An Introduction to the Technology

Mobile Mapping Systems

Over the last 20 years, mobile mapping systems have slowly developed, at first mainly in academic research establishments. More recently, a number of commercially operated systems have appeared. These have mostly been one-off systems that have been developed in-house by the companies that are operating them. Most of them have been utilized for the collection of data on road infrastructure or building facades. However, over the last two or three years, some very big companies such as Google, Tele Atlas and NAVTEQ have adopted the technology on a large scale, introducing substantial fleets of mobile mapping vehicles for their imaging and mapping operations. This has resulted in the further rapid development of the technology which can now be regarded as being well established and proven.

This article offers an introduction to and survey of the present state-of-the-art of the technology.

By Gordon Petrie

This survey of the technology will be conducted in three main parts.

(i) The first deals with the main components of mobile mapping systems. These include the digital imaging devices; the laser ranging and scanning devices; and the positioning (or geo-referencing) devices which are the principal building blocks that are being used in the construction of such systems. (ii) The second part will cover the system suppliers who integrate these different components and offer the resulting systems for sale to users. (iii) The third part covers a representative selection of service providers, but paying particular attention to the systems used by the large imaging and mapping organisations that have been mentioned above in the introduction to this article.

I - Main Components

Imaging Devices

Arising from the speed of movement of the mapping vehicles and the close proximity of the target objects (of a few tens of metres), the digital frame cameras and pushbroom line scanners that are familiar to the mapping community from their airborne imaging operations are simply not suitable for use with mobile mapping vehicles. Although imaging (pushbroom) line scanners have been used experimentally in certain mobile mapping vehicles that are being operated by academic research groups, so far they have had little use in commercial mapping operations. Instead digital frame cameras are used almost universally. However the format sizes are very small (1 to 2 Megapixels is typical); framing rates are high (typically 7 to 15 frames per second); exposure times are very short (to eliminate image blur); and the use of multiple camera arrays to provide 360 degree panoramic images in the horizontal plane is very common. Taking as an example a mobile mapping vehicle that is being driven in an urban area at 30 kph, it travels a distance of 1 km in 120 seconds or 8.3 m in one second. If it travels at 60 kph, it travels a distance of 16.7 m in one second. If the imaging system has to acquire successive sets of frame images at intervals of 2 to 8 m from four to eight cameras simultaneously to ensure the continuous coverage of a street or road, then it is obvious that very high rates of data transmission and storage of the images will need to be implemented. This involves the use of interfaces and cabling technologies such as FireWire or i.LINK (that adhere to the IEEE1394 standard) [Fig. 1]. These devices can transmit uncompressed image data from multiple cameras either at 400 Megabits per second (50 Megapixels per second) – which is the IEEE1394-A standard - or at 800 Megabits per second (100 Megapixels per second), which is the IEEE1394-B standard.

The individual cameras that are being utilized to implement and satisfy these requirements are digital video frame cameras using very small-format CCD or CMOS area arrays as their imaging sensors. These cameras are manufactured in large numbers for industrial use by numerous suppliers such as Sony, Hitachi and Toshiba (Japan); IMI (Korea); IMPERX, Pelco and Arecont Vision (U.S.A); PixeLINK (Canada); and AVT, PCO and Basler (Germany). A typical type of digital video camera that was used in early mobile mapping operations was the Sony DFW-500 model that could acquire 640 x 480 pixel (0.3 Megapixels) colour frame images at rates up to 25 frames per second. More modern types of Sony CCD cameras can output images having the much larger frame size of 1,024 x 768 pixels (0.8 Megapixels) at the rate of 15 frames per
second or frame images that are 1,280 x 960 pixels (1.2 Megapixels) in size at a rate of 7.5 frames per second. These individual cameras will often be deployed in multiple in different configurations depending on the specific types of features that need to be mapped [Fig. 2]. Usually each of the individual cameras that are mounted on a mobile mapping vehicle will be enclosed in a special housing that will protect it from rain and dust. Often the housing will be equipped with a Sun shroud and also with a heater/defroster unit, the latter helping to keep the camera operational in cold weather conditions.

However the use of fully integrated **multiple camera** units is now very common in mobile mapping vehicles. As will be seen later, the Ladybug series of multiple cameras built by **Point Grey Research**, based in Richmond, B.C., Canada, have been adopted widely for use in mobile mapping systems [Fig. 3]. The company’s **Ladybug2** multiple camera unit has six Sony CCD digital video cameras. Five of these cameras are arranged concentrically in a horizontal ring pointing outwards to produce a 360 degree panoramic image within the horizontal plane, with the sixth camera pointing vertically upwards. These cameras have a FireWire-B (IEEE1394-B) 800 Megabit interface and cabling to provide camera control and power and to implement video data transmission at the rate of 15 uncompressed frame images per second, each image being 1,024 x 768 pixels (= 0.8 Megapixels) in size. The Ladybug2 unit also has a set of six Sony CCD cameras arranged in a similar circular five-camera configuration (plus a single vertical camera) but with still larger formats (1,600 x 1,200 pixels). Thus it can generate six 2-Megapixel images that can be streamed as uncompressed images at the rate of 7 frames per second or as compressed JPEG images at a 15 frames per second rate. Each Ladybug multiple camera unit can be supplied attached to a mast that can be mounted on a roof rack that has been placed on top of the mapping vehicle to provide a clear view of the surrounding objects.

Another integrated multiple camera unit that has received a great deal of publicity and attention from the media because of its distinctive shape and appearance is the **Dodeca 2360** [Fig. 4] The name is derived from the geodesic geometry of the dodecahedron, which is a 12-faced solid figure (with each face having a pentagonal shape) that approximates to that of a sphere. The overall Dodeca 2360 unit utilizes eleven of the 12 faces, in each of which a small-format camera is mounted, while the twelfth face forms the base on which the camera is mounted. Usually the camera will be attached to a mast that can be mounted on the roof of the mapping vehicle. The Dodeca camera was devised by another Canadian company, **Immersive Media Corporation Inc. (IMC)**, based in Calgary, Alberta. Originally the camera was manufactured by Freestone Systems in Dallas, Texas. In 2007, IMC acquired the Freestone company, which was then renamed **IMC Sensors Inc.** Each of the Dodeca cameras generates a frame image that is 640 x 480 pixels in size, the overall size of the resulting merged and stitched “spherical” image formed from the multiple individual images is 2,400 x 1,200 pixels.

The **Google** company made use of this type of Dodeca frame imagery when it introduced its “Street View” service in 2007. However Google then switched to using its own multiple camera units thereafter. The Google integrated multiple camera system comprises nine individual CCD cameras, eight of which are arranged, spaced equally, in a concentric ring pointing outwards, with the ninth camera pointing vertically upwards [Fig. 5]. The individual cameras are reported to have been supplied by an American company, **Elphel Inc.**, which is based in Salt Lake City, Utah. The Elphel 313 and 333 models are digital network cameras using CMOS area arrays that are delivered with software source code supplied under Open Source terms (like those applying to the Linux operating system or the Firefox browser). The Elphel 313 camera generates images with a frame size of 1,280 x 1,024 pixels at the rate of 15 frames per second or larger images, e.g. with 1,600 x 1,200 pixels, at a lower rate. The later Elphel 333 camera can generate compressed JPEG images that are 2,048 x 1,536 pixels (3.2 Megapixels) in size at the rate of 12 frames per second.

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**Fig. 2** – These diagrams show the different configurations of digital video cameras that have been utilized on the mobile mapping vehicles that are being operated by Tele Atlas. Diagrams (a), (b) and (c) show alternative arrangements using four cameras, while (d) shows a six-camera arrangement. (Source: Tele Atlas; Redrawn by Mike Shand)

**Fig. 3** – The cylindrical-shaped Ladybug2 (left) and the pentagonal-shaped Ladybug3 (right) integrated multiple camera systems, which are operated with FireWire-B (IEEE1394-B) interfaces and cabling. (Source: Point Grey Research)

**Fig. 4** – The Dodeca 2360 integrated multiple camera system produced by Immersive Media comprises eleven individual video cameras firing simultaneously. (Source: Immersive Media)

**Fig. 5** – The integrated nine-camera system that is mounted and operated on the Google company’s cars that acquire imagery for its Street View service. (Source: Google)
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Laser Ranging & Scanning Devices

The numerous, varied and well-established types of tripod-mounted 3D laser scanners that are in widespread use by land surveyors undertaking terrestrial or ground-based laser scanning – including both panoramic and camera-type laser scanners; the use of the phase measuring technique for short distances; and the need for both horizontal and vertical angles to be measured – have had little part to play in mobile mapping systems. Indeed the 3D laser scanners that are available at present for surveying work can only be used for static measurements in their native 3D operational mode, even when mounted on a vehicle - since the scanning operation at a single fixed location often takes several minutes. However a very small number of 3D laser scanners from the German Faro and Z+F companies have been operated on mobile mapping vehicles, but with their horizontal (azimuth) angular movements disabled – which effectively makes them into 2D laser scanners.

Indeed the main emphasis in mobile mapping is on the use of 2D laser scanners that can very rapidly acquire range or elevation profiles comprising the distance and angular values measured within a single 2D plane. These profile measurements are carried out using the laser scanner to measure the required distances and angles simultaneously within a series of successive parallel planes intersecting the road surfaces, pavements, “street furniture”, buildings and vegetation that are located adjacent to the roads or streets along which the mobile mapping vehicles are being driven. Indeed, in many respects, the 2D laser scanners that are mounted on mobile mapping vehicles are, in principle, quite similar to the laser scanners that are being used in airborne laser scanning – except that they are usually being operated over distances of a few tens of metres, instead of the several hundreds or thousands of metres that are encountered in airborne laser scanning. As with airborne laser scanning, the third dimension to the captured profile data is being created by the forward movement of the vehicular platform on which the 2D laser scanner is mounted. The location of each new range profile is being measured continuously (and very accurately) using an integrated suite of positioning devices – comprising a GPS or GNSS receiver, an IMU; and an odometer or DMI device – as the vehicle travels forward.

The 2D laser scanners that are probably the most commonly used in mobile mapping are those manufactured by the SICK company, which is based in Waldkirch, Germany. The SICK company makes an almost bewildering range of laser scanners - including bar code scanners; scanners for displacement and volumetric measurements; and scanners that are designed for proximity determination and safety purposes - together with numerous other types of encoders, switches, controllers and sensors that are designed for a wide range of industrial, logistic and commercial applications. Certain models in the SICK LMS (Laser Measurement Systems) series of laser scanner are designed specifically for outdoor use, the LMS 291 model being that mainly used in mobile mapping [Fig. 6]. This scanner combines (i) a rapid firing laser rangefinder using the time-of-flight (TOF) distance measuring principle; with (ii) a rotating mirror whose angular directions are also being measured continuously using an angular encoder. Using this technology, the LMS 291 generates a fan-shaped scanning angle of 180 degrees within its 2D scanning plane and can measure ranges of up to 80 m to objects having a reflectivity of 70%; 60 m to objects (such as a wooden house) with a reflectivity of 40%; and 30 m to objects with 10% reflectivity. The measuring resolution in range of the LMS 291 model is stated to be 1 cm, while the accuracy is +/- 6 cm. An additional LMI controller can be supplied to control the operation of multiple LMS scanners. Still longer-range 2D laser scanners are available from LASE GmbH, which is another company in the SICK Group based in Wesel, Germany. The LASE LD-LRS laser scanner can measure ranges up to 250 m with suitable highly reflective objects; 110 m to objects with 20% reflectivity; and 80 m to objects with 10% reflectivity, and has a 300 degree scanning angle. Still another company in the SICK Group, Ibeo, based in Hamburg, Germany also offer laser scanners that are suitable for mapping purposes – see the following Web page - www.ibeo-as.com/english/3d.asp
Besides the SICK scanners, there are several other TOF 2D laser scanners that are used quite widely in mobile mapping operations. These are made by specialist suppliers such as Riegl (based in Horn, Austria) and Optech (based in the Toronto area in Ontario, Canada). Both companies are well-known suppliers of airborne and terrestrial laser scanners to the surveying and mapping industry. In general terms, the 2D scanner units from these companies provide greater ranges; faster speeds and higher measuring accuracies than those provided by the SICK laser scanners. However they are also considerably more expensive. The Riegl VQ-180 laser scanner with its continuously rotating polygon mirror has been used in a number of mobile mapping systems [Fig. 7]. It has a pulse repetition frequency (PRF) of 30 kHz; a range of 150 m to targets with an 80% reflectivity; a ranging accuracy of +/- 25 mm; a scanning angle of 80 degrees within the plane in which it is scanning; and can be operated at scan rates up to 100 Hz. The recently introduced VQ-250 model from Riegl offers still higher PRF values (up to 200 kHz) and scan rates (up to 120 Hz) and it also has a larger scan angle (of 100 degrees). Furthermore Riegl has introduced a powerful new VQ-250 model that is designed specifically for use in mobile mapping. It provides a “full circle” 360 degree scan within its 2D scanning plane and can measure ranges up to 200 m (with 80% reflectivity) with PRF values up to 300 kHz and scan rates of 100 Hz, while still maintaining an accuracy of +/- 10 mm [Fig. 8].

By contrast, Optech does not sell its in-house-built laser scanners as separate products to system integrators and suppliers in the manner of SICK and Riegl. Instead it incorporates its 2D laser scanners to form part of its own LYNX mobile mapping system. The laser scanners that are used in its LYNX V200 system provide a “full circle” 360 degree scan; a PRF of up to 200 kHz; a scan rate of up to 200 Hz; and a range accuracy of circa +/- 10 mm [Fig. 9].

Mention should also be made in this account of the Velodyne HDL-64E High Definition Lidar [Fig. 10] that was developed for use by competitors in the DARPA Urban Challenge for unmanned vehicles of 2007. Indeed it was used by five of the top six finishing teams in that event. This unique 3D laser scanning device is based on a battery of 64 individual laser ranging units that are placed at specific fixed angles to provide a 26.8° angular spread within the vertical plane, thus eliminating the need for the vertical mechanical (angular) motion of the single laser rangefinder that is normally used in a terrestrial 3D laser scanner. The HDL-64E system also features high horizontal rotation rates (in azimuth) of the vertical bank of laser rangefinders as a whole around the vertical axis of the unit, at up to 15 Hz, with an angular resolution of 0.09°. The Class 1 lasers that are used in the HDL-64E instrument operate at the wavelength of 905 nm with a 10 ns pulse width. The ranging accuracy is claimed to be +/- 2.5 cm for distances of 50 m and 120 m with reflectivities of 10% and 80%, respectively. The data collection rate of 1.8 million measured points per second of the latest S2 version of the HDL-64E scanner instrument is really quite phenomenal.

The positioning systems that were used on the vehicles that took part in the DARPA Urban Challenge were completed with the addition of an integrated DGPS/IMU unit. A few examples of the results that can be achieved using this system for mapping purposes have been published. A recent announcement from Velodyne mentioned that “the HDL-64E lidar is currently in use capturing 3-D highway data for multiple states in the U.S.”. Furthermore various mobile mapping cars that have been equipped with the Velodyne HDL-64E unit on their roofs have been sighted and photographed, with the photos being published on the
Flickr Web site. However, no mapping company or organisation has yet admitted to its use of these systems, despite their obvious potential for 3D mapping and terrain modelling applications. Currently an HDL-64E Lidar is being used in conjunction with a multiple video camera system by the Real Time Race company from the U.K. to acquire the elevation and image data that is needed to form detailed 3D digital terrain models of Formula One race courses. These models will be used both for video games and during the live TV coverage of actual races.

Positioning (Geo-referencing) Devices

A dual-frequency survey- or geodetic-grade GPS or GNSS receiver remains the primary device that is used in mobile mapping systems for the determination of the absolute position of the moving vehicle and its imaging (camera) and ranging (laser scanner) devices. There are a large number of suitable GPS/GNSS receivers available from Trimble, Topcon, Leica, NovAtel, Javad, etc. that can generate the survey-quality positional data that is required. Invariably the GPS or GNSS receiver will be operated in differential mode relative to a suitable local base station or using a global DGPS service such as Omnistar. Indeed solutions based on such global services or on national monitoring networks (such as CORS) are largely replacing the use of such local base stations.

A number of mobile mapping systems feature a second GPS receiver with its antenna placed at a known distance (or base line) from that of the primary GPS receiver. The difference in position that this secondary receiver gives with respect to the primary receiver using the carrier phase observations from both receivers gives a very accurate measurement of the vehicle’s heading, even when the vehicle’s dynamics are low. However, since so much mobile mapping takes place within urban areas with tall (high-rise) buildings or in areas with dense tree canopies – where observation of the GPS or GNSS satellites may be restricted (giving rise to a weak geometry) or completely lost – the use of an inertial measurement unit (IMU) and an odometer (or distance measuring instrument) to provide additional positional information in these situations is almost standard.

There are a large number of IMU devices that can generate a continuous stream of position and orientation data when the GPS or GNSS satellite signals are unavailable. However, confining the present discussion to those that are most used in mobile mapping systems, three main types can be identified. (i) Those that use ring laser gyroscopes (RLG) are the most accurate type. However, they are expensive to manufacture, so their use is confined to those applications that demand the very highest accuracy. (ii) Fibre Optic Gyroscopes (FOG) employing long coiled optical fibres as an alternative to the optical blocks or rings of the RLG give a very acceptable accuracy and, since they are less expensive, they are widely used in the current types of IMU utilized in mobile mapping. (iii) Those gyroscopes that are based on Micro Electro-Mechanical Systems (MEMS) technology utilize tiny quartz tuning forks as sensors that are integrated on to silicon chips. They are the least expensive type. While they are also the least accurate, they are still sufficiently accurate for many purposes. So they are coming into more widespread use in mobile mapping applications. Two of the best known system integrators of the IMUs that are used in mobile mapping systems are (i) Applanix, which is a Trimble company based in the Toronto area in Ontario, Canada and produces its widely used POS LV sub-system (Fig. 11); and (ii) IGI from Kreustal in Germany which produces its TERRAcontrol sub-system. The Applanix POS LV systems use either MEMS gyroscopes in Models 220 and 420 or RLG gyroscopes (in the Model 610), while the IGI TERRAcontrol uses FOG gyroscopes. Other suppliers include Crossbow, located in San Jose, California, which supplies GPS-aided inertial systems mainly based on MEMS technology; IMAR, based in
This small specialist company, which is based in the small town of Bingham, near the city of Nottingham in the U.K., has acted as a system integrator in developing its portable StreetMapper system specifically for mobile mapping use when mounted on a suitable vehicle [Fig. 12]. The company has developed this system in close collaboration with the German systems supplier, *IGI*. For use in the StreetMapper, IGI supplies its TERRAcontrol DGPS/IMU system - which is derived from the AEROcontrol unit that it builds for use with its LiteMapper airborne laser scanning system and with a wide range of airborne digital imagers. The dual-frequency GPS receiver can come from any one of several suppliers. 3D Laser Mapping supplies the hardware and software solutions that are used for the mission planning, the control of the laser scanners and the data storage within a StreetMapper system. The control unit and its computer are housed in a cabinet that is mounted inside the mapping vehicle.

Until now, the multiple laser scanners that have been used on StreetMapper systems have been supplied by *Riegli*. On most existing StreetMapper systems, between two and four of the older LMS-Q220 scanner units (with their 150 m range) have been fitted on a roof rack, together with the IMU and the GPS antenna. However the latest StreetMapper 360 systems utilize the newer Riegli VQ-180 or VQ-250 units, the former having a 100 degree FOV and a range of up to 150 m; the latter giving a full circle (360 degree) scan and ranges up to 300 m. A choice of video or digital still frame cameras from different manufacturers can be supplied in order to generate the higher quality images that will be needed to supplement the laser scanned data. Touch screen LCD displays installed on the dashboard of the vehicle are used for the display of the captured data. On the software side, IGI also contributes its TERRAOffice software (which is derived from its AEROoffice package) for the processing of the IMU data, while the differential GPS data is processed using the Graf-Nav package that is supplied by the Waypoint division of *NovAtel*, which is based in Canada. The TerraScan/ TerraModeler/ TerraMatch suite of programs from *Terrasolid* in Finland is then utilized for the processing of the laser scan data and its transformation into the final 3D elevation model data.

The StreetMapper system has been supplied to a number of international customers, including, most recently, *Geomaat* (Netherlands), *Transport & Road Research Institute* (Lithuania), *Geokosmos* (Russia); *Tecdawn* (China) and *TerraMetric* and *GeoDigital* (U.S.A.). A StreetMapper system has also been used extensively by *Halcyon*, a large engineering consultancy company, to carry out corridor surveys along roads for high-way asset management and to capture street level data in city centres in the United Kingdom.

**Topcon**

Topcon Positioning Systems has introduced its mobile mapping system – which is called the *IP-52* Integrated Positioning System [Fig. 13] – to the market in the spring of 2009. However, when the company announced during this introduction that “more than 400 units are currently in use world-wide”, it was only too obvious that it had indeed been supplying these systems for some time – mainly, it seems, to *Google Inc*. The IP-52 system includes a Topcon dual-frequency 40-channel GNSS receiver operating at 20 Hz, which is coupled to a Honeywell HG1700 tactical-grade IMU based on a ring laser gyro (RLG) that is operating at 100 Hz. The resulting DGPS/IMU position-al data is supplemented by that generated by a wheel-mounted odometer with an angular

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**3D Laser Mapping**

*Fig. 11 – The main components of an Applanix POS LV 420 DGPS/IMU system comprising (from left to right) the primary Trimble GPS receiver; the secondary Trimble GPS antenna; the black electronics cabinet in the centre of the picture that contains the POS LV system controller and computer; and the IMU at far right. In the background is the odometer with its wheel encoder and its attached rod that carries the cables to the controller.*

*Fig. 12 – (a) A StreetMapper mobile mapping vehicle. (b) The various imaging, laser scanning and positioning elements of a StreetMapper system that are mounted on a roof rack situated at the rear of the vehicle. (Source: 3D Laser Mapping)*
encoder operating at 30 Hz to complete the overall positioning capability for the IP-S2 system. Besides these positioning devices, the imaging and laser scanning capabilities of the IP-S2 are based on well-known units that are available off-the-shelf. They include the Ladybug multi-camera unit from Point Grey Research that carries out the 360 degree panoramic imaging with framing rates of up to 15 frames per second. The laser scanning that is carried out using the standard configuration of the IP-S2 is provided by three Sick LMS 291 scanners operating at 75 Hz. One of these laser scanners is pointing directly forwards (or backwards) towards the road in front of (or behind) the vehicle, while the other two scanners point to each side to provide a continuous series of range or elevation profiles within the vertical plane. All of these imaging and scanning devices send their data to a central control box which then passes it via a high-speed FireWire-B (IEEE1394-B) link to the PC that is mounted in the vehicle for the recording and processing of the data. An LCD display screen allows the vehicle's crew to monitor the connectivity and operation of all the various positioning, laser scanning and frame imaging devices.

In the version of the system that is used in the Google Street View vehicles, the Ladybug multiple camera has been replaced by Google's own multiple camera system [Fig. 5], which is based on the use of Elphel digital frame cameras. Although the IP-S2 system has only been offered for sale by Topcon quite recently, already an example is in operation by the Geodis surveying and mapping company based in Brno in the Czech Republic.

Mitsubishi

Another Japanese system supplier is the Mitsubishi Electric Corporation, whose IT Space Solutions Department showed its MMS (Mobile Mapping System) [Fig. 14] at the Intergeo trade fair held in Karlsruhe, Germany in September 2009. This product has been developed jointly by staff members of Waseda University in Tokyo in collaboration with Mitsubishi since 2006. Several examples are already in use in Japan. The system is being offered in three different versions. (i) The most basic version is the MMS-A, which has three roof-mounted GNSS receivers arranged in a triangular pattern; an IMU; an odometer; and a sensor control box. This version is being offered mainly as a vehicle positioning device, with the choice of cameras and laser scanners and their integration being left to the customer. (ii) The second version is the MMS-S which is offered with two video cameras and two laser scanners in addition to the positioning devices included in the basic MMS-A version. (iii) Finally the MMS-X version is offered with multiple (up to 6) cameras and (up to 4) laser scanners, again in addition to the positioning instrumentation included in the

Trimble

The mobile mapping systems that are being supplied by Trimble's GeoSpatial Division were developed originally by the Geo-3D company, which is based at Brossard, near Montreal in Canada, and was acquired by Trimble in January 2008. Its main product has been its Trident-3D mobile mapping system. This has been fitted on a variety of different vehicles and in a number of different configurations as specified by the customers. Digital video and still frame cameras from various suppliers have been fitted – including, in one case, the use of a Redlake multi-spectral camera – while the laser scanners that have been used have been supplied by SICK and Riegl. The DGPS/IMU systems that are used for geo-positioning have been the POS LV units supplied by Applax (another Trimble company), including Trimble GPS receivers. The system controller and rack-mounted computers that form parts of the overall system were built-up by Geo-3D, which has also supplied the distance measuring instrument (DMI). Various display options were also offered by Geo-3D. The latest version of this vehicle-based mapping system is now called the Trimble Cougar system [Fig. 15]. Besides the hardware aspects of the overall system, Geo-3D had also developed a series of software packages for use with the Trident-3D system. These have included the Kronos package for survey data acquisition; Trident-3D Analyst for data extraction and processing, including the semi-automatic detection, recognition and extraction of objects such as road signs; and Trident-3D Vision for image viewing and analysis.

MMS-A version. In the literature that accompanied this introduction, the supplier of the dual-frequency GNSS receivers was stated to be Trimble; the IMU was from Crossbow, using a FOG gyroscope supplied by Japan Aviation Electronics; the frame cameras were supplied by IMPERX from the United States; while the laser scanners were the ubiquitous LMS 291 model from SICK.

The majority of customers for the Trident-3D mobile mapping system are agencies that are involved in road surveys, including federal, state, provincial and municipal departments of transport and a number of engineering companies that provide services to these agencies. In total, over 50 Trident-3D systems have been sold, the majority in North America. However around a dozen are in operation in Europe, principally in France and Belgium.

Optech

Optech, which is based near Toronto in Canada, entered the field of mobile mapping towards the end of 2007, when it released a completely new product, called the LYNX Mobile Mapper [Fig. 16]. This includes a purpose-built spinning laser profiling system that is designed specifically for attachment to standard vehicle roof racks with mounts for two of these laser scanners and two (optional) calibrated digital frame cameras in its standard configuration. The LYNX system also includes an Applax POS LV sub-system, complete with its IMU; a dual-frequency GPS receiver and antenna; and a Distance Measuring Instrument (DMI), for coordinate positioning purposes. The laser scanners that are used in the LYNX system are built in-house by Optech and utilize a Class I laser as the basis for their laser rangefinders. They have a maximum range of 100 m; a full cir-
At the time of its introduction, Optech announced that LYNX systems had a higher Pulse Repetition Frequency (200 kHz v. 100 kHz); and a higher – the V100 and V200. The latter gives an increased range (200 v. 100 m); and a higher scan rate (200 Hz v. 150 Hz) than the former (which is essentially the LYNX in its original form).

At the time of its introduction, Optech announced that LYNX systems had already been supplied to two European companies – the Infoterra mapping company based in the United Kingdom and the Sineco company in Italy. Since then, further systems have been sold to TopScan in Germany and Teccon in Belgium. Still more systems have been supplied to various North American users, e.g. to Aerial Data Service. Michael Baker, WH Pacific, Sanborn, Surveying & Mapping (SAM) Inc. and McKim & Creed in the U.S.A. Highway and railway infrastructure surveys and urban modelling surveys appear to be the main applications that have been undertaken by these mapping companies using their LYNX systems.

III – Service Providers

The author is very well aware that there are numerous small and large companies in the more highly developed countries that operate individual mobile mapping vehicles, offering their services especially to those agencies that are concerned with highway management and maintenance. However the principal emphasis in this section will be on the technologies being used by those companies that are carrying out street-level imaging and mapping operations on a regional, national and international scale.

Tele Atlas

Tele Atlas is a Dutch-owned mapping company that is based in the town of s-Hertogenbosch in the Netherlands. Originally an independent company, in July 2008, it was bought by and became a subsidiary of the TomTom company, which is a major Dutch supplier of car navigation systems. In practice, Tele Atlas still supplies digital map data to a wide spectrum of users besides TomTom. These have included Google, which, in October 2009, decided to stop using Tele Atlas map data for the U.S.A. – which it will now generate from its own mobile mapping activities. However Google will still continue to use Tele Atlas map data in other countries. The Tele Atlas company has a large centre in Ghent, Belgium from which it directs its European mobile mapping operations and a similar centre in Lebanon, New Hampshire for its operations in North America. The processing and analysis of the data that has been acquired by its fleets of mobile mapping vehicles is carried out partly in Poland and partly in Noida, a suburb of the Indian capital, New Delhi. In fact, the latter data centre is owned and operated by an Indian company, Infotech Enterprises, which bought the centre from the Indian subsidiary of Tele Atlas in 2005 and received a long-term contract from Tele Atlas to process its digital map data as part of the deal. See the following Web page:- www.teleatlas.com/WhyTeleAtlas/Pressroom/PressReleases/TA003239

Tele Atlas had entered the mobile mapping field in the second half of 2004 using the technology that had been developed by a Polish company, PPWK GeoInvent. By mid-2005, Tele Atlas had over 20 vans in operation in Europe, 13 of which were large Volkswagen camper vans to allow the crews to operate in more remote and less populated areas [Fig. 17]. In October 2005, Tele Atlas bought the GeoInvent company. Each of these Tele Atlas vans is equipped with either 4 or 6 digital video cameras in various configurations depending on the area being surveyed [Fig. 2]. The frame images that are generated by these cameras have a format size of 1,200 x 960 pixels and are acquired at the rate of three frames per second when travelling at normal speeds on the roads. The forward-pointing cameras can generate overlapping 3D stereo-images, which allows them
to be used as photogrammetric source material. For precise positioning, each van is equipped with a GPS unit operating at 5 Hz, which makes use of Fugro’s OmniSTAR wide-area differential GPS service employing satellite broadcast techniques. For use in tunnels and urban canyons, where the GPS signals are either lost or are much restricted, the vans are equipped with a single-axis gyroscope recording at 100 Hz that provides directional (heading) data and an odometer attached to one of the rear wheels of the vehicle. The image and positional data are continuously recorded on the PCs that are mounted in the back of the van. This data is also displayed continuously on monitor display screens for the crew to check their operation.

A similar fleet of smaller Toyota vehicles was then developed and brought into service in North America. Besides a set of digital video frame cameras, similar to those being used in Europe, most of these vehicles are equipped with twin 2D laser scanners from SICK that generate a continuous series of range profiles across the surrounding landscape at right angles to the vehicle’s direction of travel. Besides which, numerous photos that have appeared in the media also show that many of the Tele Atlas vans that are in use in North America have been equipped with additional mast-mounted Ladybug panoramic cameras providing 360 degree panoramic images of the road and its surroundings from the moving vehicles. Photos from the same media sources also show that at least some of the survey vans are equipped with full-blown inertial measuring units (IMUs) rather than the single-axis gyroscopes mentioned above. Besides the two large fleets of vans that are in operation in Europe and North America, an additional but much smaller number of vans have been deployed in south-eastern Asia – in Taiwan, Singapore and Thailand. According to press reports, in total, more than 50 mobile mapping vans are currently being operated by Tele Atlas.

**NAVTEQ**

NAVTEQ is a large American mapping company with its headquarters in Chicago. In December 2007, the company was purchased by the Finnish Nokia organisation, which is a major supplier of telecom networks and cell phones on a world-wide scale. Nokia also provides its Ovi Maps product (previously called Nokia Maps), which can be downloaded free by those customers who have purchased the company’s smart-phones that are equipped with a suitable processor, display screen and operating system. However, besides supplying digital map data to Nokia for incorporation in these products, NAVTEQ appears to operate in a fairly independent manner. Like Tele Atlas, NAVTEQ still provides digital map databases for the navigation systems that are being installed in the cars that are being built by several different manufacturers. Besides which, the company also supplies digital map data for use in portable GPS sets and in the Internet-based map applications that are provided by Microsoft (Bing Maps) and Yahoo (Yahoo Live Maps). NAVTEQ has a large map data production centre located in Fargo, North Dakota, that is supplemented and supported by a network of smaller national and regional offices world-wide.

For a number of years until recently, revision of the NAVTEQ map databases of road networks had been carried in a relatively simple manner using survey cars with a crew of two. These cars were equipped with a roof-mounted GPS receiver and a laptop computer that had been loaded with the map database (stored as vector files) for the local area that was being surveyed or revised. While undertaking the survey or revision operation, the successive positions of the survey car that were being measured by the DGPS service were being recorded and plotted continuously on the map that was being displayed on the laptop computer’s screen. All the data regarding changes or updates to the map data were being recorded simultaneously as audio files by the surveyor/co-driver using a headset and microphone. Any supplementary positional data that was required for the location of specific objects could also be entered into the computer by the surveyor using a hand-held controller or a digital data tablet. Thus initially no digital video or still camera images were being acquired for map revision purposes. However, by 2006, a digital video camera had been installed in many of the NAVTEQ survey cars to provide a video record of each survey trip.

In 2008, a new fleet of mobile mapping vehicles (comprising cars and SUVs) was introduced by NAVTEQ. Each of the vehicles in this fleet is equipped with an array of six or eight digital video cameras [Fig. 18]. These are placed on a specially designed tray that is mounted on the roof of the vehicle and they are enclosed in a transparent Perspex cover. Each of the six (or eight) cameras acquires its images every 5 metres; in total, they provide a 270 (or 360) degree coverage of the road and its surroundings as seen from the mapping vehicle at each successive position where the images are being acquired. The new vehicles are also equipped...
with an **Applanix** POS LV IMU and a **Trimble** GPS receiver, which utilizes a differential GPS service. The resulting measured image and positional data are recorded on a powerful PC. The data tablet and the head-set/microphone equipment that allows the audio recording of the features being described by the surveyor/co-driver while riding in the vehicle appear to have also been retained in these recently introduced mobile mapping vehicles. On 7th December 2009, NAVTEQ announced that it would be supplying its street-level imagery to Microsoft for incorporation in its new “Bing Maps Streetside” product.

**Google**

Google’s **Street View** is a special feature of the well-known Google Maps and Google Earth services that can be accessed via the Internet. The Street View software gives access to the panoramic images that have been acquired at intervals of 10 to 20 m along the streets of many cities within the more highly developed countries of the world – in the U.S.A., Western Europe, Japan and Australasia. The service was first introduced with coverage of a few cities in the U.S.A. in May 2007. The American coverage has been continually extended since then. Just over a year later, in July 2008, Street View was introduced to Europe, in the first instance, for those towns in France that were involved in hosting the Tour de France. Later that year, further coverage of a number of French cities was added, together with the initial coverage of certain cities in Spain, Italy, the Netherlands and the U.K. Since then, work has continued intensively and on a massive scale to extend the coverage to ever more cities and to expand the coverage of the streets within each city that is being covered.

The numbers and types of mobile mapping cars that have been used to acquire Street View imagery in different countries has varied considerably from country to country. At the start of the programme, the imaging technology that was used also varied considerably. Initially, in 2007, much of the imagery of the first batch of cities that were covered in the U.S.A. had been collected by the **Immersive Media** company on contract using its distinctive Dodeca multiple camera systems. However this contract terminated at the end of that year (2007). Since then, Google has been collecting the required image and positional data using its own vehicles, steadily expanding its fleets of mobile mapping cars for the purpose. In the U.S.A., Australasia and Japan, the cars were at first equipped with Ladybug multiple cameras [Fig. 19(a)]. However, since then, these have been replaced by the now standard nine-camera system mounted on a sturdy mast that is itself attached to a roof rack that is fitted to the roof of the car [Fig. 19(b)]. The mast and camera system can be folded down on to the roof rack when not in use.

As discussed previously, the nine digital cameras from **EpiPhy** that make up the Google multiple camera system comprise eight that, in total, provide a 360 degree panorama in the horizontal plane, while the ninth camera points vertically upwards to record the undersides of bridges and overpasses and the top surfaces of tunnels. Each car is equipped with a combined DGPS/IMU system that has been supplied by **Topcon**, together with a wheel-mounted odometer that, in conjunction with the IMU, can help establish position wherever GPS coverage is poor or has been lost in tunnels or within high-rise urban areas. The Google Street View cars also feature a pair of **SICK** LMS 291 laser scanners that continuously measure a series of range or elevation profiles on either side of the mapping vehicle. A third SICK scanner measures the road surface in front of the vehicle. Besides the car-based mobile mapping systems, Google has also introduced a number of pedal-powered tricycles (trikes) that are equipped with a similar set of cameras, laser scanners and positioning equipment [Fig. 19(c)]. These are being used for data collection in areas such as pedestrian precincts and public parks and along cycle tracks where cars cannot be operated.

**Immersive Media**

This Canadian company, which is based in Calgary, Alberta, specializes in “spherical immersive video”. Its activities include making “immersive” films of underwater activities (such as viewing coral reefs and whales) and sporting events (surfing, basketball and football) and for tourism purposes. The company’s collection of street-level imagery began in 2006 with its own in-house “Geolmersive City Collect” project to acquire street-level imagery of U.S. cities. This was followed by its work on image data acquisition for Google’s Street View service during 2007. With regard to these mapping/imagining activities, they were executed using its own Dodeca 2360 “Spherical Video System” with its 11 individual cameras capturing image data simultaneously [Fig. 4]. This multiple camera is mounted on a mast that is fixed to a roof bar which is mounted on a Volkswagen New Beetle car [Fig. 20]. As with other mobile mapping systems, each car uses a DGPS, a gyroscope and an odometer for positioning and geo-referencing purposes. According to press releases issued last year (2008), Immersive Media is still collecting street-level imagery for certain cities in North America for local customers using its small fleet of these mapping cars. A similar small fleet of cars using the same technology is operated in Europe by the **TX Immersive (TXI)** company, which is based at the Shepperton film studios in London.

**Other Service Providers**

**(a) Imaging & Mapping Applications**

There are quite a number of much smaller commercial companies that operate in the same general area of imaging and mapping as those discussed immediately above. Needless to say, being very considerably smaller and not having the same financial resources, they cannot offer the same international coverage as Google, NAVTEQ and Tele Atlas. Thus they attempt to serve national and local government and commercial customers and to operate in certain niche markets. An example is the **Facet Technology**, which is based in Eden Prairie, Minnesota. Using its vehicles equipped with cameras and laser scanners, it has developed its SightMap products that provide the digital map content for nation-wide road networks within the U.S.A., including road maps, and data for use in location-based services, vehicle navigation and portable positioning devices. Further detailed information about its activities can be obtained through an inspection of the company’s Web site **- www.facet-tech.com**. It is also worth noting
reports that Facet Technology collected the imagery for Microsoft’s street-level photography [Fig. 21] that appeared in a somewhat experimental form in February 2006 for parts of the cities of San Francisco and Seattle. See the following preview or demonstration Web site: http://preview.local.live.com. Indeed Microsoft has just announced (on 2nd December 2009) that it will be introducing an enhanced version of its Streetside photography under the title of “Bing Maps Streetside” for 56 metropolitan areas in the U.S.A. As noted above, the new imagery will be supplied by NAVTEQ.

Another example of an American company that is acquiring street-level photography is Earthmine Inc, which is based in Berkeley, California. This company uses SUVs equipped with a stereo-camera system whose design has been licensed from Caltech-JPL [Fig. 22]. This system uses four pairs of cameras, with each pair mounted vertically and spaced 90 degrees apart horizontally. The vehicles are also equipped with the NovAtel SPAN DGPS/IMU system for position location. Each pixel in the finally processed images has 3D (X, Y, Z) coordinates. At the time of writing this article, Earthmine is reported to have imaged or mapped 12 metropolitan areas, mainly in the western part of the United States. On 8th December 2009, Earthmine also announced its partnership with Aero-Metric, a large American aerial mapping company, in respect of the value-added resale of its street-level panoramic image data. More details on these developments can be obtained from the company’s Web site www.earthmine.com.

Another relatively small company that is also engaged in this general area of photo-imaging and mapping of urban areas in the U.S.A. is EveryScape www.everyscape.com, which is based in Waltham, Massachusetts. Yet another similar company concerned with street-level photo-imaging is Mapjack http://mapjack.com, which is based in San Francisco, California and has given assistance to various companies located in Sweden www.hitta.se/gatubild; Canada www.canpages.ca; and Thailand to enter this particular field. Within Europe, similar companies that undertake the photo-imaging and mapping of urban areas are SeeTy Ltd, www.seety.co.uk which is based in London; NORC www.norc.at which acquires street-level imagery of towns in Austria and Eastern Europe; and CycloMedia www.cyclomedia.nl in the Netherlands – whose activities in the mobile mapping field have already been covered in an article written by the editor-in-chief (Eric van Rees) of GEOInformatics magazine which was published in the March 2009 issue (Vol. 12, No. 2) of the magazine.

(b) Road & Rail Maintenance & Management

The other main group of commercial companies that are engaged in mobile mapping operations are those that are undertaking surveys of the road infrastructure for maintenance and management purposes on behalf of national and local government highway agencies and departments of transport. In recent years, these surveys have been extended to cover rail networks as well. Quite a number of the companies that are undertaking this type of work have already been mentioned above in the context of those customers who have purchased systems from the various systems suppliers. However there are many others that have developed their own systems in-house. A few representative examples within Europe are Omnicom Engineering www.omnieng.co.uk/index.php?id=47, which is based in York in the U.K. and is much engaged in rail as well as road surveys; and Eagle Eye Technologies www.ee-t.de from Hamburg and 3D Mapping Solutions GmbH www.3d-mapping.de/ dynasite.dhtml?isd=4324 from the Munich area in Germany. In Belgium, both the geoVISAT company www.geovisat.eu and the GeoAutomation company www.geoautomation.com/en/technology.html offer mobile mapping services, as does the GISPRO mapping company www.gispro.pl/EN/aktualnosci. dhtml from Szczecin in Poland. There are many others! In the U.S.A., there are still more. A few representative examples are EarthEye www.eartheye.com/Mobile from Orlando, Florida; Lambda Tech www.lambdatech.com/ gpstech.html from Fort Wayne, Indiana with its GPSVision vans; Blue Dasher Technologies www.bluedashertech.com which is based in Miami, Florida; Mandl Communications Inc. www.mandl.com/systems/systems.php from Madison, Wisconsin; and the Transmap Corporation http://74.218.19.11, with its On-Sight mapping vans, which are based in Columbus, Ohio and Tampa, Florida.

Summary & Conclusion

As mentioned in the introduction, the development of mobile mapping systems started quite a long time ago. Initially these developments were quite modest and were not of much interest to the mainstream mapping industry. However, over the last five years, gradually the corridor mapping of highways and rail networks and the 3D modelling of cities have become very important applications – though at first, these activities were carried out mostly using “one-off” mobile mapping systems built by the operators. Now the demand has grown to the point that there are several system suppliers offering COTS products to satisfy this particular market. Then, starting three or four years ago, the increasing demand for digital road navigation data and cartographic (vector) data that could be used in personal location devices resulted in Tele Atlas and NAVTEQ entering this field with their fleets of mobile mapping vehicles. Finally, over the last two years, the Internet giants (Google and Microsoft) have created such a huge demand for visual street-level image data that a very large number of mobile mapping vehicles have been brought into operation to satisfy it, especially by Google.

From this survey of current mobile mapping systems, it is also apparent that, not only is the technology now well established, but currently there are two main categories into which the resulting systems fall, largely depending on their intended applications and the quite different accuracy specifications that they have to meet. (i) On the one hand, there are those systems that are being used for the acquisition of digital images for street-level image display purposes and for cartographic mapping applications. (ii) On the other hand, there are those systems that are being used to collect data about the road and rail infrastructure that is needed for engineering, maintenance and management purposes. Clearly the accuracy requirements for the map or survey data that has to be measured can be substantially different in each case, with the second category usually being much more demanding in this particular respect.

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