



Vision and advocacy of optoelectronic technology developments in the AECO sector

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ABSTRACT

Purpose: This research presents a literature review of laser scanning and 3D modelling devices, modes of delivery and applications within the architecture, engineering, construction and owner-operated (AECO) sector. Such devices are inextricably linked to modern digital built environment practices, particularly when used in conjunction with as-built building information modelling (BIM) development. The research also reports upon innovative technological advancements (such as machine vision) that coalesce with 3D scanning solutions.

Design: A synthesis of literature is used to develop: a hierarchy of the modes of delivery for laser scan devices; a thematic analysis of 3D terrestrial laser scan technology applications; and a componential cross-comparative tabulation of laser scan technology and specifications.

Findings: Findings reveal that the costly and labour intensive attributes of laser scanning devices have stimulated the development of hybrid automated and intelligent technologies to improve performance. Such developments are set to satisfy the increasing demand for digitisation of both existing and new buildings into BIM. Future work proposed will seek to: review what coalescence of digital technologies will provide an optimal and cost effective solution to accurately reconstructing the digital built environment; conduct case studies that implement hybrid digital solutions in pragmatic facilities management scenarios to measure their performance and user satisfaction; and eliminate manual remodelling tasks (such as point cloud reconstruction) via the use of computational intelligence algorithms integral within cloud based BIM platforms.

Originality: Although laser scanning and 3D modelling have been widely covered *en passant* within the literature, scant research has conducted an holistic review of the technology, its applications and future developments. This review presents concise and lucid reference guidance that will intellectually challenge, and better inform, both practitioners and researchers.

KEYWORDS

Laser scanning, digital built environment, building information modelling (BIM), machine vision

INTRODUCTION

Optoelectronics has its etymological roots grounded in physics and encompasses the study, design and manufacture of electronic devices for emitting, modulating, transmitting and sensing light (Sergiyenko and Rodriguez-Quiñonez, 2016). Optoelectronic devices gather and display information at high speed but can also store and process information (Marzuki, 2016). Beneficial characteristics of these devices include their: small and portable size (Faro, 2004); highly sophisticated functionality (Marzuki, 2016); solid-state robustness (Lindner, 2016); and low-power consumption during operation (Faro, 2004). Such attributes have engendered the proliferation of optoelectronic devices throughout society, business and commerce (Rushmeier, 2002). Amongst the hierarchy of optoelectronic technologies available, optical laser scanners are frequently used for the rapid automation of millimetre precision measurement and reconstruction of tangible objects via processed optical signals from reflected light (Thiel and Wehr, 2004). Laser scanning applications are myriad throughout a disparate range of industries, including: aerospace for structural health monitoring (Derriso *et al.*, 2016); law enforcement for virtual crime scene reconstruction (Buck *et al.*, 2013); agriculture for crop growth monitoring (Cointault *et al.*, 2016); archaeology for reconstructing archaeological artefacts (Galeazzi *et al.*, 2016); and manufacturing industries for quality assurance purposes (Godin *et al.*, 1994; Mello and Stemmer, 2016). Given this strong demand, the laser scanning industry's value is forecast to exceed 5.90 Billion USD by 2022 (Markets, 2016).

The architecture, engineering, construction and owner-operated (AECO) sector encompasses the whole life cycle of buildings and infrastructure within the built environment. Within this sector 3D laser distance and ranging (LiDAR) devices rapidly construct point cloud data sets that precisely measure large volumes of physical objects, transcribed into a digital built environment (Chen *et al.*, 2015). Laser scan devices are now integral within numerous built environment applications including: construction progress tracking (El-Omari and Moselhi, 2008); quality control assessment (Wang *et al.*, 2016); site activity monitoring (Zhang *et al.*, 2016); safety assessment (Shapira *et al.*, 2014); and resource and material tracking (Szweda, 2006). Laser scanning also represents an ideal technological solution for automating as-built

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3 Building Information Modelling (BIM) validation (and model updates) for contractors and
4 facility managers (Hoffmeister, 2016). However, whilst demand has grown, laser scan
5 technology is not universally adopted in contemporary AECO practice because of issues
6 pertaining to: high equipment costs (Rushmeier, 2002; Qin and Gruen, 2014); costly human
7 resource training needed to acquire core competencies to operate the laser scanning
8 equipment (Ouédraogo *et al.*, 2014); discrepancies in spatial information (Tang and Akinci,
9 2012a, 2012b; Jung *et al.*, 2014; Laing *et al.*, 2015) lack of automation with BIM object
10 recognition from point cloud data (Ouédraogo *et al.*, 2014); timely calibration of scanning
11 equipment (Kim *et al.*, 2015a); limited point cloud capture from occlusions (Xiong *et al.*,
12 2013); and excessive time consumed with point cloud data processing (Golparvar-Fard *et al.*,
13 2011). In addition, laser-scanning applications integrated with BIM lack automation in the
14 recognition of semantic attributes from scanned data – albeit point cloud semantic recognition
15 has accrued maturity in factory automated scanning of small objects (Rushmeier, 2002;
16 Godin *et al.*, 2010).

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28 To address these limitations, research and industry practice advocate using automated image-
29 based sensing technologies to augment laser scan technology (Golparvar-Fard *et al.*, 2011).
30 Machine vision enhances laser scan capabilities through object recognition and description,
31 utilising algorithms for image processing and pattern recognition (Gao *et al.*, 2015). Such
32 advancements have been successfully applied within the manufacturing, automotive and
33 security industries – hence, advanced technology transfer into the AECO sector is feasible
34 (Flores-Fuentes *et al.*, 2016). The wider applications of integrated scanning-software devices
35 represent the next generation of revolutionary technological solutions adopted throughout a
36 building's entire life cycle (Turkan *et al.*, 2014). Hitherto, research has not reported upon
37 suitable automated image/laser-based reconstruction to manage and update the as-built BIM
38 for both new build development and/or retrospective modelling. Against this contextual
39 backdrop, this literature review aims to: i) provide a qualitative, componential analysis of
40 current as-built image/laser-based reconstruction devices and applications used to maintain
41 digital built environment data; ii) critically evaluate contemporary laser scanning and
42 automated machine vision processing developments; and iii) propose a future trajectory for
43 augmented laser scanning devices in the AECO sector.

FUNDAMENTALS OF LASER-SCAN DEVICES

Optoelectronic scanning devices have developed rapidly since initial laboratory testing was conducted by the National Research Council of Canada (NRCC) during the 1970s (Blais, 2004) (refer to Figure 1). 3D laser scanning initially lagged behind 2D laser scanning technologies in terms of image quality, rendering and ease of use (*ibid*). However, the advent of microcomputers and exponential improvements in computational processing power transformed 3D laser scanning to mirror the performance of its counterpart (Sergiyenko and Rodriguez-Quinonez, 2016). These technological breakthroughs have stimulated the development of cost-effective, automated, contactless 3D range sensor systems for various industrial applications (Hornberg, 2006). Since the early 1980s, three generic contactless methods of range measurement have emerged, namely: i) triangulation; ii) phase shift; and iii) time of flight (TOF) or pulse-based – albeit, a number of hybrid scanning devices integrate multiple methods (e.g Moiré pattern projection and fringe interference) (Creath and Wyant, 1992).

Triangulation

Triangulation is suitable for short-to-medium distance measurements (<5-10 m). An early example of triangulation based 3D laser cameras are slit scanners due to their optical and mechanical simplicity and cost (Galantucci *et al.*, 2015). Slit-scanners utilise an angled light line projected onto the target object; deformation of the straight-line projection provides information about the target surface protuberances (Hornberg, 2006). This method is limited in capacity for large volume capture since short-range slit scanners are a compromise between field of view and depth resolution (*ibid*). They are typically limited to a field of view of between 20-50 degrees.

Phase shift

Phase shift devices calculate the difference between the overlapping sent and reflected signal(s) within a certain wavelength (Lindner, 2016). This offers speedy measurement in comparison with TOF methods but the output point cloud data does suffer from higher speckle noise interference (Creath and Wyant, 1992; Beraldin *et al.*, 2000a). Whilst speckle noise can be reduced with good lighting conditions, such instances are rare on construction sites, particularly when laser scanning larger objects such as buildings (Godin *et al.*, 2010).

Time of flight

Time of flight (TOF) is suitable for long distance range measurement (10-25m) and utilises multiple single laser point reflections. By recording the time taken for millions of laser pulses to return to the sensor the distance can be calculated (Blais *et al.*, 2000). Multiple iterations of reflection propagate a vast yield of points in space, commonly referred to as point cloud data, which represent Cartesian coordinates that are processed to create a 3D model of physical objects (Gao *et al.*, 2015). The primary benefits of TOF laser scanning include an ability to quickly assimilate the measurement of large surface areas to a millimetre-level accuracy and precise spatial resolution (El-Omari and Moselhi, 2008). TOF scanners are widely adopted in the AECO sector because they capture larger range, broader field of view and higher resolution. TOF generates 3D data with an accuracy typically within 2–6 mm at 50 m and high point density up to 1,000,000 points per second (Faro, 2004) (refer to Table 1). Accuracy and range of TOF scanners are restricted by physical limitations such as speckle noise and optical resolution (Shoji, 2013).

Hybrids

By the 1980s, a range of short-, mid- and long-range 3D laser scanning devices had been developed, such as pattern projection scanners (which use either phase shift, TOF or triangulation) (Beraldin *et al.*, 2000b). Pattern projection (aka structured light 3D scanning) uses multiple stripes or patterns projected onto a target, rather than scanning a single laser line of point onto the object surface and processing the independent profiles retrospectively (Blais, 2004). Pattern projection scanners are limited to short-range scanning (circa 10-15m range) (Lindner, 2016).

COST, SPECIFICATIONS AND MODES OF DELIVERY

The exorbitant cost of commercially available equipment is a fundamental obstacle for the purchase of 3D laser scanning devices within the AECO sector (Galantucci *et al.*, 2015). Costs fluctuate depending upon the device's specification (*ibid*). Table 1 presents a qualitative, componential specification analysis of the three primary modes of conducting short-, mid- and long-range TOF laser scanning during construction and post-construction stages, namely: i) airborne; ii) mobile; or iii) terrestrial (refer to Figure 2). The criteria analysed are: number of points being generated; range of scan; weight; ranging error; optical resolution; field of view; price range; and laser class. Range of scan is the minimum measurable distance in an indoor-outdoor environment at an upright incidence to a surface

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3 with 90% reflective material. Ranging error is the degree of conformance between a
4 measurement of an observable quantity and a recognized standard or specification that
5 indicates the true value of the quantity (Blais *et al.*, 2000). Optical resolution is the minimum
6 dimension of an object feature that the 3D scanner can acquire (Faro, 2004). Field of view is
7 determined by the angle of laser scan capture capabilities between 20-360 degrees vertically.
8 Laser class is defined by International Electrotechnical Commission (IEC) document 60825-1
9 I, which assigns lasers into one of four hazard classes (1, 1M, 2, 2M, 3, 3M, 4, in ascending
10 order - 1 being the least harmful).
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18 **Airborne Laser Scanning**

19 Airborne laser scanning (ALS) devices measure the range of reflected objects on the earth's
20 surface for numerous mapping applications including: railway tracks; waterway landscapes;
21 and electrical transmission lines (Wehr and Lohr, 1999). Airborne scanners have evolved
22 from early applications in aerospace with satellites to the more widely adopted geological and
23 agricultural surveys (Andujar *et al.*, 2011; Lehtomäki *et al.*, 2015). LiDAR systems are used
24 in ALS to track geo-referenced points from the terrain (Cointault *et al.*, 2016). ALS devices
25 overlap with unmanned devices such as unmanned aerial vehicles (UAV's) (Irizarry and
26 Costa, 2016).
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34 **Mobile Laser Scanning**

35 Mobile laser scanning (MLS) devices that are fitted to vehicles continuously scan whilst in
36 motion to capture a huge volume of point data (Breuckmann, 2014; Qin and Gruen, 2014).
37 Most mobile scanning devices include LiDAR capabilities to capture transport infrastructure.
38 Construction professionals can also carry/wear MLS devices to harness laser scan data whilst
39 manoeuvring around site (Longstreet, 2010). Hand-held devices are compact and cheaper but
40 have a limited scanning range, where 1 millimetre accuracy is only achieved at a 1 metre
41 range from the target object (Faro, 2004). Mobile scanning devices such as FARO
42 *Freestyle3D*, Leica *Pegasus: Two* and Leica *Pegasus: Backpack* require expensive manned
43 management to control either the vehicle, hand-held device or backpack unit (Lehtomäki *et al.*,
44 2015). MLS devices can also provide machine vision for navigating and orientating
45 autonomous robots (Association, 2007; Lindner *et al.*, 2016). Such use is rare in the AECO
46 sector and currently the major original equipment manufacturers do not offer such devices.
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Terrestrial Laser Scanning

Terrestrial Laser Scanning (TLS) technology is the preferred method for scanning ground based discrete objects because it captures static 3D objects with high accuracy (Bosché *et al.*, 2015). Limitations of 3D TLS scanning include: the time required to perform a single high-resolution scan; the number of scan-locations required to capture an entire site or building; the high costs of equipment operation; and its stationary nature that limits both the scanning capacity with limited field of view and potential loss of data via occlusions (Godin *et al.*, 2010;) Bosché *et al.*, 2015; Brilakis *et al.*, 2010). Leica and FARO TLS models differ in range capabilities and price – for example, the *Leica C10* is reasonably affordable but accuracy performance and range are lower (refer to Table 1). Lower specification models available are more suited to as-built and topographic high-definition surveying applications but are more harmful to humans with a laser classification of 3R.

LASER SCANNING APPLICATIONS

To undertake a thematic literature review of TLS technology applications, a keyword search was conducted (using ‘laser scan’ or laser-scan’ as the search terms) across several prominent journal databases such as Emerald and Science Direct. Relevant journal papers were then categorised into four thematic groupings, namely: progress tracking; quality assessment; structural health monitoring; and development of as-built data (refer to Figure 3). Within each theme, the frequency of published work is presented by industry sector (architecture, engineering, construction, operations and other).

Progress Tracking

Progress tracking is a prerequisite requirement for the effective and efficient cost management of labour, plant and equipment, and materials (El-Omari and Moselhi, 2009). Traditionally, tracking progress on a construction site has been achieved through video footage (Meadati *et al.*, 2010). More recently, laser scanning technology (such as LiDAR) has been utilised to capture data for progress monitoring, therefore enabling the integration of as-designed development via BIM (Matthews *et al.*, 2015). LiDAR is particularly suited for tracking structural work progress and quality because it can reproduce 3D information with millimetre precision. The limitations of LiDAR when compared to traditional methods (such as video footage) are its high purchase cost and inability to directly monitor dynamic points of interest such as labour, materials and equipment. Dynamic components are better monitored by RFID tags which track the location and movement of machines and workers to

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3 capture their productivity and safety performance (Motamedi *et al.*, 2013; Bosché *et al.*,
4 2015). Barcodes are inexpensive and useful for progress monitoring static materials and
5 equipment in the supply chain (i.e., at prefabrication and laydown yards) (El-Omari and
6 Moselhi, 2009). However, applications in practice have declined because barcodes are easily
7 damaged and incapable of geo referencing (Lindner, 2016). Digital photography and video
8 footage are also limited in their scope to accurately capture meteorological conditions,
9 construction work progress and resource movement (Riaz *et al.*, 2006).
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16 **Quality Control and Assessment**

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18 Quality control and assessment within the AECO sector has been adopted predominantly to
19 determine the integrity of existing structural elements - henceforth, evidence of application in
20 the post-construction stages of operations and maintenance (O&M) is limited (Kim *et al.*,
21 2015a). Structural engineers can validate steel frames, pre-cast and cast in situ concrete
22 structural elements with laser scanning and post inspection of final point scan data (Zeibak-
23 Shini *et al.*, 2016). Redundancy of points poses an issue due to the excessive time taken
24 during the production of point clouds and has led to the development of innovative automated
25 quality assessment methods and procedures (Park *et al.*, 2007). For example, TLS devices
26 have been deployed to estimate dimensions of pre-cast concrete elements with geometric
27 irregularities by cross referring the data with as-designed BIM data (Wang *et al.*, 2016). TLS
28 devices are the preferred choice for conducting quality assessment and have been applied in:
29 structure deformation measurement (Monserrat and Crosetto, 2008); dimensional estimation
30 (Wang *et al.*, 2016); and identification and quantification of surface damage (Olsen *et al.*,
31 2010). To further augment this process, photogrammetry has been adopted in quality
32 assessment, either independently or combined with TLS (Scaioni *et al.*, 2014).
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45 **Structural Health Monitoring**

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47 Structural health monitoring using laser scanning devices is widely used throughout industry
48 (Barazzetti *et al.*, 2015) including: aerospace engineering (Derriso *et al.*, 2016); structural
49 engineering (Park *et al.*, 2013); geological engineering (Scaioni *et al.*, 2014); and
50 archeological surveying (Godin *et al.*, 2010; Galeazzi *et al.*, 2016). Structural engineers have
51 similarly adopted workflow in determining structural integrity with pre-cast concrete
52 structures and steel work (Zeibak-Shini *et al.*, 2016). Accuracy of the TLS point cloud data
53 has been used for defect detection for concrete structural elements (Kim *et al.*, 2015b) and
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3 piping systems (Safa *et al.*, 2015). TLS devices are used because of their higher accuracy and
4 ability to record surface quality defects (Kim *et al.*, 2013).
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8 **TRANSLATING AS-BUILT PROGRESS TO BIM VIA LASER SCANNING**

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10 Adopting digital technologies can enhance as-built data (both geometric and semantic) for
11 both new build and retrospective BIM (Love *et al.*, 2014; Patacas *et al.*, 2015). For example,
12 recent research demonstrated how rich semantic data can be integrated and visualised within
13 a new build as-built BIM using bar code scanners linked to totems (cf. Pärn and Edwards,
14 2017). Totems were built using an application programming interface (API) plug-in to
15 visualise rich semantic data in a 3D object and extend the use and application of COBie
16 (*ibid*). The main benefits for contractors of as-built BIM capture via laser scan technology
17 are: early identification of nonconformities between the as-built and as-designed situations
18 (Bosché *et al.*, 2015); faster approval of work by the main contractor so that sub-contractors
19 receive timely payment (Klein *et al.*, 2012); and handover of contemporary as-built BIM to
20 the client and/ or facilities management team (Matthews *et al.*, 2015). The facilities
21 management team (FMT) can also harness substantial benefits during the O&M phase of
22 building asset management (Pärn, et. al., 2017). These benefits include: an ability to update
23 and maintain an accurate as-built BIM; and access building specification information via a
24 centralised as-built BIM repository (linked though barcode, radio frequency identification
25 (RFID) tags or quick response (QR) codes – cf. Pärn and Edwards, 2017).
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38 Although various studies demonstrate successful implementation of laser scan technologies
39 by contractors for site reconstruction (Bosché, 2010; Zhang and Arditi, 2013; Wang *et al.*,
40 2015), the formation of a semantically rich BIM model eludes the AECO sector due to the
41 difficulties of transforming the raw point cloud data (Pătrăucean *et al.*, 2015). The process is
42 labour intensive and prone to human error (Xiong *et al.*, 2013). Semantic information vis-a-
43 vis geometric is essential for the FMT to substantiate O&M for building assets; current
44 methods of integrating point cloud data with BIM fail to fulfil this requirement (Pătrăucean *et*
45 *al.*, 2015). While extant literature is replete with studies that examine as-built development
46 (Bennett, 2009; Longstreet, 2010; Huber *et al.*, 2011; Kim *et al.*, 2013; Barazzetti, 2016),
47 studies that provide guidance/decision support on selecting suitable enabling digital
48 technology and techniques remain deficient. Primary reasons for such disparity are attributed
49 to a: i) lack of case studies on the utilisation of as-built BIM by the FMT (Becerik-Gerber *et*
50 *al.*, 2011; Hungu, 2013); and ii) paucity of research identifying successful processes for as-
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3 built BIM development using laser/image based 3D reconstruction. Whilst recent research
4 has predominantly focused upon automatic 3D object recognition to automate the integration
5 with as-built BIM, commercial tools currently available offer semi-automated options only
6 (Chen *et al.*, 2015). More recent developments that utilise 3D modelling via photogrammetry,
7 suggest a possible paradigm shift towards machine vision applications.
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12 Most literature on automated 3D modelling revolves around construction stage related
13 activities and phases (Chen *et al.*, 2015; Galantucci *et al.*, 2015). Yet this geometrical
14 representation of physical construction is insufficient – as Törmä (2013) proffers, more
15 attention should be focussed upon creating semantic detail in as-built models for the purpose
16 of accurately emulating physical assets. Although point cloud scans can provide a geometric
17 cross reference between the physical and the virtual space, this does not emulate the much
18 needed semantic level of information required by contractors, designers, engineers and the
19 FMT (Tang *et al.*, 2010; Akanmu and Anumba, 2015).
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28 **Post Processing and Information Retrieval**

29 Post processing algorithms and applications provide an opportunity to deliver automated 3D
30 laser scanning reconstruction of the as-built BIM with some degree of semantic information
31 (Sturm and Triggs, 1996; Szeliski, 2010). Utilising computational algorithms to determine or
32 identify attributes from massive point cloud data has been applied in structural engineering,
33 construction and design stages (Brilakis *et al.*, 2010; Xiong *et al.*, 2013; Barazzetti, 2016;
34 Lindskog *et al.*, 2016). Applications of computational algorithms include: tunnel cross
35 section dimensional quality assessment (Han *et al.* 2013); deformation measurement results
36 for concrete structures (Gordon and Lichti, 2007); and volume loss estimation for an in-situ
37 concrete bridge (Liu *et al.*, 2011). Analysis and post-processing of point cloud data expedites
38 interpretation of the massive yield of points into a usable format for existing workflows such
39 as BIM. Post processing tools have automated the generation of new 3D objects directly into
40 the BIM authoring platform particularly for complex mechanical electrical and plumbing
41 (MEP) projects which comprise of hundreds of intricate piping systems (Brilakis *et al.*, 2010;
42 Barazzetti *et al.*, 2015; Son and Kim, 2016).
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54 Bosch *et al.*, (2008; 2010; 2015) first coined the term ‘Scan-vs-BIM’ technique where point
55 cloud data is compared to as-designed models. The adversarial Scan-vs-BIM definition
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3 assumes that BIM merely acts as a separate point of reference for point cloud data (Son *et al.*,
4 2015). This manual workflow adopts a three stage process, namely: i) multiple scans are
5 captured from different TLS stations; ii) point cloud data from these multiple scans is
6 integrated through a process known as registration; and iii) BIM is employed to author new
7 objects using the point scans as a reference (Monserrat and Crosetto, 2008; Wang and Cho,
8 2015). Semi-automated, post processing software can expedite this process, but the procedure
9 lacks integration and full automation (Bosché, 2010; Hyojoo Son, 2015). A more
10 comprehensive definition of this process is the ‘Scan-to-BIM’ method, which incorporates
11 semi-automated post processing software packages, enabling faster model reproduction time.
12 Hence, Scan-to-BIM provides a more suitable definition for the coupling of BIM with laser
13 scanning technologies. Current literature regarding case uses and applications of Scan-to-
14 BIM during the O&M stages remain sparse despite recommendations that endorse handover
15 of the as-built BIM model to the FMT (CRC Construction Innovation, 2007; Eastman *et al.*,
16 2011; Teicholz, 2013; Love *et al.*, 2015). In a narrow sense, BIM represents a ‘central
17 information management hub’(Volk *et al.*, 2014) – however, BIM cannot become a static
18 information repository created by its corresponding designers, otherwise it becomes ‘blind’ to
19 the on-going vicissitudes of asset management (Chen *et al.*, 2015). As-built data collection
20 augmented by rapid laser prototyping and BIM integration will generate a more realistic
21 account of assets during the design-construction (Matthews *et al.*, 2015) and post-
22 construction (Volk *et al.*, 2014) stages.
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38 **AUGMENTING LASER SCANNING WITH MACHINE VISION**

39 The AECO sector is currently confronted by the fourth industrial revolution, known as
40 ‘Industry 4.0’ where cyber-physical production systems (CPS), automation, data exchange
41 and manufacturing technologies coalesce (Perez *et al.*, 2016). To keep abreast of such
42 developments, practitioners must seek guidance from other more technologically advanced
43 industries on how to better integrate widespread digital data exchange and automation in
44 digital data reproduction (i.e. BIM) (Koutsoudis *et al.*, 2014; Zou *et al.*, 2016). Machine
45 vision (aka ‘industrial vision’ or ‘vision systems’) provides automation in the mundane
46 manufacturing tasks of inspection and fault detection with broader applications automating
47 collision detection in autonomous moving vehicles and robotics (Riaz *et al.*, 2006). Machine
48 vision is achieved through the integration of laser scan data, photography and software
49 algorithms used for post processing (Sergiyenko and Rodriguez-Quiñonez, 2016). Given the
50 advent of the digital built environment and rapidly emerging technologies such as laser
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3 scanning, new opportunities for machine vision within the AECO sector simultaneously
4 emerge (e.g. site monitoring).
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8 Embryonic machine vision developments within the AECO sector have integrated laser scan
9 technology (Son *et al.*, 2015) and photogrammetry (Scaioni *et al.*, 2014). Photogrammetry is
10 used in progress monitoring on construction sites because it is cost efficient and merely
11 requires still or moving photographic data in conjunction with automated reconstruction
12 software (*ibid.*). One example of the practical application of the integrated solution is
13 merging 3D TLS data with photogrammetry for post asset inspection purposes (Monserrat
14 and Crosetto, 2008). Others such as El-Omari and Moselhi (2009) have demonstrated
15 improved site progress capture and monitoring with the combination of photogrammetry,
16 laser scanned point cloud data and post processing software PHIDIAS. This hybrid
17 development monitored and reported upon construction progress with an impressive 75%
18 reduction in the time needed to scan a site (*ibid.*). However, Golparvar-Fard *et al.*, (2011)
19 revealed that the work of El-Omar and Moselhi (2008) could be enhanced by integrating
20 accurate geo-referenceable site coordinates with photographic content. Integration provides a
21 much-needed semantic link between photogrammetry and point cloud data (*ibid.*), thus
22 enabling remote decision making by contractors based on the as-designed information
23 (Koutsoudis *et al.*, 2014; Safa *et al.*, 2015). These techniques are heavily founded upon the
24 Structure-From-Motion (SfM) and Dense Multi-View 3D Reconstruction (DMVR)
25 algorithms and newly developed photogrammetry applications are now commercially
26 available (*ibid.*). SfM and DMVR algorithms automate 3D modelling generation from an
27 unordered image collection of the target object from multiple viewpoints (Sturm and Triggs,
28 1996). The difference in SfM lies in the ‘calibration’ process, where the internal camera
29 geometry parameters, external camera position and orientation are automatically adjusted
30 using correspondences between the image features (Peters, 2010; Szeliski, 2010). SfM uses a
31 3D structure of the environment and camera motion within the scene to automate 3D
32 modelling (Szeliski, 2010). Where 3D laser scanning technology is an expensive technology,
33 image processing SfM and DMVR software is cost-effective and efficient (cf. Golparvar-Fard
34 *et al.*, 2011). As these technological innovations continue to coalesce, the management of
35 built environment assets will become increasingly reliant upon machine learning and
36 automated decision making to fully exploit a vast array of structured geometric and semantic
37 data. Machine learning algorithms will expand the capabilities of laser scanning devices
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3 during operations and maintenance of assets within the built environment and in turn,
4 improve business profitability and performance.
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8 **CONCLUSIONS**

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10 The digital built environment era has created huge demand for laser scanning technology to
11 improve the performance and efficiency of project management throughout an asset's life
12 cycle. When coupled with other digital innovations such as BIM, laser scanning provides an
13 ideal solution to rapidly creating and updating as-built BIM models. However, anecdotal user
14 experience of these technologies reveals that although they represent an improvement upon
15 traditional means of reconstructing the built environment, challenges doggedly persist. These
16 challenges include the: high cost of point cloud reconstruction processing time; considerable
17 investment needed to train and upskill personnel to use advanced technologies effectively;
18 and lack of automation of semantic attributes within BIM. Automation is needed to transform
19 raw point scan data into semantically rich BIM model data; such a process will remove the
20 need for laborious manual procedures and mitigate the propensity to introduce human error.
21 Readily available semantic information in a digestible and accessible format is crucial for
22 clients and the FMT who manage building assets post construction – this requirement is set to
23 grow in prominence given the UK government's mandate to deliver projects to a BIM Level
24 2 standard.
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36 Many issues facing the AECO sector have already been partly or wholly resolved within
37 other sectors such as forestry, aviation and automotive; a period of extrospection is advisable
38 to reconsider whether technology/knowledge transfer could resolve these challenges. For
39 example, in forestry laser scanning is used to maintain and manage ecosystems – a similar
40 approach could be adopted to maintain built environment assets. In addition, it would appear
41 that OEMs have developed a bespoke array of commercial products driven by poorly defined
42 customer specifications and commercial gain. A number of BIM platforms, 3D scanners and
43 complementary standalone software packages have evolved in an ad-hoc manner to meet an
44 insatiable demand. This uncontrolled burst of technological development now requires a
45 reflective period of amalgamation and rationalisation of technologies. For example,
46 coalescence of photogrammetry, machine vision, post processing algorithms and 3D laser
47 scanning technologies could provide the next generation of optimal and cost effective
48 solutions to accurately reconstruct, track and monitor the digital built environment throughout
49 its entire life cycle. Case studies are also required to validate the implementation of these
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3 hybrid digital solutions in pragmatic facilities management scenarios to gauge performance
4 and user satisfaction. Specifically, such work should seek to eliminate manual remodelling
5 tasks (e.g. point cloud reconstruction) via the use of computational intelligent algorithms
6 integral within cloud based BIM platforms.
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46
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48
49
50
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54
55
56
57
58
59
60

REFERENCES

- Akanmu, A., and Anumba, C. J. (2015) Cyber-physical Systems Integration of Building Information Models and the Physical Construction. *Engineering, Construction and Architectural Management*, Vol. 22, No. 5, pp. 516-535.
- Andujar, D., Ribeiro, A., Fernandez-Quintanilla, C., and Dorado, J. (2011) Accuracy and Feasibility of Optoelectronic Sensors for Weed Mapping in Wide Row Crops. *Sensors*, Vol. 11, No. 3, pp. 2304-2318.
- UK Industrial Vision Association [UKIVA] (2007) *Machine Vision Handbook*. 3rd ed. Available via: <http://www.ukiva.org/pdf/machine-vision-handbook.pdf> (Accessed: November, 2016)
- Barazzetti, L. (2016) Parametric As-built Model Generation of Complex Shapes From Point Clouds. *Advanced Engineering Informatics*, Vol. 30, No. 3, pp. 298-311.
- Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Previtali, M., and Schiantarelli, G. (2015) Cloud-to-BIM-to-FEM: Structural Simulation with Accurate Historic BIM from Laser Scans. *Simulation Modelling Practice and Theory*, Vol. 57, pp. 71-87.
- Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2011) Application Areas and Data Requirements for BIM-enabled Facilities Management. *Journal of Construction Engineering and Management*, Vol. 138, No. 3, pp. 431-442.
- Bennett, T. (2009) BIM and Laser Scanning for As-built and Adaptive Reuse Projects: the Opportunity for Surveyors. *The American Surveyor*, Vol. 6, No. 6, pp. 15.
- Beraldin, J. A., Blais, F., Boulanger, P., Cournoyer, L., Domey, J., El-Hakim, S. F., Taylor, J. (2000a) Real World Modelling Through High Resolution Digital 3D Imaging of Objects and Structures. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 55, No. 4, pp. 230-250.
- Beraldin, J. A., Blais, F., Rioux, M., Cournoyer, L., Laurin, D., and MacLean, S. G. (2000b) Eye-safe Digital 3-D Sensing for Space Applications. *Optical Engineering*, Vol. 39, No. 1, pp. 196-211.
- Blais, F., Beraldin, J. A., and El-Hakim, S. F. (2000) Range Error Analysis of an Integrated Time-of-flight, Triangulation, and Photogrammetric 3D laser Scanning System.
- Blais, F. O. (2004) Review of 20 Years of Range Sensor Development. *Journal of Electronic Imaging*, Vol. 13, No. 1. pp. 231–240.
- Bosch, A., Volker, L., and Koutamanis, A. (2015) BIM in the Operations Stage: Bottlenecks and Implications for Owners. *Built Environment Project and Asset Management*, Vol. 5, No. 3, pp. 331-343.

- 1
2
3 Bosché, F. (2010) Automated Recognition of 3D CAD Model Objects in Laser Scans and
4 Calculation of As-built Dimensions for Dimensional Compliance Control in
5 Construction. *Advanced Engineering Informatics*, Vol. 24, No. 1, pp. 107-118.
6
7
8 Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., and Haas, R. (2015) The Value of
9 Integrating Scan-to-BIM and Scan-vs-BIM techniques for Construction Monitoring
10 Using Laser Scanning and BIM: The Case of Cylindrical MEP Components.
11 *Automation in Construction*, Vol. 49, pp. 201-213.
12
13
14 Breuckmann, B. (2014) 25 Years of High Definition 3D Scanning: History, State of the Art
15 and Outlook. *Proceedings of the EVA London 2014*, July 08 - 10, 2014, pp. 262-266.
16
17
18 Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J., and
19 Makhmalbaf, A. (2010) Toward Automated Generation of Parametric BIMs Based on
20 Hybrid Video and Laser Scanning Data. *Advanced Engineering Informatics*, Vol. 24,
21 No. 4, pp. 456-465.
22
23
24 Buck, U., Naether, S., Räss, B., Jackowski, C., and Thali, M. J. (2013) Accident or Homicide
25 – Virtual Crime Scene Reconstruction Using 3D methods. *Forensic Science*
26 *International*, Vol. 225, No. 1-3, pp. 75-84.
27
28
29 Chen, K., Lu, W., Peng, Y., Rowlinson, S., and Huang, G. Q. (2015) Bridging BIM and
30 Building: From a Literature Review to an Integrated Conceptual Framework.
31 *International Journal of Project Management*, Vol. 33, No. 6, pp. 1405-1416.
32
33
34 Cointault, F., Simeng Han, G. R., Sylvain Jay, D. R., Billiot, B., Simon, J.-C., and Salon, C.
35 (2016). Chapter 8- 3D Imaging Systems for Agricultural Applications: Characterization
36 of Crop and Root Phenotyping. In *Developing and Applying Optoelectronics in*
37 *Machine Vision*, Hereshey: IGI Global, pp. 236-272.
38
39
40 CRC Construction Innovation. (2007) *Adopting BIM for Facilities Management: Solutions*
41 *for Managing the Sydney Opera House*. Cooperative Research Center for Construction
42 *Innovation*, Brisbane, Australia, ISBN 978-0-9775282-2-6
43
44
45 Creath, K., and Wyant, J. C. (1992). Chapter 16 -Moiré and Fringe Projection Techniques. In
46 D. Malacara (Ed.), *In Optical Shop Testing*: Wiley and Sons, New Jersey, pp. 653-681.
47
48
49 Derriso, M. M., McCurry, C. D., and Schubert Kabban, C. M. (2016) 2 - A Novel Approach
50 for Implementing Structural Health Monitoring Systems for Aerospace Structures A2 -
51 Yuan, Fuh-Gwo *Structural Health Monitoring (SHM) in Aerospace Structures*
52 *Woodhead Publishing*, Duxford, pp. 33-56.
53
54
55
56
57
58
59
60

- 1
2
3 Eastman, C., Eastman, C. M., Teicholz, P., Sacks, R., and Liston, K. (2011) BIM Handbook:
4 A Guide to Building Information Modeling for Owners, Managers, Designers,
5 Engineers and Contractors: John Wiley & Sons, New Jersey.
6
7
8 El-Omari, S., and Moselhi, O. (2008) Integrating 3D Laser Scanning and Photogrammetry for
9 Progress Measurement of Construction Work. *Automation in Construction*, Vol. 18,
10 No. 1, pp. 1-9.
11
12 El-Omari, S., and Moselhi, O. (2009) Data acquisition from Construction Sites for Tracking
13 Purposes. *Engineering, Construction and Architectural Management*, Vol. 16, No. 5,
14 pp. 490-503.
15
16
17
18 Faro. (2004). FARO Laser Scanner Focus Series Technical Specification. Available via:
19 <http://www.faro.com/products/3d-surveying/laser-scanner-faro-focus-3d/overview/>
20 (Accessed: November, 2016).
21
22
23 Flores-Fuentes, W., Rivas-Lopez, M., Hernandez-Balbuena, D., Sergiyenko, O., Rodríguez-
24 Quiñonez, J. C., Rivera-Castillo, J., Linder, L., Basaca-Preciado, L. C. (2016). Chapter
25 1-Applying Optoelectronic Devices Fusion in Machine Vision: Spatial Coordinate
26 Measurement In O. Sergiyenko and J. C. Rodríguez-Quiñonez (Eds.), In *Developing*
27 *and Applying Optoelectronics in Machine Vision*, Hereshey: IGI Global, pp. 1-37.
28
29
30
31 Galeazzi, F., Callieri, M., Dellepiane, M., Charno, M., Richards, J., and Scopigno, R. (2016)
32 Web-based Visualization for 3D data in Archaeology: The ADS 3D Viewer. *Journal of*
33 *Archaeological Science: Reports*, Vol. 9, pp. 1-11.
34
35
36
37 Gao, T., Akinci, B., Ergan, S., and Garrett, J. (2015) An Approach to Combine Progressively
38 Captured Point Clouds for BIM Update. *Advanced Engineering Informatics*, Vol. 29,
39 No. 4, pp. 1001-1012.
40
41
42 Godin, G., Borgeat, L., Beraldin, J. A., and Blais, F. (2010, 17-19 March 2010) Issues in
43 Acquiring, Processing and Visualizing Large and Detailed 3D Models. Paper presented
44 at the Information Sciences and Systems (CISS), 2010 44th Annual Conference on
45 Information Sciences and Systems (CISS), 17-19 March 2010, Princeton, pp. 1-6.
46
47
48 Godin, G., Roth, G., and Boulanger, P. (1994) Using Laser Geometric Sensing for Rapid
49 Product Development. *Proceedings of International Conference on Rapid Product*
50 *Development*, 31 Jan- 2 Feb 1994, Stuttgart, pp. 405-416.
51
52
53 Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S., and Peña-Mora, F. (2011) Evaluation
54 of Image-based Modeling and Laser Scanning Accuracy for Emerging Automated
55 Performance Monitoring Techniques. *Automation in Construction*, Vol. 20, No. 8, pp.
56 1143-1155.
57
58
59
60

- 1
2
3 Gordon, S. J., and Lichti, D. D. (2007) Modeling Terrestrial Laser Scanner Data for Precise
4 Structural Deformation Measurement. *Journal of Surveying Engineering*, Vol. 133, No.
5 2, pp. 72-80.
6
7
8 Hoffmeister, D. (2016) Chapter 11 - Laser Scanning Approaches for Crop Monitoring. In G.
9 R. F. A. Viviana Scognamiglio and P. Giuseppe (Eds.), *Comprehensive Analytical*
10 *Chemistry* (Vol. Volume 74, pp. 343-361). Available via:
11 <http://www.sciencedirect.com/science/article/pii/S0166526X16300319> (Accessed:
12 November, 2016).
13
14
15
16 Hornberg. (2006). *Handbook of Machine Vision* (P. D. A. Hornberg Ed.). Germany: Wiley-
17 VCH.
18
19 Huber, D., Akinci, B., Oliver, A. A., Anil, E., Okorn, B. E., and Xiong, X. (2011) Methods
20 for Automatically Modeling and Representing As-built Building Information Models.
21 *Proceedings of the NSF CMMI Research Innovation Conference*, 4-7 January, Georgia.
22 Available via: https://www.ri.cmu.edu/pub_files/2011/1/2011-huber-cmmi-nsf-v4.pdf
23 (Accessed: November, 2016).
24
25
26
27
28 Hungu, C. F. (2013). *Utilization of BIM from Early Design Stage to Facilitate Efficient FM*
29 *Operations: Chalmers University of Technology*. Available via:
30 <http://publications.lib.chalmers.se/records/fulltext/183268/183268.pdf> (Accessed:
31 November, 2016).
32
33
34
35 Hyojoo Son, J. N., Changwan Kim. (2015) *Semantic As-built 3D Modeling of Buildings*
36 *Under Construction from Laser scan Data Based on Local Convexity without an As-*
37 *planned Model*. 32st ISARC Conference, Oulu, Finland. Available via:
38 <http://www.iaarc.org/publications/fulltext/FFACE-ISARC15-3002169.pdf> (Accessed:
39 November, 2016).
40
41
42
43 Irizarry, J., and Costa, D. B. (2016) *Exploratory Study of Potential Applications of*
44 *Unmanned Aerial Systems for Construction Management Tasks*. *Journal of*
45 *Management in Engineering*, Vol. 32, No. 3, pp. 1-10.
46
47
48 Jung, J., Hong, S., Jeong, S., Kim, S., Cho, H., Hong, S., and Heo, J. (2014) *Productive*
49 *Modeling for Development of As-built BIM of Existing Indoor Structures*. *Automation*
50 *in Construction*, Vol. 42, pp. 68-77.
51
52
53 Kim, C., Son, H., and Kim, C. (2013) *Automated Construction Progress Measurement Using*
54 *a 4D Building Information Model and 3D Data*. *Automation in Construction*, Vol. 31,
55 pp. 75-82.
56
57
58
59
60

- 1
2
3 Kim, M.-K., Cheng, J. C. P., Sohn, H., and Chang, C.-C. (2015a) A Framework for
4 Dimensional and Surface Quality Assessment of Precast Concrete Elements using BIM
5 and 3D Laser Scanning. *Automation in Construction*, Vol. 49, pp. 225-238.
6
7
8 Kim, M.-K., Sohn, H., and Chang, C.-C. (2015b) Localization and Quantification of Concrete
9 Spalling Defects Using Terrestrial Laser Scanning. *Journal of Computing in Civil*
10 *Engineering*, Vol. 29, No. 6, p. 04014086.
11
12 Klein, L., Li, N., and Becerik-Gerber, B. (2012) Imaged-based Verification of As-built
13 Documentation of Operational Buildings. *Automation in Construction*, Vol. 21, pp.
14 161-171.
15
16
17
18 Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., and Chamzas, C.
19 (2014) Multi-image 3D Reconstruction Data Evaluation. *Journal of Cultural Heritage*,
20 Vol. 15, No. 1, pp. 73-79.
21
22
23 Laing, R., Leon, M., Isaacs, J., and Georgiev, D. (2015) Scan to BIM: the Development of a
24 Clear Workflow for the Incorporation of Point Clouds within a BIM Environment. *WIT*
25 *Transactions on The Built Environment*, Vol. 149, pp. 279 - 289.
26
27
28 Lehtomäki, M., Jaakkola, A., Hyypä, J., Lampinen, J., Kaartinen, H., Kukko, A., Puttonen,
29 E., Hyypä, H. (2015) Object Classification and Recognition From Mobile Laser
30 Scanning Point Clouds in a Road Environment. *IEEE Transactions on Geoscience and*
31 *Remote Sensing*, Vol. 54, No.2, pp. 1226-1239
32
33
34
35 Lindner, L. (2016) Chapter 4 - Laser Scanners In O. Sergiyenko and J. C. Rodriguez-
36 Quiñonez (Eds.), In *Developing and Applying Optoelectronics in Machine Vision*,
37 Hereshey: IGI Global, pp. 108-145.
38
39
40 Lindner, L., Sergiyenko, O., Rodríguez-Quíñonez, J. C., Rivas-Lopez, M., Hernandez-
41 Balbuena, D., Flores-Fuentes, W., Murrieta-Rico, F. N., Tyrsa, V. (2016) Mobile
42 Robot Vision System Using Continuous Laser Scanning for Industrial Application.
43 *Industrial Robot: An International Journal*, Vol. 43, No. 4, pp. 360-369.
44
45
46
47 Lindskog, E., Berglund, J., Vallhagen, J., and Johansson, B. (2016) Layout Planning and
48 Geometry Analysis Using 3D Laser Scanning in Production System Redesign. *Procedia*
49 *CIRP*, Vol. 44, No.4, pp. 126-131.
50
51
52 Longstreet, B. (2010). Finding the Right Solution to Create an As-built BIM of Portland
53 International Airport's Baggage Handling Facility. Available via: [http://www.leica-](http://www.leica-geosystems.us/en/ScanningPDX.pdf)
54 [geosystems.us/en/ScanningPDX.pdf](http://www.leica-geosystems.us/en/ScanningPDX.pdf) (Accessed: September, 2016)
55
56
57
58 Love, P. E., Matthews, J., and Lockley, S. (2015) BIM for Built Asset Management. *Built*
59 *Environment Project and Asset Management*, Vol.5, No.3, (guest editorial).
60

- 1
2
3 Love, P. E., Matthews, J., Simpson, I., Hill, A., and Olatunji, O. A. (2014) A Benefits
4 Realization Management Building Information Modeling Framework for Asset
5 Owners. *Automation in Construction*, Vol. 37, pp. 1-10.
6
7
8 Markets, (2016) 3D Scanner Market by Offering (Hardware, Aftermarket Service), Type
9 (Laser, Structured Light), Range, Product (Tripod Mounted, Fixed CMM Based,
10 Portable CMM Based, Desktop), Application, Industry, and Geography - Global
11 Forecast to 2022. Available via: [http://www.marketsandmarkets.com/Market-](http://www.marketsandmarkets.com/Market-Reports/3d-scanner-market-119952472.html)
12 [Reports/3d-scanner-market-119952472.html](http://www.marketsandmarkets.com/Market-Reports/3d-scanner-market-119952472.html) (Accessed: November 2016).
13
14
15
16 Marzuki, A. (2016) Chapter 2- CMOS Image Sensor: Analog and Mixed-Signal Circuits In
17 O. Sergiyenko and J. C. Rodriguez-Quiñonez (Eds.), In *Developing and Applying*
18 *Optoelectronics in Machine Vision*, Hereshey: IGI Global, pp. pages 38-78.
19
20
21 Matthews, J., Love, P. E., Heinemann, S., Chandler, R., Rumsey, C., and Olatunj, O. (2015)
22 Real Time Progress Management: Re-engineering Processes for Cloud-based BIM in
23 Construction. *Automation in Construction*, Vol. 58, pp. 38-47.
24
25
26 Meadati, P., Irizarry, J., and Akhnoukh, A. K. (2010) BIM and RFID Integration: A Pilot
27 Study. *Advancing and Integrating Construction Education Second International*
28 *Conference on Construction in Developing Countries (ICCIDC-II)*, August 3-5, 2010,
29 Cairo, pp. 570-578.
30
31
32
33 Mello, A. R. d., and Stemmer, M. R. (2016) Chapter 3- Automated Visual Inspection System
34 for Printed Circuit Boards for Small Series Production: A Multiagent Context
35 Approach. In O. Sergiyenko, & Rodriguez-Quiñonez, J. C. (Ed.), In *Developing and*
36 *Applying Optoelectronics in Machine Vision*, Hereshey: IGI Global, pp. 79-107.
37
38
39 Monserrat, O., and Crosetto, M. (2008) Deformation Measurement Using Terrestrial Laser
40 Scanning Data and Least Squares 3D Surface Matching. *ISPRS Journal of*
41 *Photogrammetry and Remote Sensing*, Vol. 63, No. 1, pp. 142-154.
42
43
44 Motamedi, A., Setayeshgar, S., Soltani, M., and Hammad, A. (2016) Extending IFC to
45 incorporate information of RFID tags attached to building elements, *Advanced*
46 *Engineering Informatics*, Vol. 30, No. 1, pp. 39-53.
47
48
49 Olsen, M. J., Kuester, F., Chang, B. J., and Hutchinson, T. C. (2010) Terrestrial Laser
50 Scanning-Based Structural Damage Assessment. *Journal of Computing in Civil*
51 *Engineering*, Vol. 24, No. 3, pp. 264-272.
52
53
54 Ouédraogo, M.M., Degré, A., Debouche, C. and Lisein, J. (2014) The Evaluation of
55 Unmanned Aerial System-based Photogrammetry and Terrestrial Laser Scanning to
56 Generate DEMs of Agricultural Watersheds, *Geomorphology*, Vol. 214, pp. 339-355.
57
58
59
60

- 1
2
3 Park, H. S., Lee, H. M., Adeli, H., and Lee, I. (2007) A New Approach for Health Monitoring
4 of Structures: Terrestrial Laser Scanning. *Computer-Aided Civil and Infrastructure*
5 *Engineering*, Vol. 22, No. 1, pp. 19-30.
6
7
8 Park, H. S., Shin, Y., Choi, S. W., and Kim, Y. (2013) An Integrative Structural Health
9 Monitoring System for the Local/Global Responses of a Large-scale Irregular Building
10 Under Construction. *Sensors (Basel)*, Vol. 13, No. 7, pp. 9085-9103.
11
12
13 Pärn, E.A. and Edwards, D.J. (2017) Conceptualizing the FinDD API Plug-in: A Study of
14 BIM-FM Integration, *Automation in Construction* (in press).
15
16 Pärn, E.A., Edwards, D.J. and Sing. M.C.P. (2017) The Building Information Modelling
17 Trajectory in Facilities Management: A Review, *Automation in Construction*, Vol. 75,
18 pp 45-55. DOI: 10.1016/j.autcon.2016.12.003
19
20
21 Patacas, J., Dawood, N., and Kassem, M. (2015) BIM for Facilities Management: Evaluating
22 BIM Standards in Asset Register Creation and Service Life Planning. *Journal of*
23 *Information Technology in Construction*, Vol. 20, No. 10, pp. 313-318.
24
25
26 Pătrăucean, V., Armeni, I., Nahangi, M., Yeung, J., Brilakis, I., and Haas, C. (2015) State of
27 Research in Automatic As-built Modelling. *Advanced Engineering Informatics*, Vol.
28 29, No. 2, pp. 162-171.
29
30
31 Perez, L., Rodriguez, I., Rodriguez, N., Usamentiaga, R., and Garcia, D. F. (2016) Robot
32 Guidance Using Machine Vision Techniques in Industrial Environments: A
33 Comparative Review. *Sensors (Basel)*, Vol. 16, No. 3, p.335
34
35
36 Peters, K. H. M. G. (2010) The Structure-from-motion Reconstruction Pipeline – a Survey
37 with Focus on Short Image Sequences. *Kybernetika*, Vol. 46, No. 5, pp. 926-937.
38
39
40 Qin, R. and Gruen, A. (2014) 3D Change Detection at Street Level Using Mobile Laser
41 Scanning Point Clouds and Terrestrial Images, *ISPRS Journal of Photogrammetry and*
42 *Remote Sensing*, Vol. 90, pp. 23-35.
43
44
45 Riaz, Z., Edwards, D. J., and Thorpe, A. (2006) SightSafety: A Hybrid Information and
46 Communication Technology System for Reducing Vehicle/ Pedestrian Collisions.
47 *Automation in Construction*, Vol. 15, No. 6, pp. 719-728.
48
49
50 Rushmeier, F. B. a. H. (2002) The 3D Model Acquisition Pipeline. *Computer Graphics*
51 *Forum*, Vol. 21, No. 2, pp. 149-172.
52
53 Safa, M., Shahi, A., Nahangi, M., Haas, C., and Noori, H. (2015) Automating Measurement
54 Process to Improve Quality Management for Piping Fabrication. *Structures*, Vol. 3, pp.
55 71-80.
56
57
58
59
60

- 1
2
3 Scaioni, M., Barazzetti, L., Giussani, A., Previtali, M., Roncoroni, F., and Alba, M. I. (2014)
4 Photogrammetric Techniques for Monitoring Tunnel Deformation. *Earth Science*
5 *Informatics*, Vol. 7, No. 2, pp. 83-95.
6
7
8 Sergiyenko, O., and Rodriguez-Quiñonez, J. C. (2016) Developing and Applying
9 Optoelectronics in Machine Vision. In *Developing and Applying Optoelectronics in*
10 *Machine Vision*, Hereshey: IGI Global.
11
12 Shapira, A., Filin, S., and Wicnudel, A. (2014) Quantitative Analysis of Blind Tower-Crane
13 Lifts Using Laser-scanning Information. *Construction innovation*, Vol. 14, No. 3, pp.
14 383-403.
15
16
17 Shoji, K. (2013) *Time-of-Flight Techniques Handbook of 3D Machine Vision*, Taylor &
18 Francis: Boca Raton. pp. 253-274
19
20 Son, H., and Kim, C. (2016) Automatic Segmentation and 3D Modeling of Pipelines into
21 Constituent Parts from Laser-scan Data of the Built Environment. *Automation in*
22 *Construction*, Vol. 68, pp. 203-211.
23
24 Son, H., Kim, C., and Kim, C. (2015) 3D Reconstruction of As-built Industrial
25 Instrumentation Models from Laser-scan Data and a 3D CAD Database Based on Prior
26 Knowledge. *Automation in Construction*, Vol. 49, pp. 193-200.
27
28 Son, H., Kim, C., and Turkan, Y. (2015) Scan-to-BIM – An Overview of the Current State of
29 the Art. Paper presented at the 32st ISARC Conference, Oulu, Finland. Available via:
30 http://www.iaarc.org/publications/2015_proceedings_of_the_32st_isarc_oulu_finland/s
31 [can_to_bim_an_overview_of_the_current_state_of_the_art_and_a_look_ahead.html](http://www.iaarc.org/publications/2015_proceedings_of_the_32st_isarc_oulu_finland/s)
32 (Accessed: November, 2016)
33
34
35
36
37
38
39 Sturm, P., and Triggs, B. (1996) A Factorization Based Algorithm for Multi-image Projective
40 Structure and Motion. In B. Buxton & R. Cipolla (Eds.), *Computer Vision — ECCV*
41 *'96: 4th European Conference on Computer Vision Cambridge, UK, April 15–18, 1996*
42 *Proceedings Volume II* (pp. 709-720). Berlin, Heidelberg: Springer Berlin Heidelberg.
43
44
45
46 Szeliski, R. (2010) *Computer Vision: Algorithms and Applications*. Springer: London.
47
48 Szweda, R. (2006) Optoelectronics Aiding Industrial Material Processing. *III-Vs Review*,
49 Vol. 19, No. 4, pp. 33-37.
50
51 Tang, P., and Akinci, B. (2012a) Automatic Execution of Workflows on Laser-scanned Data
52 for Extracting Bridge Surveying Goals. *Advanced Engineering Informatics*, Vol. 26,
53 No. 4, pp. 889-903.
54
55
56
57
58
59
60

- 1
2
3 Tang, P., and Akinci, B. (2012b) Formalization of Workflows for Extracting Bridge
4 Surveying Goals from Laser-scanned Data. *Automation in Construction*, Vol. 22, pp.
5 306-319.
6
7
8 Tang, P., Huber, D., Akinci, B., Lipman, R., and Lytle, A. (2010) Automatic Reconstruction
9 of As-built BIM from Laser-scanned Point Clouds: A Review of Related Techniques.
10 *Automation in Construction*, Vol. 19, No. 7, pp. 829-843.
11
12 Teicholz, P. (2013) *BIM for Facility Managers*: John Wiley & Sons: New Jersey.
13
14 Thiel, K. H., and Wehr, A. (2004) Performance Capabilities of Laser Scanners-An Overview
15 and Measurement Principle Analysis. *International Archives of Photogrammetry,*
16 *Remote Sensing and Spatial Information Sciences,*, Vol. 36, No. 8, pp. 14-18.
17
18 Törmä, S. (2013) Semantic Linking of BIM. *Semantic Computing (ICSC)*, 2013 IEEE
19 Seventh International Conference on Semantic Computing, Irvine California. Available
20 via: <http://www.cs.hut.fi/~sto/Torma-2013-BIM-LD.pdf> (Accessed: November, 2016)
21
22
23
24 Turkan, Y., Bosché, F., Haas, C. T., and Haas, R. (2014) Tracking of Secondary and
25 Temporary Objects in Structural Concrete Work. *Construction Innovation*, Vol. 14, No.
26 2, pp. 145-167.
27
28
29 Volk, R., Stengel, J., and Schultmann, F. (2014) BIM for Existing Buildings - Literature
30 Review and Future Needs. *Automation in Construction*, Vol. 38, pp. 109-127.
31
32
33 Wang, C., and Cho, Y. K. (2015) Performance Evaluation of Automatically Generated BIM
34 from Laser Scanner Data for Sustainability Analyses. *Procedia Engineering*, Vol. 118,
35 pp. 918-925.
36
37
38 Wang, C., Cho, Y. K., and Kim, C. (2015) Automatic BIM Component Extraction from Point
39 Clouds of Existing Buildings for Sustainability Applications. *Automation in*
40 *Construction*, Vol. 56, pp. 1-13.
41
42
43 Wang, Q., Kim, M.-K., Cheng, J. C. P., and Sohn, H. (2016) Automated Quality Assessment
44 of Precast Concrete Elements with Geometry Irregularities using Terrestrial Laser
45 Scanning. *Automation in Construction*, Vol. 68, pp. 170-182.
46
47
48 Wehr, A. and Lohr, U. (1999) Airborne Laser Scanning - An Introduction and Overview,
49 *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol.54, No.3, July 1999, pp.
50 68-82.
51
52
53 Xiong, X., Adan, A., Akinci, B., and Huber, D. (2013) Automatic Creation of Semantically
54 Rich 3D Building Models from Laser Scanner Data. *Automation in Construction*, Vol.
55 31, pp. 325-337.
56
57
58
59
60

- 1
2
3 Zeibak-Shini, R., Sacks, R., Ma, L., and Filin, S. (2016) Towards Generation of As-damaged
4 BIM Models using Laser-scanning and As-built BIM: First Estimate of As-damaged
5 Locations of Reinforced Concrete Frame Members in Masonry Infill Structures.
6 Advanced Engineering Informatics, Vol. 30, No. 3, pp. 312-326.
7
8
9
10 Zhang, C., and Arditi, D. (2013) Automated Progress Control Using Laser Scanning
11 Technology. Automation in Construction, Vol. 36, pp. 108-116.
12
13 Zhang, C., Kalasapudi, V. S., and Tang, P. (2016) Rapid Data Quality Oriented Laser Scan
14 Planning for Dynamic Construction Environments. Advanced Engineering Informatics,
15 Vol. 30, No. 2, pp. 218-232.
16
17
18 Zou, Y., Kiviniemi, A., and Jones, S. W. (2016) A Review of Risk Management Through
19 BIM and BIM-related Technologies. Safety Science, Available online 23 January.
20
21
22
23
24
25
26
27
28
29
30
31
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Figure 1 – Laser Scan Device Evolution Timeline

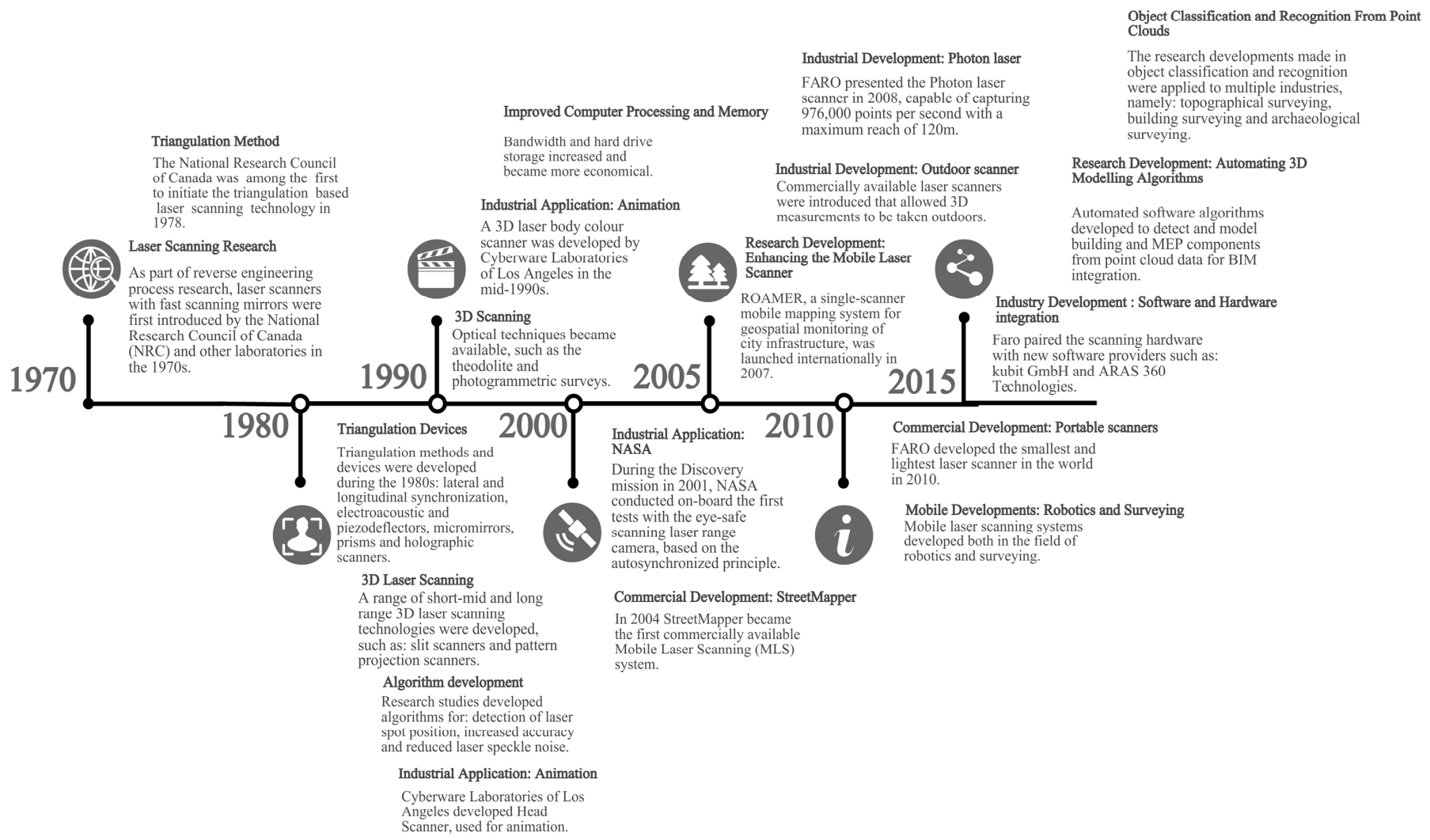


Table 1 - Componential Specification Tabulation of Laser Scan Technology

Specification Models/Brand	Number of Points			Range of Scan/ Min Range				Weight			Range Error*			Resolution			Field of View			Price Range			Laser Class			
	2000-50,000	50,000-500,000	500,000 – 1 million	0.3-3m	3-50m	50-130m	130-330m	≤2.5kg	2.5-25 kg	25-110 kg	±35µm±80µm	±1mm	±2mm	≤100 megapixels	100-170 megapixels	≥170 megapixels	≤200°	200-300°	300-360°	≤£50,000	£50,000-100,0000	≥£100,000	1-1M	2-2M	3R-3B-4	
Airborne Laser Scanning Devices																										
RIEGL-VUXL-1LR	•					•		•				•	•					•				•	•			
RIEGL-VQ-880-G	•					•		•				•	•				•					•	•			
Leica City Mapper Airborne	•					•		•				•	•				•					•	•			
Terrestrial Laser Scanning Devices																										
FARO Focus ^{3D} X 30			•		•			•		•				•					•	•			•			
FARO Focus ^{3D} X 130			•		•			•		•				•					•	•			•			
FARO Focus ^{3D} X 130 HDR			•		•			•		•				•					•	•			•			
FARO Focus ^{3D} X 330			•			•		•		•					•				•	•			•			
FARO Focus ^{3D} X 330 HDR			•			•		•		•					•				•	•			•			
Leica HDS6100			•		•			•		•					•				•	•					•	
Leica Scan Station P30/P40		•				•		•		•					•				•			•	•			
Leica Scan Station P16			•		•			•		•		•			•				•	•			•			
Leica Scan Station C10	•				•			•		•			•						•	•					•	
Leica Scan Station C5	•				•			•		•			•						•	•				•		
Mobile Laser Scanning Devices																										
FARO Freestyle ^{3D}	•			•			•		•					•	•				•				•			
Leica Pegasus: Two			•			•		•		•				•					•			•	•			
Leica Pegasus: Backpack			•			•		•		•				•				•			•	•				
Leica Pegasus: Stream			•	•				•		•				•					•			•	•			
RIEGL VMX 450			•	•				•		•				•					•			•	•			

NB: *Range error of commercially available scanners is dependent upon the individual make and model. Vendors define range error as the standard deviation of one sigma (σ), taken from a systematic measurement at around 10m and 25m. Maximum error can exceed 1 sigma, depending on the distance measured (i.e > 25m ± mm) and the reflectivity of the material being scanned.

Figure 2 – Modes of Delivery for Laser Scan Devices

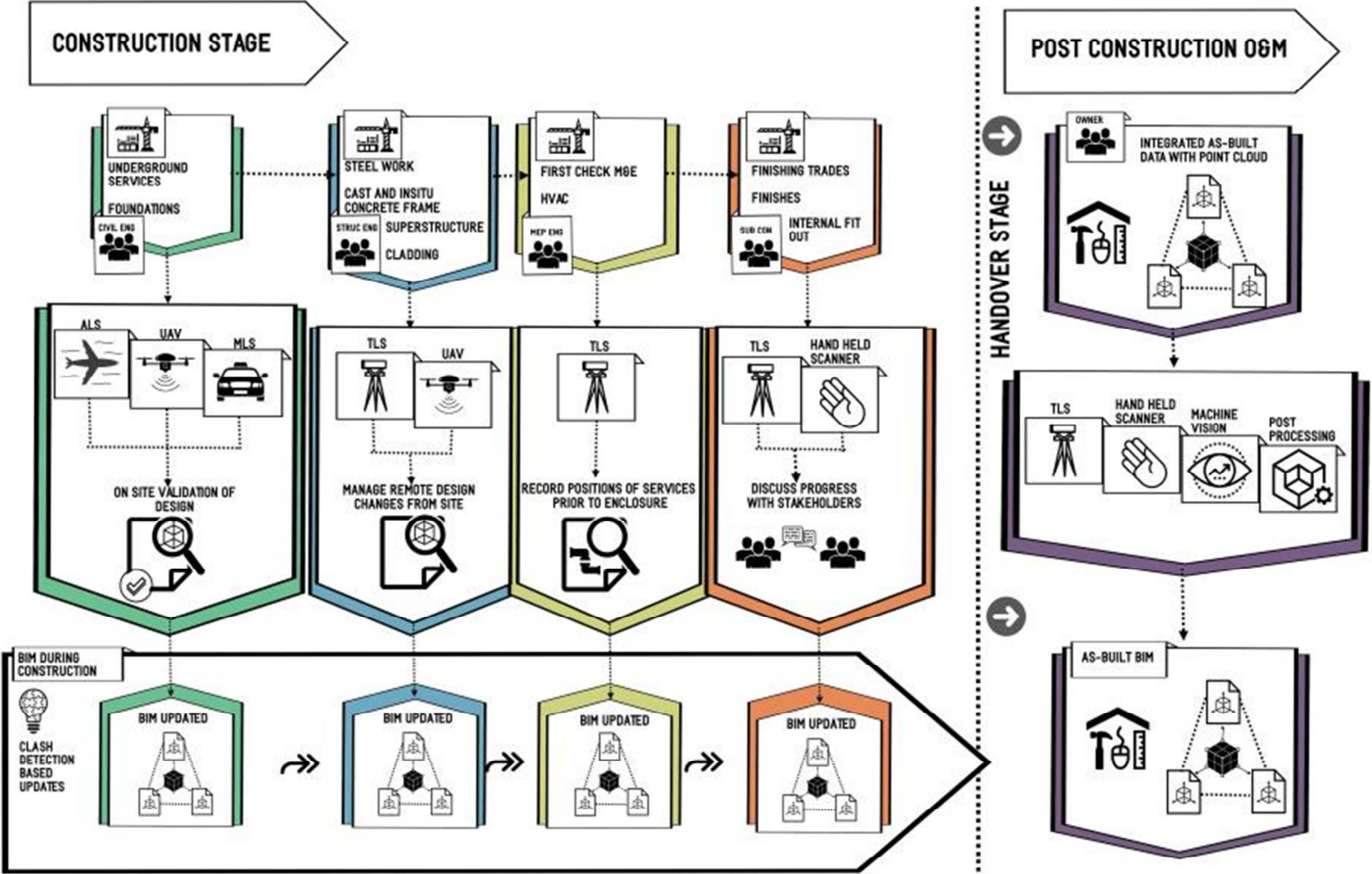


Figure 3 – Thematic Literature Analysis of 3D Terrestrial Laser Scan Technology Applications

