Mobile Mapping Systems

A Buyer’s Guide

By Dr. Christopher Cox
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Introduction

Buying a Mobile Mapping System (MMS) can be a difficult task. There are numerous systems available, with a plethora of different sensors to use and the choice of the right system with the correct sensors is critical for a successful survey mission and ultimately the success of a company.

A MMS consists of various sensors including inertial measurement units, global navigation satellite systems, laser scanners, cameras and speed sensors. For each of these sensors there are a multitude of models to choose from, ranging from high-end survey grade models to mapping grade models.

MMSs cover a wide variety of applications ranging from city modelling and highway mapping to contour mapping, volume measurement and change detection, to name just a few. Some sensors are more suited to certain applications than others.

This paper aims to inform prospective buyers as to the advantages and disadvantages that come with different MMSs to ensure that their investment is suitable for their needs and can assist with the growth of their business. Integration issues and choice of software (both capture and processing) is also briefly discussed as these also play an important factor with regard to accuracy and ease of use.

3D Laser Mapping Integration Experience

3D Laser Mapping Ltd. (3DLM) has been integrating LiDAR hardware and software since 1999. In 2005 3D Laser Mapping developed the StreetMapper MMS which, at the time, was the first commercially available MMS on the market. In 2015 3DLM released their fourth iteration of the StreetMapper MMS, named StreetMapperIV.

3DLM are hardware impartial integrators, and we rigorously test and identify the best performing components available for our systems each year, with an emphasis on quality, accuracy, usability and longevity.

Sensors and Technology

The sensors described in this paper are not exhaustive but intended to include only the most common type of sensors in a LiDAR system:

- Global Navigation Satellite System (GNSS)
- Inertial Measurement Unit (IMU) and Inertial Navigation Systems (INS)
- Laser scanner
- Speed Sensor
- Camera
GNSS

GNSS employ a constellation of orbiting satellites to provide geographical position and velocity information of a GNSS receiver antenna. Many systems are in use at this time, with the most popular including:

- United States - Global Positioning System (GPS)
- Russia – Global Navigation Satellite System (GLONASS)
- China – COMPASS / BeiDou Navigation System (BDS)
- European Union – Galileo

Position is determined from triangulating signals from satellites within clear view of the receiver antenna. Generally 4 satellites must be visible for a positional fix, and the more satellites available the more accurate the position. Therefore receivers that can track multiple GNSS constellations will generally provide more accurate positional data, especially in urban canyons where sky visibility is limited.

Due to error sources such as atmospheric delays, receiver noise, multipath and satellite clock timing, GNSS receivers are often only accurate to 1-2m. To improve the accuracy these errors must be accounted for and the most common methods are precise point positioning (PPP), post-processing, and real time kinematic (RTK).

PPP uses precise satellite orbit and clock data to calculate a precise position accurate to decimetres or better. The advantages of this method is that no other hardware is needed to determine an accurate position. The disadvantages of this method is that good accuracy will only be possible if the signals from the satellites are uninterrupted, so it is fine for airborne or farming applications, but not suitable for mobile mapping. Furthermore, rapid orbit and clock data is available to download within hours of the survey, whereas the more accurate final data usually takes a few days before it is available.

Post-processing and RTK methodologies are similar in that they both reduce errors by using corrections from a reference (base) station with a fixed known position. Both methods assume that the reference station is receiving the same errors as the roving receiver and so it can therefore cancel out the error. This assumption only works if the two receivers are within the vicinity of each other, and so accuracy is determined by how close the two receivers are. Assuming good GNSS visibility and less than 20km distance between the receivers, this technique can provide centimetre accuracy, and is suitable for most MMS applications, especially in harsh GNSS conditions. RTK systems receive the corrections in real-time, whereas post-processing systems have the corrections applied after the survey. RTK systems require more complex and expensive hardware than post-processed systems. Additionally, post-processed GNSS systems generally result in a more accurate solution than RTK.
IMUs and INSs

IMUs

The purpose of an IMU is to measure the rotation and acceleration of the MMS. An IMU is typically composed of three gyroscopes mounted at right angles to each other and three accelerometers also mounted at right angles to each other in order to measure rotation and acceleration in three axes. The measurements are processed at high rates, typically between 100-512Hz depending on the IMU.

There are many types of IMU, the three most common types in mobile mapping applications are:

- Fibre Optic Gyro (FOG)
- Ring Laser Gyro (RLG)
- Micro Electro Mechanical System (MEMS)

Generally the FOG and RLG IMUs provide higher performance than MEMs. It should be noted that not all FOG and RLG IMUs are better than MEMS IMUs, so it is necessary to study the quoted accuracies carefully rather than just discard an IMU based on its type.

INSs

The combination of a computer and an IMU is called an INS. The INS is initially provided with its position and velocity from another source, typically GNSS, and thereafter computes its trajectory by integrating information from other external sensors, such as GNSS and speed sensors.

An INS filter, referred to as a Kalman Filter (KF), combines the different measurements taking into account estimated errors to produce a trajectory including time, position and attitude.

IMU and INS Specifications

When it comes to choosing an IMU there are numerous factors that need to be considered, including price, weight and performance and the importance of each of these factors depends upon the intended application of the MMS.

The performance of an IMU is typically presented as various types of IMU error, and the most commonly quoted errors are briefly summarised in Table 1. The performance of the INS is also often quoted and takes into account the accuracy of the GNSS and IMU when combined by the KF.
Table 1: Typical IMU error descriptions

<table>
<thead>
<tr>
<th>IMU Error</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Repeatability</td>
<td>deg/hr or m/s²</td>
<td>The difference between the real value and the output, which can change from mission to mission and affects the time taken to initialise the INS</td>
</tr>
<tr>
<td>Bias Stability</td>
<td>deg/hr²</td>
<td>The bias can change over time and has an effect on the performance of an INS during GNSS outage</td>
</tr>
<tr>
<td>Scale Factor</td>
<td>ppm</td>
<td>The relation in scale between the input and output</td>
</tr>
<tr>
<td>Random Walk</td>
<td>deg/√hr</td>
<td>The noise of the sensor, which causes INS error to grow over time during GNSS outage</td>
</tr>
</tbody>
</table>

Table 2: Typical INS performance descriptions

<table>
<thead>
<tr>
<th>INS Performance</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>m</td>
<td>The absolute positional accuracy</td>
</tr>
<tr>
<td>Velocity</td>
<td>m/s</td>
<td>The velocity accuracy</td>
</tr>
<tr>
<td>Roll/Pitch</td>
<td>deg</td>
<td>The roll/pitch accuracy</td>
</tr>
<tr>
<td>True Heading</td>
<td>deg</td>
<td>The heading accuracy</td>
</tr>
<tr>
<td>Data rates</td>
<td>Hz</td>
<td>The measurement speed of the IMU</td>
</tr>
</tbody>
</table>

For long range applications, the important features to consider will be the accuracy of the heading, roll and pitch, since these errors grow with range. A high data rate is also important because scanners will generally be recording at a much higher rate than the IMU and so errors with interpolation will occur which will also grow with range.

If the application requires driving with very few dynamics (low speed, very few turns) then an IMU with a low bias and low random walk will be beneficial. It should be noted that heading drift can be reduced during a low dynamic survey by using a dual GNSS antenna system.

For surveying in areas of poor GNSS, such as city mapping, the most important factor will be the bias and random walk since these errors dictate how quickly and to what extent heading drift occurs. For example, if the INS has no GNSS for one minute, a low grade IMU could result in an error of over 2m, and a high grade IMU an error of less than 20cm.
Coupling

A further factor to consider is how the INS and GNSS interact with each other, a term referred to as coupling. A loosely coupled INS is where the position and velocity from the INS and GNSS are combined to form a trajectory. A tightly coupled INS goes a step further by also combining the GNSS raw measurements with the INS, therefore allowing GNSS position updates with fewer than four satellites (four satellites are usually the minimum requirement for a GNSS position fix). The deeply coupled approach is similar to the tightly coupled approach, except information is also passed from the INS filter to the GNSS filter, which enables faster GNSS signal reacquisition.

It is common for some INS to use a combination of these different coupling techniques and will generally be given different terminology to those described above, so it may be necessary to ask the MMS supplier how the INS and GNSS interact with each other.

Laser Scanners

Time of Flight and Phase Based Scanners

There are many different types of laser scanner, but the most common scanners for mobile mapping systems are time of flight (TOF) and phase shift scanners.

TOF scanners, also known as pulse-based scanners, work by emitting a pulse of light from a laser source and timing how long it takes for the pulse to reflect off an object and return to the laser receiver. Since we know the speed of light we can work out the distance of the object. Phase shift scanners, also known as phase based scanners, emit a constant beam of laser energy. The scanner measures the phase shift of the returned laser energy to determine the distance.

Both types of scanner either use a moving mirror to measure on a 2D plane (for some scanners the whole laser head rotates). Some scanners use a rotating mirror and others an oscillating mirror. Rotating mirrors are the most common for mobile mapping systems, and generally oscillating mirrors are only used for airborne systems.

To measure in 3D the scanner must either rotate or move along a trajectory. 3D rotating scanners are more commonly used for static applications, whereas 2D scanners are more commonly used for mobile mapping (although some MMSs use 3D scanners in 2D mode).
Common Scanner Specifications

Choosing the correct scanner is vital to achieving a successful mobile mapping survey. Things to consider include:

- Effective measurement rate
- Range
- Rotation/mirror speed
- Accuracy and precision (also known as noise or repeatability)
- Field of view
- Multiple target capability
- Ruggedness
- Price

The effective measurement rate is how many usable points are emitted by the scanner. Be careful not to confuse this with pulse repetition rate (PRR) which defines the total number of points emitted by the scanner regardless of whether they can be used or not (for example, a scanner with a rotating polygon mirror can only use a certain percentage of the mirror surface area so many points are lost).

Modern scanners, both phase based and TOF can emit up to 1 million points per second. However, for TOF scanners the PRR has to be decreased in order to obtain longer ranges. Some TOF scanners can scan up to 6km, although the TOF scanners that are usually used for MMSs have a range up to about 250m at maximum PRR. For phase based scanners, the maximum range is usually about 120m.

Rotation speed dictates how many scan lines are measured per second. Depending on the scanner, the rotation speed is either set at a fixed speed or is user definable. If you are driving fast and require a uniform grid point spacing then you will most likely need a scanner with a fast rotation speed. Speeds up to 250 rotations per second are now common.

One common source of confusion when looking at scanner specification sheets is scanner accuracy. The terms accuracy, precision and noise are often referred to, and different scanner manufacturers or MMS suppliers can often use these terms to mean different things. For example, Riegl define accuracy as the degree of conformity of a measured quantity to its actual (true) value, and precision as the degree to which further measurements show the same result (Figure 1). Fortunately, for most scanners the accuracy and precision (noise) are often very similar values, so you could find that only one figure is stated in the scanner specifications. One other term that is commonly referred to is relative accuracy, and although the term is not rigidly defined, it can be considered to be the accuracy of two points in relation to each other, independent of other error sources. Therefore we can think of relative accuracy as a combination of both scanner accuracy and precision.
Field of view is an important factor to keep in mind when choosing a scanner and also when determining how many scanners will be required. For mobile mapping applications a 360 degree field of view is optimal so that there is no missing data in your scene. For scanners with a field of view less than 360 you may require an additional scanner to fill in the missing part of the scene. For applications where only part of the environment is required, such as road surface mapping or mapping from a boat then a scanner with a limited field of view will suffice.

When a TOF scanner emits a laser pulse, the laser pulse may hit more than one object and therefore return more than one pulse (Figure 2). For example, if a pulse is sent towards a tree in front of a house there could be numerous returns from the different leaves and a return from the house. Some TOF scanners have the ability to record some or all of these returns, and this scanning feature is referred to as multiple target capability. The benefit of multiple target capability is that it enables better penetration of vegetation and a richer pointcloud.
In contrast, phase based scanners are prone to range averaging when multiple targets are encountered. This makes the data noisy around the edges of objects. Furthermore, phase measurements can also be ambiguous, thus phase based scanners can find it difficult to resolve ranges when there is a discontinuity in a surface, resulting in incorrect range measurements (although this can generally be corrected during post-processing).

Ruggedness of a scanner is very important for mobile mapping since the scanner is subject to some harsh conditions including rain, snow, smoke, dust and loose gravel, all of which can damage the scanner. In particular the mirror is very sensitive so scanners with exposed mirrors are not recommended for MMSs.

Which Scanner?

Table 3 below lists some typical MMS applications and some recommended scanner features.

### Table 3: Recommended scanner features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Highway surveying</th>
<th>Tunnel mapping</th>
<th>Coastal mapping (from a boat)</th>
<th>Asset mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanner Type</td>
<td>TOF or phase</td>
<td>TOF or phase</td>
<td>TOF</td>
<td>TOF or phase</td>
</tr>
<tr>
<td>Effective measurement rate</td>
<td>&gt;500kHz</td>
<td>&gt;500kHz</td>
<td>&gt;500kHz</td>
<td>&gt;100kHz</td>
</tr>
<tr>
<td>Range</td>
<td>50m</td>
<td>10m</td>
<td>200m</td>
<td>50m</td>
</tr>
<tr>
<td>Rotation/mirror speed</td>
<td>&gt;200rps</td>
<td>&gt;200rps</td>
<td>&gt;30rps</td>
<td>&gt;50rps</td>
</tr>
<tr>
<td>Accuracy/precision</td>
<td>&lt;10mm</td>
<td>&lt;10mm</td>
<td>&lt;50mm</td>
<td>&lt;50mm</td>
</tr>
<tr>
<td>Field of view</td>
<td>180</td>
<td>360</td>
<td>60</td>
<td>360</td>
</tr>
<tr>
<td>Multiple target capability</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ruggedness</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>

### Intensity and Reflectivity

Intensity is the strength or amplitude of the scanner's laser emission. Different objects reflect different amounts, for example tarmac does not reflect very well whereas white paint markings do. We can use this information to view a pointcloud by its intensity, so if we apply a greyscale colour scheme the pointcloud will look similar to a black and white photograph.

The intensity of a return signal decreases with range and the angle of incidence. This can lead to non-uniform intensity if there are multiple drive passes from different ranges. This effect can be reduced by some scanners that are calibrated to take range into account, and the intensity is thereafter referred to as reflectivity.
**Speed Sensors**

Speed sensors are commonly used by MMSs to improve trajectory accuracy and are especially useful when GNSS visibility is poor such as in tunnels or urban environments. Speed sensors are not only useful when moving, but also useful when static as they reduce INS drift by providing Zero Velocity Updates (ZUPTs) to the INS filter.

There are three main types of speed sensors that are used for mobile mapping:

- Wheel speed encoder
- Non-contact optical sensor
- Engine Computer Unit (ECU) device

**Wheel speed encoder**

Wheel speed encoders are mounted directly on one of the vehicle’s rear wheels and provide accurate speed measurements. Modular mounting systems allow the wheel encoders to be fitted to most vehicle wheels. The biggest disadvantage to the wheel speed encoder is that it protrudes from the vehicle and requires very careful calibration to ensure accuracy. Additionally, for railway applications a wheel speed encoder may not be permitted to be installed onto the railway vehicle.

**Non-contact optical sensor**

Non-contact sensors use optics to measure speed. The sensor usually fits on the underside of the vehicle (near the rear wheels if possible). They are more accurate and reliable than wheel speed encoders, and easier to set up and use. They can also be installed onto a vehicle discreetly unlike a wheel speed encoder. Because they have no moving parts and do not make contact with the road or wheel they resist damage and wear. This also makes them very useful for railway applications.

**ECU device**

An ECU device (also referred to as a ZUPT sensor) uses the information from the vehicle’s ECU to determine if the vehicle was stationary or not. This is very useful when the vehicle is stationary for a long period of time when there is poor GNSS, since it helps to reduce INS drift. The ECU devices will be of no use when the vehicle is in motion as the reported velocity data from the ECU is not accurate enough to assist the INS solution, and could even make it worse, which is why they are only used for detecting ZUPTs.
Cameras

Camera Types

The three biggest advantages of using a camera for a MMS are:

- Measuring features (either from photogrammetry methods or from the pointcloud overlaid onto the photo)
- Identifying features that may not be identifiable in the pointcloud alone
- Colouring the pointcloud

There are a multitude of camera types used in the LiDAR industry, but the three most common camera types for MMSs include:

- Industrial
- Digital Single Lens Reflex (DSLR)
- Mirrorless compact system
- Medium format

Georeferenced Photographs

To be able to use the photographs with the pointcloud the photographs must be accurately georeferenced. This is achieved by logging the precise timestamp of when each photograph was taken. For industrial cameras an event out cable can be used which sends a signal to the INS which is then logged. For DSLR and mirrorless compact cameras a cable attached to the flash shoe can be used to send a signal to the INS.

The timestamps are integrated with the INS trajectory to determine the precise position and attitude of each photograph. Additional information such as lever arms (the position of the camera relative to the trajectory source), image size, focal length and lens distortion parameters are also required to ensure the photographs align correctly with the pointcloud.

Spherical and Panoramic Cameras

Spherical cameras consist of numerous individual cameras which have been configured and calibrated in such a way as to produce a 360 degree panoramic image.

Some spherical cameras are often referred to as panoramic cameras, but it should be noted that some panoramic cameras do not produce 360 degree panoramas and only produce widescreen panoramas.

360 degree panoramic images are very useful for GIS applications and used in software such as Google Street View or OrbitGT’s MM Asset Inventory (Figure 3).
Figure 3: Panoramic images overlaid onto a pointcloud in OrbitGT software

Table 4: Camera features

<table>
<thead>
<tr>
<th>Camera</th>
<th>Resolution (megapixels)</th>
<th>Image Quality</th>
<th>Weight (kg)</th>
<th>Size</th>
<th>Cost (€)</th>
<th>Framerate (images per sec)</th>
<th>Ruggedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>2-30</td>
<td>Average</td>
<td>&lt;0.5</td>
<td>Small</td>
<td>500-5000</td>
<td>15</td>
<td>Good</td>
</tr>
<tr>
<td>DSLR</td>
<td>12-40</td>
<td>Very good</td>
<td>1-2</td>
<td>Large</td>
<td>200-7000</td>
<td>1</td>
<td>Poor</td>
</tr>
<tr>
<td>Mirrorless</td>
<td>12-40</td>
<td>Good</td>
<td>0.5</td>
<td>Medium</td>
<td>200-4000</td>
<td>2</td>
<td>Poor</td>
</tr>
<tr>
<td>Medium format</td>
<td>50-100</td>
<td>Best</td>
<td>1-3</td>
<td>Large</td>
<td>40000+</td>
<td>1</td>
<td>Good</td>
</tr>
</tbody>
</table>

Which camera?

Table 4 below identifies some typical features of each type of camera.

For applications where the vehicle will be moving fast then it is advantageous to choose a camera with a high framerate, otherwise features could be missed or too far away to be clear enough to identify.

Ruggedness if also an important feature. MMSs will most likely experience bumps and high vibrations, so cameras with moving parts can often not be 100% reliable. Furthermore, some cameras, such as DSLR and mirrorless compact cameras, are not really designed for taking thousands of pictures at fast intervals.

The quality of a photograph generally is determined by the quality of the camera sensor. It should be noted that just because a camera is high-resolution, it does not necessarily mean that the image will be of good quality. Care should be taken to investigate the sensors performance specifications too.
About the Author

Dr. Christopher Cox has over 11 years’ experience in the LiDAR industry. He was awarded a PhD in 2003 by the University of Nottingham for his thesis entitled ‘The Use of Computer Graphics for Visual Impact Assessment’. Chris joined 3D Laser Mapping in 2005 and specialises in mobile mapping and airborne LiDAR research and development, as well as software support and training.

Since joining the company, Chris has tested numerous MMS components, both hardware and software, from various suppliers from all over the world.

About 3D Laser Mapping

3D Laser Mapping is an independent systems integrator and supplier of mobile mapping hardware and software.

We pride ourselves on using best of breed hardware and software and we annually test and review different sensors and software to ensure we continue to offer the best.

We launched the first commercially available mobile mapping system back in 2004 and continue to offer mobile mapping systems that meet the needs of our customers.

We have reviewed and tested the following brands of hardware:

Laser Scanners:
- Riegl
- Z&F
- Leica
- Velodyne
- Sick
- Tyto
- Neptec

Inertial Navigation Systems (INS):
- IGI
- NovAtel
- Applanix
- OxTS
- Navtech