# TOWARDS AUTOMATIC ROAD MAPPING BY FUSING VEHICLE-BORNE MULTI-SENSOR DATA


Y. Shi [a,*], R. Shibasaki [a], Z.C. Shi [b]

[a] CSIS, The university of Tokyo, 277-8568 Chiba, Japan - (shiyun, shiba)@iis.u-tokyo.ac.jp
[b] Musashi Institute of Technology, 224-0015 Yokohama, Japan - shizc@yc.musashi-tech.ac.jp



**Commission ICWG V/I**

**KEY WORDS:** Mobile mapping system, Integrated sensor system, Multi-sensor data fusion, Direct-georeferencing, Close-range Photogrammetry, Automatic object extraction and recognition.



**ABSTRACT:**

The demand of spatial data has been an explosive growth in the past 20 years. This demand has numerous sources and takes many forms, but it is an ever-increasing thirst for spatial data, which is more accurate and higher density (Called as High-Definition Spatial Data), which is produced more rapidly and acquired less expensively. This research aims to satisfy with the high demands for the road spatial data. We presents an automatic road mapping technology by fusing vehicle-based navigation data, stereo image and laser scanning data for collecting, detecting, recognizing and positioning road objects, such as road boundaries, traffic marks, road signs, traffic signal, road guide fences, electric power poles and many other applications important to people's safety and welfare. In the hand of hardware, a hybrid inertial survey system (HISS) which combined an inertial navigation system (INS), two GPS receiver, and an odometer acquires the posture data was developed. Two sets of stereo camera systems are used to collect colour images and three laser scanners are employed to acquire range data for road and roadside objects. On the other hand, an advanced data fusion technology was developed for the purpose of precise/automatic road sign extraction, traffic mark extraction, and road fence extraction and so on, by fusing collected initial navigation data, stereo images and laser range data. The major contributions of this research are high-accuracy object positioning and automatic road mapping by fusion-based processing of multi-sensor data. A lot of experiments were performed to certify and check the accuracy and efficiency of our fusion-based automatic road mapping technology. From achieved results of these experiments, our developed vehicle borne multi-sensor based mobile mapping system is efficient system for generating high-accuracy and high-density 3D road spatial data more rapidly and less expensively.


## 1. INTRODUCTION

### 1.1 Background

The demand of spatial data has been an explosive growth in the past 20 years. This demand has numerous sources and takes many forms, but it is an ever-increasing thirst for geospatial data, which is *more accurate* and *higher density* (we call that High-Definition Spatial Data), which is produced *more rapidly* and acquired *less expensively*. This research aims to satisfy with the high demands for the spatial data. We presents an automatic technology by fusing vehicle-based navigation data, stereo image and laser scanning data for collecting, detecting, recognizing and positioning road objects, such as road boundaries, traffic marks, road signs, traffic signal, road guide fences, electric power poles and many other applications important to people's safety and welfare.

As well know, the spatial data of road objects has traditionally been collected using terrestrial surveying technology and aerial photogrammetric technology; and as a new technique, mobile mapping system such as vehicle-borne laser mapping system begins to be used for road mapping. But these are some limits of the two front methods, such update frequently is difficult/not so accuracy in height. To solve these drawbacks, people developed land-based mobile mapping system. The most important benefit of MMT is a reduction in both the time and cost of data collection.

Land-based Mobile Mapping System (MMS) is just the platform system with using mobile mapping technology. Most of MMS integrate navigation sensors and algorithms together with sensors that can be used to determine the position of points remotely. All of the sensors are rigidly mounted together on a platform, such as truck. The navigation sensors determine the position and orientation of the platform, and the remote sensors determine the position of points external to the platform. The sensors that are used for the remote position determination are predominantly photographic sensors and thus they are typically referred to as imaging sensors. However, additional sensors such as laser range finders (Reed et al., 1996) are also used in MMS and therefore the more general terms of mapping sensors may also be used when referring to the remote sensors.

The strength of MMS lays in their ability to directly georeference their mapping sensors. A mapping sensor is georeferenced when its position and orientation relative to a mapping co-ordinate frame is known. Once georeferenced, the mapping sensor can be used to determine the positions of points external to the platform in the same mapping co-ordinate frame. In the direct georeferencing done by MMS the navigation sensors on the platform are used to determine its position and orientation. This is fundamentally different from traditional indirect georeferencing where the position and orientation of the platform are determined using measurements made to control points. These control points are established through a


* Corresponding author.

field survey prior to data acquisition and their establishment is typically expensive and time-consuming. Also, for many terrestrial surveys, the establishment of sufficient control points is virtually impossible. For example, consider the control requirements to map an entire city using close-range photogrammetry. Finally, for some mapping sensors such as laser scanners or push-broom CCD arrays (Line CCD camera), it is difficult or impossible to establish control. The use of these sensors is not practical unless direct-georeferencing is performed.

### 1.2 Related Works

The first operational land-based MMS was developed by the Centre for Mapping at the Ohio State University. Their system (called GPSVan) integrated a code-only GPS receiver, two digital CCD cameras, two colour video cameras and several dead reckoning sensors (Goad, 1991; Novak, 1991). All components were mounted on a van. The GPS provided the position of the van and the images from the CCD cameras were used to determine the positions of points relative to the van. The dead reckoning sensors, which consisted of two gyroscopes and an odometer (wheel counter) on each of the front wheels, were primarily used to bridge GPS signal outages. These sensors were also used to provide orientation information for the exposure stations; however, there is little – if any － published information that examines the orientation accuracy of the GPSVan's dead-reckoning sensors and the poor accuracy of similar sensors suggests that the orientation information they provided would have been of marginal quality at best. The two video cameras were used solely for archival purposes and to aid attribute identification – no relative positioning was performed from the video imagery. Using bundle-adjustment techniques with relative-orientation constraints, the GPSVan was able to achieve relative object space accuracies of approximately 10cm. Unfortunately, because only carrier-smoothed code-differential GPS was used, absolute object-space accuracies were limited to 1-3 m.

GPSVan successfully illustrated how land-based multi-sensor systems could improve the efficiency of GIS and mapping data collection. However, ①Due to poor navigation sensors, the absolute accuracy of the object space points was too poor for many applications, especially when compared with competing technologies. ②Because GPSVan were simple stereovision system as its mapping sensor, automatic extraction of objects is difficult or impossible. Therefore, further developments of land-based mobile mapping system focused on these two points ①to increase absolute object space accuracies by using more high accuracy hardware or using more sophisticated processing techniques; ②to equip more mapping sensors for enabling more flexible data collection , better imaging configuration of objects and easier object extraction and recognition automatically. Based on the two points, the following expression is extended by introducing contributions of various research groups.

**Works to improve/stabilize mapping accuracy**

The obvious techniques for improving absolute object space accuracy were to use carrier-phase GPS, while the obvious choice accuracy dead-reckoning sensor was a high precision IMU. The use of an IMU has an additional advantage over other types of dead-reckoning sensors in that it also provides high-accuracy orientation information for the exposure stations. Later land-based MMS added dual-frequency carrier-phase differential GPS, more accurate IMUs, and more sophisticated processing techniques for navigation sensor data. Typical example system is the VISAT™ system (Schwarz et al., 1993). VISAT had absolute object space accuracies that had previously been unattainable (about 30 cm with absolute accuracy).

This 30Cm accuracy looks very excellent, but this accuracy is not direct from navigation sensor, and it should be do "image-based bundle adjustment" to improve georeferencing accuracy of image like triangulation of aerial photogrammetry (Schwarz et al., 1993). So it can be said that bundle adjustment is efficient method to improve accuracy, but it is difficult to do it full automatically duo to fallible image matching for tie point.

The other intelligent techniques for improving absolute object space accuracy were to use more sophic data processing of multiple navigation sensors like GPS, IMU, and ODO. This works can be found in Geomobil (Talaya 2004) and StreetMapper (Hunter 2006). The Geomobil system use POS/LV navigation sensor and it's corresponding software-Pospac, so that the absolute accuracy can reach to 30 cm.. The StreetMapper use TERRAcontrol navigation sensor system by IGI, and the accuracy also can get the same level of Geomobil. But, however, this level accuracy is should keep system in good GPS signal condition.

**Works to extract object as automatically as possible**

For more flexible data collection, better imaging configuration of objects and easier object extraction and recognition automatically, the obvious methods is to equip more kind type of sensor such as laser sensor, which can get 3D geometry information of object surface (see Reed et al 1996, and Talaya 2004). But because there are also disadvantages of laser sensor, the further development focus on fusion of CCD camera, which can get color information, and laser. This kind of research can be found in Zhao 2003. GeoMaster™ in research of Zhao 2003 was notable because of fusion of laser range finder data and CCD line camera. Where previous land-based MMS were simple stereovision systems employing only two forward facing cameras, GeoMaster™ have 6 CCD line camera and 3 laser scanners that enable more flexible data collection and better imaging geometry. But Due to easy geometry deformation of line camera, automatic recognition of object becomes difficult. The mobile systems which are equipped with laser sensor and vision sensor also can be found in following research groups, such as Geomobil (Talaya 2004), StreetMapper (Hunter 2006) and Waseda system (Ishikawa 2006). But, however, these systems are just to use two kinds of data for different object, not to fuse them for detect and extract same object for automatic processing by overcome the drawbacks of individual sensor. But it is obvious that fusion of multiple mapping sensors is efficient method to detect and extract object because data fusion processing can overcome the drawbacks of camera or laser sensor.

### 1.3 Our Research Objective

Based on the above discussion, the primary objective of this paper is to develop a serial of methods for collecting more accuracy, higher density (called as high-definition) spatial information data of road objects with more rapid and less costly by fusing vehicle-based navigation data, vision data and laser range data.

The system based on our developed methods can overcome the drawbacks of current mobile mapping systems – namely not high position accuracy and not high ratio of automatic mapping

– which have restricted their widespread adoption in the survey and mapping industries. The system will satisfy the demand for a mobile mapping system that can compete in both more high position accuracy and automatic mapping, which will be discussed in the following sections.

## 2. HIGH-ACCURACY POSITIONING BY FUSING MULTI-SENSOR DATA

Due to poor navigation sensors, the absolute accuracy of the object space points was too poor for many applications – especially when compared with competing technologies. So for broad utilization in more application, it must increase absolute object space accuracies by using more high accuracy hardware or using more sophisticated processing techniques. In this research, the POS/LV™ of Applanix corp. is utilized as our navigation sensor, the power of the navigation system consumedly improve the position accuracy of mapping. But in some of case such as in poor GPS signal area, it also cannot get ideal accuracy.

As well known, bundle adjustment is efficient method to improve accuracy, but it is difficult to do it full automatically duo to fallible image matching for tie point. Based on this knowledge, this paper presents a robust automatic extraction method for tie points. And then, photogrammetry bundle adjustment technology is developed to improve and stabilize accuracy of positioning.

### 2.1 Robust Automatic Extraction of Tie Point

With the obtained tie points, a bundle adjustment can achieve an improved exterior orientation of the camera, which results in the final mapping position accuracy. To extract tie points in image sequence robustly and precisely is the prerequisite condition for Photogrammetry Bundle Adjustment. But, automatic and robust extraction of tie points in image is one of the most challenging problems in computer vision and digital photogrammetry. The difficulty of tie point extraction is image matching of these extracted feature points (corners), due to easily happened amphibolous matching. The traditional and efficient solution of the matching problem is to use rectified images, which reduce the complexity of the matching algorithms from 2D to 1D search.

But, even if the epipolar geometry is used to image matching, the amphibolous matching problem also happens along epipolar line. For solving this problem perfectly, the laser 3D point clouds are used for image matching to solve that amphibolous matching problem. The figure 1 shows how laser 3D points facilitate the solution of the image matching problem with any no-amphibolous matching. With referring to 3D laser point clouds, the extracted feature point can achieve its 3D coordinate in mapping frame, then the initial coordinate of that feature point in the next image can be computed by projecting 3D coordinate to image plane. Finally, just inching adjustment is performed by image matching. Because the adjustment is done in small area, the amphibolous stereo image matching can be solved and matching become more robust.

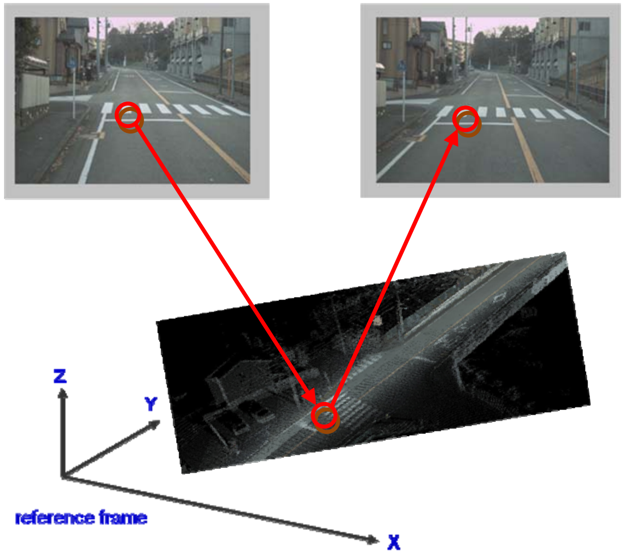


Figure1. Automatic Tie Point Extraction by Supporting of Laser Point Cloud

### 2.2 Method of Data Fusing Processing for High-Accuracy Positioning

The key step for our high-accuracy positioning is automatic accurately tie point extraction by supporting of laser point could, which have been described by detail in the above section. As the figure 2 shown, the navigation data should be calculated for initial position and orientation for laser and camera, so that the tie point of image can be extracted automatically with help of the initial laser point cloud.

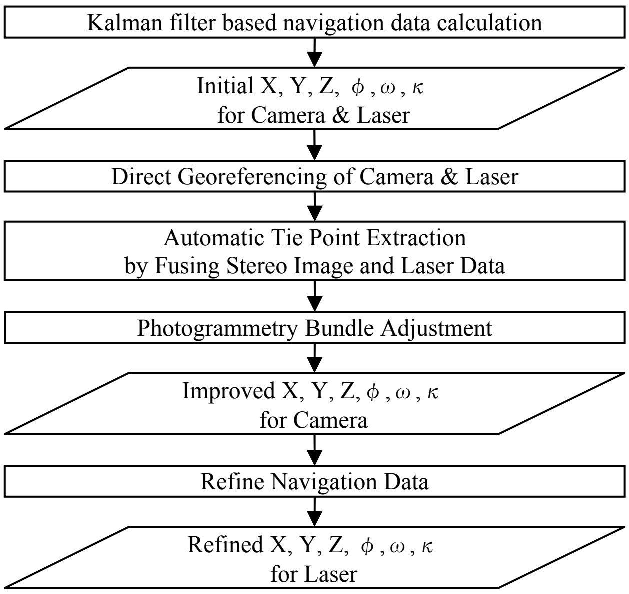


Figure2. Data Fusion Processing for High-accuracy Positioning

With using accurate extracted tie points, bundle adjustment (which is almost exclusively don in close-range photogrammetry) is processed for improving accuracy of camera position and orientation (X, Y, Z, $\phi$, $\omega$, $\kappa$). The improved position of camera is then used as control point for refine navigation data and then the improved position and orientation for laser is calculated.

### 2.3 Positioning Accuracy from Our Experiments

Positioning accuracy is the integrated accuracy with navigation sensors and mapping sensors. Mapping accuracy of some GCPs is listed in comparison with terrestrial surveying, which is cm-level accuracy. It is believed that our system mapping accuracy can reach to about 30 cm order by our high-accuracy positioning technology by fusion processing of GPS/IMU, Stereo image sequence and laser point cloud. Our high-accuracy positioning method also acquires good position accuracy in the area of poor GPS signal and multi-path.

## 3. AUTOMATIC ROAD MAPPING BY FUSING IMAGE AND LASER DATA

The term automatic road mapping in this research is defined as to automatic extract, recognize and position road objects from collected data by vehicle-based mobile mapping system. The main topic in this section is to discuss how to automatically collect road spatial information by fusing stereo image and laser data which are captured by our vehicle-borne multiple sensor mobile mapping system. The keywords of this section are data fusion and automatic mapping; data fusion is processed for better automatic mapping, and automatic mapping is done for more efficient and less costly generating high-definition road spatial data.

### 3.1 Why need fusion of image and laser data

For automatic extraction and recognition, typically, there are image-based approach, laser-based approach, and fusion approach. Image-based approach base on digital image processing thesis, utilize color, shape, texture to recognize object. Image-based approach has very long development history; many of the techniques were developed in the 1960s at the Jet Propulsion Laboratory, MIT, Bell Labs, University of Maryland, and a few other places. Although well developed image-based approach has many successful applications, it has some inherent drawbacks as below:

1. Occlusion problem own to it's center perspective projection;
2. Be sensitive to environment conditions such as light and shade;
3. Mosaic from piece of images is costly (FIgure3-a);
4. Stereo matching based 3D positioning is difficult for full automation.

Laser scanner is active sensor, so that laser-based approach is insensitive to environment conditions. Because laser scan object through point by point, exclusion problem of laser-based approach is not so serious with comparison of image-based approach. And laser scanner can acquire the continuous 3D point cloud, so there are no mosaic problem and also no stereo matching problem. From the above analysis, it is obvious to say that laser-based approach just can solve those unsolvable problems by image-based approach. However, laser-based approach also has its inherent drawbacks such as no gray or color information so that recognition becomes difficult. BUT that is just strong point of image-based approach.

The Figure 3 shows some typical merits of road object automatic extraction by fusion method. (b) demonstrates that color-rendered laser point cloud is easy to extraction road data without mosaic processing; (c) shows that color-rendered laser point data can be used for detecting road mark; (d)(e) show laser point cloud can support road object detection and recognition using its robust shape due to active sensor.

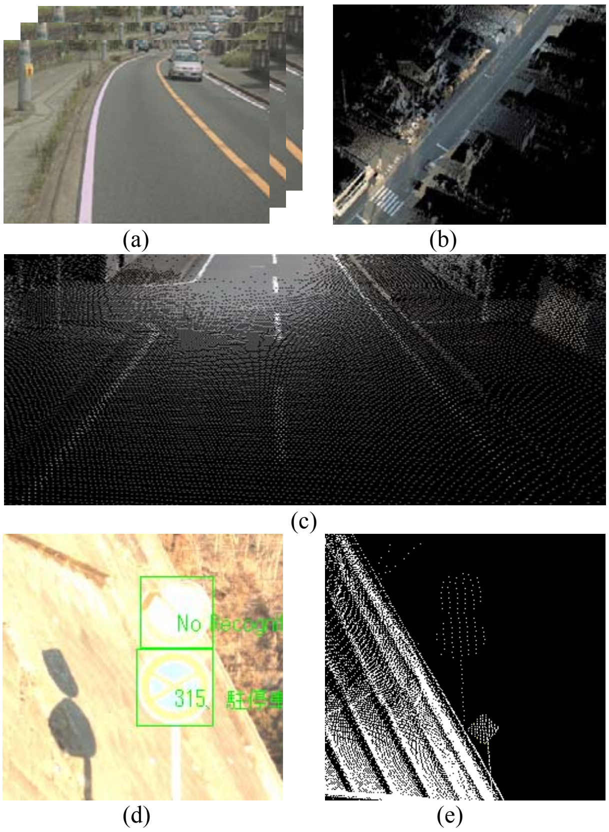


Figure3. Comparison of image and laser data for automatic object recognition and extraction

### 3.2 Automatic Road Object Extraction by Fusing Stereo Image Sequence and Laser Point Cloud

From the above discussion, it is easy to know data fusion method can get over those inherent drawbacks of individual approach. Our developed approach is based on fusion of image and laser approach. The data origin is laser range data, stereo image sequences, and automatic acquiring of road spatial data is done by fusion method. The processing flowchart of fusion method is drawn in figure 4. The processing includes five key steps as 1.Direct geo-referencing; 2.Laser point rendering; 3.Image Positioning; 4. Laser point cloud based candidate extraction using shape, color and position and 5. Image and laser data fusion based final robust extraction.

**Direct Geo-referencing**

Direct geo-referencing is to identify the spatial position of the objects scanned by mapping sensors at any time while the vehicle is moving with reference to a common coordinate system. The detailed information can be reviewed in chapter 5. By high-accuracy positioning technology, we have calculated high-accuracy instant sensor posture (X,Y,Z, $\varphi,\omega,\kappa$) when laser point or image is recorded. Based on the posture, laser 3D point cloud can be generated, and stereo image sequences also can be registered for mapping.

**Laser Point Rendering and Image Positioning**

For better fusion processing, we should know the corresponding relationship between any point of laser 3D point cloud and image sequences, which is called as image linking. Based on the linking information, it is easy to know which images are including the appointed point of laser point cloud; and the position of any place of image by back-projected laser 3D point, which is called as image positioning. When the linked image has been calculated, the color information of that point also can be acquired from that image, which is called as laser point rendering. The point rendering technology gives color information to laser 3D point cloud so that laser point cloud based extraction can be performed well because of additional color information.

For laser point rendering, it is possible that a laser point is covered by foreground object in that image so that error color information is acquired. Our solution is using stereo image checking. As you know, if a point is covered really by foreground object, the two projected points in image pair become non-matchable. Based on this checking, the color information can be searched in round stereo image pair until the two projected point can be matched (Detail in Shi 2008).

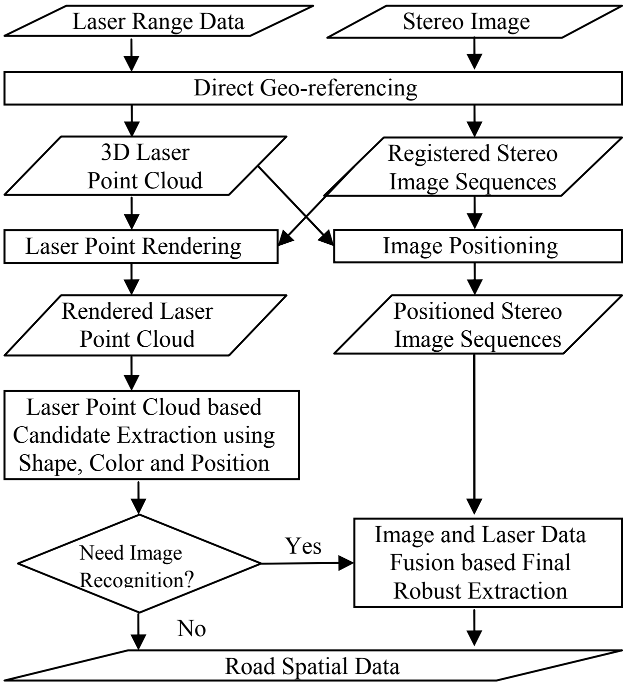


Figure4. Flowchart of Fusion Processing for Automatic Road Object Extraction

**Laser Point Cloud based Candidate Extraction**

Rendered Laser 3D Point Cloud not just has color information, but also it is seamless 3D data. Just because it is seamless, the extraction of linear object, such as road traffic lane mark, becomes less costly with “No-mosaic”.

Typically, road surface is flat but pavement surface is higher than road surface. The feature just makes extraction possible by using shape of laser data. The boundary point can be easily done if the road have curb. Because of the road curb, if height of a laser point suddenly changes, the boundary point is detected. But for these no-curb roads, the next processing—image and laser fusion —is used for boundary point detection. The detailed description for automatic extraction of road boundary and road mark is reported in the reference paper (Shi 2008).

**Image and Laser Data Fusion based Final Robust Extraction**

Like road sign, the fusion method can detect it more robustly. Road signs use particular colors and geometric shapes to attract driver’s attention, so typical algorithms of image based detection and recognition use their inherent color, shape and texture to detect and to extract sign type and legend. On the other hand, road sign also stand alone in roadside, so it has inherent features in laser 3D space. Based on these features in laser 3D space, road sign can be easily detected. This step fuse laser data and image to detect as successful as possible.

### 3.3 Success Extraction Ratio from Our Experiments

In 10km experiment data, success extraction of road boundaries reaches to 95%; but for traffic mark, because of no-capture image data on curving place of road, the missed ratio reaches to about 13.4%. For reducing the miss ratio of traffic mark, system should capture images on curving place as dense as possible.

For seeing effectiveness of fusion method for road sign recognition, we compare the fusion method with image method.
(1) Fusion method can detect most of road sign (more than 94%) especially in sun day, in which image method just have about 51% success ratio because of the effect of sun-shining.
(2) In cloud condition, the recognition ratios of image method and fusion method are more than 90% too, but in sun-shining condition, fusion method has more recognition ratio than image method. Although the ratio is 71.4%, it is easy to check its type by extracted image (its extracted ratio of fusion method reach to 94.3%).

| Whether | Type | Existing RS | Detected | Recognized |
|---|---|---|---|---|
| Cloud | Image | 161 | 153 (95.03%) | 145 (90.06%) |
| | Image& Laser | 161 | 157 (97.5%) | 148 (91.93%) |
| Sun-shining | Image | 35 | 18 (51.4%) | 16 (45.7%) |
| | Image& Laser | 35 | 33 (94.3%) | 25 (71.4%) |

Table 1. Success ratio of road sign extraction

## 4. CONCLUSION

In this paper, we aim to satisfy with the high demands for the road spatial data. We presents high efficient road mapping technology by fusing vehicle-based navigation data, stereo image and laser scanning data for collecting, detecting, recognizing and positioning road objects, such as road boundaries, traffic marks, road signs, traffic signal, road guide fences, electric power poles and many other applications important to people’s safety and welfare.

The high efficiency can be seen by comparison with other method. It is well known that aerial photogrammetry is more efficient in comparison with terrestrial surveying for road mapping. So we just compare our method with aerial photogrammetry for getting mapping efficiency. From the table 2, aerial photogrammetry needs about 1.6 day/person for one kilometer data, but our method just needs 0.2 day/person, which is 8 times of mapping efficiency. And not just saving mapping time, our method can get denser road spatial data than aerial photogrammetry like road sign. From the two aspects, it is clear that our method is efficient method for capturing 3D road spatial data.

| Aerial Photogrammetry | | Our Fusion-based Method | |
|---|---|---|---|
| Course Length | 9.5Km | Course Length | 10Km |
| Photo Taking | 0.5 day/person | Data Capturing | 0.5 day/person |
| GCP Surveying | 6.0 day/person | Geo-Positioning | 0.5 day/person |
| Aerial Triangulation | 0.8 day/person | Result Editing | 1.0 day/person |
| Field Investigation | 6.0 day/person | - | - |
| Mapping | 1.0 day/person | - | - |
| Editing | 1.0 day/person | - | - |
| Total | 15.3 day/person | Total | 2.0 day/person |
| Mapping Efficiency | 1.6 day/person/km | Mapping Efficiency | 0.2 day/person/km |

Table 2. Mapping Effectiveness in Comparison with Aerial Photogrammetry

The high efficiency of our method also can be found in the following table 3. The table compares our fusion-based method with the method which just uses CDD stereo image. Because the automation ratio of image-based method is much less than our fusion-based method, it spends more time in manual editing of extracted results. From this comparison, it is clear that fusion-based method is an efficient solution for 3D road mapping.

| Image-based Method | | Our Fusion-based Method | |
|---|---|---|---|
| Course Length | 10Km | Course Length | 10Km |
| Data Capturing | 0.5 day/person | Data Capturing | 0.5 day/person |
| Geo-Positioning | 2.0 day/person | Geo-Positioning | 0.5 day/person |
| Result Editing | 3.5 day/person | Result Editing | 1.0 day/person |
| Total | 6.0 day/person | Total | 2.0 day/person |
| Mapping Efficiency | 0.6 day/person/km | Mapping Efficiency | 0.2 day/person/km |

Table 3. Mapping Effectiveness in Comparison with Image-based Method

## ACKNOWLEDGEMENTS

The authors would like to express the appreciation to the De-tech Co. Ltd and their staffs for kindly cooperating with experiment and the other relative support through this work.

## REFERENCES

Deriche, R., Giraudon, G., 1993. *A computational approach for corner and vertex detection*, Journal of Computer Vision, Vol. 10, No. 2, pp. 101-124.

El-Sheimy, N., 1996. *The Development of VISAT – A Mobile Survey System for GIS Applications*, Ph.D. Thesis, University of Calgary, Calgary, Canada.

El-Hakim, S.F., C.Brenner, G.Roth, 1998. *A Multi-sensor Approach to Creating Accurate Virtual Environments*, JSPRS Journal of Photogrammetry &Remote Sensing, vol.53, pp.379-391.

Goad, C. C., 1991. *The Ohio State University Mapping System*: The Positioning Component, Proceedings of the 47th Annual Meeting, pp. 121–124.

Hunter G., Cox C., Kremer J., 2006. *Development of A Commercial Laser Scanning Mobile Mapping System – StreetMapper*, Processing of 2nd International Workshop of the future of Remote Sensing.

Hutton, J., Savina, T., Lithopoulos, L., 1997. *Photogrammetric Applications of Applanix's Position and Orientation System (POS)*, ASPRS/MAPPS Softcopy Conference, Arlington, Virginia, July 27 - 30.

Reed, M., C. Landry, and K. Werther, 1996. *The Application of Air and Ground Based Laser Mapping Systems to Transmission Line Corridor Surveys*, Proceedings of Position, Location and Navigation Symposium (PLANS 1996), pp. 444–451. Institute of Electrical and Electronics Engineers (IEEE), Atlanta, GA

Shi Y., Shibasaki R., Shi ZC., 2007. *High-accuracy Positioning for Land-based Mobile Mapping System by Fusing Multi-Sensor Data*, ACRS 2007 Conference Proceeding (CD-ROM).

Shi Y., Shibasaki R., Shi ZC., 2008. *High An Efficient Method for Extracting Road Lane Mark by Fusing Vehicle-based Stereo Image and Laser Range Data*, EORSA 2008 Conference Proceeding (CD-ROM)

Talaya,J., Bosch,E., Alamús,R., Bosch,E., Serra,A., Baron,A., 2004. *GEOMÒBIL: the Mobile Mapping System from the ICC*, Proceedings of 4th International Symposium on Mobile Mapping Technology (MMT 2004). Kinming, China.

Wang Z. Z., 1990. *Principles of photogrammetry (with remote sensing)*, Publishing House of Surveying and Mapping.

Wong K. W., 1975. *Mathematical formulation and digital analysis in close-range photogrammetry*, PE & RS, 1975.11, pp.248-256.

Zhao H., Shibasaki R., 2003. Special Issue on Computer Vision System: Reconstructing Textured CAD Model of Urban Environment using Vehicle-borne Laser Range Scanners and Line Cameras, Machine Vision and Applications, Vol. 14 (1), pp. 35-41.