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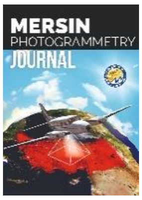

Accuracy comparison of mobile mapping system for road inventory

Hüseyin Kurşun *1

1 *Istanbul Technical University, Department of Geomatics Engineering, Türkiye*

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Abstract

Mobile Mapping Systems (MMSs) stand out as the preferred solution for achieving highly precise 3D environmental models, particularly in urban planning, highway mapping, asset inventory, corridor mapping, traffic safety evaluation, autonomous vehicle, digital twin, and emergency response mapping where traditional aerial or satellite surveys often fall short in providing precise data. Understanding the intricate factors that impact the accuracy of mobile mapping is pivotal to harnessing the full potential of this advanced measurement technique. This study analyzes the spatial accuracy of geographical data produced by the mobile mapping method, considering factors such as the speed of the mobile mapping tool, measurement time difference, camera shooting distance of the produced data, and differences in picture shooting distances. The acquired results were examined for their applicability in the production of inventory along the highway route, revealing their practical usability through analysis and findings. This investigation delves into the proficiency and precision benchmarks of mobile mapping systems, specifically in the context of creating road inventory and supporting decision-making for road systems. The study discusses the usability and accuracy criteria of mobile mapping systems for creating transportation inventory and decision support systems.

1. Introduction

The enormous growth of everyday socioeconomic activity and the long-term sustainability of contemporary societies depend on the proper utilization of road networks. Road infrastructure has the potential to be a significant financial asset for society and the economy in many developing nations, but this potential is frequently overlooked. This is primarily due to a lack of awareness regarding its true value. Furthermore, the absence of comprehensive information, insightful perspectives, and an understanding of the importance of investing sufficiently in road maintenance has led to chronic underfunding and gradual decline in quality. The degradation of the road network leads to the loss of essential infrastructure, particularly impacting connectivity. Additionally, poor management of road inventories has given rise to significant challenges, including a surge in uncontrolled traffic accidents and a lack of reliable data for autonomous high-definition mapping systems [1].

According to the Turkish Statistical Institute (TSI), between 2003 and 2022, as shown in Figure 1 an in-depth analysis of investments and funding of the transport and communication sector, focusing particularly on the month of June. Unveiled a substantial allocation of 1,670 billion intended to strengthen Türkiye's transportation system. This strategic allocation is poised to yield significant benefits, supporting critical areas like maintaining infrastructure, seamlessly expanding the highway network, and refining the road management system.

Significantly, substantial resources have been allocated to the highway sector, demonstrating a clear commitment. It's worth mentioning that a budget of 979.9 billion has been earmarked for highway development. This financial dedication aims to expedite the deployment of Information and Decision Support Systems, which are crucial instruments for proficiently overseeing Türkiye's expansive road network. However, the situation takes a different turn when we consider the staggering numbers. In Türkiye, the total number of registered vehicles reached a remarkable 27.525.301 by the end of June 2023, with land vehicles dominating the statistics. This significant volume of vehicles significantly contributes to the ongoing traffic crises and a surge in

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* **Corresponding Author**

*(huseyinkursun@gmail.com) ORCID ID 0000-0002-0342-5210

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accidents. This pressing issue calls for immediate action to expand the road network and to enhance the management system for these roads.

In the expansive landscape of Türkiye, the transportation system stands as a vast network of highways. With the road length depicted in Figure 2, Türkiye's highway infrastructure paints a picture of connectivity and accessibility, playing a pivotal role in shaping the country's mobility and economic dynamics.

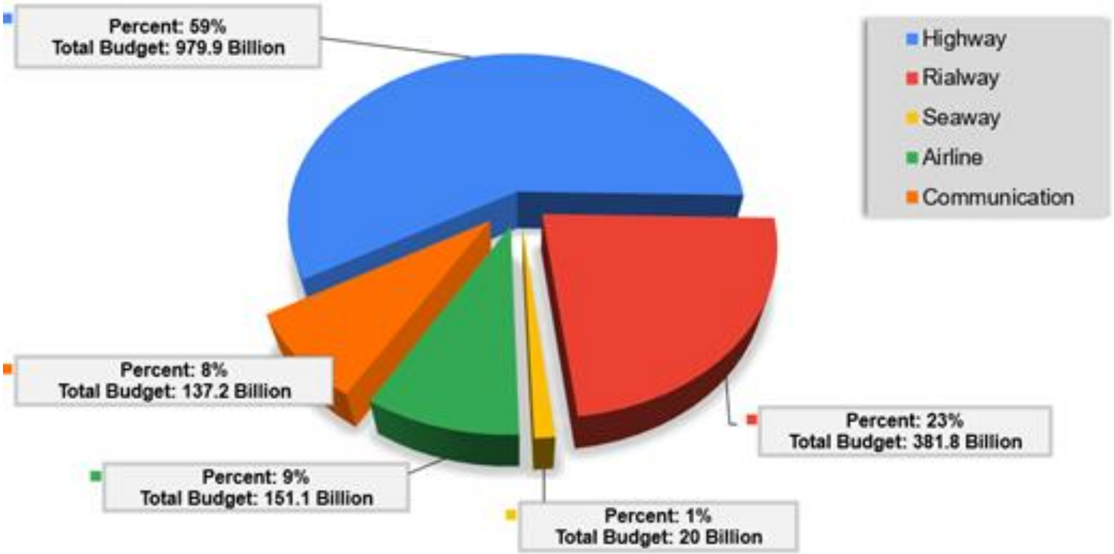

Figure 1. The distribution of transport and communication sector budget in 2022.

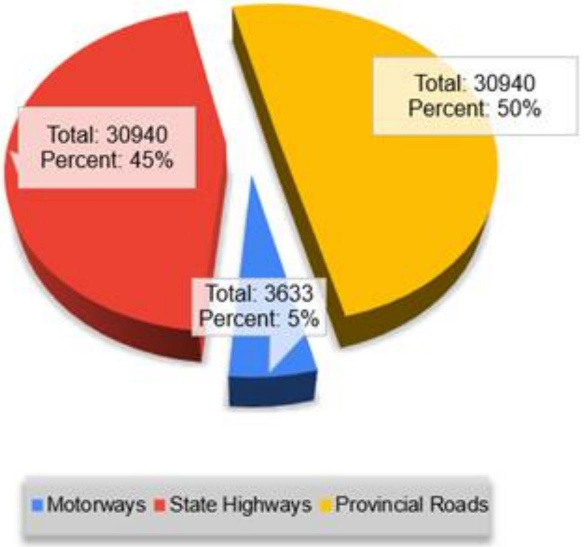

Figure 2. Road network according to surface types (km) in 2023.

The total road length in Türkiye stretches over 68.689 kilometers, and when considering both directions, it extends to 96.047 kilometers due to dual carriageways. This expansive road network includes numerous components, like guardrails spanning thousands of kilometers, road markings covering hundreds of thousands of kilometers, tunnels spanning hundreds of kilometers, thousands of bridges, over one hundred thousand intersections, millions of traffic signs, tens of thousands of signal lights, and a variety of other elements. Collectively, these elements contribute to an exhaustive inventory comprising over 4 million diverse items.

While technology aids data collection, visual inspections remain vital. Traditional methods like GNSS and total station require more teams, more times, and more costs. However, they're inefficient, lack adaptability for updates, and pose safety risks [2]. These limitations also hinder their support for varied data needs like animations and autonomous driving.

All of the mentioned disadvantages outlined herein are anticipated to be mitigated in the mobile mapping system, similar to how it can assist in inventory activities and maintenance and repair operations on linear routes such as highways and railways. Through the utilization of artificial intelligence technology, automatic inventory production can be achieved, and autonomous vehicles can utilize the data as sensors for HD map generation [3]. Furthermore, it is envisaged that this technology can be employed for incident scene investigation and information extraction from various vehicle accidents on highways. It inherently facilitates data quality control and enables the measurement of advertising display areas along roadways, among numerous other benefits.

It is also projected that the data acquired can be actively applied in various engineering projects, and as of the data collection date, new data can be generated for distinct research purposes.

Given the immense scope of the area and for large scale maps, the utilization of a Mobile Mapping system (MMS) emerges as a highly efficient and suitable approach.

Field studies differ in terms of cost, accuracy, detail and speed according to the measurement method used. In addition, depending on technological developments, measurement techniques and methods of obtaining spatial data have also changed throughout history. Spatial data from past to present are collected with different techniques and mapped at different scales.

Depending on the rapid developments in technology, at the end of the 1990s, classical measuring instruments are largely replaced by fully automatic measuring equipment, sensors and satellite technology. Although both terrestrial photogrammetry studies and classical field measurements are sufficient in terms of accuracy, in large areas it hardly provides sufficient performance in terms of speed and workforce on long roads. Therefore, there is a need for mobile mapping systems that will highlight the speed parameters.

The first studies within the scope of mobile mapping date back to the 1970s. In the 1970s, mobile mapping methods were used by photographic recording systems used by many road transport units in North America to monitor pavement quality, road maintenance efficiency, road obstructions, and for similar applications.

With the development of GNSS, IMU and other sensors have been integrated and used for positioning. Urban developments and growth in transportation infrastructure and developments in construction production speed have necessitated the development of more efficient and improved mobile mapping techniques. Some studies attempt to identify and categorize a sizable number of things. One such effort uses a patch-based match graph structure to discriminate between seven kinds of objects, including various types of vegetation. [4,5]. Extract urban objects. However, these systems encountered accuracy issues when a point cloud's resolution was insufficient to discriminate between a traffic sign's precise meaning, necessitating the analysis of optical pictures [6]. To enhance and better comprehend the dynamics of mobile mapping systems, it's imperative to delve into the contributing factors and their effects. These systems rely on a range of elements, including vehicle speed, time intervals, and image capture distances. Analyzing the potential influence of these factors on accuracy is a key aspect of optimizing mobile mapping techniques.

The systems can achieve centimeter-accurate instrument positioning of measured objects from geo-oriented image sequences and 3-dimensional coordinate accuracy in meters or sub-meter. Another advantage of mobile mapping systems is that the outbound data connection to a geodatabase is easy and simple. In general, the advantages of these sensors are numerous. Apart from the fact that 3D data has a well-established reputation for high dependability, employing a 3D point cloud to create 3D maps makes the process considerably simpler. In contrast to other 2D sensors, the 3D LiDAR dependably functions in all weather and lighting situations [7].

The collected geometric and attribute information can be used directly to create and update a database. With the development of rapid communication and image compression technologies, real-time image data can be transferred from mobile mapping system to the GIS database in the office environment. Moreover, such data can be studied and updated live with web, mobile and desktop applications.

Mobile mapping devices using CCD cameras or video cameras have been developed recently for mapping the inventory of roads. Road markings' size, shape, and color characteristics have been employed as crucial indicators for road marking extraction [8-10]. As a result, MMS technology delivers an inventive method for updating geospatial data, distinguished by quick data collecting and direct georeferencing over vast areas. Highway mapping, corridor mapping, and traffic safety evaluation are common MMS uses [11,12].

MMS finds diverse applications across multiple industries, serving as a versatile tool for a broad spectrum of technology-driven use cases.

When it comes to maintenance and disaster management, for instance, map updates might be too infrequent to fulfill the demands of regions that are developing quickly. Large-scale maps may often be updated using lidar data, satellite and aerial photos, and other data sources. The development of MMS technology over the past three decades provides several benefits for the collecting of geographical data, especially its low cost and excellent effectiveness [11-13].

Due to their great precision, speed, and cost-effectiveness in gathering 3D data as well as their use of autonomous driving technology, MMSs are now often used for Building Information Management (BIM) projects. Based on exact 3D positional data, high-definition maps offer the required road data for autonomous driving, such as lanes, signs, and road facilities [14]. The 3D reconstructed model of an asset is created using the gathered point clouds and pictures, which are then subjected to semantic segmentation or classification to extract comprehensive information about each constituent in the asset. The completed result is subsequently uploaded to the BIM software for the purpose of extracting and simulating crucial data pertaining to the project's life cycle. Typically, MMS can deliver data that are accurate enough for the generated BIM products [15].

The Digital Twin (DT) has been used in a variety of industries recently to develop more intelligent maintenance techniques [16]. DTs have been adopted for operation and maintenance in the road sector, including dealing with the maintenance of tunnels [17], bridges [18, 19], or road pavement [20]. The suggested models included both a detailed collection of classification metadata, such as materials, functions, and interactions between the components, and 3D geometry of the infrastructure components. The focus is on creating comprehensive models that encompass 3D geometry and semantic information about materials, functions, and relationships, with maintenance management systems being a key application of the Digital Twin concept.

The primary aim of this study is to establish a to make accuracy assessment for the usability of mobile mapping systems in road inventory production. This study focuses on a road inventory project conducted using a mobile mapping system developed in-house, comprising a laser scanner, panoramic camera, and Inertial Measurement Unit (IMU). To evaluate the accuracy of the mobile mapping system developed for road inventory collection, a precision comparison was carried out within a scenario created on the ITU Ayazaga Campus. This comparison took into account factors such as distance, speed, and the brightness of the sun. In this study, data generation rate, usage areas and location accuracy of the data produced, especially the production and manageability of transportation data and asset management data in transportation networks were investigated using mobile mapping methods. From the obtained panoramic images and LiDAR data.

1.1. Using MMS in asset management system

Asset management is an essential component of infrastructure and superstructure projects. Updating and maintaining asset information comes with a hefty price. Recently, it has become possible to solve the difficulties arising from time and cost in data collection with MMS methods.

Making intelligent choices regarding the administration and upkeep of infrastructure is made easier with the use of GIS, which offers a tangible mapping between geographical data and associated attribute details. Recent developments in GIS technology have increased the effectiveness of asset and stock management [21,22]. Viewing a positioned asset provides better visualization and helpful decision making. Enforcement of connectivity, constraints, and topologically located relationship constraints helps urban maintain data integrity and inconsistency. A range of commercial software with Enhanced Maintenance Management System features has been very popular in the GIS industry for almost fifteen years. From road inventory management to public safety in road, electricity, water, gas, and utilities, GIS asset management systems are applied to nearly every area of utility.

MMS has contributed to the development and collection of the asset inventory database in terms of time, cost and quality. The most prominent features include road centerlines, road boundaries, lanes, sidewalks, curbs, pillars, signage, and roadside vegetation/trees. Transport assets mainly consist of roads and sidewalks. However, other assets such as signage, signal lights, poles and electricity, telecommunications and water utilities found above and below roads and sidewalks also belong to the main components of transportation assets. These assets help increase the efficiency of the road network and thus improve transportation safety [23].

MMS differs from the traditional mapping method with its fast data collection and low cost. For example, MMS can collect more than 3000 kilometers of road data per month. It basically differs from the traditional mapping method with its fast data collection speed and low cost. Although mobile mapping systems greatly reduce data collection time, it often takes more time and resources than data collection times to extract the requested data from the collected data. Therefore, most of the time and resources to create an inventory of assets are spent digitizing the data and entering its details. Due to the heavy workload during the digitization of data, research involving semi-automatic and automatic feature extraction methods from mobile mapping data has gained importance and some progress has been made.

Traffic signposts serve as a crucial part of our transportation system. They have a significant role within the Intelligent Transportation System (ITS), ensuring safety and providing route guidance through the power of Artificial Intelligence (AI). The information of pole-like objects may be utilized for ITS-related applications such as semantic mapping, improved driver assistance, road infrastructure maintenance, and smart city applications. For example, the location of street light poles may be utilized to enhance the stability of road monitoring for a driver assist system [24].

2. Mobile mapping system

The concept of a mobile mapping system integrating multiple sensors of a mobile platform dates back to the past. Although satellite positioning technology such as GNSS was not available during this time, a combination of accelerometers, gyroscopes, and odometer were used to determine the vehicle's motion and direction. Photographs are georeferenced according to recorded vehicle locations [23]. In addition, the possibility of precise positioning and direct georeferencing emerged using GNSS in kinematic mode. The combination of direct georeferencing advances and digital imaging technology has allowed for reduced costs, better precision, and increased flexibility and evolution of the Mobile Mapping System. Obtaining the third dimension and point cloud from overlapping stereo images or panoramic images is possible with the development of software technologies, while the cameras record the existing images of the field. On the other hand, laser scanners calculate the spacing and direction of laser points and directly output the three-dimensional coordinate of each point in the scene. Thus, combining laser scanners with this system allows us to obtain the coordinates of points in three-dimensional space. Integrating this geo-referenced multi-sensor data offers better opportunities to find solutions to specific problems in the spatial domain [25].

An important consideration when moving from traditional mapping methods to mobile mapping technology is the high initial cost of the system. The feasibility of creating an affordable MMS utilizing low-cost laser scanners and budget-friendly cameras has been achieved through diverse methodologies.

2.1. MMS requirements

MMS consists of laser scanner(s), GNSS, an IMU, a DMI, and digital camera(s) [26,27].

The main components of the MMS built for data collection purposes include the following:

2.1.1. One or more laser scanners

LiDAR records 3D point data of the environment in the frame of the data generation scene, which helps to create a 3D model of the scene and extract features.

2.1.2. One or more camera

Cameras capture pictures/video frames of the site, thus providing their managers with digital pictures or videos showing the conditions of the assets.

2.1.3. Global navigation satellite system receiver (GNSS)

The common system to determine the accurate 3D positions in open areas is Global Navigation Satellite System (GNSS). It uses triangulation method with using multiple satellite systems such as GPS, GLONASS, Galileo, and BeiDou to determine precise position. The accuracy of this system is around meter-level however it can be decreased to centimeter level with using these 2 methods which are Differential GPS (DGPS) and Real-Time Kinematic GPS (RTK-GPS) [28]. All in all, Mapping System (MMS) aims for 5-50 mm accuracy with fusion sensors even at high speeds in open areas.

2.1.4. Inertial measurement unit (IMU)

The Inertial Measurement Unit (IMU) is a self-contained sensor that records relative orientation, acceleration, and magnetometer data in 9 axes. It can calculate the position from the start point since it doesn't use any external sources. The measurements from the accelerometer, gyroscope, and magnetometer are used by an onboard computing unit with a dead reckoning algorithm for real-time positioning, forming an Inertial Navigation System (INS). The accuracy of this device mainly depends on the accuracy of sensors used. IMUs can function indoors, outdoors, and in GNSS-denied environments, but the accuracy is limited to short periods relative to the start point due to dead reckoning. Fusing the IMUs and GNSS is a common approach for precise positioning.

2.1.5. Distance measuring instrument (DMI)

The Distance Measurement Instrument (DMI) is used to measure the distance traveled. This system used in the MMS to increase the accuracy of MMS system. This unit can measure the distance, velocity and acceleration after it calibrated.

2.1.6. On-board computer

It is equipped with software or programs that control the operation of sensors and record their data. Point cloud data obtained from the laser scanner at hundreds of thousands of points per second, panoramic images captured at desired intervals, GNSS data, and IMU data are quite voluminous. There is a recording unit and a video card with a high data recording speed. If a laptop/tablet is used for remote connection, it is important to enable Wi-Fi on the computer.

2.1.7. Mobile platforms

Such as a car or truck in land applications, an airplane or drone in aerial applications.

Figure 3 presents a detailed visual representation of the components found within MMS.

Figure 3. MMS data lifecycle.

$$\begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} = \begin{bmatrix} X_{GNSS} \\ X_{GNSS} \\ Z_{GNSS} \end{bmatrix} + R_{IMU}^{M}(\omega,\varphi,\kappa).\left(R_S^{IMU}(\Delta\omega,\Delta\varphi,\Delta\kappa).\, r_P^{s}(ad) + \begin{bmatrix} L_X \\ L_Y \\ L_Z \end{bmatrix}_S^{IMU} - \begin{bmatrix} L_X^{\overset{G}{I}} \\ L_Y^{\overset{G}{I}} \\ L_Z^{\overset{G}{I}} \end{bmatrix}_{GNSS}^{IMU} \right) \tag{1}$$

Mobile laser scanning systems work in the global geodetic coordinate system [29,30]. The measuring principle of mobile LiDAR systems coordinates can be calculated by the Equation 1 [31].

Where;X_P, Y_P, Z_P : Location of the target P in the ECEF Coordinate system;

$R_{IMU}^{M}(\omega,\varphi,\kappa)$: Rotation matrix between IMU and ECEF (Earth Center Earth Fixed);

$R_S^{IMU}(\Delta\omega,\Delta\varphi,\Delta\kappa)$: rotation matrix between the IMU and the laser scanner; $X_{GNSS}, Y_{GNSS}, Z_{GNSS}$: Location of GNSS antenna in ECEF System; L_X, L_Y, L_Z : Lever-arm distance from the navigation and IMU origin to the laser scanner origin; $L_X^{\overset{G}{I}}, L_Y^{\overset{G}{I}}, L_Z^{\overset{G}{I}}$: Lever-arm offsets from the IMU origin to the GNSS origin;

R_S^{INS} : Rotation matrix between the laser scanner and IMU; r_P^{S} : Relative position vector of Point P in the laser scanner coordinate System.

Refer to Figure 4 for the coordinate system visual.

3. Case study

3.1. Designed MMS architecture

Vehicle design involves harmonizing onboard equipment, calibrating components, optimizing their placement, and managing the associated software, ensuring seamless functionality and synergy.

As a Panoramic camera on the vehicle, Ladybug 5+ brand camera with 30 MP resolution, Velodyne VLP-32c, LiDAR sensor and instant acceleration during picture taking. IMU works in integration with the Applanix Poslv MMS and the Odometer (DMI), which enables panoramic shooting by triggering according to the determined quantity and two GNSS antenna cameras to receive precise coordinates. MMS system used in this study was designed and integrated by our research team. Figure 5 above provides visual insight and the graphical representation of the top view of the system is also shown in Figure 6.

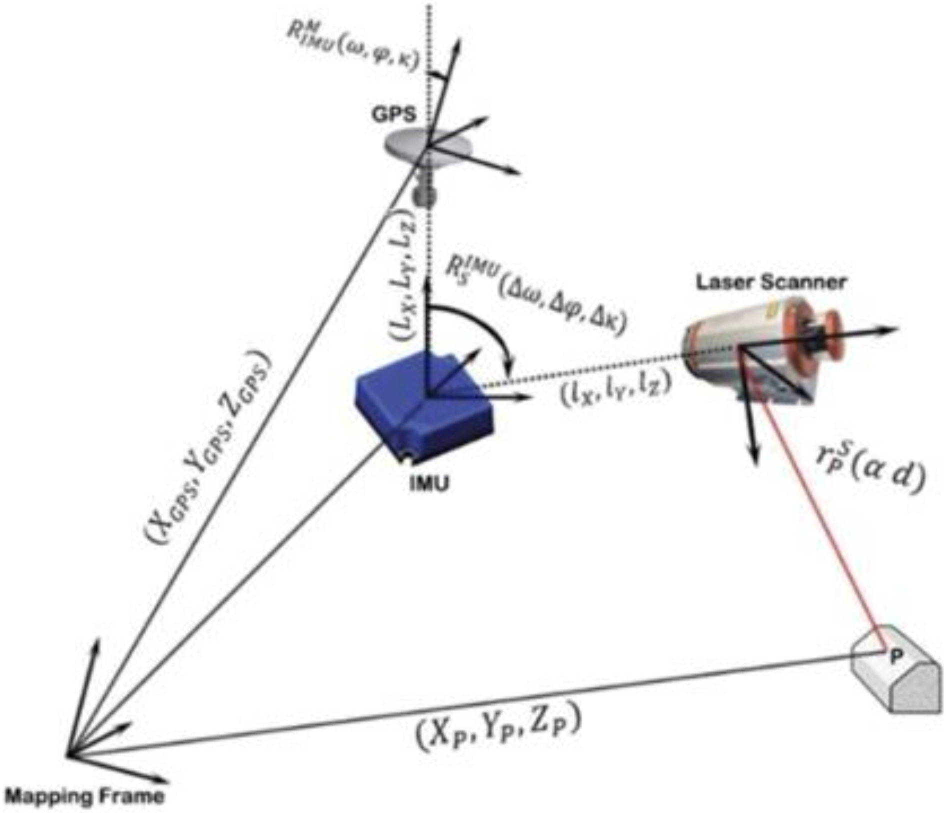

Figure 4. Mobile LiDAR geometric measurement coordinate system [28].

Figure 5. Image of MMS designed by our research team.

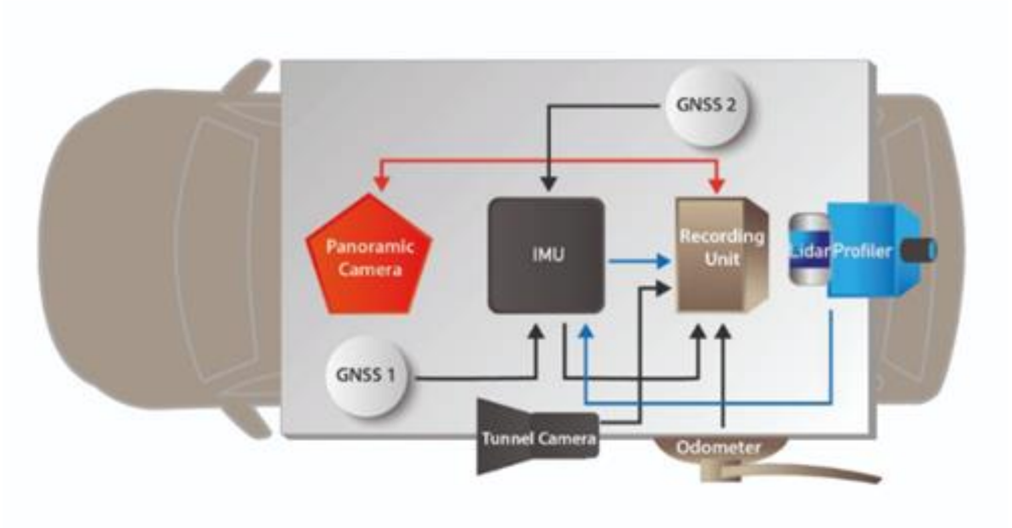

Figure 6. Top view of MMS designed by our research team.

3.1.1. Velodyne VLP-32c laser scanner

For mapping purposes, the Velodyne laser scanner is often used. These scanners, which are primarily used for obstacle detection in robotics applications, feature just one laser diode, as seen in Figure 7. Velodyne features 32 channels and a laser with a vertical range of +15 to -25 degrees.

Figure 7. Velodyne VLP-32c in the test measurement.

With a range accuracy of up to 3 cm, the LiDAR head can spin 360 degrees in a two-dimensional plane. The sensor works on an infra-red band with a wavelength of 903 nm. equipped with an angular resolution (Horizontal/Azimuth): 0.1° to 0.4°, and frame rate: 5 Hz to 20 Hz.

3D Lidar Data Points Generated:
Single Return Mode: ~600,000 points per second
Dual Return Mode: ~1,200,000 points per second

The range of these locations is calculated using the duration of flight technique. The sensor's normal range is 1 to 200 meters. Velodyne is a natural candidate for creating affordable mapping solutions because of these qualities. Velodyne Lidar (2022) specifications (https://velodynelidar.com/wpcontent/uploads/2019/12/63-9378_Rev-F_Ultra-Puck_Datasheet_Web.pdf) (2023).

3.1.2. Flir Ladybug5 panoramic camera

Ladybug5+ camera, takes 360-degree panoramic pictures and is widely used in mobile mapping systems as shown in Figure 8. Here are some of the features of this camera:

- It consists of 6 cameras of 5 Mega Pixel. A total of 30 megapixel and frame rate panoramic images are obtained.
- Data output in various formats is provided with Global Shutter readout method in 8-bit, 12-bit, 16-bit, JPEG.
- Image resolution 2048 x 2448 and pixel size Mar.45.
- It has the capacity to shoot video up to 60 fps and it has the capacity to broadcast live 360-degree video.
- Various adjustments can be made via its own software, such as gamma value, white adjustment, etc.
- Triggers can be given externally.
- It has day and night shooting features.

Figure 8. Ladybug 5+ in the test measurement.

For more information explore the homepage: (Teledyne Flir (2022) Ladybug5+ specifications www.flir.com/products/ladybug5plus/?vertical=machine+vision&segment=iis) (2023). It takes pictures at equal distances and collects detailed data about the route along the route. Tigger box (trigger box) instrument is used to collect data at equal distances. This device transmits the trigger received from the DMI (Distance Measuring Indicator) to the camera and records the time the picture was taken to the computer along with the picture.

3.1.3. Applanix Pos lv 420 IMU/GNSS/DMI

A GNSS-IMU integrated solution is provided by the Applanix Poslv420 instrument. It is composed of a GNSS that offers locations with a horizontal precision of 2 cm and a vertical accuracy of 5 cm in L1/L2 post-processed mode, and a horizontal accuracy of 3 cm and a vertical accuracy of 5 cm in L1/L2 Sensors real-time kinematic mode.

The desired absolute precision of feature points for a mapping application is <20 cm. Its 420 unit is lightweight and well suited for mobile mapping applications because it weighs 2.6 kg and is 158 x 158 x 124 mm. At a frequency of 200Hz, it offers a navigational answer. Several GNSS performance requirements include:

X,Y Position (m): Accuracy of 0.020 meters.

Z Position (m): Precision of 0.050 meters.

Roll & Pitch (degrees): Deviation limited to 0.015 degrees.

True Heading (degrees): Error within 0.020 degrees.

For more information and for a visual representation, refer to Figure 9 and the homepage below: Applanix (2022) POS LV420 specifications www.applanix.com/downloads/products/specs/POS-LV-Datasheet.pdf (2023).

Figure 9. We used IMU in the test measurement

3.2. Data Collection

To establish the basis for investigations into the feasibility of using mobile mapping systems for road inventory production, we selected a test area for accuracy determination studies. ,At the Istanbul Technical University ITU Ayazaga Campus, our study area spans a 250-meter measurement zone along the intersecting routes of Prof. Dr. Bedri Karafakıoğlu street alongside the sport road, shaping a perpendicular alignment as shown in Figure 9. For point position precision measurements, triangulation was made at 3 different points, static measurements were made, and the coordinates of the points were calculated. Along the measurement route area, used on sidewalks, building corners and details, routing signs, lighting poles and guardrails, etc. At 40 points, the detail points to be measured were established by sticking paper reflectors that can remain until the completion of our field work at Figure 10. The establishment of MMS was strategically guided by identifying optimal locations and the specific types of details essential for measuring and producing comprehensive database information. Using total station measurement devices installed at triangulation points, a series of precise measurements were conducted for each point, resulting in the calculation of their coordinates.

The measured point coordinates were calculated according to Universal Transverse Mercator UTM coordinate systems. Heights were measured using an orthometric method.

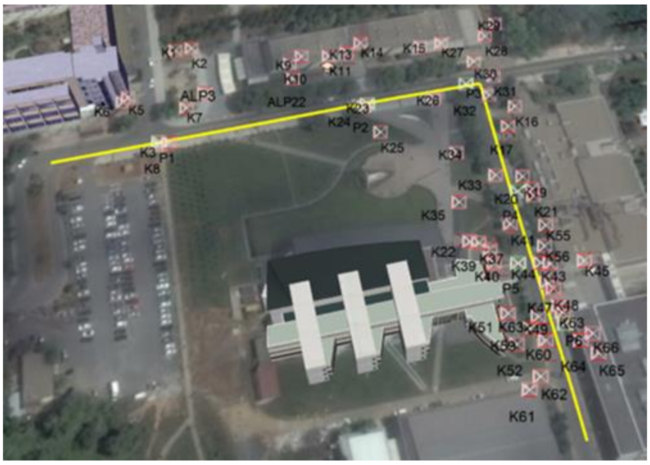

Figure 10. ITU Ayazağa Campus field studies area.

3.2.1. Data collection with mobile mapping in the field

Data were collected with MMS for point location accuracy measurements at ITU Ayazağa Campus. In order to collect data with the MMS, panoramic pictures were taken at 20 and 40 km speeds, 3, 5, 10 m intervals as shown in Figure 11 and laser point cloud data were collected with the Mobile Mapping tool at different times in the morning, noon and afternoon on two different days.

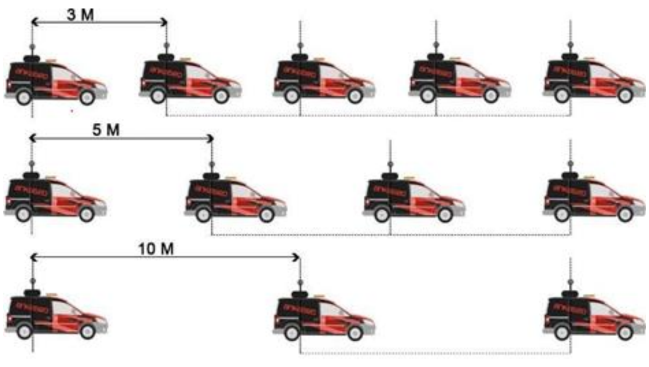

Figure 11. Measurements based on captured image distance intervals

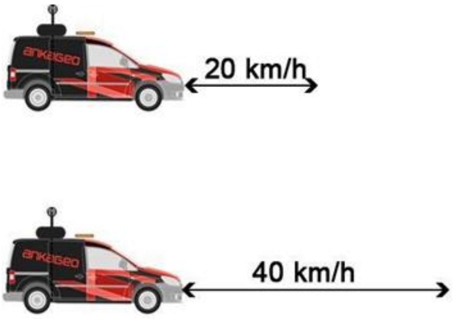

Figure 12. Speed measurements within interval ranges.

Data was collected from the field on December 19, 2018 at 14:00 and 16:50, and on Saturday, December 20, at 9:30, 12:30 and 16:50, 2 days in 5 different time intervals. At each measurement time, 25 different data collection processes were carried out with different parameters at 5 different time intervals from the field at 20 km/h and 40 km/h vehicle speeds as referred in Figure 12, and at each vehicle speed at 3 m, 5 m and 10 m picture shooting intervals.

3.2.2. Mobile mapping data and Geo-Coordinating of data

The relative GNSS positioning method was used based on the reference station named ISTN belonging to TUSAGA-Active CORS Network. On the Mobile Mapping Web application software, the coordinates of 40 points were measured by marking the panoramic images and taking their positions from the laser points where the comparisons were made by making a full series of measurements of the same points by taking the geodetic point of departure from the triangulation point on the campus.

4. Results and Discussion

4.1. Post-Processing of data collected by MMS from the field

Data from Panoramic camera, Lidar, IMU, GNSS, and DMI in the field are recorded in real time from the recording unit. These data are pre-processed with special software, aimed at reducing the margin of error in real-time data collected from the field. Firstly, the data coming from the recording unit is loaded into the post-processing software. Additionally, Rinex data taken from the fixed stations closest to the location where the data was acquired is uploaded to the software. It is important to determine the fixed stations that are near the data from the field. To ensure high accuracy in spatial details, a post-processing technique was applied where the raw real-time trajectory data is refined using the POSPac MMS software as referred in Figure 13. The collected data from the field is in its raw form, often accompanied by GNSS error biases. To rectify this, POSPac MMS software is employed along with data from static GNSS stations located near the capture site. This combination allows for post-processing of the data. Subsequently, the refined information is integrated with reference stations using the Rinex format, resulting in the extraction of accurate trajectory data. By post-processing method generating position data with an accuracy of up to 1 cm with the assistance of Rinex data.

Figure 13. Post-processing method in POSPac MMS software.

4.2. Accuracy Comparison

In this study, coordinates were calculated on the measurements of 40 target points along the road route for point location precision. The x and y coordinates of the points were calculated by making a predictive calculation with the data obtained from the electronic length meter. Since the distance measurement accuracy of the electronic length meter used was 2 mm ± 2 ppm, the predictive data were used for validation. For comparison with the MMS method, the coordinates of the points measured on the software were compared. The coordinates obtained with the geodetic method were taken as the real values and the coordinates obtained with the MMS were compared by calculating the mean square error. The obtained results are shown in Table 1. This study focused on developing MMS and assessing its real-world performance, including applicability, accuracy, and usability, through field measurements.

Table 1. Comparison of data.

Time	Picture Taking Range (m)	Speed (km/h)	Differences (cm)			
			Min.	Max.	Mean	KOH
Morning	3	20	3,3	20,4	11,56	12,17
		40	2,8	17,9	10,36	10,91
	5	20	3,8	32,8	11,23	12,62
		40	2,6	21,4	10,03	10,72
	10	20	3	23,8	13,14	14,05
		40	2,4	21,2	10,1	10,75
Noon	3	20	2,7	19,1	10,6	11,13
		40	1,6	18,3	8,7	9,4
	5	20	2,2	19	10,11	11,28
		40	2,5	25	10,29	11,52
	10	20	1,1	22,5	10,77	11,99
		40	4,2	16	10,29	10,85
Evening	3	20	3,2	19,9	10,28	11,12
		40	2,5	23,7	10,2	11,38
	5	20	1,9	17,9	10,9	11,74
		40	1,4	17,5	9,07	9,89
	10	20	1,8	25,2	13,26	14,66
		40	3,3	28,3	10,41	11,55

4.3. Comprehensive analysis and uncovering result

Analyzing Measurement Variability in Shooting Range Data: Insights and Implications based on the measurements in Table 1.

4.3.1. Consistency across shooting ranges and time variations

The shooting range distances of 3 m, 5 m, and 10 m did not yield significant differences in measurements. Notably, measurements at 3 m and 5 m intervals exhibited remarkable proximity. The variation observed across different times of the day (morning, noon, and evening) was consistently below 2 decimeters (dm).

4.3.2. Impact of image density on measurement differences

There was a correlation between image density and measurement variations. Notably, increased image density yielded comparable differences for sections up to 25 meters.

4.3.3. Spatial features and measurement variability

While measurements generally presented differences below 2 dm, variations between 1 cm and 1 dm were evident. Notably, objects such as curbs, guardrails, advertisement signboards, and lighting poles contributed to these variations. Most of these objects exhibited a parallel or close alignment with the camera.

4.3.4. Time of day and measurement precision

Measurements taken at noon exhibited enhanced accuracy, indicating a 1-2 cm improvement compared to morning and evening measurements. This difference may stem from factors like varying lighting conditions and temperature-induced systemic changes during the morning and evening.

4.3.5. Impact of vehicle speed on measurements

Measurements taken at a speed of 40 km/h demonstrated greater accuracy compared to those taken at 20 km/h. This disparity is attributed to challenges in stabilizing the vehicle at lower speeds.

4.3.6. Optimal picture intervals for accuracy

Picture intervals of 3 m and 5 m yielded superior results compared to the 10 m intervals. The latter intervals led to data loss, impacting measurement precision.

4.3.7. Range dependency and measurement precision

Measurements conducted within the 0-10 m range consistently provided more accurate results than measurements within the 10-25 m range.

To sum up, this comprehensive analysis of shooting range measurements underscores the nuances influencing measurement variability. Factors like image density, spatial features, time of day, vehicle speed, and picture intervals all play crucial roles in shaping the accuracy and reliability of measurements. These insights offer valuable considerations for enhancing the precision of shooting range data collection and analysis.

5. Conclusion

This study has explored the usability of mobile mapping methods in road inventory and asset management systems. Both image technology and laser technology were utilized in the mobile mapping process, resulting in accurate and consistent data collection. The obtained measurements were compared with the geodetic measurement method as an accuracy reference.

The research revealed that mobile mapping systems can efficiently collect point and linear data, such as traffic signs, lighting poles, road centerlines, trees, building corners, and more, along with attribute information and symbology. The achieved location accuracies demonstrated that this technology is highly effective for city road, highway, and railway inventory collection, as well as building facade surveys. While the Mobile Mapping System data might not meet the precision requirements for cadastral surveys, its panoramic imagery offers extensive visual insights and verification possibilities. As a result, it proves to be a valuable asset for urban planning, asset management, and road safety improvement.

The study highlights the Mobile Mapping System's potential to revolutionize map applications, bringing a three-dimensional dimension to the mapping experience in terms of accuracy where the successful implementation of a low-cost system, maintaining high-quality georeferenced information, underscores the practicality and efficacy of this approach. The obtained data from mobile mopping can be used in production high resolution map HD maps for autonomous vehicles.

In addition to its practical applications, the Mobile Mapping System plays a crucial role in enhancing road safety by managing and increasing the sustainability of road safety equipment data, supporting Regional Operations and Engineering Services. Considering its diverse applications and numerous advantages, the Mobile Mapping System emerges as an indispensable tool in today's data-driven landscape. As the technology continues to advance, it promises to reshape asset inventory mapping and solidify its position as a key component of modern mapping practices.

In this study, the method employed involves a mobile mapping system that, in addition to measurement purposes, has a broad range of applications in various fields. However, the lack of a nationally accepted regulation (standard) for its use could potentially limit the practicality of the study. It is believed that this study could make a significant contribution to the process of preparing such a regulation, which would facilitate the utilization of this technology.

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Conflicts of interest

The authors declare no conflicts of interest.

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