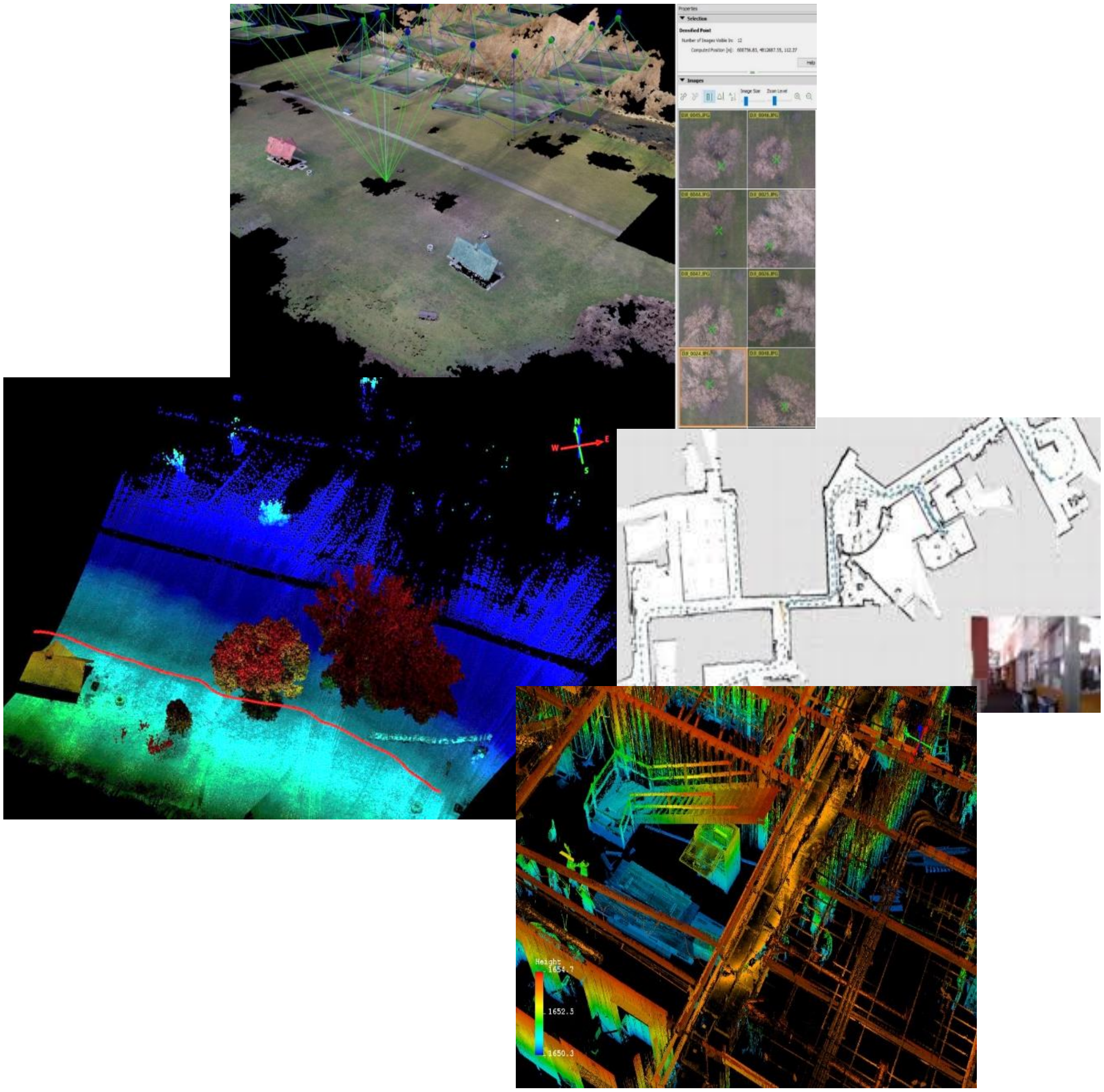

DIGITAL TWIN 3D (OUTDOOR & INDOOR) MAPPING REPORT

Smart Campus Integrated Platform Development

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Table of Contents

Digital Twin 3D Mapping Report
Smart Campus Integrated Platform Development

Sub-Project Title:	SP4: Digital Twin Development		
Project Phase:	SP4	**Estimated Sprint Completion Date:**	Aug 31, 2020

Deliverable	June & August 2020	**Project Lead**	Ahmed Shaker
Project Description	Remote Sensing to Support Smart Campus Management		

1. Overview

This is a highlight report about the conducted in-depth literature review for *Outdoor* & *Indoor* systems and mapping approaches entailing: pros and cons, different sensors used, associated cost, time for data collection and processing, data structure and format, etc. The report provides an introduction about 3D mapping, the different scanning approaches (Passive and Active), direct and indirect georeferencing mapping approaches, advantages and disadvantages of different systems and approaches. In addition, the report covers an in-depth categorization of the LiDAR 3D mapping systems modes of operations and detailed specifications for a number of the state-of-the-art 3D mapping systems both for outdoor and indoor systems. The report concludes with key findings and recommendations.

2. Introduction

Context-aware analysis and visualization for accurate 3D mapping models is one of the fundamental foundations for the creation of smart campus digital twin (DT). The mapped environment can be classified as indoor or outdoor. The main differentiator between both environments is the ability to receive global navigation satellites systems (GNSS) signals. The GNSS signals can subsequently be used for positioning and mapping. The outdoor environment generally allows for the GNSS signals reception while the indoor environments lacks this ability. Thus, the algorithms and workflows along with mapping systems requirements used for indoor mapping differ from that used for outdoor mapping. The GNSS allow for absolute localization and mapping while the indoor mapping generally provides relative localization and mapping. It is worth noting that there are specific procedures that can be followed to link the mapped indoor environment to the outdoor environment to offer an absolute localization and mapping of the indoor environment. The usage of these specific procedures are part of the ongoing requirement gathering process with other project domains stakeholders.

3. Outdoor Mapping

Three-dimensional (3D) Maps are integral component in many traditional applications such as geographic information systems, resources monitoring, surveying, and navigation as well as in many new indoor and outdoor applications, such as smart cities, autonomous vehicles, asset management, virtual and augmented reality, as-built drawings, etc. Thus, the end-user segments that require 3D maps are exponentially expanding and it is anticipated to expand even more in the future.

The pace of technological advances in 3D scanning sensors is rapidly accelerating. Active and passive sensors are the two main sensor types of remote sensing sensors (RSS) that are typically used for 3D mapping. LiDAR scanners are considered the main active senor type while optical cameras are the main passive RSS. LiDAR scanners are considered the standard sensors used for 3D scanning. Some factors that affect the quality of the resultant 3D scan are; the scanned environment, the LiDAR sensor capabilities, the targets reflectivity, the algorithms used to stich multiple scans together and the data acquisition mode. The higher rate and volume of data acquisitions due to the sensors technological advances add to the challenge of the 3D mapping. Subsequently, 3D mapping process needs carful attention.

There are two main approaches in the 3D mapping process, the direct and indirect georeferencing. The indirect georeferencing requires the usage of ground control points (GCPs) – points in the environment with known coordinates- to define the relation between the mapped environment and the RSS intrinsic and extrinsic parameters. The direct georeferencing (DG) in contrast, does not require GCPs to build the relation between the mapped environment and the RSS intrinsic and extrinsic parameters. The direct georeferencing uses a GNSS and an inertial navigation system (INS) sensors instead to build the relation between the RSS and the mapped environment. The position and orientation of the RSS can be calculated through the integration of the GNSS/INS data measurements. Since the direct georeferencing approach does not require the usage of GCPs and is more suited with the irregular nature of the LiDAR data (reflective targets are needed if the indirect geo referencing approach is to be used with LiDAR data), it is considered a more practical and time-efficient approach.

The mapping system in the direct georeferencing mapping approach consists mainly of three components: 1) the active and/or passive RSS to sense the environment; 2) the GNSS/INS system to allow the DG; and 3) the data management unit for control, power and data acquisition storage. The mapping system is mounted on a platform which defines the acquisition mode. Single/multi-LiDAR scanners are used in LiDAR-based mapping systems. The acquisition mode may be either Terrestrial Laser Scanning (TLS) or Airborne Laser Scanning (ALS). More specifically, TLS can be categorized according to the platform onto which the mapping system is mounted, as being either a stationary STLS (usually a tripod) or Mobile Mapping Systems (MMS) (a kinematic platform, typically a vehicle or on an operator backpack); the ALS platforms may be either a manned aircraft or an Unmanned Aerial Vehicle (UAV).

The mapping system characteristics differ significantly according to the intended acquisition platform used. For instance, the constraints regarding the mapping system Size, Weight, and Power (SWaP) consumption are much more stringent with a UAV-based mapping system than those for a STLS. There has been a paradigm transferral in the mapping process since the introduction of MMS almost two decades ago, as it allowed for rapid data acquisition over large mapping areas that is time- and labour-prohibitive with traditional TLS. In contrast, recent advances in UAV technology, including its low cost as a mapping platform, relative ease of deployment, high maneuverability, ability to be deployed in human-risky environments and appeal to many end-user segments, could explain the rapid growth in the UAV market.

Additionally, advances in computer vision algorithms are positively affecting the 3D mapping process. One workflow for 3D mapping from optical imagery is the Structure from Motion (SfM) technique. The recent advances in SfM photogrammetric technique, coupled with its relatively low cost compared to LiDAR scanners and its ability to produce dense point clouds and comparable results, prove it to be a viable alternative. Nevertheless, one shortcoming of the SfM is its relatively low performance in poorly textured areas and places with repetitive patterns, as well as its dependency on lighting conditions and imagery-capturing geometry to produce reliable results.

3.1 LiDAR-based 3D mapping

A LiDAR scanner is an active Remote Sensing Sensor (RSS) like radar and sonar, but it uses light as the source of target illumination. The LiDAR unit emits a pulsed light beam or a continuous wave that hits the target area and reflects back. The precise measurement of the Range (R) follows one of two main methods. The first method is the accurate measurement of the Time Of Flight (TOF), which is the time interval that has elapsed between the emission of a short but intense light pulse by the sensor and its return after being reflected from an object. From this, R can be calculated, as illustrated in Equation (1). The precision of the time measurement determines the range measurement precision, as defined in Equation (2).

$$R = v.t/2 \qquad (1)$$

Where

R is the range

v is the speed of the electromagnetic radiation(very accurately known)

t is the time interval measured

And the range precision can be determined as follows

$$\Delta R = \Delta v.t/2 + v.\Delta t/2 \qquad (2)$$

Where

ΔR is the range precision

Δv is the speed of the electromagnetic radiation precision

Δt is the time interval

In the second method, the sensor emits a continuous beam of laser radiation instead of a pulse. The accurate measurement of the phase difference between the emitted wave signal and the signal received by the sensor after being reflected from the target determines the slant range to the object, as shown in Equation (3). The first method is more common.

$$R = (M\lambda + \Delta\lambda)/2 \qquad (3)$$

Where

R is the range

M is the integer number of wavelengths(λ)

$\Delta\lambda$ is the fractional part of the wavelength

The laser unit steers the light beam through a mirror or a prism mechanism to cover the vertical direction, when coupled with a controlled and measured motion in the azimuth direction (in the STLS case), a sequence of profiles around the vertical axis of the laser unit is measured and a 3D point cloud of the area around the laser unit is generated. However, if the laser unit is mounted on a moving platform, the controlled and measured motion in the azimuth direction may be substituted by the platform movement, as it covers the third dimension.

Another factor that affects the 3D point cloud generated is beam divergence. Beam divergence is an angular measure that relates the increase in the beam radius or diameter to the distance it travels after being emitted by the laser unit. Although the light beam is collimated when emitted from the laser unit, the beam will diverge as it propagates, and the divergence will affect the footprint that is measured by the beam. Thus, the measured distance will represent a wider area on the target and, in turn, will decrease the specificity of the measured distance, as it will miss any position variation within the footprint. The effect is further stressed with long-range sensors, such as those used in ALS. This explains the narrow beam divergence in the sensors used for ALS (which is typically 0.5 mrad or less), as this translates to a laser footprint of 50 cm or less at a flying height of 1000 m.

In addition, laser scanners can measure the amount of energy that has been reflected from the target after being illuminated with the scanner emitted pulse. The amount of reflected energy from each point measured constitutes the intensity as measured by the sensor. This measurement can prove valuable in a number of applications as asset management and lane marking extraction. The intensity measured depends on the target reflectivity, which affects the amount of energy reflected that can be detected by the sensor. As the target reflectivity decreases, the amount of reflected energy diminishes, thus weakening the signal returned to the sensor and deeming the target undetectable. The range and incidence angle to the target also affects the measured intensity.

Unlike 2D laser scanners that depend on the platform movement to cover the third dimension, a new type of laser scanners was introduced recently to meet autonomous vehicle industry requirements. These new LiDAR scanners are known as spinning multi-beam LiDAR scanners. Instead of having a single beam laser and a rotating mirror or prism, the new sensors have multiple beams with pairs of an emitter and a receiver for each beam. Each beam is oriented at a fixed vertical angle from the sensor origin. The multiple beams spin mechanically around a spinning axis with up to a frequency of 20Hz with Velodyne LiDAR sensors (as an example) covering a 360° Horizontal Field of View (HFOV). This builds a fast and rich 3D point cloud of the vehicle's environment, enhancing its 3D perception. Velodyne laser VLP-32c and Quanergy M8 are two examples of these sensors, as shown in Fig. 1.

(a) (b)

Fig 1: Examples of spinning multi-beam laser sensors,

a) The velodyne VLP-32c and b) Quanergy M8

Another laser scanning technology is the solid-state flash LiDAR. Unlike the previously discussed sensor data measurement mechanisms, this new technology illuminates large areas simultaneously and measures the reflected energy on a photonic phased array. The measuring mechanism is an analogous resemblance of the digital camera complementary metal–oxide–semiconductor (CMOS) sensor. The sensor does not have any moving parts and the miniaturization allows on-chip lasers. Velodyne velarray, Quanergy S3 and Leddartech M16 are examples of these sensors, as shown in Fig. 2.

It is worth noting that the current rapid increase in laser sensor technology is being driven by the automotive autonomous vehicle application domain. The solid state LiDAR sensors are a very promising technology but are not yet well-suited for 3D mapping applications, as they are specifically designed for vehicle environment grid occupancy detection and collision avoidance. As the technology advances, however, it is anticipated that the solid-state LiDAR technology will have a positively disruptive effect on the 3D mapping field.

(a) (b) (c)

Fig 2: Examples of solid state LiDAR,

a) The velodyne Velarray b) Quanergy S3 and (c) Leddartech M16-LSR

LiDAR-based Mapping platforms

The introduction of **Mobile Mapping Systems MMS** has dramatically altered the 3D mapping process since its introduction almost two decades ago. The rapid mobile terrestrial-based data acquisition and mapping of large areas in a short time has been considered a major breakthrough in the mapping field. One of the earliest research efforts in the development of a MMS is the work of the center of mapping at Ohio State University, where the MMS GPS-VAN was developed by integrating a code-only GPS receiver, passive sensors (CCD and video cameras), and dead-reckoning sensors. LiDAR-based mapping systems followed in the late 2000s and early 2010s. Large companies like TOPCON and Trimble along with medium-sized companies like OPTECH, RIEGL, MDL, SITECO, 3D LASER MAPPING and IGI are well-established suppliers of MMS for the mapping community. Examples of these high-end commercially available MMS are the OPTECH Lynx system and the Trimble MX8, shown in Fig. 3. Although these mapping systems provide a very dense accurate point cloud, they are still bulky and expensive and require skilled operators along with a lengthy time for data processing. These issues make them difficult to obtain for a wide spectrum of end-users that may need the technology.

a) b)

Fig 3: Examples of Commercial MMS,

a) Optech Lynx and b) Trimble MX8

Some of the innovative MMS that were recently developed by commercial companies are the Optech Maverick, Trimble Mx2, and Topcon IP-S3 (Fig. 4). These three MMS have a smaller form-factor, and two of them (the Maverick and the IP-S3) use one of the new spinning multi-beam LiDAR SMbL scanners. Mapping-grade MMS normally achieves sub-meter accuracy and costs ~$300 k, while survey-grade MMS achieves cm-level accuracy and typically costs ~$700 K Thus, these MMS are considered cost-prohibitive for many end-users, along with the difficulty of special considerations that are required for mounting.

a)

b)

c)

Fig 4: Examples of recently developed commercial MMS,

a) Optech maverick b) Trimble MX2 and c) Topcon IP-S3

The technological advances in LiDAR sensors coupled with the advances in the GNSSS/INS sensors prompted a number of recent research efforts to exploit the development of purpose-built mapping systems that utilize the new spinning multi-beam LiDAR SMbL scanners. This is a very new area of research, as these sensors were released only a few years ago.

The development of **UAV-based LiDAR** 3D mapping systems constitutes most of the new commercial state-of-the-art 3D mapping systems. These mapping systems typically utilize the new spinning multi-beam LiDAR SMbL scanners. This could be attributed to the compact size and light weight of the new spinning multi-beam LiDAR scanners, which prove advantageous, as they satisfy the stringent SWaP requirements for UAV deployment. UAV originated for military applications and then quickly gained utilization in civilian applications almost a decade ago. UAV can be categorized according to different parameters. The most common one used is the UAV ready-to-fly system weight, as this is the weight that is compared to the aviation regulations. The different UAV platform classes are enumerated in Table 1. Note that the UAV platforms used in civilian mapping applications generally belong to the micro and mini classes.

Table 1: UAV classes, adopted after Rehak[1]

	Mass (kg)	Range (km)	Flight Alt. (m)	Endurance (h)
Micro	<5	<10	250	1
Mini	<20-25	<10	500	<2
Close range	25-150	10-30	3000	2-4
Short range	50-250	30-70	3000	3-6
Medium-range	150-500	70-200	5000	6-10

UAVs have a number of different types and sizes, with the selection of a UAV as a mapping platform depending on several factors. The key ones that need to be considered are endurance, payload capacity, type of equipment to be deployed, take-off and landing method, cost, and ease of use. The endurance will affect how long and how far the system can be deployed, consequently defining the area that can mapped. UAVs suitable for small-area mapping and close-range photogrammetry are different from those required to suit aerial mapping of large areas. Payload capacity is another defining factor in the selection of a UAV, as this will limit the type of sensors that can be deployed on the UAV. It also defines the total system weight, which has to meet the regulations. Additionally, vibration performance and system interference will affect the type of equipment that can be used. According to UAV type, special considerations may be required for take-off and landing, which affects the UAV selection process. Cost also plays a role. Lastly, how easy the UAV is to operate and whether or not manual flying of the UAV is required likewise affects the selection process. Fig 5 shows a number of different UAV types that may be used in the 3D mapping process.

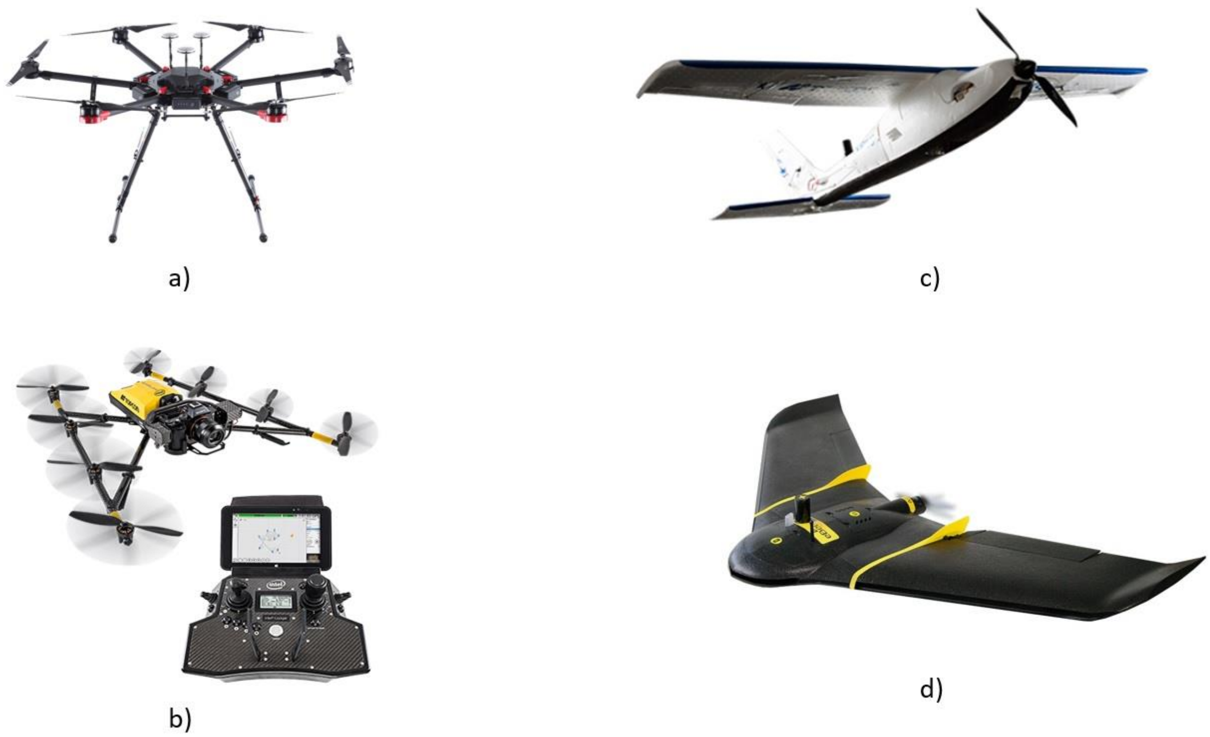

Fig 5: Examples of different UAVs types, Multirotor a) DJI M600, b) Topcon Falcon and Fixed wing c) Topcon Sirius pro, d) ebee sensefly

A number of commercial state-of-the-art UAV-ready LiDAR systems have also been developed recently. For example, Phoenix LiDAR systems developed the Alpha AL3-32, integrating the HDL-32E and a fiber-optic INS and giving a position accuracy of 1 cm + 1 ppm RMS horizontal and attitude and heading RMS errors of 0.019 / 0.074°. This system is shown in Fig. 6. In addition, Routescene developed a compact UAV LiDAR-based system known as the Lidarpod, which encompasses a HDL-32E scanner along with an RTK GNSS/INS and a radio telemetry to send the RTK corrections from the provided ground base station. The stated absolute positional accuracy is given as 4 cm at a 20 m range. Figure 7 illustrates the system.

Fig 6: Phoenix AlphaAL3-32

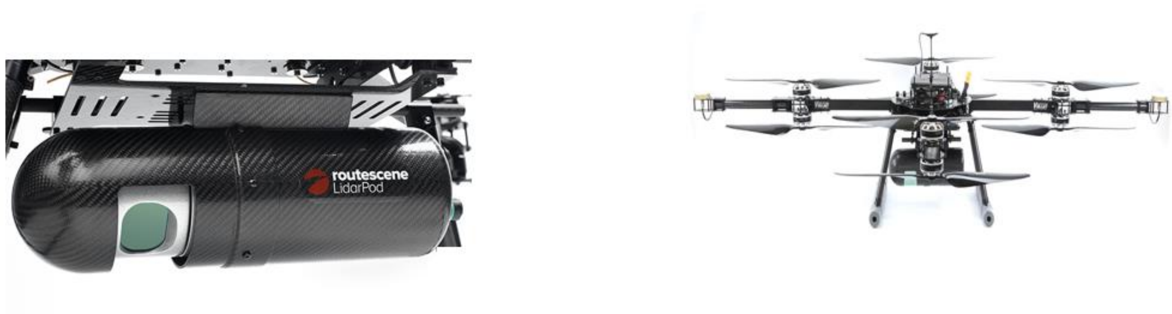

Fig 7: Routescene Lidarpod

The Yellowscan surveyor is yet another UAV-ready LiDAR-based lightweight mapping system, thus adding to the suitability of its usage on UAVs with small payload capacity. The Yellowscan surveyor system employs a VLP-16 scanner and the APX-15 GNSS/INS system, giving a positional accuracy of 5 cm (1σ at 50 m) at nadir, as shown in Fig. 8. The Rigel VUX-240 is a new LiDAR-based mapping system offered by Riegl which entails a high-end Riegl continuous waveform LiDAR scanner with a constantly rotating polygon mirror and a measurement rate of up to 1.5 million measurement/sec. It gives a reported accuracy of 2 cm (1σ at 150 m) and is shown in Fig. 9.

One advantage of purpose-built mapping systems over commercially available ones is the ease of applying modification and upgrading system components as needed. Moreover, purpose-built mapping systems tend to have substantial cost reductions compared to commercial ones. However, it is worth noting that both the few research efforts and the commercially available mapping systems were initially designed to serve one mode of operation (ULS), and so lack the flexibility and ease of deployment in the other two mapping modes (MMS and stationary).

Fig 8: Yellowscan surveyor

Fig 9: Riegl Vux-240

Static Terrestrial LiDAR Systems (STLS) is another type of LiDAR scanner that is intended to be used in stationary mode. STLS technology is considered relatively new, as its development started in the early 2000s, mainly for surveying applications. These scanners tends to have higher accuracy and richer 3D data than the MMS and ALS. Its enhanced accuracy is in the cm or even mm range. The Trimble SX10, released October 2016, has a maximum measurement range of 600 m and is one example of a recently developed STLS. It provides a reported accuracy of 2.5 mm at a 300 m measuring range. Furthermore, the Faro focus-350 is another example of an STLS with a measuring range of 350 m and a stated accuracy of 1 mm.

It is worth noting that the weight of STLS is usually around 10 kg, so the Faro focus-350 (weighing just 5 kg) is considered a lightweight STLS. Moreover, Teledyne Optech recently released (March, 2017) Polaris as a new STLS that can survey targets up to a 1,600 m range, with a stated range accuracy of 5 mm (1σ at 100 m). The scanner weight is 11.2 kg and a few of its usage applications are in civil engineering, construction, mining, geology and transportation.

STLS typically use indirect georeferencing techniques if real world coordinates are required. Another STLS recently (November, 2016) introduced by Leica is the BLK360, which has a very small form factor and is quite lightweight compared to the other scanners in the STLS category. The dimensions of this scanner are height 165 mm, diameter 100 mm, and weight 1 kg, and it has a maximum range of 60 m. The BLK360's stated accuracy is 7 mm (1σ at 20 m). All of these STLS (the Trimble SX10, the Faro focus-350, the Polaris and the BLK360) are enumerated in Fig. 10.

Fig 10: Examples of different STLS, a) Trimble SX10, b) Faro Focus-350

c) Optech Polaris, and d) Leica BLK360

Table 2 provides some attributes of a number of state-of-the-art LiDAR-based 3D mapping systems including (range, accuracy, weight, etc.) and the cost.

Mode	Brand	Model	Weight	Range	Accuracy	Cost
Stationary	Teledyne Optech	Polaris HD	11KG	125-250m	5 mm @ 100 m	~90K
Stationary	Teledyne Optech	Polaris ER	11KG	Max 750m	5 mm @ 100 m	~105K
Stationary	Teledyne Optech	Polaris LR	11KG	Max 2000m	5 mm @ 100 m	~125K
Stationary	FARO	FocusM 70	4KG	Max 70m	3 mm @25m	~98K
Stationary	FARO	FocusM 150	4KG	Max 150m	1 mm @25m	~116K
Stationary	FARO	FocusM 350	4KG	Max 350m	1 mm @25m	~132K
Stationary	Leica	ScanStation P50	12KG	Max 570m	1.2-3 mm + 10ppm depending on range	~160K
Mobile	Teledyne Optech	Maverick	8KG	Max 100m	±3cm	~300K
Mobile	Teledyne Optech	Lynx HS600	>12KG	Max 130m	Better than ±2 cm, 1 σ	~600K
Airborne	Fagerman Technologies	Scanlook:TreX	~2KG	<100m	4.7cm@50m	~85K

3.2 Structure from Motion SfM Photogrammetry

As highlighted in the previous sections, LiDAR scanners and platforms have experienced rapid technological advances in the past few years. At the same time, there has been swift progress in computer vision processes, contributing to the phases of photogrammetry (optical-based mapping) workflows. Photogrammetric principles are embedded in the SfM workflow.

Traditionally topographic mapping applications have dominated photogrammetry but require metric cameras and a number of well-established workflows. One of the main photogrammetry applications is extracting 3D information from 2D imagery, but this requires overlapping imagery. Aerial (typically using manned airplanes) and close range photogrammetry are proven mapping technology that has been deployed for decades, traditionally stereo-imagery are used to extract 3D information from 2D imagery. Typically indirect geo referencing has been used for optical-based 3D mapping. The introduction of DG approach allowed a number of new optical-based 3D mapping systems generally UAV-based as the ebee X drone mapping system. It is worth noting that the optical cameras that can be used covers different bands of the electromagnetic waves spectrum. The true color RGB, multispectral RGB and near infra red band. Also, specific bands as the red edge is used mainly for agricultural studies and crop health monitoring. Thermal cameras may also be deployed for such applications as buildings insulation efficiency mapping. It is worth noting that in order to expedite 3D coverage for optical-based 3D mobile mapping systems, camera rig (multi-camera system) is needed to allow for wider field of view.

SfM is yet a relatively recent workflow that revived optical-based 3D mapping. SfM is used to build the 3D representation of an object by using overlapping 2D images acquired from a wide array of different viewpoints and by solving the correspondence and matching problem in photogrammetry the 3D representation is generated. Automatic image matching has been boosted by the influential work of Lowe[2], who developed the correspondence and matching Scale Invariant Feature Transform (SIFT) algorithm. The SIFT algorithm is invariant to change in scale, rotation, translation and to some extent is invariant to change in illumination and viewpoint. It is one of the most popular and robust algorithms for solving the automatic correspondence and matching of features within images.

SfM uses matching features in multiple overlapping images to solve for the interior and exterior orientation parameters and scene geometry simultaneously. This can be achieved by highly redundant matched features, along with a bundle block adjustment process. Furthermore, camera-posing information and/or a sufficient number of ground control points are not a prerequisite to solve for scene triangulation and reconstruction in the SfM workflow. Nevertheless, in the absence of this information, the output of SfM will lack the scale and orientation provided by ground-control coordinates or the external camera pose measurements by a GNSS sensor. The result of applying SfM only is a sparse 3D point cloud, which is typically followed by a multi-view stereopsis (MVS) algorithm to densify the 3D point cloud to several orders of magnitude.

4. Indoor Mapping

Indoor mapping has experienced recent rapid growth. The 3D reconstruction of the indoor environments gained momentum in the recent years. This may be attributed to the technology advancement in the data acquiring sensors and the rapid increasing applications. For instance, the required data for the Building Information Model (BIM) and the new end-user segment that it represents has allowed for the introduction of a number of indoor mapping systems. Some of these systems are deployed as a handheld or backpack mapping systems. Typically, the mapping utilizes the Simultaneous Localization and Mapping (SLAM) approach, whether visual-SLAM or LiDAR-based SLAM. However, these mapping systems are intended for indoor environments, so they are not well suited for outdoor mapping.

Similar to the outdoor environment active or passive sensors can be used for the data acquisition. The active sensors used are mainly LiDAR while passive sensors are mainly optical cameras. Another sensor type that is increasingly used for indoor mapping is the RGB-D sensors. This type of sensor acquires the visual components of the environments mainly in the RGB domain in addition to the depth per pixel. One drawback of this sensor type is its relatively short range (few meters, up to 10m) and another drawback is its relatively poor performance in outdoor environments. The 3D mapping of the indoor environments mainly depends on data-driven registration approaches due to the absence of the GNSS signals. Inertial measurement unit (IMU) might also be used to aid in the mapping process along with Wi-Fi and/or Bluetooth signals.

Due to the absence of GNSS signals, the localization and mapping approaches used for mapping indoor environments are relative localization and mapping. Some of the challenges of indoor mapping are sensor noise, limited resolution and misalignment due to drift. In addition, the indoor environment suffers more from occlusion than in the case of outdoor environments. The data acquisition part for indoor 3D mapping is typically followed by data abstraction. The 3D reconstruction of indoor environments is challenging due to under-sampled and missing data due to occlusion, in addition to the relatively dominant presence of poor textured areas such as walls that pose great challenges in the 3D reconstruction process when using passive sensors. Thus, the 3D indoor mapping workflow can be divided into two main schemes: i) data acquisition and ii) data abstraction.

A number of different abstraction schemes may be used to describe the indoor environment structure, geometry and appearance. Some structure prior is needed to guide the 3D reconstruction process. Common abstraction schemes include (Floor/Wall, Cuboid, Manhattan world, Atlanta world, Indoor world model, Vertical walls and Piecewise planarity).

Some of the challenges that are encountered with model reconstruction for indoor mapping are as follows: i) room segmentation, ii) bounding surfaces reconstruction, iii) indoor object detection and reconstruction, iv) integrated model computation and v) visual representation generation.

4.1 Data Acquisition for 3D indoor mapping

The sensors that are mainly used for data acquisition in indoor environments can be classified into passive sensors and active sensors. The passive sensors like optical cameras captures the visual aspects of the indoor environments, and through specific algorithms, the scene geometry can be inferred. On the other hand, the active sensors, which are mainly LiDAR scanners, directly measures the scene geometry but lacks the visual and texture aspects of the indoor environment. The passive sensors includes standard optical cameras, stereo cameras and panoramic 360 cameras. It is worth noting that panoramic 360 cameras offers a better alternative to standard and stereo optical cameras as it is less affected by the clutter and occlusion that are common in indoor environments. Recently an increasingly used sensor type for 3D mapping in indoor environments is RGB-D sensors. This type of sensor provides the RGB visuals for the environment along with the depth information per pixel. The RGB-D sensors tend to be low cost and easy to operate nevertheless it suffers from its short range. Table 3 and Figs 11-14 show a number of 3D sensors for indoor mapping.

Sensor	Technology Type	Depth Range	3D resolution	RGB resolution	Frame rate	FOV	Physical Dimensions	Interface
Microsoft® Kinect™ 2.0	Time of flight	0.5 to 4.5 m	512 x 424	1920 x 1080	30 fps	70° H, 60° V	~250x70x45 mm (head)	USB 3.0
ASUS® XtionPro™ Live	Structured light	0.8 to 3.5 m	640 x 480	1280 x 1024	30 fps	58° H, 45° V	~180x40x25 mm (head)	USB 2.0
ifm O3D303	Time of flight	0.3 to 8 m	176x132 and 352x264	N/A	25 fps	60° V, 45° H	120x95x76 mm	Ethernet
ifm O3X100	Time of flight	0.05-3.0 m	224 x 172	N/A	20fps	60° V, 45° H	80mm x 43.5mm x 21mm	Ethernet
Stereolabs® ZED™	Embedded stereo	1.5 to 20 m	2208 x 1242 max	2208 x 1242 max	15 fps	96° H, 54° V	175x30x33 mm	USB 3.0
Carnegie Robotics® MultiSense™ S7	Embedded stereo	0.4 m to infinity	2048 x 1088	2048 x 1088 max	15 fps	80° H, 45° V	130x130x65 mm	Ethernet
Ensenso® N35-606-16-BL	Structured light	N/A	1280 x 1024	1280 x 1024	10 fps	58° H, 52° V	175x50x52 mm	Ethernet
SICK® Visionary-T™	Time of flight	N/A	144 x 176	N/A	30 fps	69° H, 56° V	162x93x78 mm	Ethernet
e-Con Systems Tara Stereo Camera	Embedded Stereo Camera	N/A	752 x 480	N/A	60 fps	60° H	100x30x35 mm	USB 3.0
Nerian SceneScan	FPGA Stereo Camera	N/A	1856 x 1856 max	1856 x 1856 max	100 fps	Variable	144x41x35 mm	USB 3.0 to cameras, Gigabit Ethernet to Host
Intel® RealSense™ Camera D415	Active IR Stereo	0.3 to 10 m	1280 x 720 max	1920 x 1080 max	30 fps	63.4° x 40.4°	99 mm x 20 mm x 23 mm	USB-C 3.1 Gen 1

Sensor	Technology Type	Depth Range	3D resolution	RGB resolution	Frame rate	FOV	Physical Dimensions	Interface
Intel® RealSense™ Camera D435	Active IR Stereo using Global Shutter Sensors	0.105 to 10 m	1280 x 720 max	1920 x 1080 max	30 fps	85.2° x 58°	99 mm x 25 mm x 25 mm	USB-C 3.1 Gen 1
Intel® RealSense™ Camera D435i	Active IR Stereo using Global Shutter Sensors and IMU	0.105 to 10 m	1280 x 720 max	1920 x 1080 max	30 fps	85.2° x 58°	99 mm x 25 mm x 25 mm	USB-C 3.1 Gen 1
Intel® RealSense™ Tracking Camera T265	6DOF tracking and Visual SLAM solution					2 Fisheye with combined 163±5° FOV	108 mm x 24.5 mm x 12.5 mm	USB 3.1 Gen 1
FRAMOS Depth Camera D435e	Active IR Stereo using Global Shutter Sensors	0.2-10 m	1280 x 720 max	1920 x 1080	30 fps	86 H x 57 V	108 mm x 24.5 mm x 12.5 mm	Ethernet M12
Orbbec® Astra Mini™	Structured Light	0.6 m to 5.0 m	640 x 480 max	640 x 480 max	30 fps	73 D x 60 H x 49.5 V	80 x 20 x 20 mm	USB
Photoneo® PhoXi® 3D Scanner L	Structured Light	0.87-2.150 m			5 fps	1100 x 800 x 900 mm	77 x 68 x 616 mm	Gigabit Ethernet
roboception® rc_visard™	Stereo Camera	0.5 m to 3.0 m	640 x 480 max	1280 x 960 max	25 fps	61 H x 48 V	230 x 75x 84 mm	Ethernet
duo3d® DUO MC™	Stereo Camera	0.23 m to 2.5 m	752 x 480 max	752 x 480 max		170 W with 30 mm Baseline	57 x 30.5 x 14.7mm	480 Mbps USB 2.0 Micro-B

Sensor	**Technology Type**	**Depth Range**	**3D resolution**	**RGB resolution**	**Frame rate**	**FOV**	**Physical Dimensions**	**Interface**
Zivid One+	Structured Light	300-800 (Small), 600-1600 (Medium), 1200-2600 (Large)	1920 x 1200		13 fps	Variable	226 x 165 x 86 mm	USB 3.0
Arcure Omega	Stereo Camera (with IMU)	0.3 - 50 m	1280x1024 pixels	1280x1024 pixels	60 fps	120 H x 90 V	200 x 83 x 79 mm	Ethernet
MYNT EYE	Stereo Camera (with IMU)	0.5 to 18 m	752x480		60 fps	146° D, 122° H, 76° V	141.9 x 61.5 x 68.4 mm	USB 3.0

Table 3: A number of Different sensors used for 3D indoor Mapping

Fig 11: Some of 3D indoor mapping sensors; a) Microsoft® Kinect™ 2.0, b) ASUS® XtionPro™ Live, c) ifm O3D303, d) ifm O3X100, e) Stereolabs® ZED™, f) Carnegie Robotics® MultiSense™ S7

Fig 12: Some of 3D indoor mapping sensors; a) Ensenso® N35-606-16-BL, b) SICK® Visionary-T™, c) e-Con Systems Tara Stereo Camera, d) Nerian SceneScan, e) Intel® RealSense™ Camera D415, f) Intel® RealSense™ Camera D435

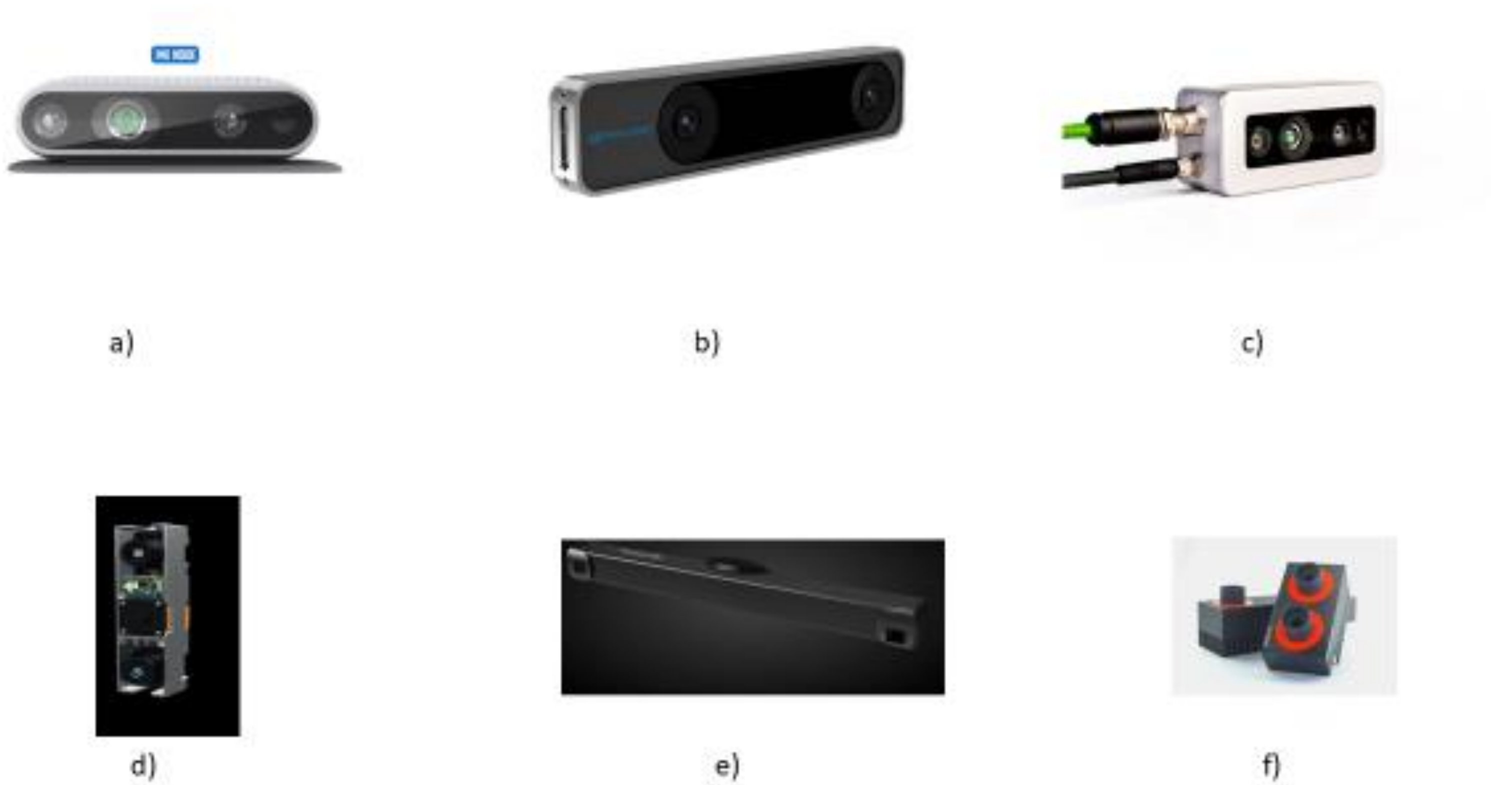

Fig 13: Some of 3D indoor mapping sensors; a) Intel® RealSense™ Camera D435i, b) Intel® RealSense™ Tracking Camera T265, c) FRAMOS Depth Camera D435e, d) Orbbec® Astra Mini™, e) Photoneo® PhoXi® 3D Scanner L, f) roboception® rc_visard™

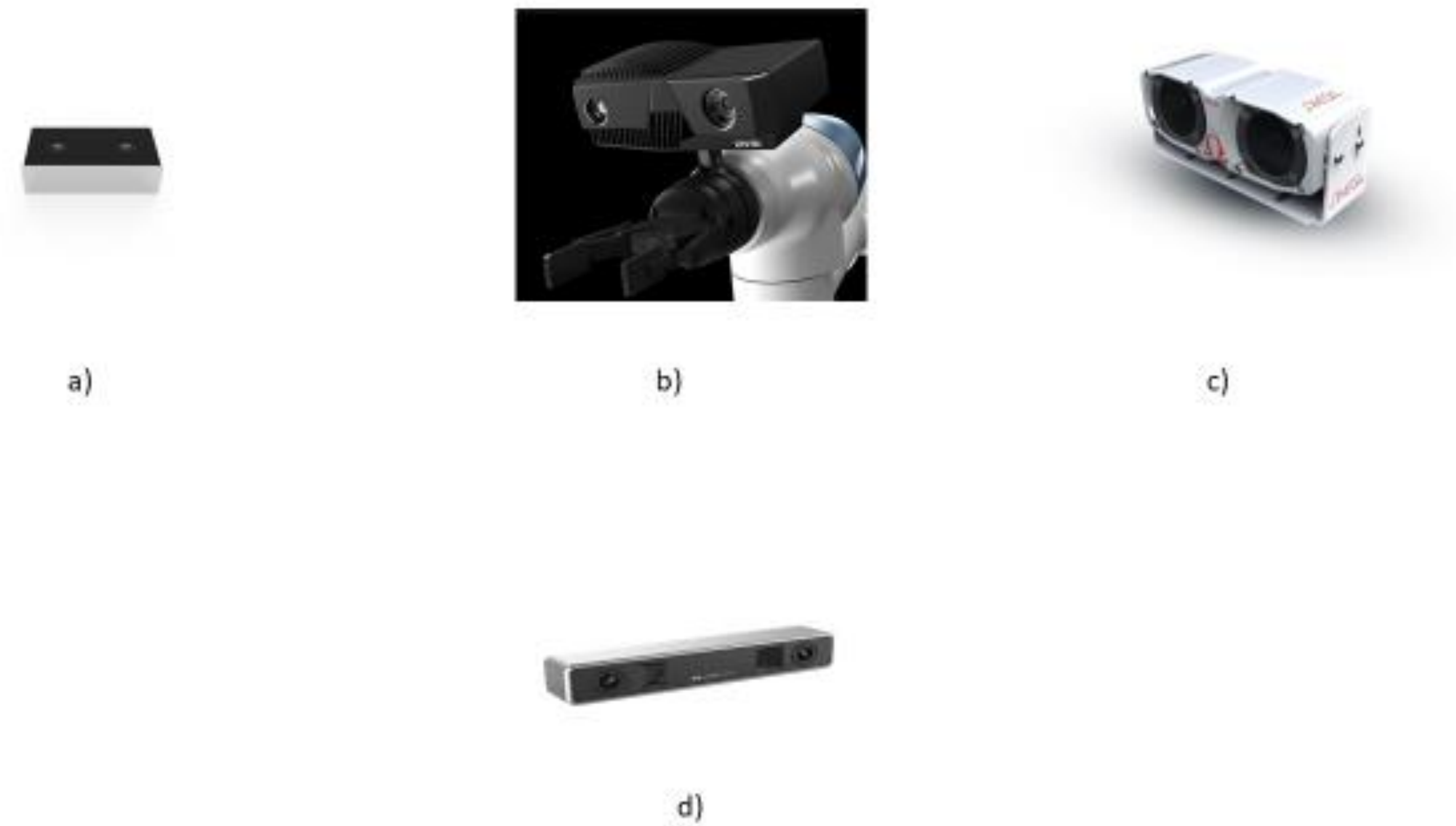

Fig 14: Some of 3D indoor mapping sensors; a) duo3d® DUO MC™, b) Zivid One+, c) Arcure Omega, d) MYNT EYE

As shown in Table 3 and figures 11-14 there exist a variety of relatively very cheap sensors (up to few thousands dollars) that depend on different types of technologies that can be used in 3D indoor mapping. Although the main drawback of these sensors is the short range it can sense besides sensor noise, limited resolution and misalignment due to drift, it offers a very attractive solution for 3D indoor mapping for small sized rooms and the like.

There exist a number of more precise higher end sensors that can be utilized for 3D indoor mapping. NAVVIS VLX and NAVVIS M6 are two indoor mobile mapping systems that can reach survey grade accuracy, Table 4 and fig 15 depicts the difference between NAVVIS VLX and NAVVIS M6. It is worth noting that the cost of NAVVIS systems ranges from $50,000-$100,000.

	NAVVIS VLX	NAVVIS M6
BEST FOR:	- Mid-size construction and refurbishment projects	- Large commercial properties
	- Complex environments with staircases and obstacles	- Industrial facilities
	- Narrow spaces such as technical rooms	- Digital twins for manufacturing facilities
IDEAL PROJECT SIZE:	<5000sqm	>5000sqm
TYPE OF DEVICE:	Wearable	Push cart
SCANNERS:	2 LiDAR sensors	4 LiDAR sensors
CAMERAS:	4	6
CONTROL POINTS:	Wall and ground control points	Ground control points
TRANSPORT:	One case	Four cases
INTERFACE:	5.5" touchscreen	10.1" touchscreen
WORKING TIME:	1.5 hours per battery set	3.5 hours per battery set
BATTERIES:	Two batteries that can be hot swapped	Four batteries that can be hot swapped

Table 4: NAVVIS VLX and NAVVIS M6

a) b)

Fig 15: Some of high-end 3D indoor mapping sensors; a) NAVVIS VLX, b) NAVVIS M6

Another high-end 3D indoor mapping system is the Leica BLK2GO. This is a handheld 3D LiDAR-based indoor mapping system. A similar system from Leica as well is the BLK360 but unlike the handheld BLK2GO, it is tripod mounted. The BLK360 costs around $30,000 while the BLK2GO costs around $ 65,000. It is worth noting that the mode of operation in the 3D indoor mapping can range from terrestrial static (typically tripod-mounted) scanners or mobile scanners (handheld, backpack-e.g. Leica Pegasus-, trolley-based, or recently with the NAVVIS VLX wearable). The advantage of having a mobile mode of mapping is more flexibility, agility and speed it offers to do the 3D indoor mapping while generally the main advantage of the static mode of mapping is the higher accuracy and point cloud uniformity and higher density compared to the mobile mode of operation. Leica ScanStation P40 is yet another static LiDAR that can be used for 3D indoor mapping with very high precision results in the mm range, but it lacks the mobility of a mobile mapping system. Fig 16 shows some of the different Leica systems.

Fig 16: Some of high-end 3D indoor mapping sensors; a) Leica BLK360, b) Leica BLK2GO, c) Leica Pegasus, d) Leica ScanStation P40

5. Summary and Recommendations

In this report, the conducted in-depth literature review for *Outdoor* & *Indoor* systems and mapping approaches has been highlighted. These highlights entail: pros and cons, different sensors used, associated cost, time for data collection and processing, data structure and format, etc. The report started with an introductory about 3D mapping, the different scanning approaches (Passive and Active), direct and indirect georeferencing mapping approaches, advantages and disadvantages of each. An in-depth categorization of the LiDAR 3D mapping systems modes of operations and detailed specifications for a number of the state-of-the-art 3D mapping systems both for outdoor and indoor systems have been carried out. The key findings and recommendations for both outdoor and indoor mapping are detailed in the sections ahead.

5.1 Outdoor Mapping Summary and Recommendations

Outdoor mapping allows making use of global navigation satellite sensors GNSS measurements to provide absolute coordinates for the environment mapped. 3D data can either be captured by using active sensors (mainly LiDAR) or calculated through passive sensors (mainly optical cameras) and photogrammetric techniques. Direct and indirect georeferencing are the two main mapping approaches. In the indirect georeferencing approach ground control points (GCPs) – points in the mapped environment with known coordinates- are required. On the other hand, direct georeferencing (DG) entails the usage of i) a remote sensing sensor (RSS) either active or passive to sense the environment ii) a GNSS/ inertial navigation sensor (INS) measurements integration to relate the mapped environment to the RSS position and orientation allowing the 3D mapping generation iii) a system control unit for the system operation, power and data storage. The LiDAR-based 3D mapping systems can be categorized according to the platform where they are mounted to i) Stationary Terrestrial LiDAR Systems (STLS), ii) Mobile Mapping Systems (MMS) and iii) Aerial LiDAR Systems (ALS) with a sub-category when mounted on a UAV as (ULS). LiDAR-based 3D mapping systems directly capture 3D data in contrast with optical-based 3D mapping which requires some specific procedures with the way the 2D imagery are captured and post-processing algorithms to extract 3D information from the 2D imagery. Thus, LiDAR-based 3D mapping systems are typically used for 3D mapping especially in MMS mode.

In the recent few years, the introduction of a new type of LiDAR sensors- spinning multi beam laser sensors (SMbL) originally developed for autonomous vehicles- allowed the production of new 3D LiDAR-based mapping systems by commercial vendors. The new sensors covers 360° and are relatively compact and lightweight which proved greatly beneficial with the ULS mapping mode.

Historically, Optical-based 3D mapping systems in aerial and close-range photogrammetry has been successfully deployed for decades but with the technology advances in LiDAR-based 3D mapping systems it is considered the standard technology for 3D mapping. However, the LiDAR-based 3D mapping systems are relatively associated with higher capital costs and lacks texture and natural colors that optical-based technology provides. But still LiDAR-based 3D mapping provides a better time-efficient turnaround time for obtaining 3D data compared with optical-based technology and better suited for mapping of power-lines and the like. The advances in computer-vision algorithms helped in the introduction of structure from motion SfM photogrammetric workflow that revived the optical-based 3D mapping. Nevertheless, SfM shortcomings includes relatively low performance in poorly textured areas and places with repetitive patterns, and its dependency on lighting conditions and imagery-capturing geometry to produce reliable results. It is worth noting that the processing of 3D data whether the output from LiDAR-based or optical-based 3D mapping requires a lot of processing power and storage especially for mapping of large areas. Thus, a cloud-based solution would be a very viable alternative. Typically the 3D data is presented as a 3D point cloud and the common file format is .las files and can be stored as an .e57 compressed file format.

The turn-key mapping systems provided by the commercial vendors tend to be cost-prohibitive to many end-user segments and require a higher level of technicality from the operator. They also lack the flexibility that custom-made mapping systems offer regarding sensor manipulation and modification, thus leading to a limitation in the applications in which they can serve. A generic mapping system with crosscutting capabilities that can be readily deployed in the three different modes of operation (STSL,MMS,ULS) and that has an indoor-mapping ability with an added layer of processing algorithm such as simultaneous localization and mapping (SLAM) will serve different domains requirements in the smart campus project. In addition, this enables a more complete coverage of the environment mapped as it can be used with an aerial, terrestrial perspective as well as in indoor mapping. Such a system would not only provide the versatility of being able to be used in different modes, thereby addressing the needs of diverse application domains, but would also be able to attain high accuracy. To aid for better visualization for the 3D models, the colorization of the LiDAR-based 3D point cloud with true-color RGB optical imagery is recommended. In addition, the fusion of multispectral and/or hyperspectral and/or thermal imagery with the 3D LiDAR data considerably enhance the ability of more feature extraction automated algorithms. It is worth noting that ground penetrating radar (GPR) systems are needed if mapping of underground utilities is required.

5.2 Indoor Mapping Summary and Recommendations

Indoor mapping lacks the ability of GNSS signal reception and thus the localization and mapping are done in a relative approach. The most common algorithm used is the Simultaneous Localization and Mapping (SLAM) approach, whether visual-SLAM or LiDAR-based SLAM. However, these mapping systems are intended for indoor environments, so they are not well suited for outdoor mapping. Active or passive sensors can be used for data acquisition in indoor environments. Active sensors are mainly LiDAR and it captures the 3D geometry of the environment directly but it lacks the color and texture provided by passive sensors as optical cameras. Thus, cameras to be used along the active sensor to provide the visual appeal and texture of the environment.

On the other hand, passive sensors mainly include standard optical cameras, stereo cameras, panoramic 360 cameras, time of flight cameras and RGB-D sensors. The passive sensors captures the color and texture of the environment directly but inferring the 3D geometry requires the application of some algorithms on the captured images. Thus, the ability of adequate 3D geometry extraction from passive data depends on the lighting conditions, data capturing geometry, and the presence of rich texture areas. The panoramic 360 cameras are less affected by the clutter and occlusion problems that are common within the indoor environments. The RGB-D sensors are increasingly being used in the 3D indoor mapping of small sized rooms as it suffers from short-range measurements ability. Still RGB-D sensors are considered a very attractive option from a low-cost point of view.

Inertial measurement unit (IMU), Wi-Fi and/or Bluetooth, ultra wide band (UWB) are all enabling technologies that may be used to aid in the localization and mapping process for the indoor environment. The registration of different scans are data driven and the aforementioned technologies can be used to enhance the accuracy of the registration.

Different mapping modes can be used for the 3D indoor mapping. The mapping modes ranges from terrestrial static scanning (mainly tripod-mounted), handheld systems, backpack and trolley-based systems. The static mode of operation requires more time for scanning and is less flexible and agile compared to the mobile mode of operation but it typically provides more accurate results with more uniformity and density of the resulting point clouds.

A number of high-end 3D indoor mapping systems exist such as NAVVIS VLS, NAVVIS M6, Leica BLK360, Leica BLK2GO, Leica Pegasus and Leica P40. It is wroth noting that these systems costs more than ten times the cost of the RGB-D sensors or even more but they provide the ability of longer range of measurements, less sensor noise, higher resolution and reduced misalignment between scans and a denser more uniform point clouds. The RGB-D systems cost a very few thousands while the high-end systems cost range in the high-end of tens of thousands.

The 3D indoor data acquisition is followed by data abstraction for 3D model generation. Different abstraction schemes to describe the indoor environment structure, geometry and appearance include (Floor/Wall, Cuboid, Manhattan world, Atlanta world, Indoor world model, Vertical walls and Piecewise planarity). Some structure prior are needed to guide the 3D reconstruction process.

The main problems that are faced with model reconstruction for indoor mapping are as follows: i) room segmentation, ii) bounding surfaces reconstruction, iii) indoor object detection and reconstruction, iv) integrated model computation and v) visual representation generation.

It is recommended to use active sensors for the 3D indoor mapping as it provides direct measurement of the 3D geometry of the environment but the fusion with visual data captured by cameras is needed for better visualization. NAVVIS VLX system provides a very good balance for a 3D indoor mapping system between the ease of operation, speed of data capturing, accuracy and cost. Nevertheless, it is not well suited to be used in outdoor environments. Thus, a generic originally outdoor mapping system that has the indoor mapping capability would be a much better selection to be well suited for the smart campus 3D outdoor mapping in mobile, aerial, terrestrial modes of operation along with the 3D indoor mapping ability. A structured representation in the form of scene graph is suggested for the 3D modelling as it provides a topological part, a geometric part and visual part. It is worth noting that the processing of captured data of the indoor environment especially for large areas are computationally demanding processes and thus a cloud-computing environment would be an ideal environment for computation

6. Outdoor Mapping Conclusions

1- 3D mapping provides the foundation as a base map for the other smart campus domains and is used for 3D visualization and geo-intelligent DT implementation.
2- Active (LiDAR-based) 3D mapping systems or Passive (optical-based) 3D mapping systems can be used for the 3D mapping generation.
3- LiDAR-based 3D mapping systems directly measures the 3D environment and thus are preferred over the optical-based systems.
4- It is recommended that a LiDAR-based 3D mapping system that has the versatility to be used in different mapping modes (stationary, Mobile and UAV-based) to be adopted.
5- Commercial Yellow-scan surveyor LiDAR-based 3D mapping system can be used in UAV-based mapping, and recently, the capability of its usage in mobile mapping mode has been added and the system costs around $100,000. It is worth noting that the operational and post-processing costs to be able to capture the 3D data and convert that to 3D maps using the system is relatively costly and costs can easily add-up.
6- Custom-made 3D mapping systems (developed by university research teams and the like) can be an alternative at a lower-cost point.
7- A unique LiDAR-based 3D mapping system (Patent pending) has been developed at the department of civil engineering, Ryerson University and we are at an advanced stage of its commercialization, the system would be a very good fit with the smart campus DT as it provides crosscutting 3D modes of operation deployment-ability and integrates the core-

components used in the yellow-scan surveyor but adds more versatility and modularity with a reduced cost.
8- It is strongly recommended to augment the LiDAR-based data with images for better visualization.
9- The fusion between hyperspectral imagery and LiDAR-data enhances the ability of automated feature extraction and helps in feature annotation
10- Thermal imagery serves as a smart tool for building insulation efficiency measurements and buildings energy-related performance.
11- 3D data processing especially for optical-based tends to be computationally heavy processes that are resource-intensive and thus a cloud computing environment is an ideal alternative

7- Indoor Mapping Conclusions

1- 3D mapping is essential for the DT 3D visualization, context-aware analysis and geo-intelligent DT implementation. It also works as a base map for the other smart campus domains.
2- Indoor environments lacks the ability of GNSS signals reception and thus the localization and mapping are done in a relative approach
3- Simultaneous Localization and Mapping (SLAM) algorithm is typically utilized for the 3D indoor mapping, whether it be visual-SLAM or LiDAR-based SLAM
4- Active (LiDAR-based) 3D mapping systems or Passive (optical-based) 3D mapping systems can be used for the 3D indoor mapping generation
5- Passive sensors include (standard optical cameras, stereo cameras, panoramic 360 cameras)
6- Panoramic 360 cameras are less affected by the clutter and occlusion problems that are common in indoor environment
7- RGB-D, Time of flight ToF sensors, Structured light sensors are also sensors that are used for 3D indoor mapping. They are relatively very cheap (costs few thousands dollars) and are increasingly used to map small sized rooms and areas as it suffers from short range measurements (typically up to 5m range), sensor noise, limited resolution and misalignment due to drift
8- 3D indoor mapping modes range from static scanning (mainly tripod-mounted), handheld systems, backpack and trolley-based systems
9- Mobile mapping modes provide a faster more flexible and agile way of data acquisition over the static mode of operation while the static mode of operation typically results in more accurate results along with more uniform and dense 3D point cloud
10- For the smart campus and DT generation, mobile mode of mapping is strongly recommended due to the large area of the campus for both outdoor and indoor environments
11- LiDAR-based 3D mapping systems directly measures the 3D environment and thus are preferred over the optical-based systems
12- A number of high-end 3D indoor mapping systems exist such as NAVVIS VLS, NAVVIS M6, Leica BLK360, Leica BLK2GO, Leica Pegasus and Leica P40. The cost of these systems is in the higher end of tens of thousands dollars

13- Commercial NAVVIS VLX system provides a very good balance for a 3D indoor mapping system between the ease of operation, speed of data capturing, accuracy and cost (around $65,000). Nevertheless, it is not well suited to be used in outdoor environments
14- Thus, a generic originally outdoor mapping system that has the indoor mapping capability would be a much better selection to be well suited for the smart campus 3D outdoor mapping in mobile, aerial, terrestrial modes of operation along with the 3D indoor mapping ability
15- Custom-made 3D indoor mapping systems (developed by university research teams and the like) can be an alternative at a lower-cost point.
16- It is strongly recommended to augment the LiDAR-based data with images for better visualization.
17- Similar to the outdoor environment context , the fusion between hyperspectral imagery and LiDAR-data enhances the ability of automated feature extraction and helps in feature annotation in indoor environment as well
18- 3D data processing for indoor mapping as well as the outdoor mapping especially for optical-based tends to be computationally heavy processes that are resource-intensive and thus a cloud computing environment is an ideal alternative

Notes:

1) *Table 1 is adopted after Rehak: Rehak M. Integrated sensor orientation on micro aerial vehicles. EPFL; 2017.*
2) *SIFT algorithm by Lowe : Lowe DG. Distinctive image features from scale-invariant keypoints. International journal of computer vision. 2004 Nov 1;60(2):91-110.*
3) *The systems and sensors images used in this report has been retrieved from the respective manufacturer online website.*
4) *The categorization of the outdoor 3D mapping follows the work done in Ashraf's dissertation.*