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Adaptive Sensor Fusion for Automatic Road Condition Surveying

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Abstract—**Road condition has a critical impact on road safety and efficiency. It is a big challenge to accurately and efficiently survey and monitor road condition, including road clearance, roughness, profile and markers etc. This paper introduces a mobile road condition surveying system, consisting of multiple sensors. A data processing scheme with two local sensor fusions (LSF) is proposed. The first LSF has federate architecture with adaptive sensor fusion to provide accurate and reliable position, velocity and attitude (PVA) information. It has three local data fusion units (DFU) with extended Kalman filter (EKF) and one master DFU with fuzzy logic. The second LSF conducts multiple road surveying functions using range and intensity data from LADAR sensors and PVA from the first LSF. A prototype system has been developed, which can survey multiple lanes at one run at normal driving speed under general weather and road condition. Experiment results on different types of road demonstrate the effectiveness of the proposed system.**

I. Introduction

The safety and efficiency of road transportation play an essential role in modern society [1]. Accurate and updated information for road condition has a direct impact on road safety and efficiency, especially for the upcoming intelligent transportation system (ITS) to operate autonomous vehicles in urban environment. Mobile surveying is a new way of efficiently collecting three-dimensional data from the road environment, and is a cost efficient and robust technique to acquire information by accessing the site with less risk to the personnel and with less impact on the traffic.

The need for capturing high resolution and accurate data for street and road inventories or city modelling is the main reason for the rapid adoption of the mobile surveying. Many interesting approaches for road mapping or surveying have been proposed. They rely on different sensing technologies, such as stereo vision; LADAR (Laser Detection and Ranging) and radar. Some other approaches aimed to build road models with the combination of various types of sensors.

For the vision-based road mobile surveying method [1] - [3], it depends on ambient light, which greatly affects the functionality of road in real-world conditions. For surveying road surface in poor illumination environment, such as inside tunnels or during evening, vision recognition method may not be applicable. A dedicated for mobile road mapping system is introduced in [1]. However, its image-based surveying cannot measure the multilane road surface in 3D that limits its ability for full-scale road profiling.

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LADAR based road condition surveying becomes popular in recently [4]-[6], but with some limitations. The laser-based road boundary detection algorithm proposed in [5] can yield fairly good results only for simple and flat road boundary, which confines its application. Road boundary information can also be surveyed by radar [7], in the test of a van-mounted radar system. It can only detect road boundary and is limited to operate at a speed up to 50 km/h, which could cause traffic congestion and affect other drivers. A one-wheel trailer was developed for estimating the road surface profile based on the vehicle dynamics motion [8]. However, it can only survey a narrow strip of a traffic lane; the condition of rest of the road is unmeasured. Some other approaches [9]-[11] perform mobile road mapping based on road models, which work with predefined road model in principle. Due to the complexity of modern road networks, however, methods mentioned above have efficiency and robustness issues.

A LADAR-based mobile surveying system developed by the authors' research team is designed to survey most of the road condition parameters accurately and efficiently at normal driving speed [12], [13]. The system integrates multi-sensors into a frame mounted on an experimental vehicle, including GNSS, INS, vehicle odometer, cameras and LADAR etc. The sensors are thoughtful arranged to avoid Doppler Effect during mobile surveying at high speed, and to be able to survey multi traffic lanes simultaneously. Both range and intensity data from LADAR have been processed to generate 3D road profiling with texture.

This paper introduces our recent redevelopment of the mobile road surveying system, mainly focusing on sensor fusion algorithm improvement. The rest of the paper is organized as follows: Section II gives a general description of the mobile road surveying system. Sensor fusion algorithms for each function of the system are introduced in Section III. The surveying results of some system functions are explained in Section IV. The conclusion is drawn in Section V.

II. Mobile Road Surveying System

In this section the road surveying system is described at three aspects. System architecture introduces the sensors used in the system and how to process their data for various surveying functions. System hardware provides information about sensors setting and their control. The data acquisition and process explain the data collection for road condition surveying. The detailed description of the system hardware can be found in [12] and [13].

A. System Architecture

Multi-sensor integration is the best approach to develop a robust road surveying system that can provide road profile in most circumstance. The key for success is appropriate system design and data processing algorithm. The aim of developing the proposed system is to build a multipurpose platform for efficient road condition surveying. Due to the complexity of multi-sensor fusion, an optimal sensor integration framework needs to be developed with accurate surveying procedures, reliable modeling algorithms and quality control.

The mobile road condition surveying system consists of LADAR, GNSS, INS, odometer and camera, as shown in Figure 1. INS is selected as the reference navigation sensor because it can provide continuous position, velocity and attitude (PVA) data but with time-accumulated drift. Vehicle odometer can continuously measure vehicle speed and mileage. GNSS is a global navigation system with assured position and velocity measurement in open space, which can be used to correct the INS and odometer errors. But GNSS cannot function well in other environments. At the same time, GNSS has accurate clock that can be used as the reference for all the sensors' time synchronization. The images from a camera is used for both the navigation and the road condition surveying as a visual reference.

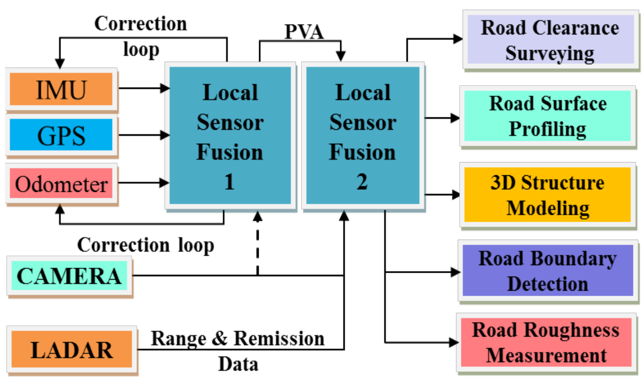

Figure 1. Multi-sensors fusion system architecture.

The Local Sensor Fusion (LSF) 1 is designed to provide accurate and reliable PVA information for the surveying system. The inputs for LSF1 come from IMU, GNSS, Odometer, camera and digital map. LSF2 is designed for conducting surveying functions indicated in the figure. LADAR is the major surveying sensor of the proposed system. Bothe range and intensity data collected by LADAR are fused in LSF2 with the PVA from LSF1 to perform all required surveying tasks.

B. System Hardware

The system hardware consists of a set of sensors (two LADAR sensors, one INS, one GNSS, one camera and vehicle odometer), two computers, communication network, power supply subsystem and mechanical structure etc. GNSS antenna, IMU and two LADAR sensors are fixed on an aluminum base mounted on a mechanical support structure at the real of the test vehicle, as shown in Figure 2. The camera and odometer are installed on the vehicle directly. The two LADAR sensors on the base was devised to let them scan road cross-sections. Whilst GNSS, INS, camera and odometer data fusion in LSF1 provides accurate PVA solutions for geo- referencing the two LADAR sensors, LSF2 can provide multi road surveying functions indicated in Figure 1.

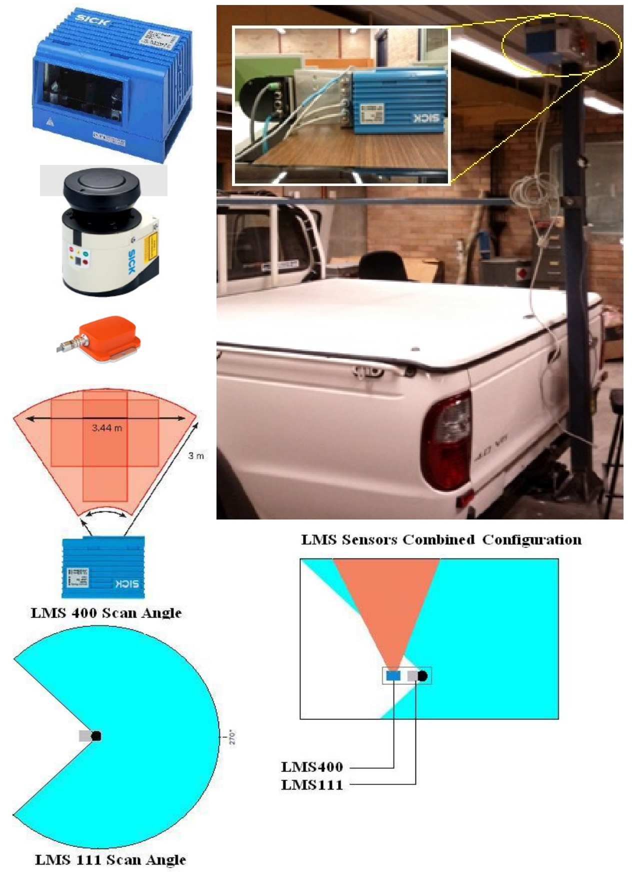

Figure 2. System sensors hardware and setting

The sensors used in the system are connected to the two laptop computers with different interfaces. LADAR sensors are connected via Ethernet, odometer and GNSS via RS-232-USB and INS via UART-USB. GNSS referenced time stamps are put into all the data recorded from difference sensors for synchronization.

C. Data Acquisition and Process

The road surveying system has two software packages. One is for real-time sensors control and data acquisition (SCADA), the other one is for processing data based on LSF1 and LSF2 to get surveying results. The SCADA is developed with JAVA socket communication and integrated with C/C++ to connect the sensors. It runs on two networked laptops and performs the following tasks:

- Sensors control and configuration;
- System and sensors calibration;
- Monitoring sensors function and performance;
- Sensors data collection and synchronization;
- Data management and quality evaluation.

There are two important issues in sensor fusion that need to be handled carefully. One is synchronization of the sensors, and the other one is the calibration of the lever arms between different sensors. Most sensors' data have timestamps of hardware clock at the sending time. When data packets arrive at a host computer, they are also designated with computer timestamps. Stochastic estimation of the hardware clock bias and data transmission delay was conducted to achieve precise synchronization results. The time of different host computers is synchronized by using Network Time Protocol (NTP) [14], and GNSS time is used as the reference. The update rate of data from different sensors may different, which are synced by linear interpolation between the nearest measurements.

The second software package is the core of the developed system, for accomplishing sensor fusion algorithms and road surveying functions. It can be run on one of the two laptops after the on-road survey, or on a third laptop for online data processing. The detail of it is introduced in the next section.

III. Sensor Fusion Algorithms

The sensor fusion of the mobile road surveying system is structured with two local sensor fusion clusters LSF1 and LSF2, as indicated in Figure 1. The output of LSF1 is the PVA of the sensor base, which is used as one of the inputs in the LSF2 for georeferencing LADAR measurements.

A. *Local Sensor Fusion One*

In order to provide robust and reliable PVA navigation information for the mobile surveying system, data from four sensors (INS, GNSS, camera and odometer) are processed in the LSF1 after synchronization and preprocessing. A federate architecture is developed for LSF1 [15], as shown in Figure 3. It consists of three local data fusion units and one master data fusion unit. INS is selected as the reference sensor as it can provide complete and continuous navigation solutions. Its nonlinear and time-varying errors are corrected by other three sensors with separate extended Kalman filters [16], [17].

GNSS provides position solutions with assured accuracy in open area, but has sharp performance degradation in signal deficient areas. GNSS/INS integration with EKF1 is the mainstream for navigation when GNSS signals are reliable. The INS errors are corrected with EKF1 and accurate PVA solutions can be provided. At the same time, the vehicle odometer bias, camera parameters, and sensors lever arms are estimated. All of them are used for odometry aided inertial navigation (OAI) and visual-inertial odometry (VIO) with EKF2 and EKF3, and the master fusion algorithm (MFA).

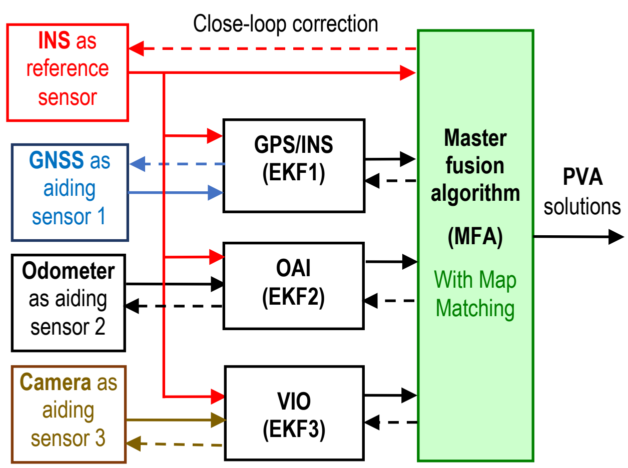

Figure 3. Federate architecture of LSF1

The complete terrestrial INS psi-angle error model in (1) and an EKF based GNSS/INS integration scheme in Figure 4 is adopted in the system [18]:

$$\begin{aligned} \delta\dot{\mathbf{v}} &= -(\omega_{ie} + \omega_{in}) \times \delta\mathbf{v} - \delta\psi \times \mathbf{f} + \delta\mathbf{g} + \nabla \\ \delta\dot{r} &= -\omega_{en} \times \delta\mathbf{r} + \delta\mathbf{v} \\ \delta\dot{\psi} &= -\omega_{in} \times \delta\psi + \varepsilon \end{aligned} \tag{1}$$

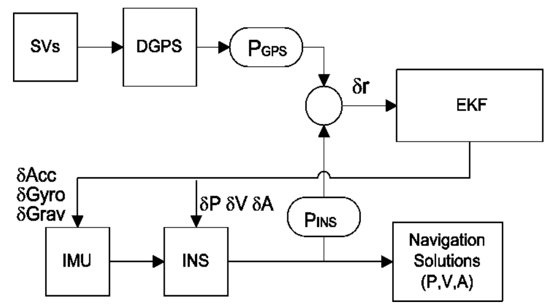

Figure 4. EKF based GNSS/INS integration

The MFA mainly consists of error modeling strategies using fuzzy logic. It can assess the quality of PVA solutions from the three EKFs in Figure 3, identify the best one and provide reliable PVA information, which can then be used in the LSF2 for processing LADAR data for road surveying functions. When the system is in areas with weak or without GNSS signal, such as in tunnels, PVA solutions from EKF1 degrade gradually. The MFA is used to evaluate the quality of measurements from GNSS, camera and vehicle odometer under different situation, and select the best one for INS error correction as the final PVA output.

As a camera can detect surrounding scenes and provide relative PVA with a scale uncertainty by mono-vision visual odometry, it is integrated with INS by EKF3 for VIO [19], [20]. Visual odometry from the camera can be used as the measurements in EKF3 to correct INS errors. As INS can continuously provide instantaneous position and orientation estimation of the camera, it can also be used to reduce image processing load. Measurements from vehicle odometer can provide information for INS error correction in OAI via EKF2, after proper correction to the odometer bias. The PVA solutions from EKF2 can be an option when neither GNSS nor camera can provide qualified measurement. In principle, GNSS, odometer and camera are employed in LSF1 to correct INS errors and to provide accurate navigation solutions.

B. *Local Sensor Fusion Two*

The LSF2 in Figure 1 is designed for geo-referencing the major surveying sensor LADARs, and generating the results for different surveying functions. Within the road services domain, road profiling is understood as detection of the road surface features, including roughness, markings as well as structure of road boundaries and geometric/spatial description of roads. The surveying functions in Figure 1 target for the automation of road maintenance, but most of them also for the generation of annotate maps to be used for the guidance of autonomous vehicles.

The PVA provided by LSF1 is used to transform LADAR 2D range data into 3D spatial coordinates for modeling. As the scanning plan of the two LADAR sensors is perpendicular to the vehicle's moving direction, there is no overlap of the scan area and therefor general SLAM algorithm cannot be applied to process the LADAR data. Accurate and reliable PVA data is important for road surveying 3D modeling.

Two types of SICK Laser Measurement System (LMS) sensors have been used by the system in general configuration. LMS-111 scans at 50 Hz over 270º with angular resolution 0.5º and ranging accuracy 12mm [21]. LMS-400 scans at 370 Hz over 70º with angular resolution 0.2º and ranging accuracy 3mm [22]. As LMS-400 has higher scan frequency and better measurement accuracy but smaller scan angle, it can be arranged to scan upward for measuring road clearness and modeling overhead structure, or downward for measuring road surface shape and roughness.

LADAR sensors can provide two types of measurements, range and intensity. Range data are the most useful and important one from LADAR. Many surveying results, such as road clearances and road surface profile can be extracted from them. Intensity from LADAR record the capability of a material reflecting the laser back. Different with cameras that depends on lighting condition to take images, intensity data from LADAR are not sensitive to the lighting condition.

Intensity data from the LMS-111 are acquired together with range data. Traffic lane marks (white lines) and other markers on road surface have significant higher intensity value than plain road surface. The surveying system can monitor the road markers' condition using intensity data. LADAR intensity data are used for extracting traffic-lanes so as to determine the clearance for each traffic lane. Concrete structure with different humidity also has unique intensity value, which may tell if the structure is leaking water.

In addition to providing information for VIO in LSF1, image data are also processed for road surveying. Many road assets characteristics, such as traffic sings, road structure and the surrounding sight are captured in image data, which are merged in the LSF2 to provide visual reference for other road surveying results.

IV. Road Surveying Results

A. LADAR Sensors Parameter Evaluation

As the scan plan of two LADAR sensors' is perpendicular to the vehicle moving direction, the gap between each scan is a linear function to the vehicle speed. Table I lists the special feature of LADAR measurements with aforementioned sensor setting at a speed of 60km/h and 2m above the road, which is the typical road surveying situation of the system.

TABLE I. LADAR Measurement Density and Accuracy

LADAR sensor	*density (m^{-1}) parallel to driving direction*	*density (m^{-1}) perpendicular*	*ranging accuracy*
LMS-111 (50Hz)	3.0	57.3	12mm
LMS-400 (370Hz)	22.2	143.5	3mm

From the data in Table I we can see the two LADAR sensors can provide high density range measurements even at 60km/h driving speed. The LMS-111 has 172 measures in one square meter road face while LMS-400 even as high as 3185. With accurate PVA information provided by LSF1 from other sensors in the system, measurements from the two LADAR sensor can be processed to provide adequate information for required road surveying functions.

It is noticed that although the LADAR sensors' scan plan is perpendicular to the vehicle moving direction, due to the speed of the vehicle, their scan lines are not with right angle to the moving direction. Instead, the angle $\boldsymbol{\varphi}$ is calculated with the equation (2).

$$\varphi = arc\cos({}^{v}/_{2\pi rf}) \tag{2}$$

The $\boldsymbol{v}$ in (2) is the speed of moving vehicle, $\boldsymbol{r}$ is the range from the LADAR sensor to road surface, and the $\boldsymbol{f}$ is the scan frequency in Table I. Under default system settings, with $\boldsymbol{f}$ = 50Hz and $\boldsymbol{r}$ =2m, $\boldsymbol{\varphi}$ is up to couple of degrees.

B. Road Clearance Surveying

Road clearance surveying is one of the important items in road maintenance for road safety. It is necessary to correctly survey and indicate road clearance for avoiding accidents of over height vehicles clash with structures overhead. With PVA information, the LADAR range measurements in polar coordinates in body frame can be transformed to Cartesian coordinate system in globe frame. Pitch-roll-yaw extracted from attitude data is used to form transfer matrixes. Individual transfer matrix is associated with each range measurement based on their timestamps. Cross-section plots are built perpendicular to the ground. Both LMS-111 and LMS-400 data are plotted in the same coordinate system. Position data are used to determinate the exact location of lowest clearance.

Figure 5 shows the surveying result of a steel structure bridge on A3 Sydney. Three lanes of the bridge are marked with 4.6m, 5.2m and 4.6m clearance respectively. Test has been conducted to check how good the clearance signs match actual road clearance. Three cross-sections in the figure are the place of the lowest clearance on each line. Our surveying results show that the clearance of left lane is 4.66m, middle lane 5.31m and right lane 4.76m. All agree with the signs for each line.

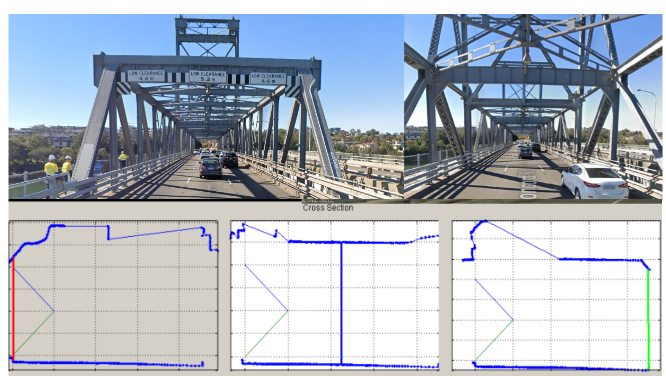

Figure 5. Clearance surveying of a steel bridge in Sydney.

The cross sections of the lowest clearance location are plotted on the bottom half of Figure 5. The lowest clearance of left and right lanes is due to the supporting structure on the side of the bridge. The red and green markers point out the location of them. The clearance surveying result can be saved as a video file and used for road maintenance reference.

C. Road Surface Profiling

Road profile is essential for road safety, as many traffic accidents were due to poor road surface conditions [23]. Faded surface markers cause drivers' confusion, and inhomogeneous road shape could make a vehicle lose control. Proper road boundary is another crucial issue for road safety. Experiments prove the proposed mobile system can measure road surface shape, boundary and markers at one run.

Road shape inhomogeneous is road deformation mainly due to heavy vehicles compressing. Surface inhomogeneous causes uncomfortable ride or lose control. Monitoring road surface condition is critical for road maintenance. Both LADAR range and INS vertical acceleration data are used to survey road surface condition. The road surface deformation can be quantified by the proposed system and represented in the road 3D model.

Road surface markers deliver important messages to road users, and their deterioration should be monitored. The road surface markers surveying algorithm utilizes both LADAR intensity and position data to quantify the condition of road surface markers. Light colored road surface markers have higher remission values in LADAR intensity than normal road surface. It is not difficult to develop an algorithm with a threshold for road surface markers extraction.

Figure 6 shows image and LADAR intensity extractions of road surface markers. Note in the image on top the mark "8" in the shadow is hardly visible, but shadow has no any effect to the LADAR data. LADAR can detect markers fading at any time of the day, independent to ambient light sources.

Road boundary detection algorithm combines both the methodologies for road surface markers detection and road shape modeling with a filter applied to remove measurements noise. Figure 7 shows the results with two sections of 3D road model on the top, and the photo of corresponding road on the bottom. White markers are clearly presented on the road surface and boundary. The light colors in the 3D model indicate the high difference on the side of the road.

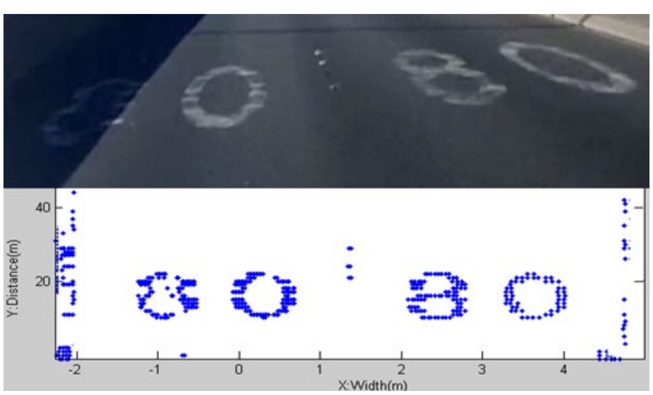

Figure 6. Road markers extraction results

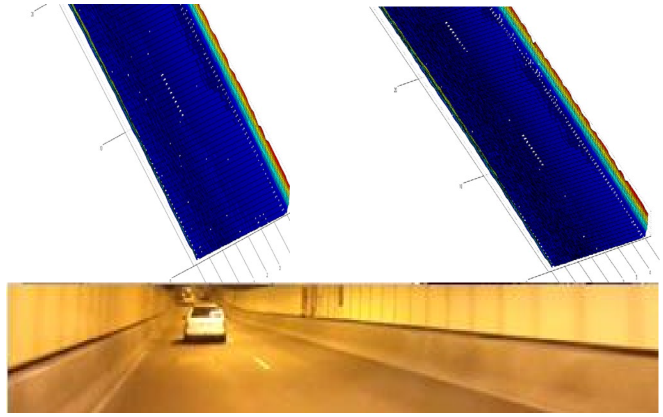

Figure 7. Road boundary detection results

D. Road 3D Structure Modeling

Road 3D models include both the road profile and overhead structure. The results of aforementioned surveying functions, such as clearance of each traffic lane and road profile, can be presented in the model. Road 3D model can be managed as a database and integrated with GIS (Geographic Information System) to monitor and manage road assets.

Example of the 3D model is shown in Figure 8, the data processing GUI (Graphical User Interface). The 3D model has most intuitional profile of surveyed objects, including lines on the road surface and the location of the lowest clearance points of each lane.

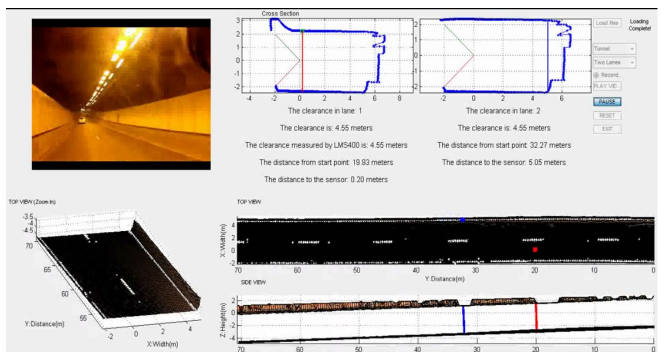

Figure 8. Road assets 3D modeling in data processing GUI

The layout of the GUI is arranged as follows: image of road assets is on the top left corner, two top windows group show the clearance occurs in each traffic lanes, bottom left window shows the section of road being processed and the bottom left window is the top and side view of 3D model. There are control buttons on the top right corner, to load data and operate the modeling. The 3D model can also be recorded as a video stream for convenient data management.

E. Road Roughness Measurements

Road roughness is presented by International Roughness Index (IRI) which quantify the tolerability of road roughness at different speeds [24]. By following the criteria of the IRI scale table, road roughness can be quantitively indicated. Different types of road (asphalt, concrete and gravel) have been tested at various speed. Table II is the test results of road roughness measurement at left and right tyres' position.

TABLE II. TEST RESULTS OF IRI FOR DIFFERENT TYPES OF ROAD

Road surface Type & Section	Avg Sampling Interval (m)	Average Test Speed (km/h)	IRI Left (m/km)	IRI Right (m/km)	IRI Average (m/km)
Asphalt 1	0.216	51.7	2.36	2.01	2.19
Asphalt 2	0.157	37.6	4.04	4.52	4.28
Concrete 1	0.160	38.3	8.31	8.70	8.51
Concrete 2	0.174	41.6	7.31	7.46	7.39
Gravel 1	0.084	20.1	20.22	22.66	21.44
Gravel 2	0.143	34.2	14.05	14.41	14.23

Two sections are selected for each type of road, as shown in the Table II. Road roughness measurement indicated by IRI for asphalt, concrete and gravel roads are around 4, 8 and 20 m/km respectively, corresponding to comfortable maximum speed at 100km/h, 70km/h and 30km/h.

V. CONCLUSION

This paper introduces a mobile surveying system for road condition surveying and monitoring, based on a sophisticated sensor fusion scheme to process data from LADAR, GNSS, INS, cameras and vehicle odometer. Two local sensor fusions are designed for specific tasks. LSF1 is for providing accurate and reliable PVA measurement of the mobile platform. LSF2 is for achieving multiple surveying functions, with range and intensity measurement from LADAR sensors. The LSF1 has a federate architecture for adaptive sensor fusion based on fuzzy logic and EKF. It consists of three local data fusion units with EKF and one master data fusion unit with fuzzy logic. INS is selected as the reference sensor, its errors are corrected continuously by other sensors with three separate fusion units using EKF.

A prototype system has been developed, which can survey multiple lanes at one run at normal driving speed under general weather and road condition. Many surveying functions have been tested, including road clearance, road surfaces profile and roughness etc. 3D model of road assets can be generated in the data processing GUI for visualization the surveying results and database management. Experiment results on different sections of road have demonstrated the effectiveness of proposed system.

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