HIGH-PERFORMANCE LONG-RANGE LASER SCANNER WITH CALIBRATED DIGITAL CAMERA: A HYBRID 3D LASER SENSOR SYSTEM

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1. Introduction

Laser scanning has already shown its outstanding advantages in acquiring 3D information on an object's surface in many different applications within the past few years. For laser scanning, a highly collimated laser beam is scanned over a predefined solid angle in a regular scan pattern. While scanning, the distance to the object is measured by measuring the time of flight of the laser signal with high precision. Different commercial systems are available with a broad range of specifications. The specifications differ in measurement range, field-of-view, measurement accuracy, data acquisition speed, robustness, compactness, and transportability. The primary output delivered by a scanning laser system is a point cloud representing a sampled replica of the object's surface. The point cloud is composed usually of a very large number of points or vertices and, for most of the systems, each vertex corresponds to a single laser range measurement.

The applications in which laser scanners are already widely used include documentation and reconstruction in archaeology, architecture, and preservation of cultural heritage, city modeling based on scan data and image data, volumetric measurements in mining, dimensional measurements of large structures in construction, airborne data acquisition (airborne laser scanning) for DEM and DTM generation, to name only a few. The post-processing procedure differs widely for different applications and include often data filtering, modeling with geometric primitives, meshing or triangulating the point cloud to obtain a surface description, and texturing.

In many applications the user is not only interested in geometrical information, but also in additional information on the object's surface. For this purpose the point cloud is frequently complemented by additional vertex descriptors containing information on, e.g., surface reflectivity or surface color. Almost all laser scanners provide, beside the geometry data, also information of the signal strength of the echo signal, commonly addressed as intensity data, which can be calibrated to deduce a measure for the reflectivity of the object's surface at the laser wavelength. Some laser sensors provide with every laser measurement also color information by converting the ambient light in the direction of the laser beam into an RGB (red-green-blue) triple (compare e.g. Ullrich et al, 2001). The geometrical data and the additional vertex descriptors are acquired synchronously and sequentially and the spatial resolution of the additional data can thus not be higher. In order to have texturing data with a higher resolution than the laser data, high resolution digital cameras can be used additionally. Texturing 3D models generated from laser scan data with image data is well-established and many of the 3D data processing packages provide at least some means for texturing the surface of a 3D model. However, using images of a camera without prior knowledge of its position and orientation requires, for example, manual definition of tie points in both the scan data and the image to calculate the image parameters. Integrating a high-resolution calibrated camera into a laser scanning system provides a very efficient, convenient, and powerful system for automatically generating accurately textured high-resolution 3D models.

2. System description

The hybrid sensors presented below are each composed of a high-performance long-range laser scanner with a wide field-of-view and a calibrated high-resolution digital camera firmly mounted to the scanning head of the laser scanner. As for every image taken with the camera the position and orientation of the camera is measured with high accuracy within the scanners own coordinate system, scan data and image data can be combined in a straightforward way without the need of user interaction.

Figures 1 and 2 show two different hybrid sensors based on two different instrument series of *RIEGL* 3D imaging sensors. Tables 1 summarizes the key specifications of the systems. One of the major differences between the two systems is, that the camera mounted on the LPM series instrument is rotated in two axis and the field-of-view of the camera can be selected significantly smaller than the scan angle range of the laser sensor. In order to cover the wide vertical field-of-view of the LMS-Z420i sensor of 80 deg, the focal length of the camera has to be 20 mm or less for a full-sized CCD or CMOS chip camera to capture images covering the whole vertical scan range.

Fig. 1. *RIEGL* LMS-Z420i with Canon EOS 1Ds

Fig.2. *RIEGL* LPM-25HA with Canon EOS 300D

Hybrid Sensor	***RIEGL* LMS-Z420i with Canon EOS 1Ds*)**	***RIEGL* LPM-25HA with Canon EOS 300D**
measuring range	Up to 800 m @ target with 80 % reflectivity	Up to 60 m
ranging accuracy	10 mm (single shot)	8 mm (single shot)
beam divergence	0.25 mrad	1 mrad
measuring rate	8000 points / sec	1000 points / sec
scan range	0 to 80 deg vertically, 0 to 360 deg horizontally	up to ±150 deg vertically, 0 to 360 deg horizontally
scan resolution	0.004 deg	0.018 deg
camera chip	4064 x 2704, full size CMOS	3088 x 2056, 1:1.6 size CMOS
camera lenses	20 mm, 28 mm, 50 mm, 85 mm focal length	28 mm, 50 mm, 85 mm focal length
camera field-of-view	84 deg x 62 deg with 20 mm lens	44 deg x 30 deg with 28 mm lens

*) Different camera model available to match application needs.

Tab. 1. Key specifications of two different hybrid 3D sensors

The system is complemented by a data acquisition system based on a standard laptop. For convenience in numerous applications, both sensors, laser scanner and camera, are connected to a small portable server and subsequently to a wireless LAN hub so the data acquisition PC can be setup remotely. Data acquisition, sensor configuration, data processing and storage are done by the companion software RiSCAN PRO or RiPROFILE. The whole system is battery powered and highly portable, but yet robust and operable in a wide range of environmental conditions.

3. Fusing data in common coordinate system

An entire data acquisition campaign is usually performed by taking several scans and images from a number of different positions. To utilize the data, scan data and images have to be registered in a common coordinate system. There are several different strategies in use to accomplish data registration based on laser data. One widely used approach is based on positioning signals (i.e., special targets) in the scan area with well-defined coordinates (also addressed as control points), subsequent automated detection of the signals in the scan data, e.g., in the intensity data in case the signals are retro-reflective, determination of the signal position in the scanner's coordinate system, and calculation of a rigid transformation which transforms coordinates in the scanner system into the common coordinate system. Alternative approaches are based on the minimization of scan data deviation in overlapping regions, or on determining the scanner's position and orientation prior to data acquisition following the strategies in the use of total stations or by using DGPS. All these approaches culminate in the determination of the six degrees of freedom describing the transformation. Planning the positions has to be carried out carefully to obtain an almost complete coverage of the object's surface. Position planning can be assisted on-the-fly by an almost real-time visualization of the data acquired so far, which requires an on-line scan registration in the field.

Data acquisition with RIEGL instruments is carried out with the companion software RiSCAN PRO or RiPROFILE. The software provides tools for setting the scan parameters (i.e., field-of-view and scan resolution), for acquiring the data, for commanding the camera and acquiring the images, for detecting and fine-scanning the signals for registration, for calculating the registration, and for carrying out some basic post processing tasks (see Section 4 for details). The software is strictly project orientated, i.e., all the data acquired within one project and all the processing results are stored in a single project structure. The project information is stored almost completely in a single project file in a documented XML based format to provide straightforward access to the data by post processing tools. Large binary data, however, such as scan data and images are stored in separate files and are referenced in the project file. The binary scan data can be decoded by use of the free RiSCAN library.

The CaMera Coordinate System (CMCS) is the coordinate system of the digital camera used. It is defined by the camera's image sensor. The Scanner's Own Coordinate System (SOCS) is the coordinate system in which the scanner delivers its raw data. The data of every RIEGL 3D laser imaging sensor comprises geometry information in Cartesian or spherical coordinates and additional properties for every laser measurement, at least intensity and optionally color information. Thus the output of the RIEGL laser scanner can be addressed as an organized point cloud in the scanner's own coordinate system with additional vertex properties. The PRoject Coordinate System (PRCS) is a coordinate system which is defined by the user. For example, PRCS might be an already existing coordinate system native to the scan site, e.g., a facility coordinate system. RiSCAN PRO requires that all geometry data within this project coordinate system can be represented by single precision numbers (7 significant digits). Thus, if millimeter accuracy is required, the largest figure of coordinates should not exceed 10 km. The GLobal Coordinate System (GLCS) is the embedding coordinate system which usually is constituted by external bodies. This coordinate system is capable of handling large coordinates.

Figure 3 shows an example for the coordinate systems GLCS, PRCS, SOCS, and CMCS. For every project there is a single global coordinate system and a single project coordinate system. For every scanner position, there is a scanner's own coordinate system. If the user takes a sequence of images at a scan position, every image has it's own camera coordinate system. The object in the example is a building seen from above. A project coordinate system is defined with the Y_{PRCS} axis being parallel to the longer side of the building and the origin of the PRCS coinciding with one corner of the building. PRCS must be a right handed system. GLCS in the example is a left handed system, e.g. northing, easting and elevation. A number of scan positions are indicated by the local coordinate systems $SOCS_i$ (axes X_{SOCSi}, Y_{SOCSi}, Z_{SOCSi}). For every scan position used during the project's data acquisition, the user initiates a corresponding "ScanPosition" in the software. Every ScanPosition will hold all data belonging to this specific posing of the instrument. Part of this data is a transformation matrix M_{SOP} (scanner orientation and position) which describes SOCS in PRCS.

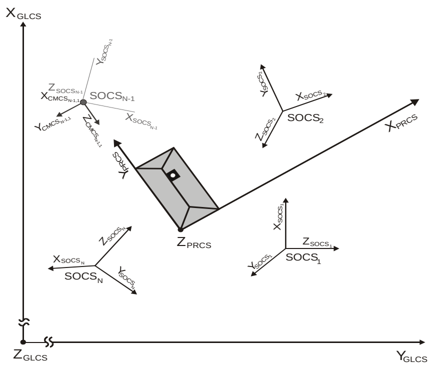

Figure 3: Example for the various coordinate systems used in a data acquisition project.

Transformations of Cartesian coordinates between the different coordinate systems are formulated by 4 x 4 matrices. Table 2 lists the matrices used by RiSCAN PRO (RiPROFILE).

matrix name	Remarks
M_{SOP}	transforms from the scanner's own coordinate system at a specific ScanPosition into the project coordinate system
M_{COP}	reflects the rigid transformation due to pan and tilt of the camera by the scan mechanism of the laser scanner with respect to a reference position (i.e., scan mechanism in position horizontal scan angle 0 deg and vertical scan angle 90 deg)
M_{MOUNT}	transforms from the scanner's own coordinate system into the camera's coordinate system in case the scan mechanism is in reference position
M_{POP}	transforms from the project coordinate system into the global coordinate system

Tab. 2. Listing of the transformation matrices used for coordinate transformation.

As the angles of the scan mechanism are well known for ever image taken, the corresponding matrix M_{COP} can be computed immediately. The mounting matrix M_{MOUNT} has to be determined once after each mounting procedure of the camera of the scanner by an easy to perform calibration routine provided by RiSCAN PRO. Once the ScanPosition is registered, i.e., the corresponding M_{SOP} matrix has been determined, not only the scan data can be transformed into the project coordinate system but also all image data and vice versa.

In order to transform points in the camera coordinate system into pixel coordinates, and also to transform pixel coordinates into rays the camera has to be modeled. RiSCAN PRO uses a simple perspective camera approach modeled by pixel size (d_x and d_y in meters), focal lengths in pixels (f_x and f_y), camera center in pixels (C_x and C_y) and with additional 6 parameters for modeling lens distortion. Without lens distortion the image coordinates in pixels are denoted as u and v, where as the image coordinates taking lens distortion into account are denoted as u_d and v_d.

The model parameters of the camera (f_x, f_y, C_x, C_y, k_1, k_2, k_3, k_4, p_1, p_2) have to be determined by calibration. Numerous calibration methods have been proposed and are in use in the field of photogrametry. Most of the methods require the use of a calibrated test field or at least a calibrated test object. As the laser scanner is capable of measuring signal coordinates in 3D, a temporary test field can be set up and surveyed by the laser scanner itself, which is then used to calibrate the camera [2, 3].

4. Utilization of scan data and Image Data

Image data acquired by the hybrid sensor can be utilized in various ways which are described in detail in the following subsections. All these capabilities can be used automatically without user interaction or at least semi-automatically due to the fact, that the camera is already calibrated and the camera's position and orientation is well-known for every image. The subsequently discussed ways of utilization comprise coloring of the point cloud (4.1), generation of textured triangulated surfaces (4.2), generation of ordinary orthophotos and orthophotos with depth information (4.3), performing measurements in single images (4.4), carrying out measurements in pairs of images (4.5), and improving the registration of ScanPositions by using image information (4.6).

4.1. Coloring point clouds

Coloring point clouds can be addressed also as determining the value of an additional vertex descriptor, i.e., the color, for every point of the point cloud of the laser scanner. As the parallax between scanner origin and camera origin is in many cases negligible, determining the color for a point is simple done by transforming the point coordinates in SOCS via M_{MOUNT} M_{COP}^{-1} into the CMCS and apply equations 1 to get the pixel coordinates and subsequently the color value. In case the parallax can not be neglected, the visibility of the points have to be checked prior to attributing the color.

In case image information consists of a series of images taken with different exposure times, brightness adjustment can be done automatically by analyzing the brightness of the color values attributed to points in overlapping regions of the images.

Although this utilization is straightforward it does not make use of the complete information content of the images as the resolution is determined by the scan data, which is in many cases less than the resolution of the image data. However, especially for an on-line visualization of the scan data in the field already during acquisition, coloring the point cloud facilitates object recognition and data interpretation.

Figure 5 shows an example of colored point cloud data acquired in Bam/Iraq in February 2004 showing destruction due to the catastrophic earthquake. Data of 25 scan positions have been used. The number of points have been reduced by spatial filtering.

4.2. Texturing triangulated data

The full information content of the images can be maintained by applying the image information as a texture to a triangulated surface extracted from the scan data. The process flow is outlined in Figure 4. In order to generate a triangulated surface, at first the scan data are triangulated in 2D by, e.g., a 2D Delaunay triangulation, as the scan data have only a dimension of 2.5D in the scanner's own coordinate system. After triangulation, the resulting mesh is cleaned by, e.g., removing "shadow" triangles interconnecting separate objects at different distances. In many applications smoothing of the mesh can be applied with advantage to reduce the effect of the inherent range noise of laser scanners. By subsequent decimation the number of triangles is reduced while ensuring a predefined modeling accuracy. This mesh is subsequently used for texturing. Before applying the texture, the images have to be undistorted, i.e., the lens distortion of the original images is removed and intermediate images of a virtually ideal perspective camera are calculated. Only for these images the edges of the triangles of the mesh are transformed into straight lines in the images. Texturing itself is performed by calculating the image coordinates of the vertices of the mesh and storing the image coordinates for every vertex. RiSCAN PRO uses the data format VTP (visualization toolkit polydata) of VTK [4].

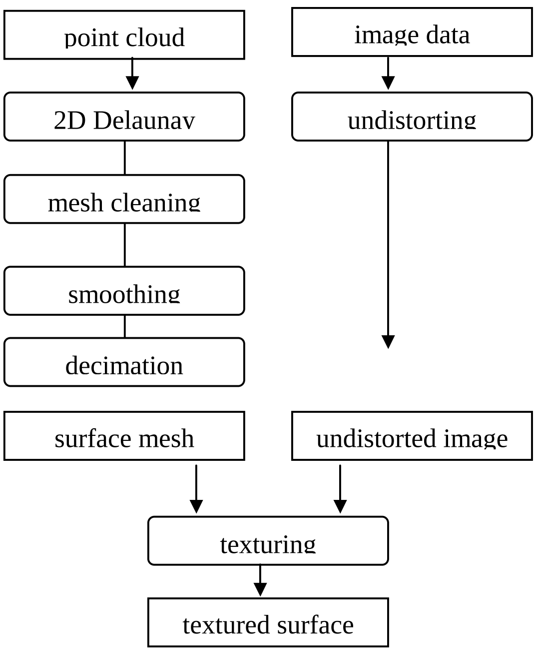

Fig. 4. Work flow for the generation of textured triangulated surfaces from data of the hybrid sensor.

In order to get a complete, e.g., watertight model, the textured surfaces of different scan positions have to be merged. Accurately textured surface can be the basis for 3D measurements with resolutions and accuracy exceeding the resolution of the scan data.

Figure 6 shows an example of data acquired with an LPM25-HA acquired in a monastery in Austria. Data processing has been executed according to Figure 4. For clarity, the data are also presented as wire frame model also.

4.3 Generation of orthophotos with depth information

Orthophotos are widely used in the field of architecture. Orthophotos have been generated usually by applying a perspective image to a coarse geometrical model, in the simplest case to a plane representing, e.g., a façade. However, distinct distortion can be observed when the geometry is not modeled accurately enough. The combination of laser scanning and imaging by using a hybrid sensor enables the automatic generation of high-quality orthophotos by modeling the geometry from the scan data and by applying the images as a texture to the modeled surface. The resulting image is addressed also as a true orthophoto.

Generation starts with defining the projection plane, the extent of the orthophoto, and its resolution. The user specifies the scan positions which should contribute to the photo. The data of every scan position is processed as described in Subsection 4.3 thus forming textured triangulated surfaces. These surfaces are subsequently rendered using an orthogonal camera model viewing the projection plane. After completion of rendering, the rendering context holds the orthophoto. The z-buffer used for rendering can be used to generate a relief. RiSCAN PRO generates additionally to the image data a so-called ZOP file containing the depth information for every pixel of the image and additional parameters to locate every pixel in the project coordinate system. This data set, image and depth information, can be imported to CAD systems with the help of third party plug-ins, e.g., ScanDig3D [5], so the user can easily digitize elements based on the orthophoto in 3D.

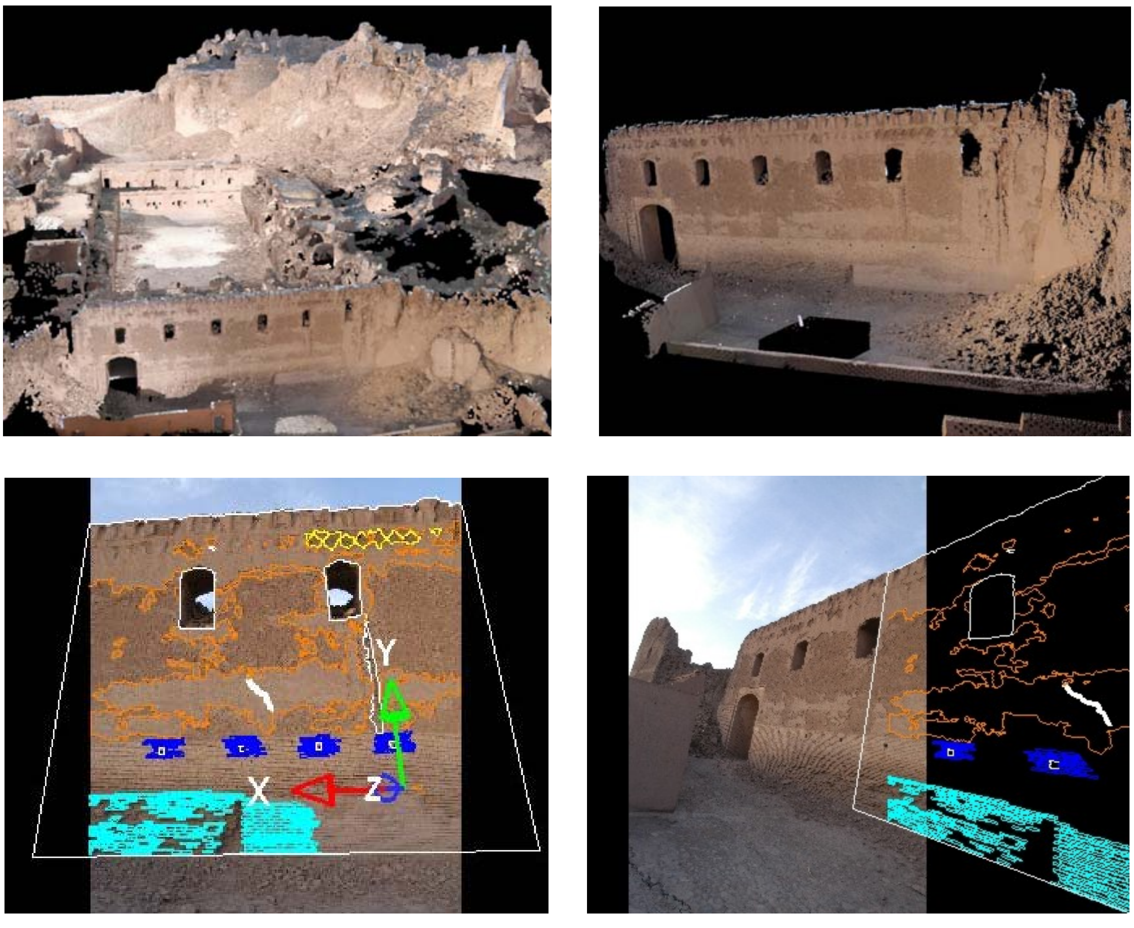

Fig. 5. Top row: Example data of colored point cloud taken with hybrid sensor based on RIEGL LMS-Z420i. Data acquired in Bam/Iraq in February 2004. Top left: total view. Top right: detailed view of one building. Bottom row: Registered camera image with reconstructed geometrical features from scan data superimposed.

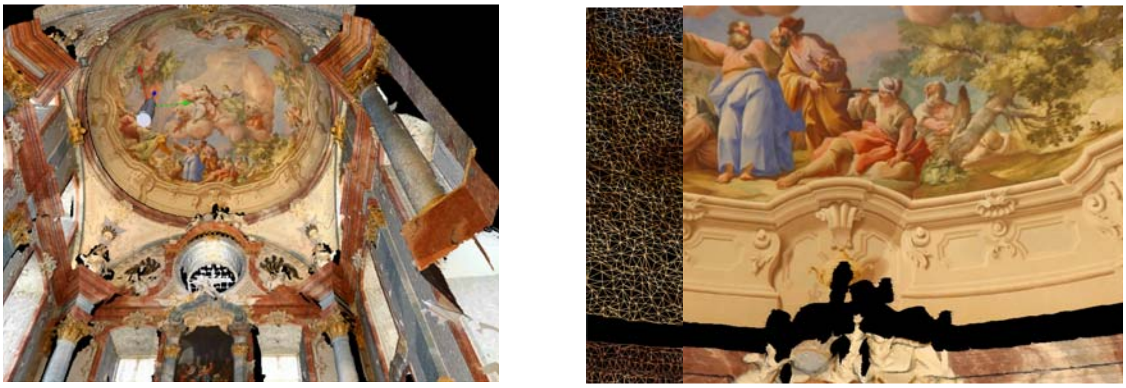

Fig. 6. Example data as triangulated textured surface. Left: visualization of a single hemispherical scan from virtual camera position below floor. Right: detail of vault as wire mesh (left insert) and as textured surface. Note that part of the perspective impression (middle of image) is only due to the artist's painting but not found in the 3D data.

4.4. Measuring in single images

As for every image taken with the camera being part of the hybrid sensor the laser scan data can be projected into the image, the scan data can also be visualized in the image as a point cloud in 2D. Measurements, e.g., the calculation of the coordinates of a pixel in the image in 3D can be carried out by calculating a least-square-fit plane through the scan data in the vicinity of the pixel and by intersecting the ray defined by the pixel with the plane. This calculation can be done on-line as the computational expenditure is quite low. Examples for the projection of 3D data into the registered images is shown in Fig. 5 [6].

By pre-calculating the 3D coordinates of every pixel in the image covered by scan data, or by pre-calculating at least the range to the object for every pixel, so-called "solid images" can be generated. These images can be used as data exchange format similar to the orthophotos to make image and scan data accessible in other software environments.

4.5. Measurements in images without the use of scan data

The images of the hybrid sensor can also be used to carry out measurements as in classical near range photogrammetry. By identifying objects in at least 2 images of registered scan positions, the 3D coordinates can be extracted. This can be especially useful to carry out measurements to objects which are not covered by laser measurements if, e.g., the range exceeds the maximum range of the laser scanner. The advantage over traditional photogrammetry is, that all images are already registered in a common coordinate system.

4.6. Improving scan position registration by using image information

The registration of the scan positions in a common coordinate system, for RiSCAN PRO the project coordinate system, is either based on determining the position and orientation of the sensor in the coordinate system by conventional surveying methods, or it is based on detecting signals of known coordinates. In laser scanning these signals posed in the scan area prior to scanning and are detected subsequently in the scan data. These signal are in many cases retro-reflective signals (flat circular reflectors) showing up in the intensity data of the laser scanner or diffusely reflecting spheres which can be detected in the 3D data of the scanner. For the hybrid sensor providing also registered images additionally to the scan data, also signals or object features can be used, which do not show up automatically in the scan data, e.g., color marked signals. As the images are calibrated and automatically registered in the scanner's own coordinate system, these signals can be used to determine the scan position parameters. Usually, these additional observations are used to improve the registration process based mainly on the scan data.

Outlook

The presented hybrid sensor comprising a high-performance long-range laser scanner and a calibrated and orientated high-resolution digital camera provides data which lend itself to automatic or semi-automatic processing of scan data and image data to generate products such as textured triangulated surfaces or orthophotos with depth information. All the tools developed for image analysis, such as edge detection or signal detection, can be used for direct extraction of 3D content from the combined image data and scan data. The discussed concept of sensor combination provides flexibility and can thus be easily extended to special cameras, e.g., thermal imagers in the infrared, to cover applications in reconnaissance.

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