Applied Geomatics (2019) 11:1–13
https://doi.org/10.1007/s12518-018-0222-6

ORIGINAL PAPER

Mobile mapping systems in civil engineering projects (case studies)

Omar Al-Bayari[1]

Received: 25 January 2018 / Accepted: 7 May 2018 / Published online: 17 May 2018

Abstract
There has been increased interest in mobile mapping system (MMS) usage, especially in the surveying and implementation of projects, for engineering and planning applications. Moreover, it is needed to enable state-of-the-art technologies implementation and usage in both modern and old (i.e., already existing) projects, especially when they are executed at sites with difficult nature and those located in crowded cities. The design of engineering projects consists of three phases: conceptual, preliminary, and detailed design phases. Surveying and site design is one of the most important parts in all these phases, in both the planning and implementation of infrastructure engineering and its layout. Examples are numerous and sometimes they are the fine line in the design and decision of the implementation of some projects, such as in roads rehabilitation, drainage networks, and railway and metro installation. The critical issue in such projects is the required accuracy, which should be achieved and guaranteed. Then, more applications and new practical and easily applied methodologies are needed. To achieve the accuracy required, we propose an effective methodology using an MMS and some software to check and guarantee that the target is met. We present an application of the methodology and a discussion of the problems faced while employing the MMS methodology. Two important projects are highlighted as case studies of our methodology application in employing an MMS in the surveying design phase of important scale infrastructures in the Kingdom of Saudi Arabia (KSA). The first is the surveying for the design of 180 km of drainage system in Jeddah and the second is the surveying of 1500 km of an existing railway network. The two surveying projects are the first applications using an MMS in the KSA where the accuracy was a necessity for the purpose of state-of-the-art management and monitoring of new and old installed systems. In this work, we discuss the new technology application and the problems faced. In addition, we address the different applications covered by an MMS.

Keywords Global Navigation Satellite System (GNSS) · Mobile mapping system (MMS) · Laser rangefinder (LRF) · Inertial measurement unit (IMU) · Inertial navigation system (INS) · Distance measurement indicator (DMI)

Introduction

The mobile mapping system (MMS) is an integrated system of surveying sensors mounted on a vehicle. It is considered as the most advanced technology for land surveying. An MMS consists of many surveying sensors, such as photogrammetric high-resolution cameras, laser scanners, Global Positioning System (GPS), inertial navigation system (INS), odometers, and distance measurement indicator (DMI), that allow the recording of georeferenced laser points and photos of all visible objects along the trajectory of the movement of a vehicle (El-Sheimy 2005; Tao and Li 2007). There are many MMSs on the market (Puente et al. 2013) and the most recently developed MMS has the possibility to be transferred and easily deployed due to its small size.

✉ Omar Al-Bayari
bayariomar@yahoo.it

1 Department of Surveying and Geomatics Engineering, Al-Balqa' Applied University, Al-Salt, Jordan

Components of an MMS

An MMS consists of a robust platform mounted on a vehicle carrying several types of equipment (Kremer and Hunter 2007; Schwarz and El-Sheimy 2007). Some MMSs have many integrated sensors (Fig. 1), while others have a limited number of sensors. The main functionality of the equipment in an MMS could be summarized as follows:

- One or more high-frequency scanning laser sensors (Lidar). The sensors are mounted on the platform in a way such that the coverage of the scanned surroundings

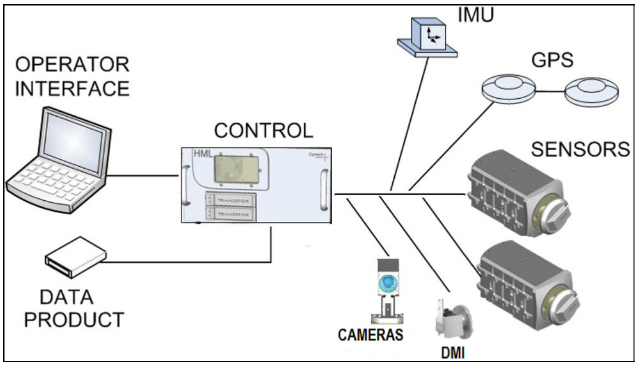

Fig. 1 Components of a mobile mapping system (MMS)

is maximized. The Lidar sensor records 3D point data of the vicinity in the surveying area, which helps create a 3D model of the surveyed area and extract features.

- Inertial measurement unit (IMU) and Global Navigation Satellite System (GNSS)/GPS computing all aspects of vehicle motion (including position, speed, acceleration, orientation, and rotations). The GPS/IMU integrated solution improves the frequency of recording positions from 1 Hz (GPS) up to 200 Hz. The computed integrated solution includes the position (X, Y, and Z) and the orientation of the vehicle (roll, pitch, and heading).
- Distance measurement indicator (DMI), a wheel-mounted encoder that measures the precise linear distance traveled.
- Digital camera system to capture georeferenced imagery while scanning.
- An operator interface device (on-board laptop computer with controller software).
- A central control unit with all the necessary electronic devices for the control and communication of all systems, as well as for the safe storage of recorded point cloud and imagery data.

Methodology for an MMS and programs used

An MMS uses many programs and softwares to facilitate the automation of field operation, data processing, and 3D feature extraction. The functionality of these softwares could be summarized as follows:

- Software for mission planning and monitoring during the execution of the field works, showing the GPS quality data and images (Fig. 2). The software is combined with Google Earth-like services and portable GPS devices on a laptop, so following the vehicle's movement on a comprehensive background is facilitated in real time.
- GPS/INS post-processing software to calculate trajectory and orientation–attitude data, in combination with differential corrections from base GPS stations. Some systems include DMI data in the processing to give a best estimate of trajectory (Fig. 2).
- Proprietary software to combine point cloud raw data and trajectory to produce a georeferenced point cloud.
- Post-processing adjustment software to make point cloud georeferencing adjustments using ground control points (GCPs) and other techniques (e.g., combine data from multiple sensors or multiple passes; Zhang and Xiao 2003).
- Post-processing software for semi-automated feature and cross-section extraction, digital terrain model (DTM) creation and general aspects required for delivery preparation.

MMSs used in the KSA

Two different types of MMS were used in the Kingdom of Saudi Arabia (KSA; Fig. 3), depending on the type of desired results.

The first type is for buildings and for updating a geographic information system (GIS) database, which depends on the collection of georeferenced image sequences of the roads and their surroundings, such as the VISAT and IWANE systems (El-Sheimy and Schwarz 1999; Shiu and Tam 2012). The accuracy of such systems is better than 30 cm for objects within the field of view of the cameras which are mounted on a moving vehicle. The cameras could capture images every 1–10 m and operate at a speed of up to 100 km/h or at the specified traffic speed. The user can then interface with the georeferenced images through photogrammetric software which is designed for feature extraction, and this software is generally fully integrated with a GIS or CAD software. We used the VISAT and IWANE systems in some GIS data collections in the KSA.

The second type of MMS is laser-based mobile mapping, which is designed for surveying projects that require centimetric accuracy (around 5 cm). This type of MMS is generally integrated with a laser rangefinder (LRF), Cameras, DMI, high precision INS, and GPS. This system collects a huge amount of spatial information using a rotating laser scanner that can collect one million points per second, such as the LYNX system (Petrie 2010; Schwarz and El-Sheimy 2012). The amount of data produced by such systems are huge, and manual processing of the data is very time-consuming, which creates a need for automatic and semi-automatic methods that can reduce the amount of manual work required to extract the 3D features and produce accurate 3D models. Many algorithms are used to extract the features from a laser point cloud based on the intensity value, image processing, and point cloud processing (Cheng et al. 2008).

Fig. 2 Components of the LYNX MMS, including a distance measurement indicator (DMI) and real-time quality control software

Case studies

The main interest of this work is to present how we achieved the accuracy needed and to clarify the potential of the laser-based MMSs that we used in important engineering projects in the KSA, in which high accuracy and short timescales were required. Also, we will discuss some problems that could degrade the accuracy and delay the field operations.

Jeddah Stormwater Drainage Program (JSDP) project

The Jeddah Stormwater Drainage Program (JSDP) consists of dams and channels, to provide stormwater flood relief for the city of Jeddah in the KSA. The main objective of the JSDP project is to mitigate the catastrophic effects of flooding due to stormwater that the city of Jeddah has experienced in the past several years, and to use the lost sweet water for the benefit of the city. The construction of channels should be done along side the already existing roads in Jeddah.

An MMS is required to provide 3D mobile laser scanning for 12 major storm drainage conveyance systems that will serve as the primary storm drainage conduits for the city of Jeddah. The initial conceptual alignments and lengths for these systems are along various roadway corridors within the city (Fig. 4). The 3D mobile laser scanning scope of services for each of these corridors shall include full scanning of the proposed corridor section starting from 10 m outside of the outermost edge of existing pavement to 10 m beyond the outermost edge of the existing pavement (Fig. 5).

The MMS is required to survey and extract the following features within a short time schedule that did not exceed 3 weeks:

- Existing pavement edge features (centerline of road, edge of road, gutter line, top of curb, back of curb, and roadway median).
- Existing sidewalks (edge of all pedestrian features within the corridor).
- Existing parking lots (pavement edge of all existing parking lots).
- Existing pavement markers (existing pavement delineators).
- Existing structural vertical features (the edge of all existing walls, buildings, columns, embankments, bridges).

Railway project

The second case study is the use of MMS in open areas, where the LYNX system has been used to survey

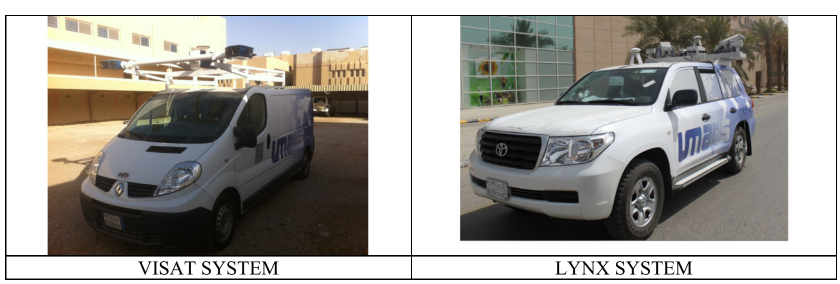

Fig. 3 MMSs used in Saudi Arabia

Fig. 4 Jeddah Stormwater Drainage Program (JSDP) preliminary design

1500 km of existing railway in the KSA (Fig. 6), to generate the as-built drawing of the railway, extract the features, and create cross-sections for cut-fill computation of the railway. Figure 7 shows the method used to execute the field operation using a locomotive. We used 3 ir 4 GPS reference stations and measured GPS/real-time kinematic (RTK) as cross-section points every 5 km. We also marked the points on the steel bars of the railway line. The daily scanning distance of this project was 90 km, which means that the field work was done efficiently in a short time. Moreover, the feature extraction was done without any problems due to the efficiency of the semi-automatic programs (PolyWorks or TerraScan software) we used in the extraction of the line features from the point cloud. The DTM and cross-sections have been created using TerraScan and Civil 3D software.

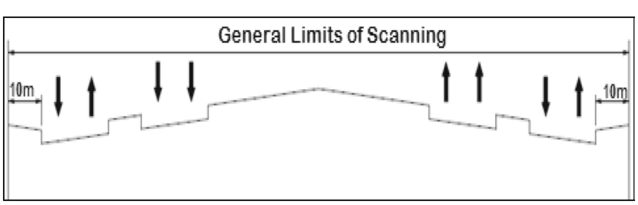

Fig. 5 General limits of scanning roads

Operation and processing methodology

The core technology of the proposed methodology for the corridor mapping survey according to the projects' requirements is the use of a Lidar-based MMS. For the implementation of these two projects, the industry-leading solution of Optech's LYNX Mobile Mapper was used. Apart from the MMS, and in order to establish the necessary geodetic networks, as well as to perform any additional or supporting survey work, dual-frequency GPS/GNSS receivers were used either in static or RTK modes of measurement, depending on the nature and the required accuracy of the points to be surveyed (Wygant 2009). The method of operation of the mobile Lidar system includes:

- Point cloud data capture at a very fast rate by laser sensors (1 M points per second).
- Imagery data captured by the camera or the video system.
- Calculation by the GNSS/GPS and INS of the system's trajectory (position through time) and orientation/attitude.
- To perform this calculation with sufficient accuracy, support from base GPS stations is required to achieve differential corrections data. The calculation can be performed in real time or in post-processing.
- Post-processing provides more accurate trajectory results by performing back and forth adjustments where the GPS signal is poor or lost. We had previously used post-processing workflows for the mentioned projects and the POSPac MMS software by Applanix.
- The IMU data we recorded at a 100 Hz or higher data rate tagged with GPS time. The raw IMU data, after correction for all systematic errors using calibration parameters, were integrated with the GPS data through a tightly coupled Kalman filter (for forward and backward processing) to derive the observed camera positional values at the instant of each image exposure.
- The captured data from all sensors, cameras, GNSS/INS, georeferenced point cloud, and imagery were produced by the MMS software.
- The typical accuracy for the georeferenced point cloud points for areas with good GPS signal is approximately ± 5 cm.
- For the purpose of enhancing the accuracy of the point cloud data in case of poor GPS signal, we measured some GCPs in the field (e.g., by GNSS/RTK), which can be identified on the point cloud (Fig. 8). Then, in the post-processing phase, using specialized software, we made additional adjustments to the georeferencing of the point cloud. For this purpose, PolyWorks software by InnovMetric and TerraMatch from Terrasolid were used.

Post-processing of the point cloud data for the production of deliverables includes vector feature extraction and DTM

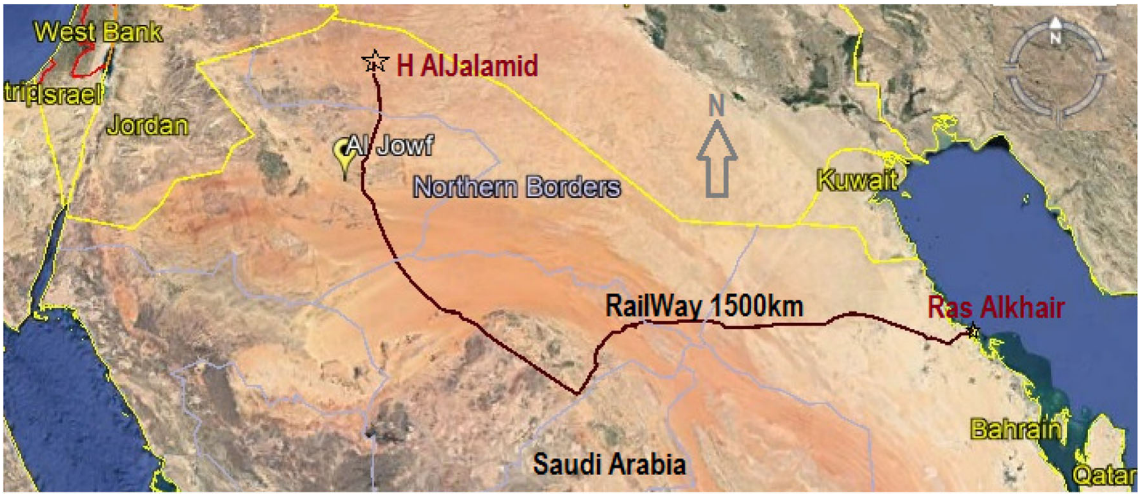

Fig. 6 Railway in Saudi Arabia from Ras Alkhair to Aljof

creation, aiming at the production of the base map, in accordance with the project requirements. Again, PolyWorks software by InnovMetric was used, with its semi-automated feature extraction techniques directly from the point cloud to enhance the productivity and reliability of the extracted feature data (Fig. 9).

Operational MMS problems

There are many advantages of using an MMS in corridor surveying, as mentioned by many authors (Tao 2000; Toschi et al. 2015), but working in crowded cities in the KSA, we faced some operational problems that should be highlighted.

MMS traffic management plan in a crowded city

Traffic jams in crowded cities prevent working on some days and at several times during the day. Consequently, a traffic management plan should be considered. Based on our experience on the LYNX MMS corridor survey projects in Riyadh and Jeddah, we proposed the following procedure for traffic management when performing the mobile mapping surveys in cities with traffic problems:

1. Perform all calibration procedures one day before the actual surveys.
2. Perform the main survey tasks on Fridays and Saturdays (at the weekend, from 5:30 AM to 10:30 AM, when traffic is considered to be minimal and lighting situations are adequate to obtain good imagery results. Other low traffic margins during weekdays may be considered if required.
3. A second car should always follow the MMS vehicle to "protect" it, to ensure a free space behind the sensors platform, to improve the Lidar sensors and camera system visibility.
4. In a 5-h survey time, with average car velocity in residential areas, 30 km of corridor length, with secondary roads and multiple passes (2–4 passes are required in many cases), can be covered. Thus, in this scenario, for the whole Jeddah project, it is estimated that 4–6 days in the field was enough.
5. A traffic management plan will minimize traffic problems, improve data quality, and ensure completeness. It

Fig. 7 Railway survey using the LYNX MMS

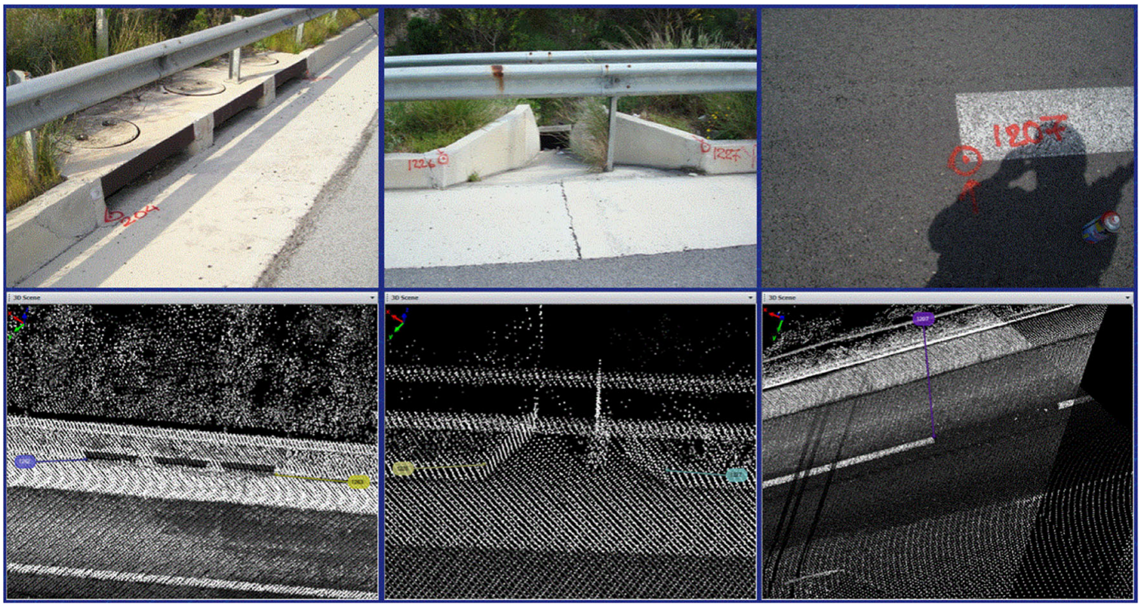

Fig. 8 Point cloud accuracy enhancement using ground control points (GCPs)

also allows intermediate production and evaluation of the point cloud and to make additional surveys in some parts if necessary.

Calibration process

A calibration drive and data collection was performed before each survey, to ensure that the boresighting parameters are correct. The general field procedure was used to collect boresighting data for a building with walls before each survey and to update the boresighting (pitch, roll, and heading) calculations and to reflect any changes in the parameters for the sensors and cameras. It is noted that, prior to any LYNX survey, either for the collection of calibration data or the collection of survey data, 1–2 short drives on a flat surface, such as a flat road, had to be conducted to prepare the POS/INS system.

Long and flat walls of a building make it easier to detect indications of boresighting misalignment, and tall walls allow calculating the pitch of the sensors and cameras more precisely (Fig. 10).

High temperature

High temperatures (exceeding 40 °C mostly) prevent the laser sensor from working properly and limits the daily working hours, from 5:30 AM to 10:30 AM.

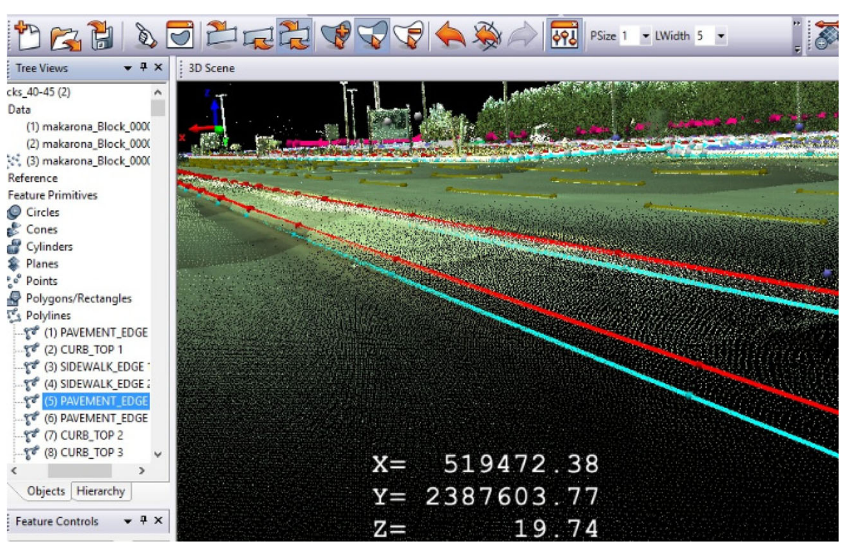

Fig. 9 Lidar MMS point clouds of a highway corridor with vector features extracted

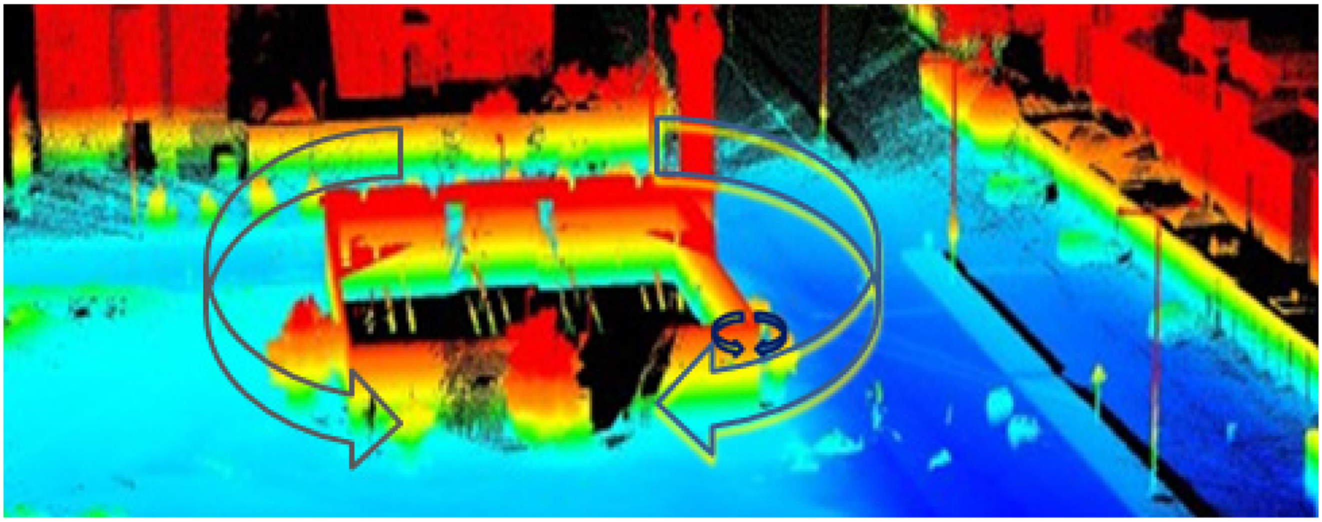

Fig. 10 Boresighting in the clockwise and counterclockwise directions around a building used for LYNX sensors calibration

MMS and tunnels survey

Tunnels are not a common case in the project's corridor. Such rare cases, in order to compensate for GNSS outage, will be dealt with by applying the following procedure/measures:

1. Stop the mobile mapping vehicle before and after the tunnel for 1–2 min to obtain additional GNSS measurements. These measurements will be used in the MMS software for post-processing, such as POSPac from Applanix or Inertial Explorer from NovAtel, in combination with INS/DMI readings, to improve the accuracy of the vehicle trajectory to be determined. The trajectory will be used to produce the initial point cloud for the tunnel area.
2. Measure GCPs at the entrance and exit of tunnel using GNSS/RTK techniques, as well as inside the tunnels using Total Station at 25-m intervals. GCPs inside the tunnel will be measured by placing the Total Station on polygonometric stations forming traverses, which will be fully dependent from both sides, using external stations established at the entrance and exit of the tunnel and measured by GNSS/RTK techniques.
3. Measured GCPs will be identified on the initial point cloud and deviations will be evaluated to check the accuracy. If required, the point cloud will be progressively processed, using the GCPs source and target coordinates, to compensate for possible trajectory inaccuracies along the tunnel. On the final point cloud, the GCPs coordinates will be compatible with their measured values and within the accuracy margins.

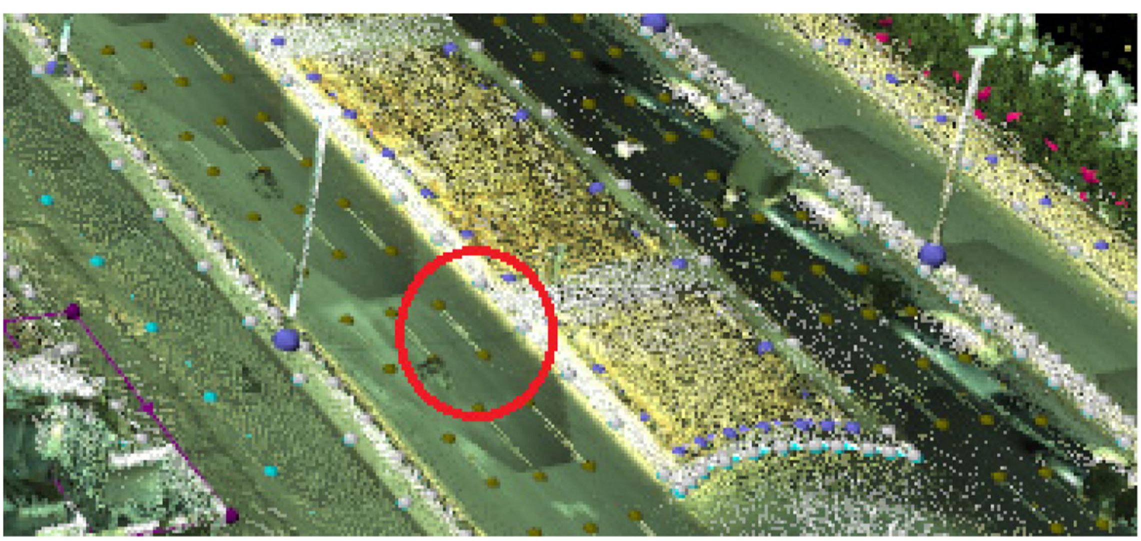

Fig. 11 Point cloud and road markings extraction

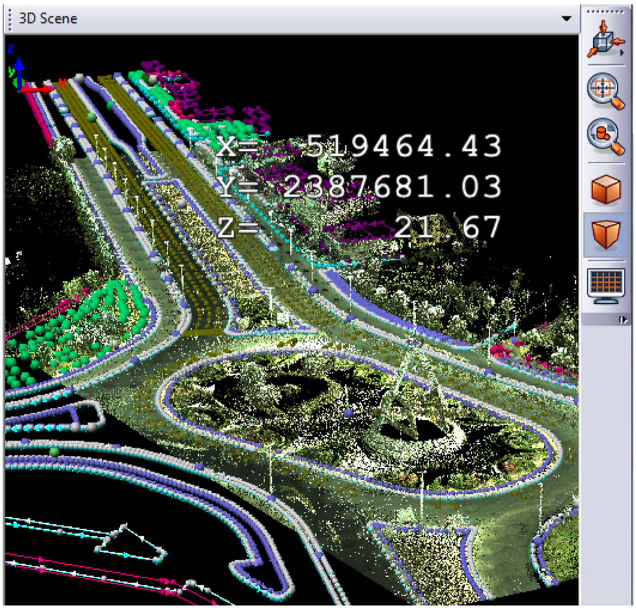

Fig. 12 Extraction of road features for the Jeddah project

Processing methodology

The most important factor in MMS data processing is the GPS observation techniques which are used for the determination of the vehicle trajectory. Using a minimum of two GPS reference stations will help the ambiguity resolution within the project area.

The MMS to be used in the survey (Optech LYNX M1) integrates all its subsystems (Lidar sensors, cameras, GNSS, INS, DMI, and also storage, power, and operator interface devices) through its central control unit. GNSS/INS/DMI systems collect position and attitude information; Lidar sensors collect point cloud information and cameras record imagery. The operator, through the control software interface connected to the central control unit, is able to monitor several items to ensure that optimal data collection practices are being followed in any given circumstance. The collected data from all sensors and systems are finally stored for post-processing. Post-processing includes calculation of trajectories and SBET files, generation of point clouds using the SBET files, colorization of point clouds using imagery, evaluation and correction of point clouds using GCPs, and other post-processing tasks in relation to the required final products.

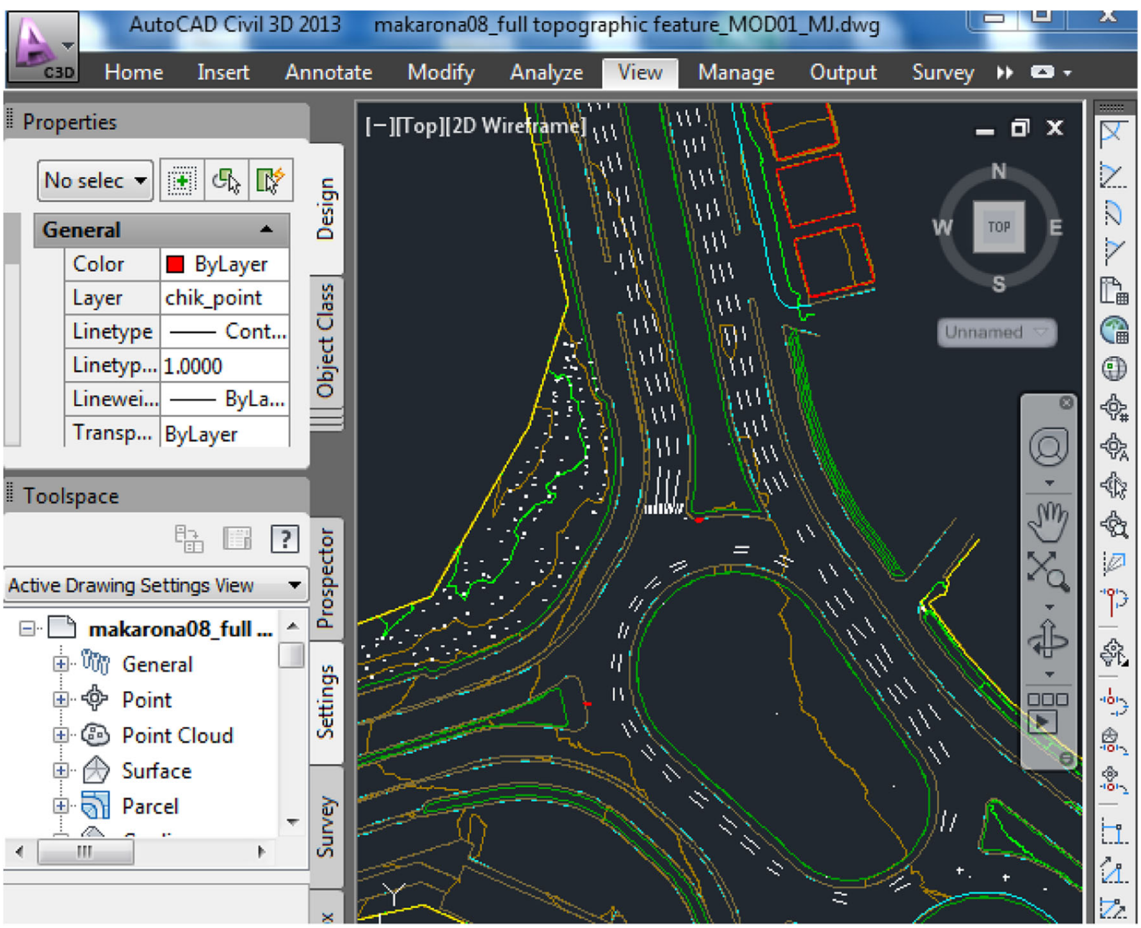

Fig. 13 Extracted features represented in a 2D AutoCAD file

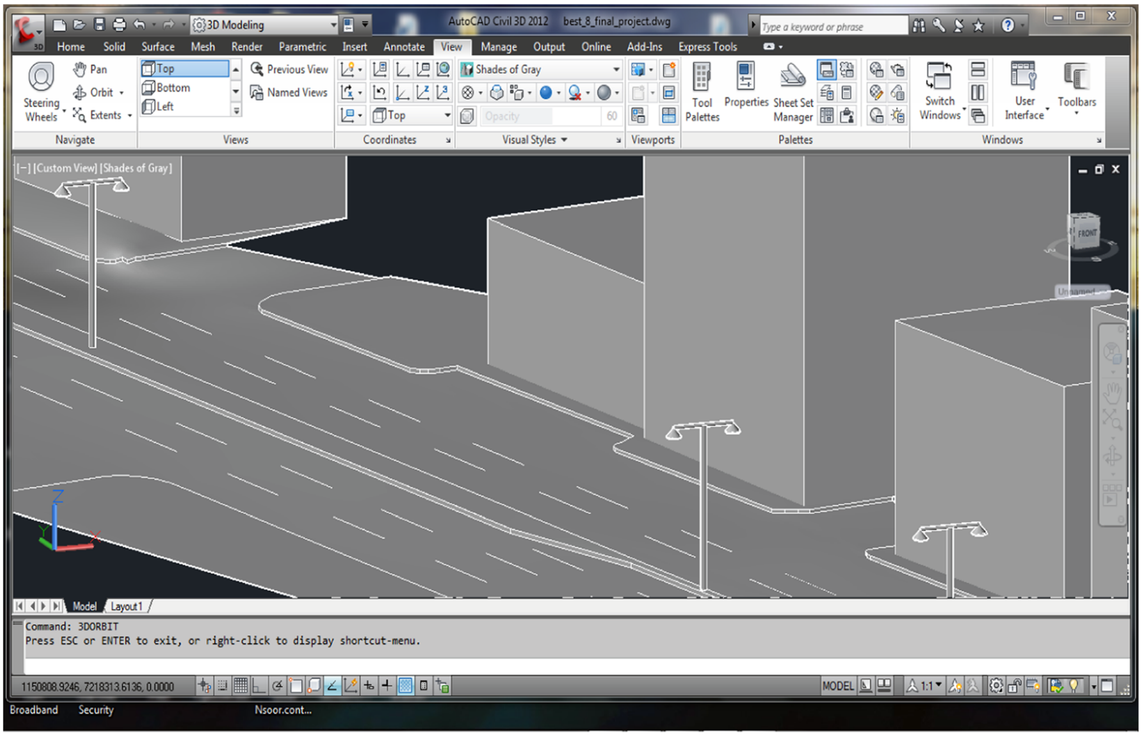

Fig. 14 Final 3D model created in AutoCAD Civil 3D for the Jeddah project

Obtaining adequate accuracy of the final point clouds is not a straightforward process, particularly when working in crowded cities, due to the fact that loss of GPS lock is very common because of high buildings and multiple paths during the field operations. Checking and adjusting the different strips of point clouds RTK/GPS measurements should be done for well-known points that already marked on the terrain and shown clearly within the point clouds. These points will improve the accuracy and rectify any errors in the georeferenced point cloud. It is important to choose control points that are clearly identifiable on the point cloud as well as images. The points ought to be well distributed in the area where data are collected. The coordinates of GCPs are recorded in the World Geodetic System (WGS) coordinate system, and should be identified on the registered point clouds. Consequently, the point clouds are corrected by applying 3D Helmert rigid body transformation using the GCPs as parameters.

Table 1 Summary of known Global Positioning System (GPS)/real-time kinematic (RTK) points compared with laser points

Length (north channel road)	9.2 km
No. of points	26
Min. points at intersection	4
Average points/km	3
STDEV horizontal	0.021
STDEV vertical	0.029

In large projects such as the Jeddah project, we mark and measure points for roads cross-sections at distances of 750 m and, at the intersections, we measured more than 300 points. These known points including the automatic tie line created by the TerraMatch software were used to adjust the final point clouds using the same program created by Terrasolid.

Feature extraction

The extraction of features from the georeferenced point clouds and images requires highly qualified CAD operators and a large amount of time. The integration of laser scanners and cameras on the vehicle will help to optimize the scope for automatic/semi-automatic feature extraction. Algorithms involving the geometry of feature points can be used in combination with image processing algorithms to obtain better results (Sairam et al. 2016). Many researchers in geomatics applications have developed numerous techniques and methods for automatic feature detection and extraction, such as road markings, sidewalks, curbstones, road signs, and linear features (Jaakkola et al. 2008; Landa and Prochazka 2014). Most of these techniques (algorithms) are implemented in MMS software, such as TerraScan, Constructor, PolyWorks, LP360, LAStools, etc. Road markings could be extracted from images or from the laser point cloud based on the intensity value of the returned pulse (Sun et al. 2011; Kumar et al. 2014). PolyWorks and TerraScan are used to extract road markings in automatic and semi-automatic techniques in an

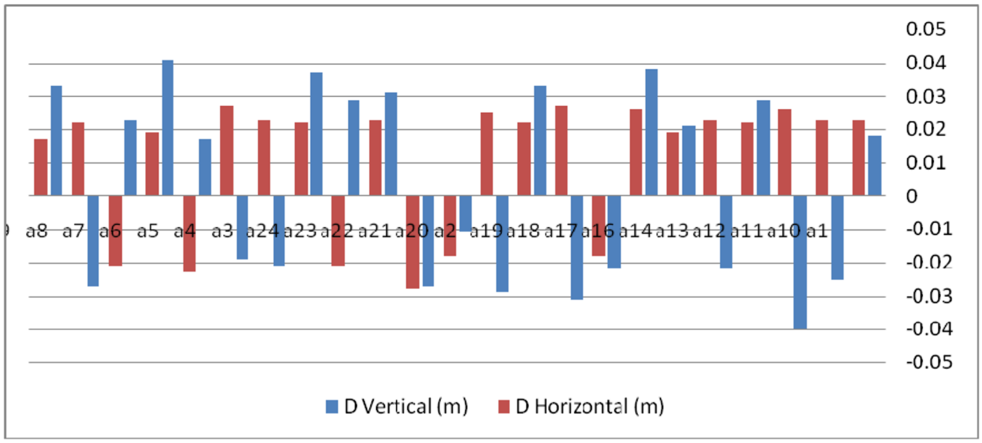

Fig. 15 Vertical and horizontal differences between GPS known points and point clouds

efficient manner, when a high density of point clouds is produced (Fig. 11).

The number of features required in an MMS project plays an important role. In the Jeddah project, the number of required features was more than 60. There is no software currently available that can automatically produce 60 feature extractions properly, but using some software such as PolyWorks and TerraScan can give a good possibility to extract the features using a semi-automatic method. Feature extraction from the point cloud is time consuming due to the huge amount of spatial information available (Figs. 12 and 13). For some projects, such as the Jeddah project, the daily feature extraction was 3 km/day when carried out by a professional CAD or GIS operator. The whole project was executed within one month with three CAD operators and the field work was done in 3 weeks.

The Jeddah project was 180 km in length and the time schedule to execute the project was fair, considering the potential of MMSs, but we have to consider the above-mentioned problems working with MMSs in crowded cities with considerable traffic jams. In the cases of high temperature and loss of lock of GPS satellites, INS installed on the LYNX system was very efficient at overcoming these problems in most cases. However, due to the traffic jams, the loss of lock of GPS signals on some roads was too long to be resolved by the integration of data between different sensors. In some cases, we resurveyed the roads during the night or in the early morning and increased the checkpoints in these areas.

An MMS captures all the visible objects in the survey area, including cars and people, which could create problems during feature extraction. The most important step in point cloud data processing is the removal of any vertical features that would distort the DTM and final 3D model (Fig. 14).

Discussion and results analysis

In order to be sure of attainment of the required accuracy (less than 5 cm) in our project, we compared the features extracted by different surveying methodologies with those extracted using an MMS:

1. Comparisons with the known RTK/GPS points: Table 1 and Fig. 15 show the comparisons between RTK/GPS points along the corridor of the surveyed area and the point clouds.

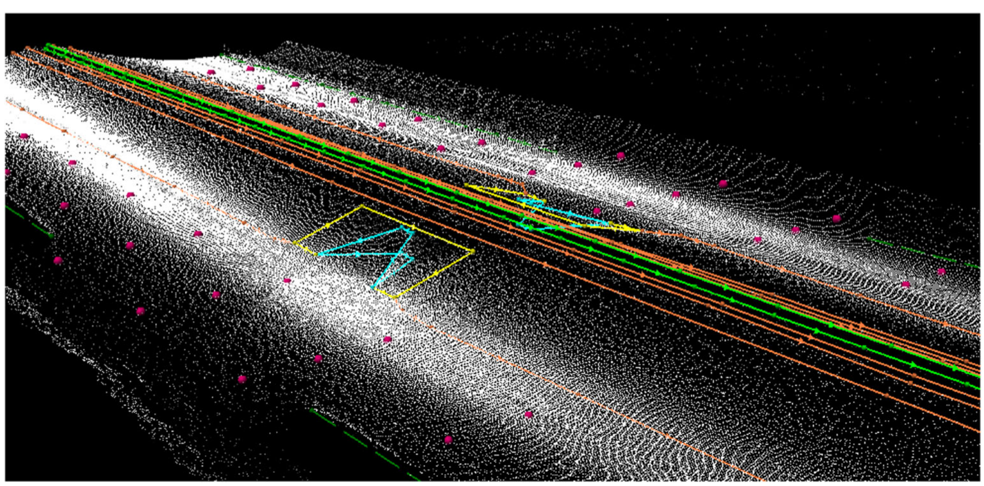

Fig. 16 Railway extracted features and digital terrain model (DTM)

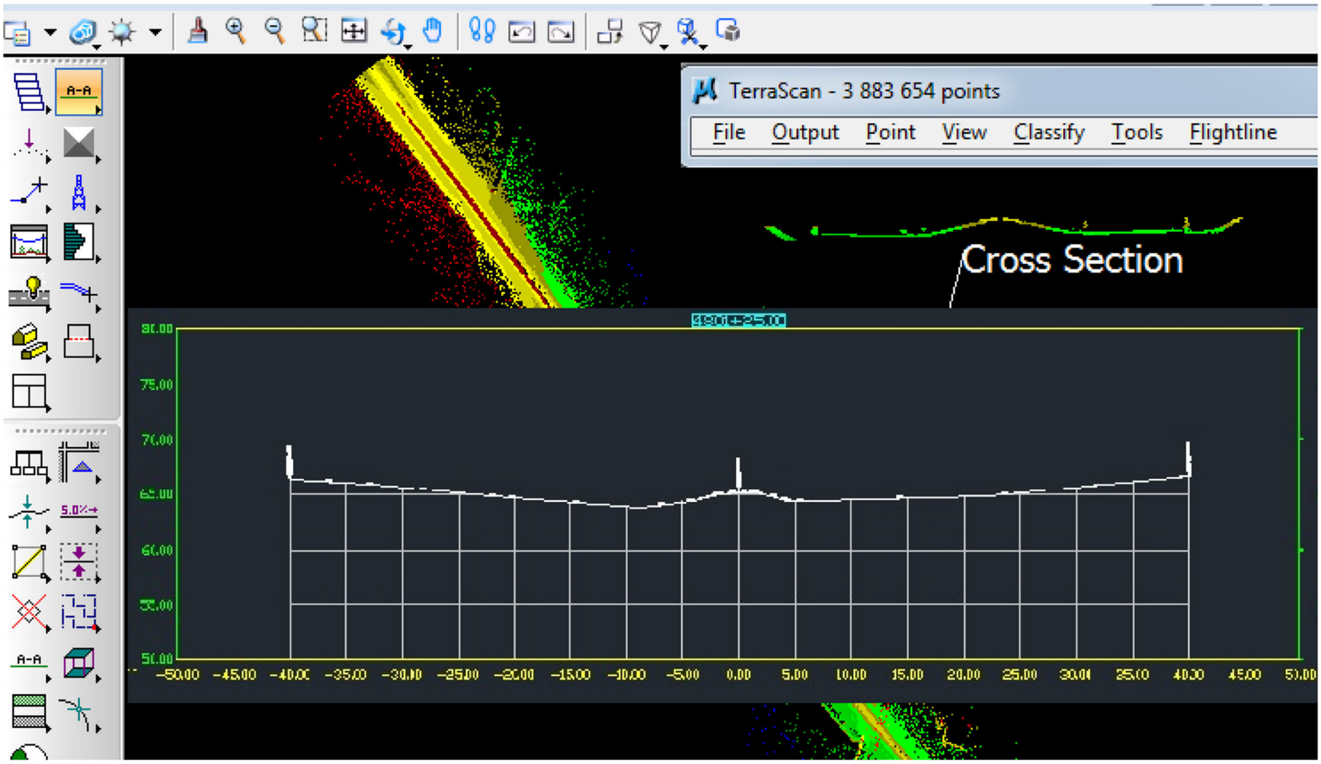

Fig. 17 Railway extracted features and DTM with comparison of existing cross-sections

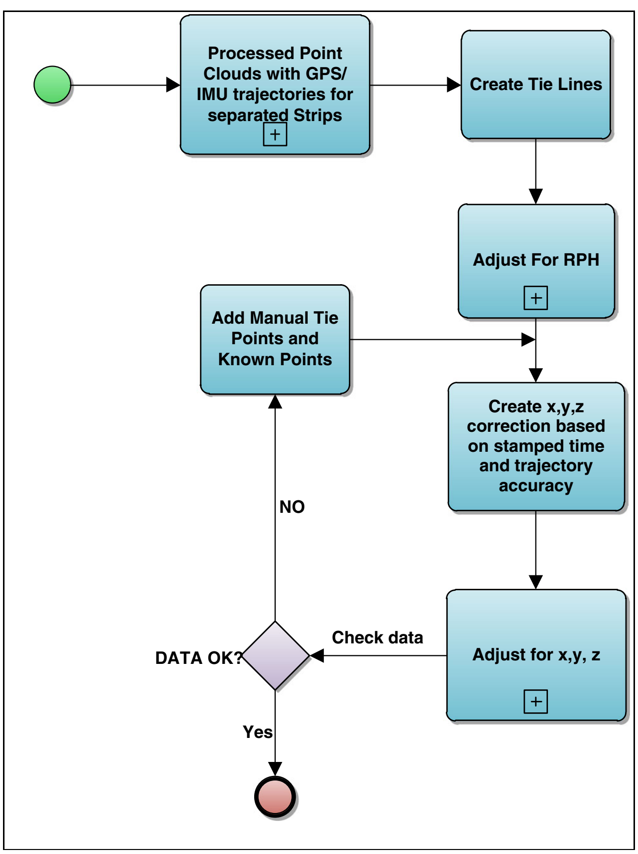

Fig. 18 Process for MMS point clouds corrections

2. Comparison in the railway project as built cross-sections and our designed sections showed good agreement and resolved the problem of differences in the quantity surveying between the contractor and the client. Checking the 1500 km of railway lines within a short time was impossible without MMS technology (Slattery et al. 2012), which offered the necessary (high) accuracy that allowed accurate quantity surveying (Figs. 16 and 17).
3. As mentioned above, the MMS is subjected to loss of lock of GPS signals due to many factors more than any other GPS observation techniques, which affects directly the quality of the vehicle trajectory and, consequently, the x, y, and z coordinates of point clouds. The best procedure is to use the trajectory corrections based on the accuracy of the trajectory position and adding tie lines and tie points to create the correction parameters for different strips. Some of these correction algorithms are included in some programs, such as TerraMatch (Soininen 2015), but they need many iterations in order to find the best solution. The flow chart in Fig. 18 summarizes the procedure and Fig. 19 shows an example of the results before and after applying the correction procedure.

The MMS Lidar-based technology has been used fairly often in the last several years, but it still has some limitations

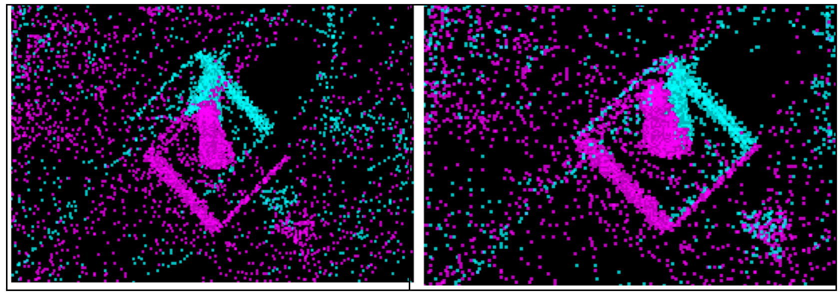

Fig. 19 Difference in x and y before and after applying the corrections (difference of about 12 cm)

and some operational problems that should be analyzed and resolved, such as: the calibration problem during surveying, the high maintenance fees compared to other systems, the high cost of the components which makes it difficult to upgrade the systems, time-consuming for feature extraction, and requirement of a large number of human laborers. Moreover, there are limitations in software capabilities for the manipulation of the huge amount of point cloud data.

Conclusions

- The usage of a mobile mapping system (MMS) for the surveying phase of engineering projects is highly accurate, very effective, and saves time.
- It needs to be assisted by real-time kinematic (RTK)/Global Positioning System (GPS) measurements in order to obtain an accuracy better than 5 cm.
- It needs to correct the differences between different strips in different missions, using tie lines and tie points.
- A laser-based MMS has some limitations in regards to high temperatures, which should be considered during the planning and execution of the field measurements.
- The usage of an MMS reduces the field work time.
- Office work time is increased due to the huge amount of captured data and the number of extracted features.
- Most processing softwares include automatic procedures for features extraction, which is not always possible, and user intervention is a must (especially in crowded cities).
- Different commercial MMSs are used in surveying, with all the advantages and without consideration of the product and results quality.
- For greater reliability and confidence in the final results, we should perform for each mission strip matching. It is performed by comparing the strips made using known GPS points and a minimum of three cross-sections surveyed by GPS observation techniques at start, middle, and end of each mission in corridor MMS surveying.

References

Cheng W, Hassan T, El-Sheimy N, Lavigne M (2008) Automatic road vector extraction for mobile mapping systems. Int Arch Photogramm Remote Sens 37(Part B3b):515–521

El-Sheimy N (2005) An overview of mobile mapping systems. In: Proceedings of the FIG Working Week 2005 and the 8th International Conference for Global Spatial Data Infrastructure (GSDI-8), Cairo, Egypt, 16–21 April 2005

El-Sheimy N, Schwarz KP (1999) Navigating urban areas by VISAT—a mobile mapping system integrating GPS/INS/digital cameras for GIS applications. NAVIGATION, Journal of the Institute of Navigation 45(4):275–286

Jaakkola A, Hyyppä J, Hyyppä H, Kukko A (2008) Retrieval algorithms for road surface modelling using laser-based mobile mapping. Sensors 8:5238–5249. https://doi.org/10.3390/s8095238

Kremer J, Hunter G (2007) Performance of the StreetMapper Mobile LiDAR Mapping System in real world projects. In: Proceedings of Photogrammetric Week 2007, Stuttgart, Germany, pp 215–225

Kumar P, McElhinney CP, Lewis P, McCarthy T (2014) Automated road markings extraction from mobile laser scanning data. Int J Appl Earth Obs Geoinf 32:125–137

Landa J, Prochazka D (2014) Automatic road inventory using LiDAR. Procedia Econ Financ 12:363–370

Petrie G (2010) An introduction to the technology: mobile mapping systems. Geoinformatics 13:32–43

Puente I, González-Jorge H, Martínez-Sánchez J, Arias P (2013) Review of mobile mapping and surveying technologies. Measurement 46(7):2127–2145

Sairam N, Nagarajan S, Ornitz S (2016) Development of mobile mapping system for 3D road asset inventory. Sensors 16:367. https://doi.org/10.3390/s16030367

Schwarz KP, El-Sheimy N (2007) Smart mobile mapping systems—state of the art and future trends. In: Tao CV, Li J (eds) Advances in mobile mapping technology. ISPRS Book Series, Vol. 4. Taylor & Francis, London. ISBN 978-0-415-42723-4

Schwarz KP, El-Sheimy N (2012) Mobile mapping systems—state of the art and future trends. Int Arch Photogramm Remote Sens Spat Inf Sci 35:759–768

Shiu W, Tam KB (2012) Evaluation of mobile mapping system (MMS) survey for public housing estates in Hong Kong. In: FIG Working Week 2012, Knowing to manage the territory, protect the environment, evaluate the cultural heritage, Rome, Italy, 6–10 May 2012. Available online at: https://www.fig.net/resources/proceedings/fig_proceedings/fig2012/papers/ts03d/TS03D_shiu_tam_6094.pdf

Slattery KT, Slattery DK, Peterson JP (2012) Road construction earthwork volume calculation using three-dimensional laser scanning. J Surv Eng 138(2):96–99

Soininen A (2015) TerraMatch user's guide. Terrasolid software. Available online at: http://www.terrasolid.com/download/tmatch.pdf. Accessed 6 Nov 2017

Sun H, Wang C, El-Sheimy N (2011) Automatic traffic lane detection for mobile mapping systems. In: Proceedings of the 2011 International Workshop on Multi-Platform/Multi-Sensor Remote Sensing and Mapping, Xiamen, China, 10–12 January 2011

Tao CV (2000) Mobile mapping technology for road network data acquisition. J Geospat Eng 2:1–14

Tao CV, Li J (eds) (2007) Advances in mobile mapping technology. ISPRS Book Series, Vol. 4. Taylor & Francis, London, 176 pp. ISBN 978-0-415-42723-4

Toschi I, Rodríguez-Gonzálvez P, Remondino F, Minto S, Orlandini S, Fuller A (2015) Accuracy evaluation of a mobile mapping system with advanced statistical methods. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-5/W4, 2015 3D Virtual Reconstruction and Visualization of Complex Architectures, 25–27 February 2015, Avila, Spain, pp 245–253. https://doi.org/10.5194/isprsarchives-XL-5-W4-245-2015. Available online at: https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-5-W4/245/2015/isprsarchives-XL-5-W4-245-2015.pdf

Wygant CA (2009) User tests of the Optech LYNX Mobile Mapping system, data QC to ground survey control. In: Proceedings of the ASPRS 2009 Annual Conference, Baltimore, Maryland, 9–13 March 2009. https://www.asprs.org/a/publications/proceedings/baltimore09/0104.pdf

Zhang K, Xiao B (2003) GPS and mobile multisensor mapping system. Wuhan Univ J Nat Sci 8(2B):557–565