generating 10 images in total and simultaneously, which are overlapping 100% with each other. The position and attitude data of the TLS camera for each time instance are acquired with GPS (Global Positioning System) and IMU (Inertial Measurement Unit). An antenna for the GPS is mounted on top of the helicopter, while a set of fiber-optic gyroscopes is incorporated next to the TLS camera into the stabilizer. In principle, such a spatial data acquisition system does not need aerial triangulation with ground control points, but the processing may be based on direct georeferencing. STARLABO Corporation acquired the patent rights for the system in Japan, the USA, Europe, Australia, and Canada (Murai, 1993).
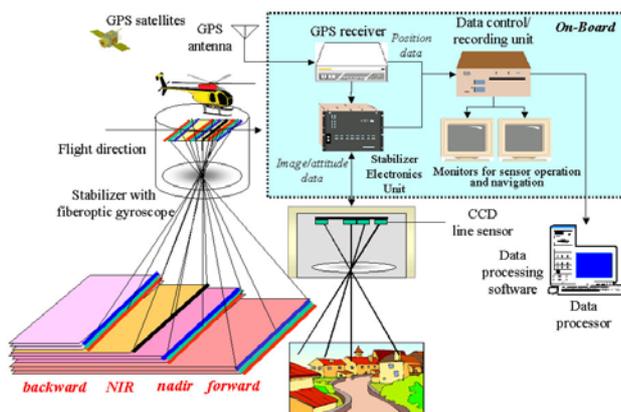


Figure 2. Principle of STARIMAGER

The advantages of STARIMAGER can be described as follows (Tsuno, 2002a; Tsuno, 2002b):

1) Photographic developing and scanning processes are unnecessary and there is no image deformation such as damage or deterioration of a film. Moreover, since the dynamic range of an output image is linearly proportional to the luminance of the image, it is possible to recover easily even objects that lie in heavy shadow areas.
2) Due to the use of a GPS/IMU the number of ground control points can be reduced and direct georeferencing becomes possible, depending on the required accuracy.
3) Due to the high-performance stabilizer, an acquired original image has no jitter and no blur. Therefore these images are suitable for real-time processing in emergency cases, where the burden for post-processing must be reduced (see Figure 3).
4) The camera can be mounted on the platform in an oblique mode, together with the stabilizer. This kind of imagery is useful for special applications, as for instance in texture mapping on the vertical walls of buildings.
5) A helicopter allows low altitude and low speed operations, leading to very high-resolution images. Since the system is less influenced by bad visibility and weather conditions,

images can be produced more frequently and with greater flexibility than in conventional aerial photography. And, it can take pictures of the linear-shaped objects efficiently by following it over at a low speed.
6) With the TLS principle, the nadir image produces almost a parallel projection in the direction perpendicular to the flight direction, and thus more suitable for ortho-image generation. The system basically does not need mosaic processing in the flight direction and it can extract the spatial data of linear-shaped objects seamlessly, such as roads, railways, rivers, etc. The system produces images with continuous three-fold overlap, leading to less field survey burden after the data acquisition. Furthermore, a corresponding point search in image matching is easier and the measurement accuracy improves due to image triplet matching (see Shibasaki, Murai 1987 and Morita et al., 2001). It produces multi-spectral data with three RGB channels and one infra-red channel, having better interpretation potential than just monochromatic images.
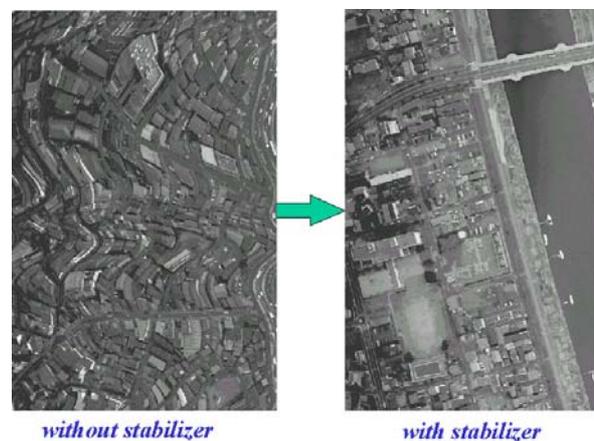


Figure 3. The Stabilizer's effect on image quality

## 2.2 System configuration

The focal distance of the TLS camera lens system is 60 mm, the stereo angles are 17, 23 and 40 degrees, between forward and nadir, nadir and backward, and forward and backward, respectively (see Table 1 for the STARIMAGER SI-250 system specifications). Each line sensor consists of 14 400 CCD pixels with 5 m spacing, and acquires 500 line images in 1 second (2 msec acquisition interval), recorded with a controlling and recording device installed in the helicopter cabin. In addition, as shown in Figure 4, a GPS antenna acquires the camera position signal at 5 Hz and the IMU on the top of the TLS camera acquires the camera attitude signal 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 stabilizer has a vibration-absorbing spring and 5 gimbals, absorbing the fluctuations of the helicopter, and keeps the optical axis direction of the TLS camera stable within a single pixel of the line sensor. The TLS camera and stabilizer are controlled by the electronic devices in the helicopter cabin, which record images, position and attitude data (see Figure 5).

| configuration | item | | specification |
|---|---|---|---|
| TLS Camera | CCD Elements | pixels/line | 14,400 |
| | | pixel pitch | 5 µm |
| | Number of Sensors | | 10 (3 directions – with RGB - and NIR) |
| | Intensity dynamic range | | 9 bits or more |
| | Lens focal length | | 60 mm |
| | Stereo angle | | 17˚, 23˚, 40˚, etc. |
| | Number of capturing lines | | 125, 250, and 500 lines/sec |
| Stabilizer | Angle resolution in attitude | | 0.00125˚ |
| | Spatial stability | | 0.00029˚ |
| | Maximum angle velocity | | 30˚ /sec |
| | Data output (acceleration/attitude) | | 500 Hz |
| GPS Receiver | 2f kinematics (post processes) | planimetric accuracy | 2 cm + 2 ppm |
| | | height accuracy | 3 cm + 2 ppm |
| | Data output | | 5 Hz |
| Recorder | HDD recording | recording speed | 150 MB/sec or more |
| | | recording capacity | 320 GB |

Table 1. SI-250 system specifications



Figure 6. Spectral channels for SI-250

As a result, STARIMAGER produces seamless high-resolution images (5 – 10 cm footprint on the ground) with three viewing directions (forward, nadir and backward). There are two configurations for image acquisition. The first ensures the stereo imaging capability, in which the three CCD arrays of the red channels are read out. The second configuration uses the RGB CCD arrays (see Figure 6 for the spectral channels) to deliver color imagery.



Figure 4. Sensors for STARIMAGER



Figure 5. Electronic units in the helicopter cabin

After the collection of the GPS/INS raw data, the kinematic position and attitude data are calculated. This results in drift values for the IMU observations, which currently have to be recovered, together with possible other systematic errors, by triangulation.

### 2.3 Camera calibration

STARLABO performs both laboratory calibration and field calibration before utilizing the TLS camera for 3D measurements to ensure a certain level of accuracy. The laboratory calibration (see Figure 7) includes geometric tests (CCD pixel position, distortion, MTF, etc.) and radiometric tests (sensitivity, PRNU, linearity, S/N, etc.). The field calibration uses self-calibration to determine the camera distortion data (Chen et al., 2003).
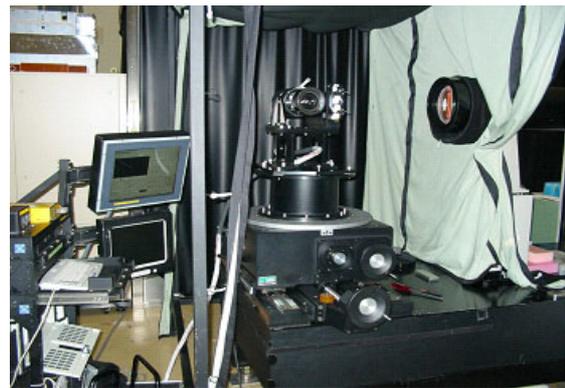


Figure 7. Optical system for laboratory calibration

The TLS camera tester (see Figure 8) provides day-to-day maintenance services including quick checking of a variety of sensing capabilities including sensitivity, MTF, S/N, etc. before the actual operations.



Figure 8. TLS Camera Tester

## 3. DATA PROCESSING

Unlike with frame-based photography, the three-line geometry is characterized by a nearly parallel projection in the flight direction and perspective projection perpendicular to that. The sensor model for the TLS images is based on modified collinearity equations and uses different forms of trajectory models. These models are used for the improvement of the measured exterior orientation parameters for each scan line by a modified photogrammetric bundle adjustment procedure, called TLS-LAB (Linear Array Bundle adjustment). This is part of a comprehensive package of new methods and the related software for the processing of TLS imagery, which is described in this chapter .

### 3.1  TLS Digital Photogrammetry System

The outline of the TLS data processing chain is shown in Figure 9 (Gruen et al., 2003).
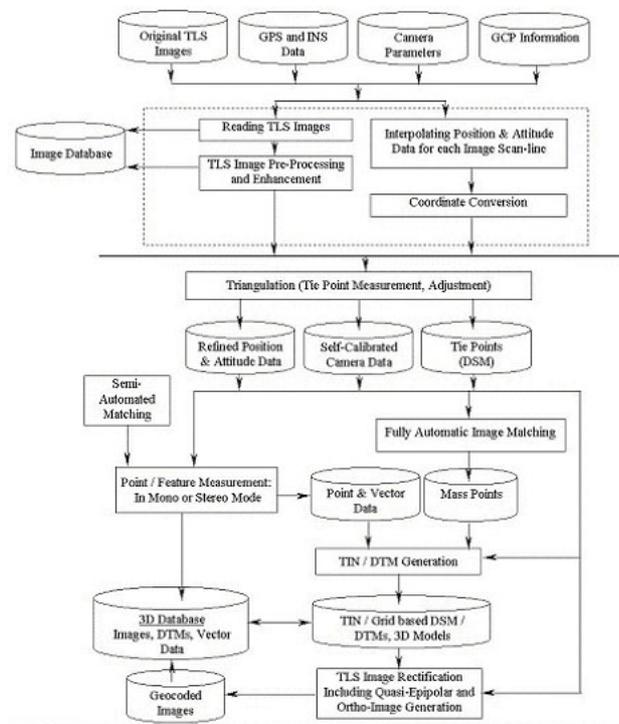


Figure 9. TLS data processing chain

The processing modules include:

1)  User interface and measurement system: The user interface allows the display, manipulation and measurement of images. It includes the mono and stereo 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 available) view direction images simultaneously.

2)  Triangulation: This module consists of two stages. At the first stage, the directly measured GPS/IMU data is taken as input and the exterior orientation elements for each scan-line are calculated/interpolated for the time of image capture. 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. For high accuracy applications however we recommend a triangulation. The related software is a modified bundle adjustment called TLS-LAB. The software includes a special TLS camera model and offers three different trajectory models: DGR (Direct Georeferencing Model), PPM (Piecewise Polynomial Model) and LIM (Lagrange Interpolation Model). The self-calibration technique for systematic error compensation is currently implemented (Gruen, Zhang, 2003). The triangulation module also covers new methods for semi- and fully-automated pass and tie point measurement. Tie points in multi-strip/cross-strip configuration, with different image scales and image directions can be measured semi- or fully automatically through least squares matching.

3)  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. 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/DSM (of whatever quality) in replacement of the object plane. This latter method reduces the remaining y-parallaxes substantially. It should be realized that the notion of "epipolar" images does not exist for this kind of linear array-based images. Therefore these transformed images can be regarded as "quasi-epipolar".

4)  DSM/DTM generation: A new matching strategy is devised and implemented for the automatic generation of Digital Surface Models (Zhang, Gruen, 2004), 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, edge matching, relational matching, 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, edges, textureless areas, etc.). The matching module can extract large numbers of mass points by using multi-images. Even in non-texture image areas reasonable matching results can be achieved by enforcing the local smoothness constraints.

5)  Ortho-image generation: This is a special solution for fast derivation of ortho-images given the sensor geometry, orientation and the DTM/DSM.

6)  3D object extraction and modelling: For 3D object extraction two different semi-automated modes have been realized: (a) Point-based object extraction: This is achieved by interfacing the TLS software with CyberCity Modeler. For details see Gruen et al., 2003. The key points are manually measured in stereomode, producing a 3D point-cloud. The 3D model is generated automatically. (b) Line-based object extraction: The lines of interest are measured manually and monoscopically in the nadir image, while the corresponding lines in the forward and after images are then matched automatically.

These procedures and products are represented by the following software components:

**TLS-SMS:** User interface; image measurement in mono and stereo; 3-ray forward intersection (point positioning); image and shadow enhancement

**TLS-IRS:** Quasi-epipolar rectification to plane or via DSM/DTM and ortho-image generation

**TLS-LAB:** Sensor/trajectory modeling, triangulation; automatic and semi-automatic tie-point generation

**TLS-IMS:** Image matching for DSM/DTM generation, DSM/DTM modeling and interpolation

Adaptation of methods and software for ALOS/PRISM processing

Feature/object extraction, e.g. city modeling: CC-TLSAutotext. A 3D city model obtained through 3D object extraction and modelling can be draped with textures as shown in Figure 10 (Gruen et al., 2003).



Figure 10. A sample 3D model of Shin-Yokohama

### 3.2 Image GIS

The consequent integration of images and their processing potential into GIS (Geographic Information System) has not been successfully achieved yet. We present here a concept called "Image GIS", whose emphasis is on combining image measurement functions with GIS database functionality on one unique platform. Figure 11 shows an example of such a Image GIS viewer. An ortho-image may serve as a background for a 2D map that is obtained from another source. The system allows one to make measurements, like distances and areas on both the map and the image. In addition, the Image GIS viewer is equipped with a mono-image measurement system, where, as the center of the ortho-image moves, the target images for the 3D measurement system move as well. When one wants to measure the 3D position of a point precisely by pointing to it on the ortho-image, the viewer brings one with its corresponding image set (forward, nadir and backward) to the approximate position for the 3D measurement. The result can be stored in a database management system (GeoBase with MSDE and Access). The Image GIS viewer can for example measure the cross-section of a line-shaped object like a river, road, railway, etc. by combining automatic sampling and semi-automated matching as shown in Figure 11.
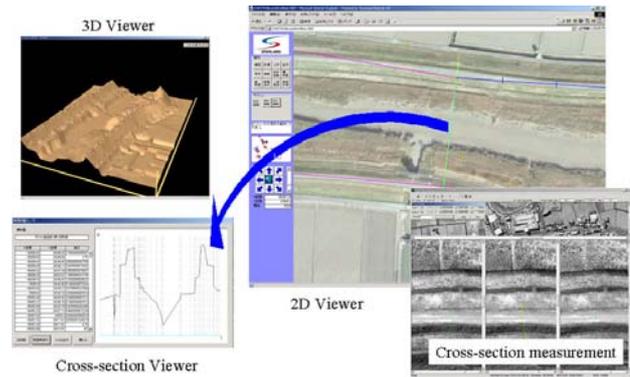


Figure 11. Image GIS Viewer

## 4. APPLICATIONS

The new features of the TLS system and the image data are stimulating more demands for 3D seamless information extraction of line-shaped objects and landscape modelling at high resolution. Line-shaped man-made objects include roads, bridges, railways, power cables, pipelines, etc. Images and spatial information are needed for investigation before the construction of those, maintenance and management after the construction, and as base data for a variety of GIS applications (Tsuno, 2002b). Figure 12 is an example for the investigation of the environment of a river, and can be used for the investigation of vegetation, the gravel grain diameter distribution of a dry riverbed, the river floor profile, etc. (Fukami et al., 2002).
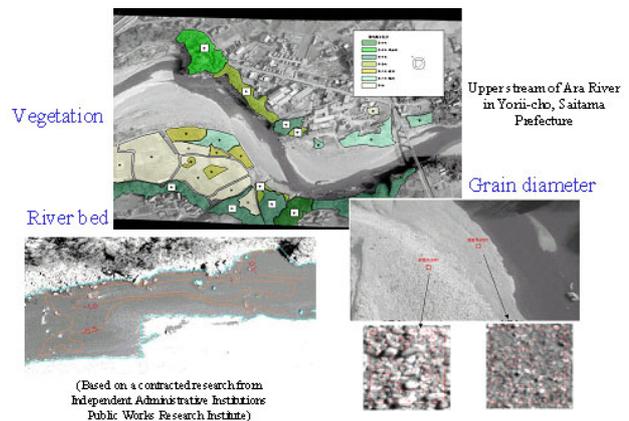


Figure 12. River environment investigation

TLS imagery can also be applied to generate base ground data for flooding simulation with high precision, in order to judge whether water goes over a Japanese raised floor or below. High definition 3D city models are used in city planning, landscape simulation, auto-navigation, gaming and so on. When the helicopter flies along a road, wall texture facing the road can be acquired with a nadir-looking or oblique-looking image. The wall textures that are perpendicular to the road can be acquired with either forward-looking or backward-looking images. Textures can be semi-automatically mapped onto 2D polygons in 3D space.

Figure 13 is an example of a true ortho-image (TrueOrtho[TM]) where the TLS data is taken with a high overlap between neighbouring strips. The data has been processed in cooperation with ISTAR, France.

Using the characteristics that images of the same area can be taken with a constant time lag, the system can measure the

speed of cars and other objects. So it can be applied to traffic flow measurement, illegal parking investigations and other problems where object kinematics plays a role.

Semi- or fully automated extraction of man-made objects such as buildings and roads through a data fusion procedure such as combining TLS images with laser scan data is one of the important themes to explore (Figure 14). Nakagawa, 2001 describes such an approach to build 3D models by simply tracing the outlines of buildings on TLS nadir images with assistance of laserscan data, aiming at a simple mapping system to be used for non-skilled operators.
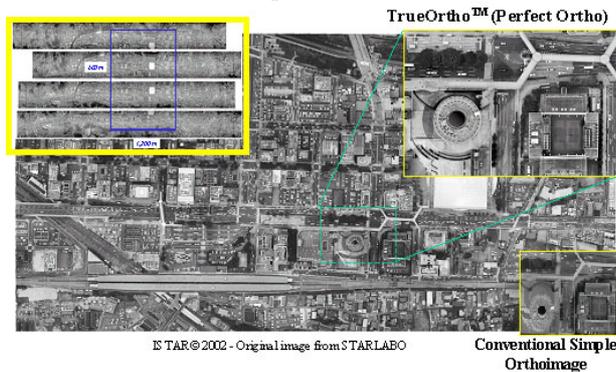


Figure 13. True ortho-image
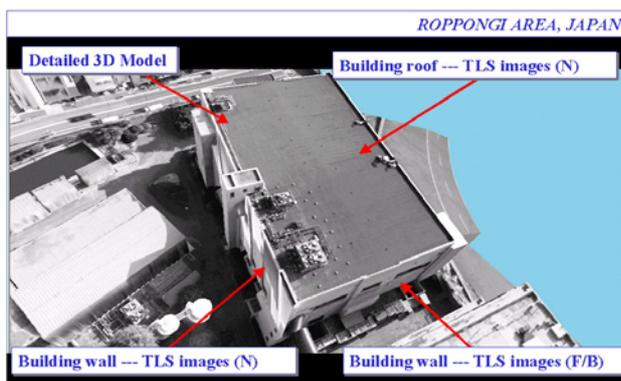


Figure 14. 3D modeling by data fusion, combining TLS image data and laserscan data

## 5. CONCLUSIONS

Today we see a strong trend towards the use of sensors that provide digital data right away, as for instance very large format digital aerial cameras. This paper presented the principles of the TLS (Three Line Scanner) system of STARLABO Corp, Tokyo and some of its possible applications. Many other applications are of course foreseeable. We reported about hardware and software issues. We have shown that with the new sensor model and image acquisition concept new possibilities for algorithmic design in data processing arise, which are already implemented in software. Currently the biggest problem left is to improve the measurement accuracy of position and attitude of the TLS camera perspective center and the optical axis by the GPS/IMU system in order to get very high accuracy measurements with as few control points as possible. Furthermore, the automated detection of changes between images of two different times is also an important theme to be explored. Semi- or fully automated extraction of man-made objects such as buildings and roads is a further topic of interest, which will also be addressed through the concept of

sensor fusion such as using TLS images in conjunction with laserscan data (Nakagawa, 2001; see Figure 14). Also, the velocity measurement of cars and rivers is another topic under investigation.

The TLS system has reached a stage of maturity and effectiveness that makes it well suited for many projects in traditional fields of photogrammetry, but also opens new application areas and a whole new array of scientific, technical and business opportunities.

## References

Chen, T., Shibasaki, R., Murai, Sh., 2003. Development and calibration of the airborne three-line scanner (TLS) imaging system. *Photogrammetric Engineering & Remote Sensing*, Vol. 69, No. 1, pp. 71 – 78.

Fukami, K., Okada, T., Yoshitani, J., 2002. A study on an information collection method for river blocks with TLS. *JSPRS Conference*, J-4 2002.7 pp.185–188 (in Japanese).

Gruen, A., Zhang, L., 2003. Sensor modeling for aerial triangulation with Three-Line-Scanner (TLS) imagery. *Photogrammmetrie, Fernerkundung, Geoinformation (PFG),* No. 2, pp.85-98.

Gruen, A., Zhang, L., Wang, X., 2003. Generation of 3D city models with Linear Array CCD-sensors. In: *Proceedings Int. Conference on Optical 3D Measurement Techniques, Vol.II,* Zurich, September 2003, pp. 21-31.

Morita, K., Shibasaki, R., Chen, T., Urabe, B., Noguchi, M., 2001. Accuracy evaluation of aircraft-borne photographic device. *JSPRS Conference*, Fall   2001.11 (in Japanese).

Murai, S., 1993. Airborne photographic apparatus (Patent 02807622), 1993.12.

Murai, S., Matsumoto, Y., 1994. 3D measurement with three-line scanner (TLS). *Journal of the Japan Society of Photogrammetry and Remote Sensing*, Vol. 33, No. 5, pp. 21-25 (in Japanese).

Nakagawa, M., 2001. Study on making 3D urban model with TLS image and laser range data. *Proceedings Asian Conference on Remote Sensing*, November

Shibasaki, R., Murai, S., 1987. A simulation on improvement of the accuracy and the stability of stereo matching using triplet linear array sensor data. *Journal of the Japan Society of Photogrammetry and Remote Sensing*, Vol. 26, No. 2, pp. 4-10 (in Japanese).

Tsuno, K., 2002a. Practices in spatial information technology: Three-line scanner and its applications, *JSPRS* (in Japanese).

Tsuno, K., 2002b. Three-line scanner and its applications. *Journal of the Japanese Society of Photogrammetry and Remote Sensing*, Vol.41, No. 4, pp. 37-40 (in Japanese).

Zhang, L., Gruen, A., 2004. Automatic DSM generation from Linear Array imagery data. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Istanbul, Turkey, Vol.XXXV, in press.