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실내 환경에서의 3차원 공간데이터 취득을 위한 IMU, Laser Scanner, CCD 센서의 통합

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Acquisition of 3D Spatial Data for Indoor Environment by Integrating Laser Scanner and CCD Sensor with IMU

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요 약

최근 들어 보행자 내비게이션을 위한 3차원 공간데이터의 요구가 급증하고 있다. 보행자 내비게이션에 있어서, 3차원 모델은 일반인의 시각에서 구체적으로 표현되어야 할 필요가 있다. 보행자 내비게이션을 위한 공간을 상세하게 구현하기 위해서는 실외 환경뿐만 아니라 지하쇼핑센터와 같은 실내 환경에서도 적용될 수 있는 3차원 모델을 개발하는 것이 필수적이다. 그러나 GPS 없이 모바일 맵핑만으로 3차원 데이터를 효율적으로 취득하기란 대단히 어렵다. 본 연구에서는 3차원 형상을 레이저 스캐너로 측정하고, 표면 텍스쳐는 CCD 센서로 취득하였으며, 계속적으로 변화하는 센서의 위치와 높이는 IMU를 통해 측정하였다. 또한 IMU의 위치데이터는 GPS의 위치보정 없이 CCD 이미지의 상대 표정을 통해 수정하였다. 연구결과로써, 디지털 카메라 및 레이저 스캐너와 IMU와의 통합을 통해 실내 환경에서 신뢰성 높고, 빠르며, 간편하게 3차원 공간 데이터를 취득할 수 있는 방법을 제안하였다.

주요어 : 3차원 모델, 레이저 스캐너, CCD 디지털 카메라, 관성측정장치

ABSTRACT

3D data are in great demand for pedestrian navigation recently. For pedestrian navigation, we needs to reconstruct 3D model in detail from people's eye. In order to present spatial features in detail for pedestrian navigation, it is indispensable to develop 3D model not only in outdoor environment but also in indoor environment such as underground shopping complex. However, it is very difficult to acquire 3D data efficiently by mobile mapping without GPS. In this research, 3D shape was acquired by Laser scanner, and texture by CCD(Charge Coupled

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Device) sensor. Continuous changes position and attitude of sensors were measured by IMU(Inertial Measurement Unit). Moreover, IMU was corrected by relative orientation of CCD images without GPS(Global Positioning System). In conclusion, Reliable, quick, and handy method for acquiring 3D data for indoor environment is proposed by a combination of a digital camera and a laser scanner with IMU.

KEYWORDS : 3D Model, Laser Scanner, Digital Camera, IMU(Inertial Measurement Unit)

INTRODUCTION

There is a big demand for 3D spatial information of urban area, such as 3D GIS, navigation system, digital archives, simulation, computer games, and so on. In order to express a real world, it is necessary to acquire 3D shape and its texture together. In order to acquire these data efficiently, it is necessary to measure from mobile platform. A lot of researches have been done for mobile mapping systems, such as air borne mapping system and ground vehicle borne mapping system (Nagai et al., 2003; Manandhar et al., 2002). The mobile mapping has been developed since late 1980's. The development of the mobile mapping system became possible due to the availability of GPS (Global Positioning System) and IMU(Inertial Measurement Unit). IMU has a rising quality, but it is still affected by systematic errors. GPS is used to correct IMU systematic errors. That is, combination of GPS and IMU is the key of mobile mapping.

Nowadays, a lot of huge indoor spaces such as underground shopping complexes are being constructed. 3D spatial information for underground shopping complexes is a great demand for pedestrian navigation. However, in indoor environment, it is impossible to receive GPS signals with enough accuracy for mapping. Therefore, it is very difficult to acquire the data efficiently by mobile mapping system.

In this research, digital camera and laser scanner are used with an IMU. A series of images is applied for IMU correction instead of GPS by computation of image orientations. Namely, digital camera, laser scanner, and IMU are integrated to acquire 3D data at indoor environment.

SYSTEM DESIGN

A digital camera, laser scanner, and IMU are integrated in this mapping system. Points cloud data are acquired from a laser scanner. Images are acquired from a digital camera. And their positions and attitudes are acquired from an IMU. These sensors are synchronized in detail during measurements. In previous mapping systems, such as air borne mapping system or vehicle borne mapping system, geo-referencing is done by ground control points, GPS measurements, or integration of GPS/IMU. However, in this proposed mapping system, it is done by an IMU without GPS measurements in indoor environment.

In this research, all the sensors are loaded on a hand-trolley. These sensors are tightly fixed on the hand-trolley during measurements to keep their relative orientations. Figure 1 shows the configuration of sensors on the hand-trolley. This hand-trolley is pushed to go forward while measuring the side of objects in indoor environment. Since this hand-trolley system is prototype, it is desirable to use electric cart in the future experiment. Table 1 shows specifications of sensors used in this research. The digital camera is a single-lens reflex camera for non-professional purpose. The laser scanner is non-contact measurement system, which scans their surroundings two-dimensionally. The IMU is Ring-laser Gyro, which is used for aircraft navigation.

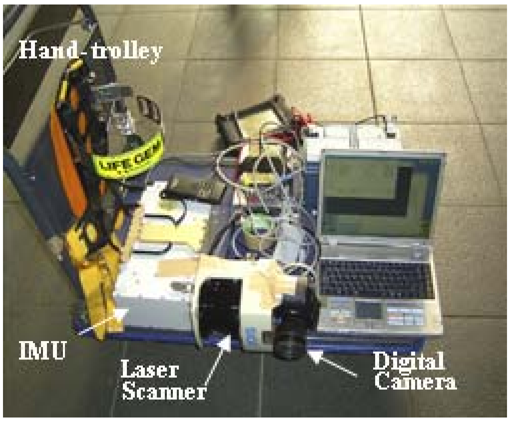

FIGURE 1. Configuration of Mapping System

TABLE 1. Specification of sensors

Sensor	Specification
Digital Camera	Canon EOS D-60 Pixel size: 3027 x 2048pixels CCD size: 22.7mm x 15.1mm Lens: EF24-85mm F3.5-4.5 USM
Laser Scanner	SICK LSM291 Angular resolution: 0.25° Max. Distance: 80m Observation Angle: 100º
IMU	Tamagawaseiki Co., Ltd.(Japan) Ring-laser Gyro 10Hz ZUPT interval: 30sec

SENSOR CALIBRATION

Calibrations of sensors are necessary due to two reasons; to correct image distortion of digital camera and to fix relative orientation of sensors each other. All sensors are loaded on the hand-trolley to establish rigorous geometric relationships. The purpose of calibration is basically to integrate all sensors to a single coordinate system, so that captured data can be integrated and expressed in terms of a single coordinate system for reconstructing 3D model by direct geo-referencing.

1. Interior Orientation

Calibration for the digital camera is conducted to decide interior orientation parameters, principal point (x0, y0), focal length (f), and distortion coefficient (K1). Control points for camera calibration are taken from stereo images several times. Camera calibration is performed by the bundle adjustment using control points. Interior orientation parameters which are computed in this interior orientation are shown in Table 2.

TABLE 2. Interior orientation parameter

x_0	1,532.9966 pixels	f	24.6906 mm
y_0	1,037.3240 pixels	K_1	1.5574E-008

In order to estimate appropriate lens distortion for digital camera, lens distortion mode is shown in Eq. (1) and Eq. (2). These equations consider only radial symmetric distortion.

$xu = x' + x' (K_1r^2)$ (1)
$yu = y' + y' (K_1r^2)$ (2)
where $x' = x - x_0$
$y' = -(y - y_0)$
$r^2 = x'^2 + y'^2$
(x, y): image coordinate

2. Exterior Orientation

Calibrations of the digital camera and the laser scanner are conducted to estimate exterior orientation parameters. This needs shift and orientation between each of sensors including the IMU, which is computed from calibration. At first, rigorous geometric relationship between laser scanner and digital camera is established. This relationship is strongly fixed at all times during measurements. Then, geometric relationship between the digital camera and the IMU is established. Using these relationship, geometric relationship between laser scanner and IMU is theoretically established. Figure 2 shows the concept of calibration to decide exterior orientation parameter.

For laser scanner calibration, a solar cell is used. The solar cell connects to an earphone. If the solar cell receive a laser beam from the laser scanner, the earphone beeps. In this way, pointing of a laser beam is measured for calibration even though laser beam is invisible.

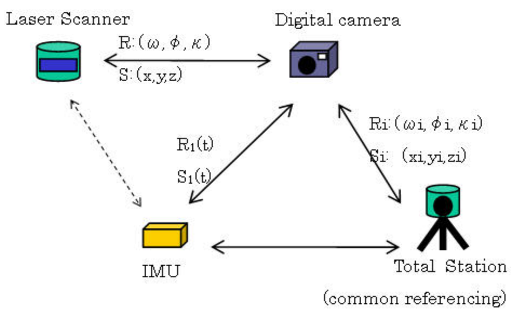

FIGURE 2. Concept of calibration for exterior orientation

Orientations of laser range data and digital camera images are done by computing the rotation matrix, R, and shift vector, S with IMU. All the points scanned by the laser scanner, x, and digital camera, (xu, yu), in terms of local coordinate system is converted to a single coordinate system as given by Eq.(3) and Eq.(4).

$Xworldlaser = (Ri \times R)\ x + (Si + S)$ (3)
$Xworldimage = f\ (Ri, Si, f, x_u, y_u)$ (4)
Where f( ): collinearity condition equation

EVALUATION OF IMU

The system obtains positioning information through an inertial navigation device similar to the high accuracy Ring-laser Gyroscope used in aircraft operating navigation systems. The angular velocity and acceleration signal is received at 200Hz from the IMU of the INS (Inertial Navigation System) main component and the results of inertial navigation calculation performed by the NAV PROC (Navigation Processor) is transmitted to the pen computer at 10 Hz. Figure 3 shows that flow chart of strap down calculation (Kuamgai et al., 2000) Angular velocities and accelerations which are acquired from gyro and accelerometer are used for strap down calculation. Drift error of IMU is corrected by ZUPT (Zero Velocity Update). ZUPT carries out positioning correction by resetting all values to zero by physically coming to a stop for IMU error calibration. The previous data are then recomputed to revise the error of the navigation system and calculate the specific position of the sensor. Number of ZUPT during measurements is related to the accuracy of positioning. However, if ZUPT is conducted too much, it takes a lot of time to measure. In this research, ZUPT is conducted every 30 seconds, which is the most convenient for accurate and efficient measurement.

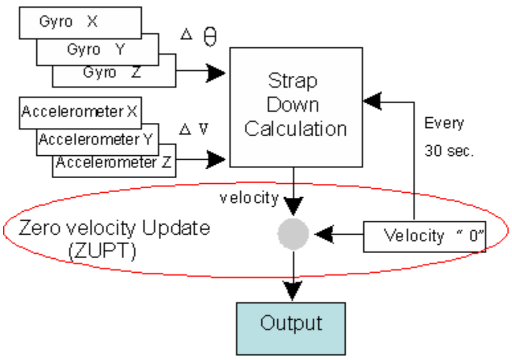

FIGURE 3. Strap down calculation

In order to evaluate the feasibility of the developed system, a field experiment has been performed in indoor environment (Suh et al., 2003). After marking the appropriate points, the accumulation of error with time was evaluated at each point. Figure 4 shows actual trajectory and the points where measurements were made for accuracy verification in the horizontal direction.

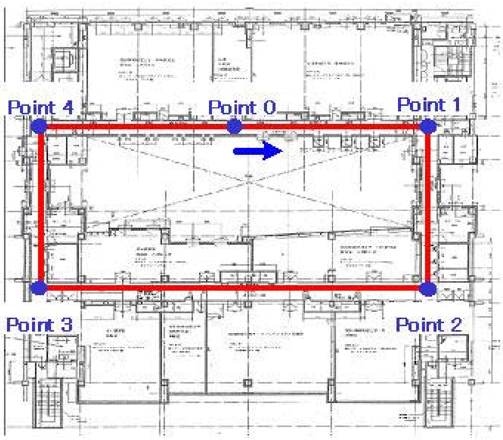

FIGURE 4. Map of testing site and trajectory

Figure 5 shows trajectory of IMU with ZUPT to indicate the accuracy of IMU in the horizontal direction. In comparison the trajectory with ZUPT to the actual trajectory, as shown in Figure 5, accuracy of IMU is 10 - 20cm horizontally.

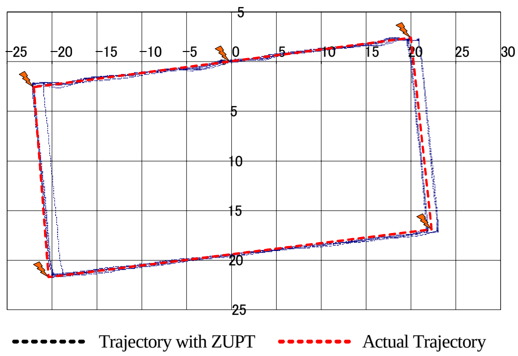

FIGURE 5. Accuracy of IMU in horizontal direction

Figure 6 shows trajectory of IMU without ZUPT. In comparison to the trajectory with ZUPT the trajectory without ZUPT are erroneous, ZUPT is a very effective method to correct IMU drift error.

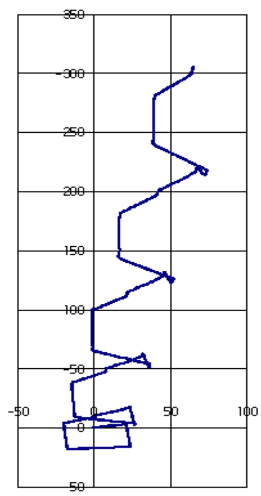

FIGURE 6. Trajectory without ZUPT

Measurement is taken and the accumulation of error is verified moving along the stairways from the 3rd floor to the 5th floor. As with the case of the previous experiment, the IMU is placed on the ground during data acquisition to obtain a more accurate value and also when ZUPT is being operated. The results of accuracy verification in the vertical direction are shown in Figure 7. Accuracy of IMU is 5 – 10 cm in the vertical direction.

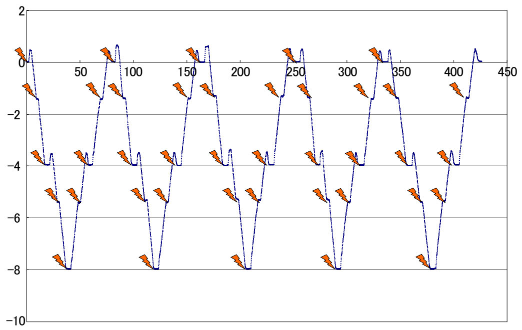

FIGURE 7. Accuracy of IMU in vertical direction

CORRECTION OF IMU ERROR

ZUPT alone may be enough for error correction, if the IMU is used only for determining trajectory of sensors. However, in this research, IMU is used for geo-referencing of laser range data. It would be better to get more accurate position and attitude for mapping. The positioning and attitude of sensors are determined by integration of the IMU and CCD images. One of the main purposes of this research is to integrate sensors for developing a high precision positioning system in all circumstances. Position and attitude can be estimated very highly accurately with bundle adjustment of CCD images, though the images are taken every ten seconds. Bundle adjustment is used for the determination of the orientation parameters of all CCD images. Bundle configuration increases both the reliability and the accuracy of object reconstruction. Bundle adjustment is a non

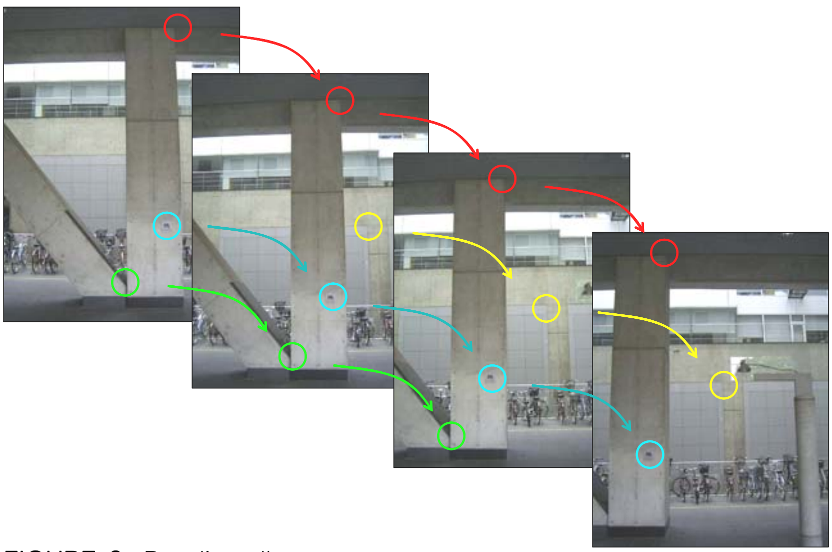

FIGURE 8. Bundle adjustment

linear least squares optimization method using tie-points as shown in Figure 8. An object point is determined by intersection from more than two images, which provides local redundancy for gross error detection and which makes a better intersection geometry as a result. So, in this research, CCD images are taken with more than 60% overlaps in forward direction.

Table 3 shows the result of bundle adjustment. "cp" is the control points which are measured by total station as true values. "ba" is the computation result by bundle adjustment. Accuracy is estimated by comparing with 20 control points and the result of bundle adjustment. Average of residual of its plane of images (X, Y) is approximately 3cm to 6cm while accuracy with ZUPT correction is 5 - 10cm. Average of residual of its height in images(Z) is approximately 10cm while accuracy is 10 - 20cm in only ZUPT. That is, this result is very accurate compared with IMU and ZUPT. These image orientation results which are computed by bundle adjustment are used for strap down calculation of IMU.

TABLE 3. Result of bundle block adjustment

Num	cpX(m)	cpY(m)	cpZ(m)	baX(m)	baY(m)	baZ(m)	residual:X	residual:Y	residual:Z
1	0	0	−12.584	0.0094	−0.059	−12.311	0.094	0.059	0.273
2	11.3105	0	−12.3825	11.293	−0.062	−12.48	0.0175	0.062	0.0975
3	20.8395	0.168	−12.4065	20.79	0.111	−12.515	0.0495	0.057	0.1085
4	32.588	0.2885	−12.441	32.527	0.229	−12.564	0.061	0.0595	0.123
5	46.196	0.5035	−12.5105	46.103	0.447	−12.518	0.093	0.0565	0.0075
6	0.074	−8.1735	−12.515	0.173	−8.145	−12.336	0.099	0.0285	0.179
7	11.3245	−7.905	−12.428	11.346	−7.891	−12.458	0.0215	0.014	0.03
8	20.5425	−7.7703	−12.4345	20.525	−7.72	−12.499	0.0175	0.017	0.0645
9	30.677	−7.315	−12.406	30.622	−7.341	−12.575	0.055	0.026	0.169
10	46.7025	−7.81	−12.566	46.608	−7.849	−12.459	0.0945	0.039	0.107
11	0.4485	−14.9755	−21.473	0.551	−14.917	−12.376	0.1025	0.0585	0.0097
12	11.6895	−15.058	−12.4075	11.734	−15.019	−12.483	0.0445	0.039	0.0755
13	20.3605	−14.902	−12.419	20.361	−143.891	−12.518	0.0005	0.011	0.099
14	30.447	−15.3555	−12.47	30.424	−15.347	−12.503	0.023	0.0085	0.033
15	46.3735	−15.455	−12.5715	46.289	−15.456	−12.401	0.0845	0.001	0.1705
16	0.353	−24.139	−12.443	0.453	−24.072	−12.522	0.0995	0.067	0.079
17	11.911	−23.7855	−12.455	11.987	−23.721	−12.466	0.076	0.0645	0.011
18	20.594	−23.461	−12.453	20.623	−23.421	−12.507	0.029	0.04	0.054
19	30.176	−23.1665	−12.4505	30.165	−23.13	−12.491	0.011	0.0365	0.0405
20	46.258	−22.5005	−12.5545	4.62	−243493	−12.39	0.058	0.0075	0.1645
						ave	0.05655	0.0376	0.09915

This is the key of high accuracy position and attitude estimation in indoor environment without GPS.

The combination of bundle block adjustment and the IMU is conducted to achieve higher accuracy. The results of bundle block adjustment are assumed to be true position values. IMU is initialized for strap down calculation using the result of bundle block adjustment. Namely, after every computation of bundle block adjustment, IMU and its error are corrected. Figure 9 is the strap down navigation for integrating IMU with the result of bundle block adjustment. The combination of IMU and bundle block adjustment can be called "corrected IMU".

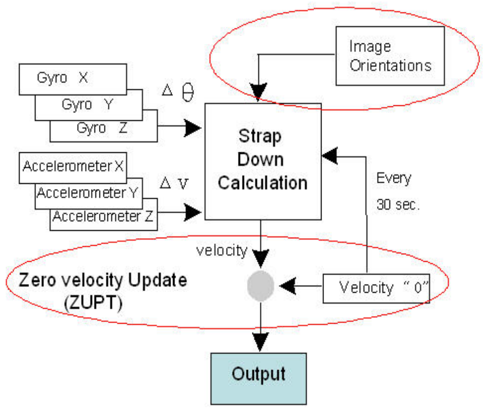

FIGURE 9. Image aided strap down calculation

CONSTRUCTION OF DSM

The point cloud data acquired by the laser scanner are geo-referenced by the corrected IMU data (Zhao et al., 2000). All the points scanned by the laser scanner, x, and digital camera, (x_u, y_u), in terms of local coordinate system are converted to world coordinate system as given by Eq.(5) and Eq.(6). t is the time function of IMU. Rotation matrix, R_t, and shift vector, S_t, are changing with time and they are acquired from corrected IMU data. This IMU is corrected by ZUPT and orientations of CCD images in this research. Relative orientation "R" and shift vector "S" is estimated by sensors calibration in previous section.

$$X_{worldlaser} = (R_t \times R)\ x + (S_t + S) \quad (5)$$

$$X_{worldimage} = f(R_t,\ S_t,\ f,\ x_u,\ y_u) \quad (6)$$

f(): collinearity condition equation

f: focus length

Figure 10 shows the point cloud data which are converted by Eq.(5) and acquired by laser scanner at indoor environment. These data present with world coordinate system. The integrated laser data show a good matching between the different sensor data indicating the calibration result. The DSM is a 3D model of the object surface that is manipulated using a computer. It is comprised of 3D measurements that are laid out on a grid. These measurements are the 3D point cloud data which are derived from the laser scanner.

Figure 11 shows the concept of draping texture. Each point of geo-referenced laser point data corresponds to a pixel of geo-referenced CCD image in the same coordinate system, because coordinate conversion of laser range data are done by Eq.(5) with IMU. The IMU drift error is corrected by image orientation of CCD images. Therefore, laser range data and CCD images overlap each other accurately. In this research, 3D point cloud data take on a color from the corresponding image pixels for textured digital surface model.

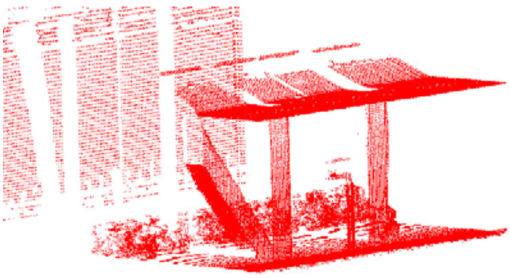

FIGURE 10. 3D point cloud data

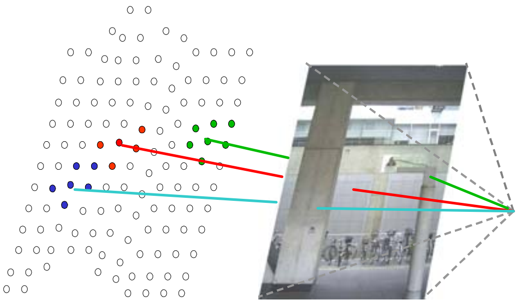

FIGURE 11. Draping texture

CONCLUSION

In conclusion, all the sensors, laser scanner, digital camera, and IMU are integrated for constructing DSM in indoor environment. In this research, a new method of IMU correction is proposed by the combination of bundle adjustment and ZUPT. Using this corrected IMU data, direct geo-referencing is done for developing 3D modeling in indoor environment. Because of the aiding of bundle block adjustment, geo-referenced laser range data and CCD images are overlapped correctly in the common world coordinate system. All the sensors and equipments are assembled and loaded on a hand-trolley as an experiment for efficient mapping as indoor mobile mapping system. This paper focus on how to integrate these sensors with mobile platform. Finally, accurate trajectory of sensor is computed in this research and it is used for direct geo-referencing for laser range data and CCD images to construct 3D model.

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