A History of Laser Scanning, Part 2: The Later Phase of Industrial and Heritage Applications

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Abstract

The second part of this article examines the transition of midrange terrestrial laser scanning (TLS)–from applied research to applied markets. It looks at the crossover of technologies; their connection to broader developments in computing and microelectronics; and changes made based on application. The shift from initial uses in on-board guidance systems and terrain mapping to tripod-based survey for as-built documentation is a main focus. Origins of terms like digital twin are identified and, for the first time, the earliest examples of cultural heritage (CH) based midrange TLS scans are shown and explained. Part two of this history of laser scanning is a comprehensive analysis upto the year 2020.

Introduction

Having started out in the first part of this history of midrange terrestrial laser scanning (TLS) with space, defense, and research-driven applications (in the initial phase of its development), the second part now explores how technologies made the transition to other fields, like the nuclear industry and cultural heritage (CH). This was particularly the case in and beyond the 1990s. Building on earlier digital processing tools, new ways emerged to analyze and display the data from laser scanners. This second phase in the development of laser scanning is also one where the adoption of technology found nongovernmental organizations working as facilitators in documenting CH. Case studies were generated either to market the technologies to a wider audience or to help educate people about the technologies used. The sponsorship of such projects was supported by corporate backers wherever it proved possible. The third phase, led by tripod based systems and nonprofit corporations—which came out of California—developed and democratized its take-up. Finally, in the fourth phase, the automotive and mobile-computer industries are driving the commoditization of sensors. Phase four was still in place when this article was published.

Laser System Architecture: The Essentials

See Figure 1, next page.

Laser Scanning in Its Commercial Era (from 1979 Onward)

After the end of the first phase of development in the space and defense sectors (see part one of this article), the focus of development shifted to the commercial sector, where it still remains. The technologies that now comprise TLS in general—be it close, midrange, or long range—are all centered on measurement devices and techniques in this commercial era of use. They are geared toward the rapid documentation of scenes and objects to a high level of detail. More specifically, TLS is a form of active sensing where a laser makes contact with a surface in order to generate accurate and precise point-cloud information (“Project Development Plan” n.d.). This information is then processed using software that is compatible with the dense point clouds of 3D information thus generated (Takase *et al.* 2003). Software packages can be proprietary in nature—such as Leica Geosystems’ Cyclone, Riegl’s RiScan, Trimble’s RealWorks, Zoller + Fröhlich’s LaserControl, and Autodesk’s ReCap (“Leica Cyclone” 2020; “ReCap” n.d.; “RiScan Pro 2.0” n.d.; “Trimble RealWorks” n.d.; “Z+F LaserControl” n.d.)—or open source, like CloudCompare (Girardeau-Montaut n.d.). There are even plug-ins for preexisting computer-aided design (CAD) software packages. For example, CloudWorx enables AutoCAD users to work with point-cloud information (“Leica CloudWorx” 2020; “Leica Cyclone” 2020). Like many services and solutions, AutoCAD predates the incorporation of 3D point clouds into design-based workflows (Clayton 2005). Enabling the user base of pre-existing software to work with point-cloud data in this way–in packages they are already educated in–is a gateway to increased adoption of midrange TLS. Distributed computing has also made large data sets like point clouds more accessible to a broader spectrum of people.

The term "midrange" is used to describe the rapid acquisition of 3D point-cloud data collected to known accuracies, repeatability (in terms of performance), and resolutions over a known distance (Boehler, Bordas Vicent and Marbs 2003; Spring, Peters and Minns 2010). It takes the notion of dynamic range—the ratio between the largest and smallest values (including surfaces in a scene returned as points)—into account when documenting an environment or object as a 3D image (Boehler, Heinz and Marbs 2001; Boehler and Marbs 2002; Mettenleiter *et al.* 2016). Information pertaining to its earlier uses, which are outlined later in this article, suggests that it is best viewed within a range of up to 1000 m. This updates the measurement to application parameters based on object complexity set out by Boehler *et al.* (2001; Historic England 2018)—that is, by including advancements in accuracy, repeatability, and resolution over a greater range in the period since that work was published. Current midrange TLS solutions collect up to 1 million points of data per second at optimum resolutions of millimeters up to around 5 cm—typically as a near-360° panorama of points (Mettenleiter *et al.* 2016)—depending on the size and scope of the project (also known as the *end deliverable*). Speed of data collection has continued to increase; as of July 2020, it takes anywhere from 4 to 7 min on newer units like the RTC360 and Z+F 5016 (Mettenleiter *et al.* 2016; Wujanz *et al.* 2017; Biasion *et al.* 2019)—when they are set to high accuracy, rate at which signals of points retrieved are sampled, resolution, quality, and range. Laser scanners are like still photography cameras in that they document a scene (Spring and Peters 2014). Instead of generating 2D pixels, however, they use a laser to create a 3D image commonly referred to as a point cloud (Spring 2015).

Point-cloud information is integral to a midrange TLS workflow. In this type of workflow, points are made up of x (ω), y (φ), z (κ), red, green, blue, and grayscale data (Levoy and Whitted

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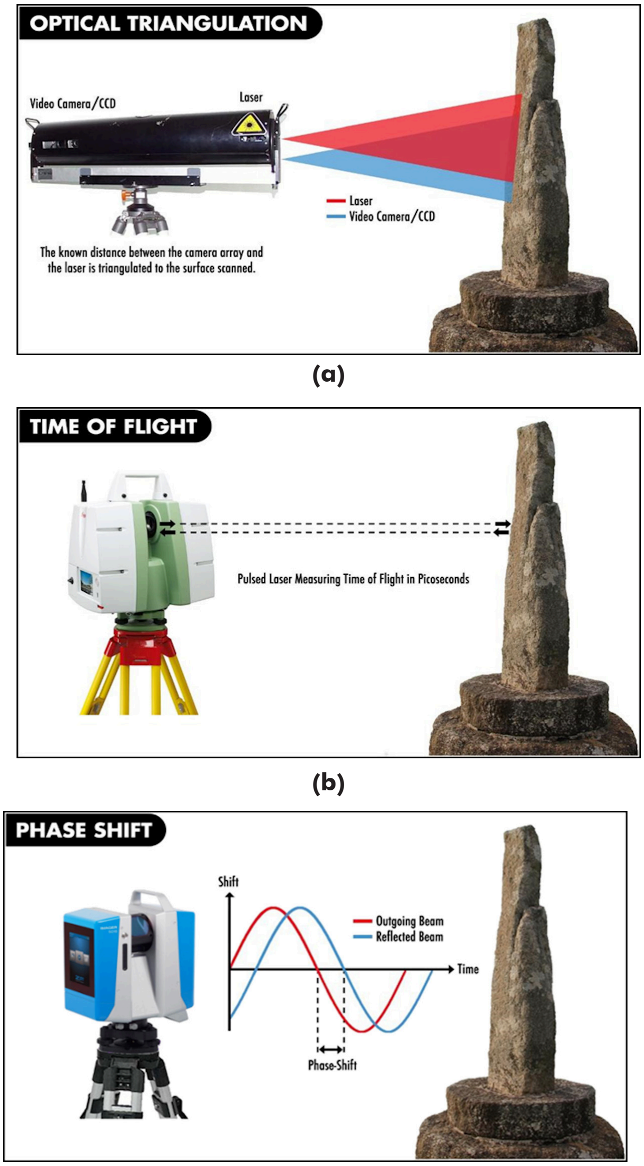
Laser System Architecture: The Essentials



(a)

(b)

(c)

Figure 1. (a) The principle of optical triangulation was initially used in Mensi SOISIC scanners to inspect nuclear facilities owned by Électricité de France (EDF) (Fuchs *et al.* 2004). The known distance between the sensors on the scanner head and the area of overlap projected onto a surface was used to gather metrically accurate information (Learning Tools for Advanced Three-Dimensional Surveying in Risk Awareness Project [3DRiskMapping] 2008). Incorporating a laser into the system architecture of the SOISIC also extended the range at which information could be collected using this method (X. Chen & Schmitt 1992). Optical triangulation was used in low-cost consumer products by 2010 (Garcia and Zalevsky 2008; Vance 2010): For example, PrimeSense triangulation-enabling depth sensors were used in the Xbox Kinect 360 and the Project Tango prototype mobile-phone (Mantis Vision provided the structured light sensor for the tablet) ("PrimeSense Supplies 3-D-Sensing Technology" 2010; Keralia, Vyas and Deulkar 2014). PrimeSense was acquired by Apple in 2013 (Etherington 2014).

(b) 3D point-cloud data are collected by time of flight (ToF) via a pulsed beam (3DRiskMapping 2008). The Cyrax HDS 2400 and Riegl LMS-Z160/Z210 were the first ToF systems to be released when midrange terrestrial laser scanning (TLS) made the transition into commercial markets in 1997–1998 (Flatscher *et al.* 1999). Similar to the commoditization of triangulation systems via the Xbox Kinect 360, the Project Tango mobile phone-based architecture incorporated ToF sensors via the ASUS ZenFone AR phones in 2017 (Franz, Irmler and Rüppel 2018). Project Tango's failure in leading to a commercially successful product, even with ASUS's distribution network, did not stop ToF from making its way into mobile phones again (Kastrenakes 2017; Petrov 2018). Samsung introduced ToF sensors into its 10+ 5G and Note units by 2019 (Petrov 2018). Their positional use in virtual and augmented reality-based applications was the driving force behind this move (Saran, Lin and Zakhor 2019).

This trend continued to develop at Google after Project Tango was absorbed into its ARCore augmented reality system in December, 2017 (Kastrenakes 2017). The ARCore led Depth API–which created depth maps from the RGB camera in a smart phone or tablet–was announced in December, 2019 (Izadi 2019). It became available to developers, June 25th, 2020 (Hayden 2020).

(c) Phase-shift (PS) solutions collect point-cloud data via the modulation pattern of a continuous wave pattern (3DRiskMapping 2008). The use of PS in commercially available midrange TLS systems is greatly influenced by research that came out of the Robotics Institute at Carnegie Mellon University (CMU) and the Technical University of Munich (Thorpe *et al.* 1987; Hebert and Krotkov 1992; Froehlich, Mettenleiter and Haertl 1997; Flatscher *et al.* 1999; Fienup 2013). For example, K^{2}T formed as a company in 1990 (Guzzo 2004). It produced a variety of 3D imaging solutions based around CMU research or initiatives before the Franklin Scanner evolved into SceneModeler (Shaffer 1995; Froehlich *et al.* 1998; "Project Development Plan" n.d.). These include the GFR series of short-range (up to 2 meters) light-stripe range finder and the Blitzen and Typhoon scanners—with the latter two considered for hazardous environments and vehicle-based applications (Shaffer 1995; "Project Development Plan" n.d.). SceneModeler from K^{2}T/Quantapoint was the first PS-based midrange TLS scanner to enter the market. This was followed, however, by the Zoller and Fröhlich (Z+F) 5003 from the German team that were brought in as a core part of developing SceneModeler (Shan and Toth 2009). Z+F developed a fundamental component of the K^{2}T scanner: the LARA rangefinder (Froehlich *et al.* 1998; Hancock, Hoffman *et al.* 1998; Hancock, Langer *et al.* 1998; Langer *et al.* 2000). iQvolution brought out its iQsun 880 PS scanners two years after the Z+F Imager 5003, in 2003 (Becker and Volz 2004)—before being acquired by FARO in 2005 (Pritchard 2005). This eventually led to the FARO Focus^{3D} line of scanners. Surphaser also produces PS systems.

Before considering the succeeding three phases of development to that of early space of defense applications (phases two to four), it is important to define the measurement systems involved in laser scanners. Both ToF and PS are time-based measurement systems in that point clouds are generated by measuring the time frame between two events (Van Genechten *et al.* 2008). For example, ToF systems - also known as pulsed systems - measure the time it takes a laser to return to the scanner against the speed of light - 299,792,458 meters per second in a vacuum and 90 km/s slower when travelling through air (Boehler *et al.* 2002; Van Genechten *et al.* 2008). As demonstrated in 1b, the pulse rates used to generate point clouds accurate and repeatable to resolutions in millimeters and centimeters are measured in picoseconds (10-12 of a second) (Van Genechten *et al.* 2008). In a PS system, the power of the continuous beam emitted from the scanner is modulated (Van Genechten *et al.* 2008; Mettenleiter *et al.* 2016). The time and difference in signal pattern returning to the scanner is used to obtain a measurement (Van Genechten *et al.* 2008). 1c shows how these phases of modulation are used to acquire measurements by comparing the outgoing and returning wave patterns of the laser as the scanner collects data (Van Genechten *et al.* 2008; Mettenleiter *et al.* 2016).

Mensi replaced their triangulation based SOISIC scanners with a longer range ToF solution called the GS 100 in 2001 (Shan and Toth 2008). This resulted in time-based measurement becoming the main solution used for data collection in commercial mid-range TLS workflows (Shan and Toth 2018; Chen et al 2005). It also brought the company more in line with Cyra Technologies and Riegl, who had successfully released commercial ToF systems by 1998 (Kacyra *et al.* 1997; Shan and Toth 2008; Gaiani *et al.* 2000; Ullrich et al 1999).

1985; Ullrich and Studnicka 1999; Levoy 2007; Spring and Peters 2014; Mettenleiter *et al.* 2016). The location of the data is fixed to a known (0,0,0) coordinate location at the point where the laser reflects from an oscillating or rotating mirror (3DRiskMapping 2008). Surfaces are reconstructed through the process of scanning, which requires the sensor to be moved to a position where at least 25% overlap exists between scans. This continues to be reduced by incorporating other sensors into scanning instruments, such as inertial measurement units (IMU) and camera tracking systems (Biasion *et al.* 2019). The captured scene can also include targets, as seen in Figure 2 and Figure 3. These are compatible with the laser systems being used, which are explained in the "Laser System Architecture: The Essentials" box.

Targets used in the act of scanning vary from black-and-white checker pattern to matte white spheres or retroreflective surfaces (Figure 2). They are used to increase the known accuracy of the data returned to the scanner, and to reference the local coordinates of the point cloud to absolute coordinate systems. For example, matte white spherical targets are used in phase-shift (PS) and time-of-flight (ToF) solutions set to a comparable wavelength on the electromagnetic spectrum (3DRiskMapping 2008). This is depicted in Figure 3, where a FARO Focus^{3D} set to a wavelength of 1550 nm was used to document the Tristan Stone, a medieval inscribed stone in Cornwall, UK (Spring and Peters 2014). As discussed in Gregory C. Walsh's (2010) patent on retro detector systems, dynamic range can also be used alongside the wavelength when developing target systems for midrange TLS. The retroreflective targets used for Riegl systems set to a near-infrared wavelength may provide some indication for this, in that the 1550-nm wavelength usually does not work well with high-reflective surfaces—not without it being compensated for within the system architecture of a laser scanning workflow.

The resolution and distance at which data are collected are also determined by the type of laser system inside the scanner (3DRiskMapping 2008; Mettenleiter *et al.* 2016). The type of scanner selected for a project should be determined by the scene being scanned, the environmental conditions in place, and the rationale for data capture (Boehler *et al.* 2001; Spring and Peters 2014; Historic England 2018). Once all point clouds have been collected, they are connected through a software-based registration process. As discussed in the "Phases of Development" box, seen in Figure 4, this is derived from the iterative closest point (ICP) algorithm-based approach, which is also optimized via other proprietary algorithms or functions when using commercial software (Besl and McKay 1992; Y. Chen and Medioni 1992). The registration process minimizes the difference between two or more point clouds (Girardeau-Montaut n.d.).

Figure 2. Retroreflective surfaces, spheres, and checkerboards are the primary types of artificial targets used in laser scanning. Note: the first set of Cyra Technologies based targets were a green retro-reflective surface, and later changed to the blue retro-reflective target surface seen above.

Variation is measured in nanometers (nm) (3DRiskMapping 2008). Wavelength in nanometers can result in different laser scanners reacting to the reflectivity of a surface in different ways (Boehler *et al.* 2003; Mettenleiter *et al.* 2016; Riquelme, Ferrer and Mas 2017). For example, the FARO family of laser scanners would not return usable data from the retroreflective targets used in Leica Geosystems scanners set to 532 nm, or Riegl scanners set to 1550 nm with a system architecture that incorporates single-photon avalanche diodes (Spring *et al.* 2010; Walsh 2010; Spring and Peters 2014).

Three laser-based solutions were originally used for mid-range TLS between 1987 and 2001: optical triangulation, ToF, and PS (X. Chen and Schmitt 1992; Amann *et al.* 2001; Boehler and Marbs 2002; Shan and Toth 2009; 3DRiskMapping 2008; Mettenleiter *et al.* 2016). They are outlined in more detail in the "Laser System Architecture: The Essentials" box. Mensi replaced its triangulation-based SOISIC scanner with a longer-range ToF solution called the GS 100 in 2001 (X. N. Chen *et al.* 2005). It brought the company more in line with Cyra Technologies and Riegl, who had successfully released ToF solutions by 1998 (Kacyra *et al.* 1997; Ullrich *et al.* 1999; Gaiani *et al.* 2000). This is also discussed in more detail in the section "Transitions in Midrange TLS (Second Phase)", as well as part one of this article.

ToF- and PS-based solutions had become the primary way to collect point-cloud information with a laser by 2020 (3DRiskMapping 2008). ToF measures the time it takes a laser to return to the scanner against the speed of light (Mettenleiter *et al.* 2016). As demonstrated in the "Laser System Architecture: The Essentials" box, the pulse rates used to generate point clouds that are accurate, repeatable (in terms of performance), and to resolutions of millimeters and centimeters are measured in picoseconds (Wilson *et al.* 1999). In a PS system, the power of the continuous beam emitted from the scanner is modulated. Figure 1c shows how these phases of modulation are used to acquire measurements by comparing the outgoing and returning wave patterns of the laser as the scanner collects data. Both ToF and PS are time-based measurement solutions: The time frame between two events is integral to the collection of all information.

Figure 3. Checkerboard targets, crosshair black-and-white targets, and matte white spheres are used as targets in midrange TLS when the laser beam is set to a certain wavelength. The first-generation FARO Focus^{3D}—here being used to document the Tristan Stone, a medieval inscribed stone in Cornwall, UK—is set to a 1550-nm wavelength on the electromagnetic spectrum. Not all laser scanners are set to the same wavelength. The dynamic range of the information returned to the scanner can also be taken into account, as discussed in the section "Laser Scanning in Its Commercial Era (from 1979 Onward)."

Phases of Development

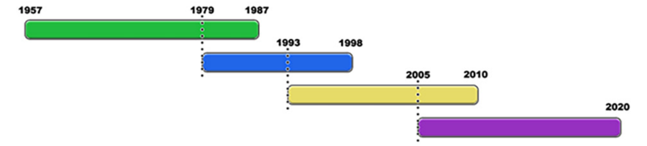


Figure 4. Four phases of development, including periods of transition, spanning 1957–2020.

Phase 1: 1957–1987

The laser was invented and Sputnik went into orbit, 1957. Sputnik immediately led to the formation of the Defense Advanced Research Projects Agency (ARPA/DARPA) in 1958 (Catmull 2014). Thus, starting the funding environment required to develop the early system architectures for midrange TLS. That is, via funding for the space and defence applications outlined in both parts of this article.

The turning point year for transition to Phase 2 starts is circa 1979 (and carries on to the formation of Mensi and favourable business acts getting passed in France and the USA by 1987). It is the year when business interest groups like the "Association pour le développement du mécénat industriel et commercial" (ADMICAL) are formed in France–by three students, who drew influence from observing the philanthropic model in the USA (Gautier *et al.* 2013). ADMICAL would soon be followed in the USA by the Stevenson-Wydler Technology Innovation Act of 1980 (Gautier *et al.* 2013). This essentially led to a number of acts that encouraged technology transfer from entities like DARPA to industry, such as the Small Business Technology Transfer Act of 1992.

Incidentally, the maintained cultural impact of applied government funded research on business cultures in the USA can be seen in phases 3 and 4. That is, via the DARPA Grand Challenge that influenced Velodyne, as well as Regina Dugan's (former Head of DARPA) role at Google running Advanced Technology and Projects (Metz 2016).

Phase 2: 1979–1998

Phase 2 has its seeds in the philanthropic movement coming out of France. It helped shape policies that encouraged business communities to contribute to projects in the cultural sphere. These policies influenced a working environment where Mensi systems could be applied to projects outside of Électricité de France (EDF). Otherwise, the SOISIC scanner was primarily being used to address their internal facility management needs by the early 1990s. This changed, however, when it was used as part of a project to upgrade parts of the city lighting of Paris–and the first CH midrange TLS scans were carried out in 1993 (Thibault, Email, July 4th, 2020; Thibault and d'Aligny 1994). This is discussed in more detail in Figure 11a.

The formation of Mensi by Auguste D'Aligny and Michel Paramythioti presents the beginnings of tripod-based systems geared to high levels of accuracy, repeatability and resolution (Bandiera *et al.* 2011; Paramythioti, M. and D'Aligny 1989). That is, for documentation and inspection as opposed to terrain mapping for autonomous vehicles. The transitional period leading to Phase 3 is seen to occur in 1993. This is the year Mensi carried out its first CH scans in Paris, as outlined in Figure 11a (Thibault, Email, July 4th, 2020; Thibault and d'Aligny 1994). Cyra Technologies was founded as a company in the same year–based on private funding and commercially derived observations. That was, for site design and inspection applications more in line with CAD based user communities of the time. Midrange TLS became the way to obtain design drawings for actual conditions of an industrial plant–using the as-built information gathered via a point-cloud (Deveau *et al.* 2005). Cyra Technologies was a "hit the ground running" scenario for Ben Kacyra and Jerry Dimsdale. Neither of these pioneers had much involvement with laser scanning prior to founding the company.

It should be noted that K^{2}T was formed as a robotics company in 1990–to bring CMU Robotics Institute initiatives to market. Their previous involvement with DARPA projects is outlined in more detail in part one of this article. Influences from business outreach strategies built into the university system (in the USA) is discussed in Similarities to Personal-Computer Markets as well. K^{2}T began to outline ideas for scanners like SceneModeler by 1993-94 ("Project Development Plan" n.d.; Hebert *et al.* 1992; Kweon and Kanade 1992). Like K^{2}T, the Austrian company Riegl had strong ties to universities as well. Johannes Riegl–its namesake and founder–had been working on avalanche pulse generators at the Vienna University of Technology (VUT). This was prior to forming his company in 1978.

The Eureka PROMETHEUS Project (the largest R&D project ever in the field of driverless cars at time of publication) would also support self-driving vehicle initiatives at this phase– 1987–1995 (Dickmanns 2002; Nwagboso 1993; Maurer *et al.* 1995).

Phase 3: 1993 to 2010

The transition to Phase 3 begins when other entities to Mensi start to develop their own midrange TLS systems. It is at this point that the custom manufacture of hardware–which had been necessary in projects like the Adaptive Suspension Vehicle (ASV) and Autonomous Land Vehicle (ALV) to make them possible–can be replaced with development based around hybridization (Gage 1995; Gleichman *et al.* 1988; Waldron and McGhee 1986; Song and Waldron 1989). This is the concept of taking different available components, and bringing them together to make a new product.

Cyra Technologies, K^{2}T and Riegl all show examples of hybridization in their early systems. For example, Cyra technologies combined the green laser from Massachusetts Institute of Technology (MIT) Lincoln Laboratory with a timing circuit repurposed from Los Alamos National Laboratory to create the Cyrax range of scanners (Wilson *et al.* 1999; Zayhowski 2010; Zayhowski 2018). K^{2}T used a scanning mechanism they had designed at CMU–and combined it with a laser system developed by Christoph Froehlich–for the Franklin and SceneModeler units ("Project Development Plan" n.d.; Shaffer 1995; Froehlich *et al.* 1997; Langer *et al.* 2000). Riegl repurposed their own LD90-3 distance meter released for the rangefinder electronics in the LMS-Z160/Z210 (Flatscher *et al.* 1999; Riegl 2014; Studnicka 1999). This was for the European Space Agency (ESA) funded Active Surface Imaging System (ASIS) project (Flatscher *et al.* 1999; Riegl 2014; Studnicka 1999). Prior to this, they had also developed a shorter range scanner for the ESA project "Demonstrator of Advanced Laser Sensors" (DEAL) in 1996 (Riegl 2014).The ICP algorithm–developed by Besl and McKay at General Motors–made point cloud registration easier for a general user as software's also got developed.

The market that emerged by 1998 was solidified by the acquisitions of Cyra Technologies and Mensi–by Leica Geosystems and Trimble separately, 2000-2003. Two points of convergence then occurred in 2005. That is, signaling the beginning of the next era, which is greatly influenced by commoditization of sensor hardware and simultaneous and localised mapping (SLAM).

Velodyne enters the laser scanning design story via the DARPA Grand Challenge–developing a multibeam ToF system that would be adopted massively in car-based applications. They would also bring and apply their business experience in selling consumer products to the laser scanning market. PrimeSense also formed as a company at this time. This brought triangulation-based 3D imaging to consumer products, initially via the Xbox Kinect and then tablets / smartphones.

Phase 3 stops at a point where Google invests in Velodyne (and starts to familiarize the general public to self-driving vehicles outside of the defense researcher domains); Xbox Kinect incorporate the PrimeSense triangulation unit into their gaming solution; and most midrange TLS units now have a computer and battery source built into their architecture. For the latter, this makes it easier to incorporate commercial midrange TLS units into SLAM based deliverables at Phase 4.

Incidentally, the influence of philanthropic entities on midrange TLS–first seen in France in Phase 2–is continued via The Kacyra Family Foundation in this period. That is, via the formation of CyArk and its promotion of technologies through high profile CH projects, 2003 onwards. This is discussed in more detail in the section "The Non-profit Corporations (Third Phase)."

Phase 4: 2005 to 2020

The transition to this phase began when Velodyne–a manufacturer of consumer level products at the time–entered the laser scanning market in 2005. It is a period where the emphasis on commoditization increases to where a mass market is forming around laser scanning hardware by 2020. There is also a strong influence on the market from investments and hardware coming from China (Ackerman 2016a; Shan and Toth 2018; Simai Surveying Instruments 2020; GPS World 2015).

There were, for example, significant announcements at the Consumer Electronics Show centered around low-cost laser scanning hardware from Velodyne (Velabit) and Livox (Mid-Series) in 2020 (Ohnsman 2020; "DJI Showcases" 2019). Livox was also a subsidiary of DJI (both based out of Shenzhen in China)–a company with a proven track record in bringing technologies like drones / unmanned aerial systems to a mass market of users ("Breaking Through" 2014). Amazon has also acquired the self-driving vehicle company Zoox for a rumored USD 1.2 Billion by July 2020 (Wiggers 2020).

Earlier indicators of this move to cheaper, 'plug in and develop out from' type systems could be seen by around 2015. That is, when Velodyne sensors started to get incorporated into tripod-based systems like those seen in Figure 1b of Part 1 of this article, as well as when mobile mapping solutions had started to incorporate Velodyne sensors into their hardware as well. For example, Topcon and Leica Geosystems vehicle mount systems use Velodyne scanners alongside their own systems. IQvolution had also explored a similar idea of a modular approach for midrange TLS in the article *iQsun 880 A New Modular Concept For 3D-Laser Scanning,* 2004 (Becker & Volz 2004).

This fourth phase also saw the emergence of low cost, build your own kits from companies like Scanse (Ackerman 2016b). This kind of activity–which brings down development costs and gets the technology into the hands of a broader spectrum of people–mirrors patterns of behaviour seen in the formative years of the personal computer market. It is examined in more detail in the section about "Parallels to the Personal Computing Market."

What was typically hobbyist level activity around midrange TLS via systems like the Scanse was stimulated by companies like PrimeSense. Through the notable impact platforms like Xbox Kinect had on bringing point-cloud data to a wider audience. The rise of sensors like those from PrimeSense–and later in the same decade Infineon/PMD (2019)–would also go on to influence Google projects like Project Tango in 2014 (Etherington 2014). Early examples where 3D imaging technologies in general were integrated into mobile phones and tablets. Where people could scan a room by walking through their environment with the device.

By the time this article was published, midrange TLS solutions were being increasingly influenced by developments shaped via wearable or mobile devices, as well as vehicle-based applications. Tripod based systems were increasingly being packaged to fall in line with SLAM based ideas about mapping (Biasion *et al.* 2019). For example, integration of midrange TLS systems with hardware like onboard camera tracking systems and IMU sensors–to make the scanner more aware of its position in an environment as it moved from each position–was a relatively new standard of expectation from the user (Biasion *et al.* 2019). The technology was increasingly presented as not being tethered to the tripod in the same way as it had previously. Distributed computing–either onsite via a tablet or phone, or at a desktop over the cloud or via "Edge Computing"–was also part of the zeitgeist from 2010–2020 (Spring 2015). The seeds for additional commoditization from another source were also planted when China started to develop their own tripod-based midrange TLS systems in 2015 (Simai Surveying Instruments 2020; GPS World 2015).

The Shift from US Government Space and Defense Programs to Commercialization, Set in Three Phases of Further Development in Laser Scanning Technologies

The Second Phase: Commercialization, Business Models, and Philanthropy (1979–1998)

In the second phase, it was in France that business interest groups like the Association pour le Développement du Mécénat Industriel et Commercial (ADMICAL) first started to help create the necessary working conditions (Gautier *et al.* 2013). As the leading association for corporate philanthropy in France, ADMICAL helped transform midrange TLS from applied research (funded by defense and other government grants) to a commercially viable product. As discussed later under "Application to Cultural Heritage (Second and Third Phases)," ADMICAL was the catalyst for two significant laws getting passed by the French government. Both laws supported corporate philanthropy, and in doing so, they also aided transitions in the application of midrange TLS to industrial and CH settings (Brillault, Thibault and Guisnel 1995; Pot, Thibault and Levesque 1997; Moulin *et al.* 1998).

Broader technology trends coming out of the USA also contributed to a business culture developing around the technology. The rise of the World Wide Web and the dot-com boom coincided with the development of companies like Cyra Technologies (Kacyra *et al.* 1997; Hwang and Stewart 2006; Morris and Alam 2012). This part of the story straddles both the second phase and the early years of the third phase of midrange TLS development. It spans from around 1993 through the period of commercialization to the end of the year 2000 (Phillips and Yu 2011). The dot-com boom made it easier for larger companies, such as Leica Geosystems, to see the value in digital survey tools like laser scanners. In fact, it gave them increased market value in an emerging world where information and communication technologies would play a key role (Stiroh 2002), because instruments like Cyra Technologies' original concept of a Field Digital Vision (abbreviated to FDV) machine enabled their users to collect objects and buildings as computer-based assets—used to manage, maintain, or inspect a given environment (Wilson *et al.* 1999). The acquisition of Cyra Technologies by Leica Geosystems solidified the midrange TLS market in a way, because it was the first example of a large company openly taking over the direction in which technologies would develop ("Leica Geosystems Acquires Oakland-Based Cyra Technologies" 2000). It was also shortly followed by Trimble's acquisition of Mensi in 2003 ("Trimble Navigation Acquires Mensi S.A." n.d.).

On the technical side in the second phase of development, close-range TLS also became a testing ground for the use of scan data in the reverse engineering of surface information. Companies like Cyberware and General Motors made it easier for more general users to work with point clouds and meshes

(Rioux and Bird 1993; Besl 1988). For example, the work carried out by Paul Besl and Neil McKay (1992) on iterative closest point matching, which came out of their time at General Motors, helped define the process for connecting multiple point clouds into one. It created a foundation algorithm that software packages like CloudCompare and Cyclone would later bring into their registration pipeline (Mettenleiter *et al.* 2016). This and a more detailed outline of the relationship between close-range and midrange TLS is discussed in the section "Close-Range Scanning (Second Phase)." In the third phase, a market formed around these technologies.

The Third Phase: Market Development (1993–2010)

In the third phase, market development was encouraged through nonprofit entities like CyArk promoting technologies via heritage sites. The CyArk 500 and Scottish Ten projects are two of the more notable examples linked to the California-based 501(c)(3), which was set up by Ben Kacyra in 2003 (Kacyra 2009; "New Lanark, Scotland" n.d.). The work of early adopter Kevin Cain is also outlined in the "Cultural Heritage as Marketing (Second and Third Phases)" and "Nonprofit Corporations (Third Phase)" sections. Cain formed his Institute for the Study and Integration of Graphical Heritage Techniques (INSIGHT) nonprofit corporation in 1999.

The Fourth Phase: Simultaneous and Localized Mapping (2005 Onward)

By 2020, the fourth stage of development was being shaped by applications based on simultaneous and localized mapping–otherwise referred as SLAM. Commodity sensors had emerged from efforts to make autonomous vehicles a commercially available product. Technologies had also become small enough to be worn or carried around by their users as they mapped an environment. For example, the first DARPA Grand Challenge—which was geared toward improving sensors for autonomous vehicles and took place in 2005—led to the creation of the Velodyne range of sensors (see figure 1a and 1b in part one of this article; Halterman and Bruch 2010). These went on to be integrated into hand-carried units, backpack-based systems, vehicle-based mapping systems, and even tripod-based units (Figure 5). The Grand Challenge also brought Velodyne as a developer into the midrange TLS community. Before this, it was a company with a proven track record in commodity-based business and distribution models for sound equipment like subwoofers (Robson 2017).

Handheld and wearable solutions that took the movement of their operator into account also emerged in this period. One of the more interesting systems was the Zebedee (Figure 5a), which came out of the Melbourne-based Commonwealth Scientific and Industrial Research Organization (CSIRO) in 2012 (Bosse *et al.* 2012). It used a 2D laser scanner and an inertial measurement unit mounted on a spring. A series of custom algorithms worked alongside the hardware to optimize data retrieved, including all six degrees of freedom of movement (x, y, z, ω, φ, κ) along with the laser's position in space as it captured information. Zebedee—named after the

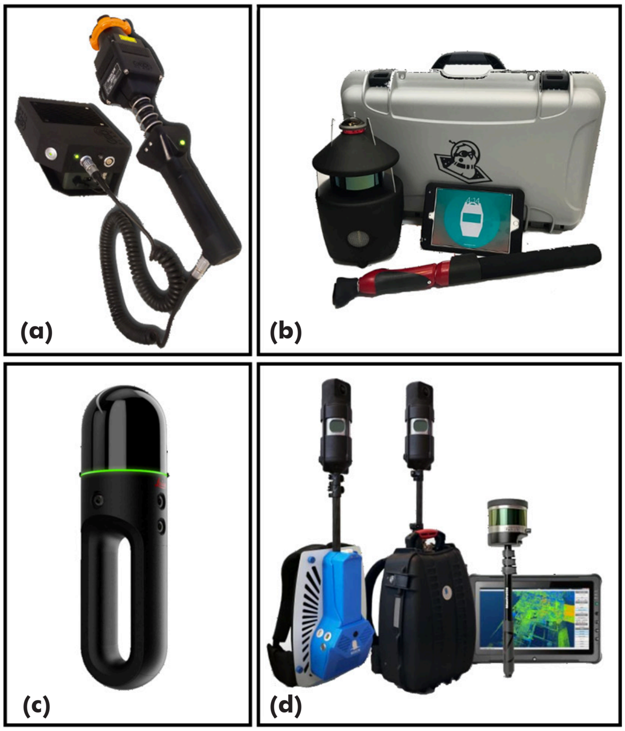


Figure 5. Handheld and wearable laser scanning technologies were being marketed in the same application areas as midrange TLS by 2020. (a) The Zebedee unit developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) was commercialized by Nottingham, UK-based 3D Laser Mapping in 2013. By 2020, it had been followed by the ZEB REVO, ZEB REVO RT, ZEB Horizon, ZEB Pano, and ZEB Discovery. Software in the form of GeoSLAM Hub was developed in 2015, and then 3D Laser Mapping merged with GeoSLAM in 2018. The ZEB Discovery unit also incorporated the iSTAR Pulsar 360-degree photography camera developed by Edinburgh-based NCTech into its system architecture. NCTech is the same company that produced the LASiris VR seen in figure 1b in part one of this article and discussed in the section "Designed for Documentation and Inspection." (b) Florida-based Paracosm was founded in 2013 and then acquired by Occipital—a San Francisco-based company that had been working on affordable 3D solutions since 2008—in 2017. The PX-80 integrated a Velodyne VLP-16 channel-based sensor into its system architecture. Users document a scene as they walk around the given object environment. Paracosm incorporated table-based computing into its workflow to work with the data collected in real time. (c) The BLK2GO was launched by Leica Geosystems in 2019. It was a handheld unit marketed around its dual-axis lidar system and suitability of use in workflows based on SLAM. It was also positioned around "adaptive reuse projects in the architecture and design industries to location scouting, pre-visualization, and VFX workflows for media and entertainment," bringing it more in line with the inspection aspects of midrange TLS (GIM International 2019). The Cyclone and Register suites of software developed by the Hexagon-owned Leica Geosystems were all compatible with the BLK2GO. (d) The HERON range of backpack and handheld solutions incorporated the Velodyne HDL-32E and Puck Lite sensors into their system architecture, along with tablet computers. They were created by Italy-based GEXCEL, which had been developing 3D image-based solutions since 2007. GEXCEL also developed software for the mining industry called Open Pit Mine Monitoring System, which was optimized for use with the Teledyne Optech Polaris systems seen in figure 1b in part one of this article. The HERON and Reconstructor software from GEXCEL also got resold by ClearEdge3D (2019), which Topcon had acquired in 2018 to help position itself in emerging "reality capture" markets. The term *reality capture* (also sometimes seen as *reality computing*) was first outlined by Cyra Technologies, brought in line with the idea of "high-definition surveying" after the brand's acquisition by Leica Geosystems, and then later reintroduced to midrange TLS communities by Autodesk (Cyra Technologies 1999; Frei *et al.* 2005; Autodesk 2013).

Explanation Box: Building Upon Navigation Based Initiatives–Who and What?

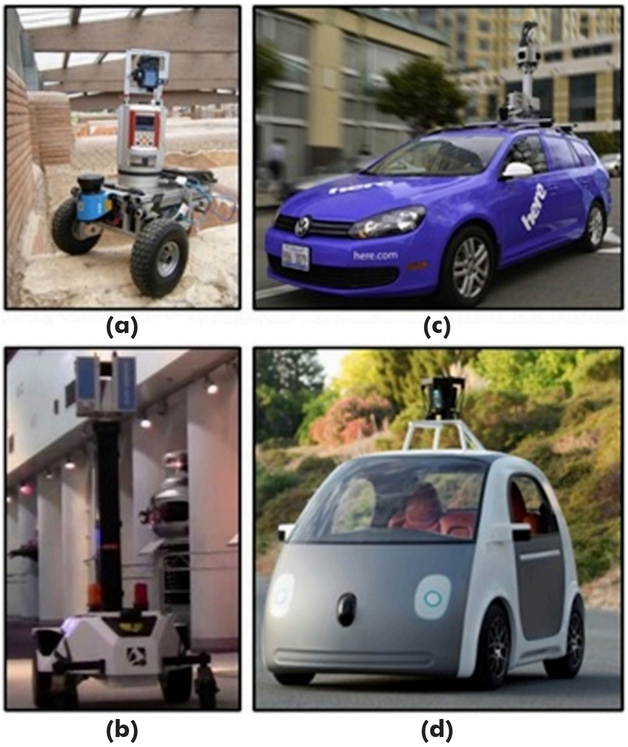


Figure 6. Midrange TLS solutions were being revisited as mobile mapping solutions in everyday life by 2020—outside the otherwise closed networks seen in the first and second phases of development. Some of the earliest examples are shown in Figure 6. (a) The Irma3D is an autonomous vehicle created by Andreas Nüchter of Jacobs University Bremen in Germany. It incorporated a Riegl VZ-400 laser scanner into its system architecture. (b) Similar solutions made it into industrial sectors via Allpoint Systems, which primarily worked with Zoller and Fröhlich scanners. The company was founded by CMU graduates and became part of Autodesk's ReCap suite of solutions in 2013. (c) Nokia acquired a company called Earthmine as part of its HERE mapping service in 2012. Earthmine was formed by John Ristevski, a former employee of CyArk, in 2006. He brought Oliver Monson (a former project manager at CyArk) into the company as a data manager a year later. Earthmine patented stereo photogrammetry-based technologies from the JPL for its early mapping solutions. HERE was acquired by Audi, BMW, and Daimler in 2015. (d) Google's self-driving cars are revisiting the concepts explored through projects like the ALV, the CMU Navigation Laboratory, and PROMETHEUS. The company has made notable investments in, and uses midrange TLS sensors from, companies like Velodyne for terrain modeling and computer-vision purposes. More detail is provided in the "Waves of Developments Driven by Its Users—How and Why?" box.

The development of midrange TLS for site documentation and survey (late 1990s) does not break away from original uses in mobile applications. It is part of a process that refines hardware and software–feeding into the infrastructures and networks established from phase one of development onwards.. For example, Cyra Technologies examined the work carried out by ERIM, employed CMU graduates like Mark Wheeler (who went on to become Chief Technology Officer of the autonomous-vehicle company DeepMap in 2016; "DeepMap" 2018), and visited the CMU Robotics Institute when the Cyrax HDS 2400, seen alongside the follow-up HDS 2500 in Figure 8, was starting to take shape. Jerry Dimsdale, the system architect for the early Cyrax systems, went on to develop the Topcon GLS series of midrange laser scanners under his company Voxis from 2003 through 2008 ("Topcon Acquires Voxis" 2008; Wan Aziz *et al.* 2012) after Cyra Technologies was acquired by Leica Geosystems in 2000 ("Leica Geosystems Acquires Oakland-Based Cyra Technologies" 2000). Launched in 2008, the Topcon scanners combined a ToF solution with a PS algorithm in order to improve the quality of scan data produced. Systems like the GLS 2000 also incorporated first- and last-pulse recording.

Gregory C. Walsh, Jerry Dimsdale's successor at Leica Geosystems, was introduced to laser scanning in 1992 when he was an engineer on a Mars rover project, funded by the ESA, called Hilare (Walsh *et al.* 1994). He went on to design five ToF systems for Leica Geosystems: the HDS 3000, ScanStation 1, ScanStation 2, ScanStation C10, and RTC360. He also contributed to the laser and photography camera systems used inside the P-series scanners developed after the P20.

jack-in-the-box from the children's television show *The Magic Roundabout*—was commercialized by companies like 3D Laser Mapping almost immediately after they saw the technology. 3D Laser Mapping later merged with its sister company GeoSLAM to place an emphasis on such solutions (GeoSLAM 2018). Robert Zlot, one of the developers of Zebedee, had received his PhD in robotics from CMU in 2006.

Transitions in Midrange TLS (Second Phase)

ToF and PS solutions had evolved by 2001. It was now possible to collect data at greater distances and accuracies. This was not the case, however, when Mensi was formed as a company in 1987 (X. Chen and Schmitt 1992). It had a close working relationship with EDF, a company that required detailed information in order to maintain its industrial power plants (Fertey *et al.* 1995; Pot *et al.* 1997). EDF acquires a stake in MENSI S.A. in 1997 ("About Us [Mensi]" n.d.). When the company was formed, however, ToF solutions were not yet accurate enough, and PS solutions could scan at the resolution needed only over a short range (Xin Chen, email to author, October 18, 2013; Fienup 2013). Mensi resolved these issues by borrowing from both passive and active sensing, with a laser increasing the range at which measurements could be collected using optical triangulation (X. Chen and Schmitt 1992). As seen in the "Laser System Architecture: The Essentials" box, the SOISIC scanner compared the known distance between the sensors inside it to the area of projected overlap on the surface being scanned.

The solution Mensi had created fed into preexisting workflows linked to "as-built" information being used by EDF (Fertey *et al.* 1995; Pot *et al.* 1997). SOISIC enabled users to gather information pertaining to actual surface conditions of the object or scene being managed. This meant it was able to give an engineer or project team working with the point-cloud information it generated a clear understanding of the actual conditions in place inside a nuclear power plant rather than design-perfect ("as-designed") conditions depicted in CAD drawings or preexisting site plans (Deveau *et al.* 2005). Early developers of the technology like Mensi recognized the shortcomings of preexisting workflows. Plan-based information alone had the potential to contain a wide level of detachment from the end product or scenes being scanned. These were predominantly design- and manufacture-based communities, driven by clearly defined metric and procedural parameters in an otherwise 2D CAD space, such as industrial pipe modeling or drafting (Pot *et al.* 1997).

As Built

Early applications of midrange TLS—whether CH, defense, space, or safety-driven workflows in environments like nuclear power plants—all shared a unifying need for the collection of "as-built" or "as is" information (Figure 7; Pot *et al.* 1997;

Figure 7. Mensi technologies were developed in order to collect as-built information. They made their way into the North American market by 1996, through Atlanta-based Catco (Kacyra, Dimsdale and Kung 2005). Then Ken Shain helped form Mensi USA in 1999 (Monroe 1999). Mensi was acquired in 2003 from EDF by Trimble.

Gentle Giant Studios used a customized purple Mensi SOISIC scanner to document props on the set of *Star Wars Episode II: Attack of the Clones*. When they traveled to Paris to scope out the technology, the Gentle Giant team discovered that the SOISIC scanner unit had originally been designed to be mounted on vehicles (Steve Chapman, email to author, November 14, 2012). It was intended for use in areas of contamination in nuclear power plants, for remote information retrieval or inspection in areas too hazardous for humans. Photograph courtesy of Steve Chapman.

Stephan *et al.* 2002). For example, as-built was how practitioners in CH measured objects (O. Coignard *et al.* 1998; Cain 2000; Cain, Sobieralski and Martinez 2003). The gathering and analysis of information was centered around physical interaction with an object or site. In essence, adaptation for commercial sectors in the late 1990s involved bringing these as-built midrange TLS solutions and workflows more in line with the needs of user communities who were more familiar with as-designed information (Kacyra *et al.* 1997; Pot *et al.* 1997).

It was only when communities driven by an as-designed mind-set started to lean toward the use of as-built information that a move toward midrange TLS, as well as other 3D imaging techniques in general, started to occur (Kacyra *et al.* 1997; Mettenleiter *et al.* 2016; "Project Development Plan" n.d.). In the case of Mensi, early adoption of midrange TLS emerged out of past experiences with photogrammetry and surface modeling. The latter is seen in this article through the Digital Karnak project, where CAD-based software was used to reconstruct the dimensions of real-world environments such as monumental architecture (Boccon-Gibod and Golvin 1990). That is in contrast to a photogrammetric or laser scanning-based solution, which depends on actual documentation of physical remains that are still available. EDF engineers had obtained 3D metric information reconstructed from 2D photographs before the Mensi scanning solution was developed.

Saisie Optique Informatisée de Structures Industrielles Complexes (SOISIC)

Midrange TLS crossed over into industrial work environments for the first time via the first Mensi scanners, called SOISIC. The French acronym SOISIC stands for "Saisie Optique Informatisée de Structures Industrielles Complexes" (Bandiera *et al.* 2011, p. 93), which means "computerized optical capture of complex industrial structures." It was used internally by EDF to map and model industrial plants in France by 1992, though work on the project actually began in 1987—the same year the Digital Karnak Project took shape (Boccon-Gibod and Golvin 1990).

Figure 8. Early stages of development for the Cyrax scanners from Cyra Technologies. All photographs were kindly provided to the author by Dr. Jerry Dimsdale (Top: Email to author, January 10th, 2020; Bottom: Email to author, March 27th, 2013). The top photograph is of the early bench prototype for what was initially described as the Field Digital Vision machine (Wilson *et al.* 1999). It did not include the time-interval interpolation circuit from Los Alamos National Laboratory at this point, although the green laser from Massachusetts Institute of Technology's (MIT) Lincoln Laboratory was in use. (Prior partnering with the MIT Lincoln Laboratory, Dimsdale and Ben Kacyra visited numerous experts in the field of laser scanning, including at the Environmental Research Institute of Michigan and the CMU Robotics Institute.) Instead, a larger box pulse generator from Stanford Research Systems was used. The unit was fitted into a Volkswagen Vanagon to make it portable (bottom left). Once the time-interval interpolation circuit had been repurposed to reach the required rate of picoseconds, the hybridized system architecture of the 532-nm green laser from the MIT Lincoln Laboratory and the Los Alamos National Laboratory time circuit were used in the smaller Cyrax HDS 2400 and HDS 2500 systems (bottom right). This was prior to the 2000 acquisition of Cyra Technologies by Leica Geosystems, toward the end of the dot-com boom.

The accuracy of ToF systems soon increased to subcentimeter standard via the San Francisco start-up Cyra Technologies. Jerry Dimsdale, its founding Chief Technology Officer, improved upon the findings of the JPL Laser Rangefinder project (Lewis and Johnston 1977; Kacyra *et al.* 1997; Wilson *et al.* 1999). The Cyrax HDS 2400 developed was not, however, the only ToF system brought to market by 1998 (Figure 8). Riegl's LMS-Z160/Z210, released in both iterations in 1997 and 1998, had longer range but were accurate to 2.5 cm (Studnicka n.d.). Prior to its short-lived release as the LMS-Z160, Riegl had developed this Active Surface Imaging System (ASIS) for the ESA in 1997 (Flatscher *et al.* 1999).

Experience gained from the ESA project took Riegl's preexisting technology in a new direction. For example, the Riegl LD90-3 distance meter (released in 1993) was used for the range-finder electronics in the LMS-Z160/Z210 (Studnicka n.d.).

The hybridization of Riegl systems, through other technologies within the company's portfolio of sensors, laid the foundation for the range at which data could be collected (Riegl ground-based sensors can also collect data at kilometer-plus range). This started a trend in development based on integration of all airborne, vehicle, and tripod-mounted sensors (Figure 9). As a result, later technological developments like full waveform and echo digitization were devised to compensate for pulse shape deviation (Rieger, Ullrich and Reichert 2006; Ullrich and Pfennigbauer 2011).

Johannes Riegl had a background in time-based measurement linked to avalanche pulse generators—a way of producing circuits where pulses can be measured at very high speeds (nothing to do with snow and ice; "Riegl Timeline" 2014). He formed his company in 1978, after spending 10 years at the Vienna University of Technology.

Figure 9. Riegl's entry into the unmanned aerial vehicle market is an extension of its long-term multisensory approach. The company's first foray into midrange TLS—the LMS-Z160/Z210—was made possible by its work with the ESA for shuttle landing sensors. Distance-sensing technology from its preexisting portfolio of instruments was also modified to create its new laser scanning sensor.

Close-Range Scanning (Second Phase)

Close-range and midrange TLS intersect in several ways. These include attempts to commercialize sensors like those from ERIM, the emergence of robotics as a discipline running parallel to the development of 3D imaging as applied research (demonstrated in early examples like Shakey and later developments like the Robotics Institute at CMU), and the use of 3D imaging in the automotive and entertainment industries (Besl 1988; Rioux and Bird 1993; Kelly 1994). It is the latter—in the form of companies like Cyberware—that raised public awareness of 3D imaging as a way to reverse engineer surfaces in the early 1990s (Kweon, Hoffman and Krotkov 1991; Rioux and Bird 1993). More behind-the-scenes activities, especially from Perceptron and CMU, show that a consistent link to space and defense applications existed as well ("Project Development Plan" n.d.).

Perceptron

Perceptron looked to commercialize the ERIM scanning system, outlined in part one of this article, by the early 1990s (Kweon *et al.* 1991; Matthies 1999; "Project Development Plan" n.d.). University-based research like the Autonomous Planetary Rover, which resulted in the six-legged Ambler robot, is one example where the Perceptron midrange TLS system was applied (Bares *et al.* 1989; Matthies *et al.* 2007). Failure to commercialize the system, however, resulted in Perceptron continuing to focus on close-range scanners as it had done previously (Paul Besl, email to author, January 22, 2019). The company was founded in 1981, having been born out of the automotive industry and the General Motors Institute (now Kettering University; "About Us [Perceptron]" n.d.). Perceptron was still developing close-range TLS and robotic systems for CAD and manufacture at the time this article was published.

Automotive Industry

Uses of TLS outside of space and defense applications can be identified in communities working with close-range scanning, especially from the 1980s onward. It was the automotive industry that started to demonstrate a use for accurate, repeatable (in terms of performance), and high-resolution laser scans (Besl 1988, 1994; Khetan and Besl 1990). This was for the reverse engineering of surfaces, which included fully assembled vehicles. For example, synchronous scanning systems (developed by companies like Hymarc Limited) were used at General Motors as alternatives to physical models in wind-tunnel tests (Paul Besl, email to author, February 7, 2019; Lamb, Baird and Greenspan 1999). That was while Paul Besl and Neil McKay—developers of the ICP algorithm—were working on active scanning systems as an alternative to clay and RenShape 450 models. These were being used at General Motors to test vehicle aerodynamics, RenShape 450 being an easy enough material to shape using computer numeric control milling machines–as well as capable of withstanding test conditions at higher speeds in a wind tunnel.

Computer numeric control allows digital models to be converted into instructions for rapid prototyper devices such as milling machines and resin modelers. Tolerances for the digital molds created in automotive industries were typically 0.2–2 mm in the 1980s to early 1990s. Companies who had previously worked in the automotive industry, such as Callidus, became some of the first to develop midrange TLS scanners after they were commercialized ("The Callidus Precision Systems" n.d.)—that is, after 1998, when Cyra Technologies, K^{2}T, Mensi, and Riegl had all released units.

Digital Molds

Point-cloud and mesh information presented the opportunity for a digital mold to be created of what is described in robotics as the object environment. This is because in 3D imaging the environment being documented is literally being treated like an object from which a cast is being taken (see, e.g., Peers, Hawkins and Debevec 2006, pp. 7–8). The Coignard family discusses this in their work in terms of "la modèle numérique," "la recomposition numérique," and "reproduction numérique" (B. Coignard and Szewczyk 2016). In fact, the heritage conservation community in France (and early practitioners like Benoit Coignard) were some of the earliest, if not the first, to explore what became known in English-speaking countries as *digital surrogates* and *digital twins*. Scans of the Colossus of Ramses II in Figure 14 is one of many examples from this body of early CH based work.

In the case of manufacturing environments like General Motors, the objects of interest were automotive vehicles like cars and trucks (Khetan and Besl 1990; Besl 1994). The point clouds and meshes created from scanners like the Hymarc enabled users to refine designs on computers, because of the level of detail, quality and resolution of the as-built information collected (Besl 1988; Lamb *et al.* 1999). The algorithm for ICP-based registration stemmed from such practical applications, with elements also coming from Neil McKay's experience in the study of robotics (Paul Besl, email to author, February 18, 2020).

Cyberware

One of the most famous and important public examples of close-range scanning was produced by the California company Cyberware (Figure 10), whose laser-based triangulation systems became famous for use in visual effects for films. Mechanically, they also shared influences seen in systems like the Hymarc, which could also use a fixed-arm system where the sensor moved around the object as it collected information. Its first film usage was in 1986, in *Star Trek IV: The Voyage Home* (Wilder 1991; Hoffmeister *et al.* 1996). Cyberware presented to the public the kind of applied research that was otherwise being carried out internally at companies like General Motors. Close-range examples like this also lay the groundwork for companies like Cyra Technologies and Mensi to capitalize on. For example, both companies had their scanning solutions on the sets of films like *Starship Troopers* and *Star Wars Episode II: Attack of the Clones* by the end of the 1990s to 2000s (Steve Chapman, email to author, November 12, 2012; Jacobs 2017).

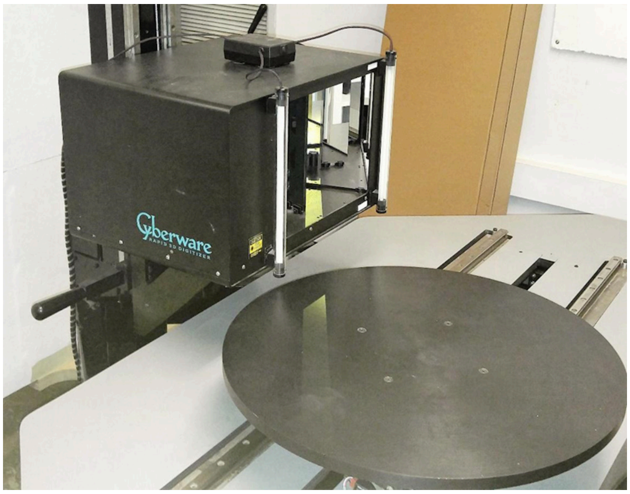


Figure 10. Artists like Dan Collins—discussed under "Commercialization in the Late 1990s (Third Phase)"—and film-industry visual-effects professionals started working with short-range Cyberware laser scanners in the early 1990s.

Lasers in Canada

The Hymarc laser scanner discussed in the section "Close-Range Scanning (Second Phase)" stemmed from research and development at the National Research Council of Canada (NRCC; Lamb *et al.* 1999). Funding came from the Canadian Space Agency (CSA) via the Strategic Technologies for Automation and Robotics Program, which also funded research conducted by Optech that was used in the development of the Laser Radar Instrument (LRI) for JPL in California (Tripp *et al.* 2003). The commercial offshoot of this was the Intelligent Laser Range Imaging System (ILRIS-3D), released in 2000.

The NRCC and CSA have helped shape and fund research and development in Canada since each was formed as a government entity (Blais 2004; Gainor 2012; Nelson 2013). Neptec, for example, is another Canadian company that has ties to the NRCC and CSA (Samson *et al.* 2004). Commercial products like the Opal-360 stemmed from research and development funded by both NASA and the CSA, in the same way as for Optech with the LRI and ILRIS-3D (Tripp *et al.* 2003; English 2010; Deslauriers *et al.* 2014). Neptec developed triangulation-based imaging first outlined in the Advanced Space Vision System prior to the Opal-360 range of scanners, shown as (r) in figure 1b of part one of this article (Blais 2004). The underlying research for these systems was started by the NRCC to examine vehicle collisions in the 1970s ("Space Vision System" 2008), then transferred to Neptec in the 1990s (Laurin 2017).

As Far Back as the First Laser Systems

The NRCC research facilities in Ottawa had been working with lasers since January 12, 1961 (Nelson 2013). There, Alexander Szabo and Boris Stoicheff demonstrated a synthetic ruby laser system in the Spectroscopy Laboratory to early laser pioneers like Arthur Schawlow. This demonstration came shortly after Theodore H. Maiman built the first working laser using this ruby-based system at California's Hughes Research Laboratories, on May 16, 1960 (Hecht 2005, 2010).

These early developments in active sensing lay the fundamental groundwork in Canada for the following:

- The formation of companies that would turn automation-driven research and development into "off the shelf" mid-range TLS solutions, such as Optech in 1974 and Neptec in 1990 (Tripp *et al.* 2003)
- The formation of the CSA as a strategy-making group and funding body in 1989
- The work of notable researchers at the NRCC Institute for Information Technology, such as Marc Rioux (1984; Rioux and Bird 1993), François Blais (2004), Jean-Angelo Beraldin (Beraldin *et al.* 2011), and Michael Greenspan (Lamb *et al.* 1999)

Both the NRCC and the CSA contributed to the story of mid-range TLS because of their symbiotic relationship with each other and with research and development communities in other countries, most notably France and the USA.

Multidisciplinary Application (Second Phase)

A self-sustained funding structure, whose main sponsor was EDF research and development, encouraged a multidisciplinary relationship between the Coignard family as artists and Guillaume Thibault as the principal engineer overseeing all CH projects (Figure 11a and 11b; Bommelaer and Albouy 1997; B. Coignard 1999; Thibault and Martinez 2007). Based on this work, finite element analysis (pertaining to the analysis of structures and their integrity), testing, the creation of a virtual wind tunnel, and a simulation of seismic activities were all applied to the scans of the Colossus of Ptolemy II from Alexandria, Egypt (O. Coignard *et al.* 1998; Moulin *et al.* 1998; Schmitt 1993; Schmitt *et al.* 1993). As seen in Figure 11, the Mensi team was the first to experiment with midrange TLS in CH and such a way. (The use of scan data along such lines had yet to be re-implemented into CH workflows overall at the time of publication of this article.) In the late 1990s, 2D CAD drawings and 3D visualization pipelines were used to repackage technologies for general users.

Landscapes, sites, and artifacts (the basic data types in cultural heritage) are documented from two perspectives in a CH-based workflow. The first is concerned with aesthetics and art-historical issues (Latour and Lowe 2011). The second is concerned with forensically reconstructing past actions and behaviors based on the material culture at hand (Hunter and Cox 2005; Remondino 2011). Midrange TLS can be used to obtain both sets of information, due to the resolution and range at which data are collected (Spring *et al.* 2010). It provides a way to document and inform archaeological restoration processes using quantifiable data. For example, the Delphi promotional video captured in Figure 12 demonstrates how point-cloud data were used to reconstruct the tholos at the base of Mount Parnassus (Bommelaer and Albouy 1997). Besides the use of scan data as a template for modeling the structure, fragments of sculpture and architectural remains were documented and reconstructed using 3D matching algorithms that identified fitting points between blocks. This was not wholly automated, as the software operator helped match blocks like a 3D jigsaw puzzle (O. Coignard *et al.* 1998; Lavigne 1998; R. Coignard, Coignard and Coignard 1999). It did, however, demonstrate that attribute information could be ascribed to scan data. It created more than a 3D image, showing that shapes in a scene could be extracted. As a result, the relationship between different objects could be examined. This part of the project was overseen by Guillaume Thibault (Thibault and Martinez 2007; J. L. Martinez and Thibault 2012).

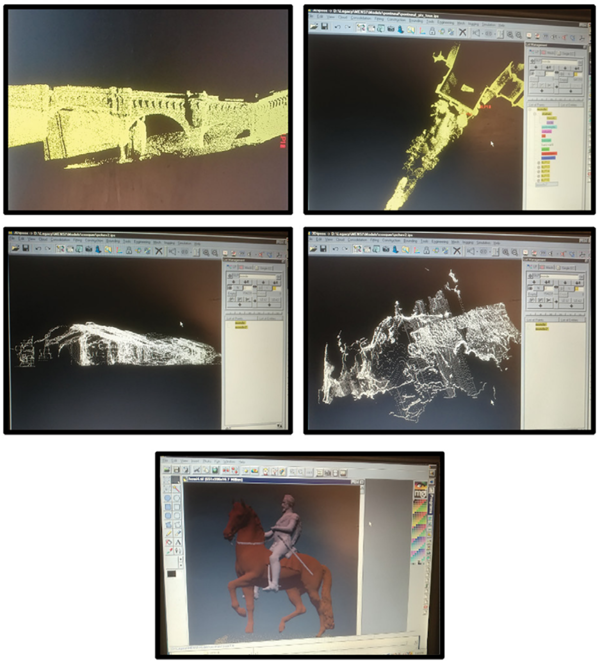


Figure 11. (a) Scans of the Pont Neuf Bridge (top, two boxes), Pont Marie Bridge and Henri IV Statue (lower box) were conducted in Paris, 1993 (Thibault, email to author, July 4th, 2020; Thibault and d'Aligny 1994). These scans were used to measure and model the bridges and statue (Thibault, Email, July 4th, 2020). The models were then run through radiosity software developed by the *Centre national de la recherche scientifique* (CNRS), as part of a computer simulation focused on how to best light the bridges and statue in the future (Thibault, email to author, July 4th, 2020). Tourism was a consideration for this project, which was part of an effort to upgrade how Paris was lit (Thibault, email to author, July 4th, 2020). It was soon followed by scans of the Vielmouly cave in the Beune Valley (France) and Cosquer Caves (middle, two boxes) in 1994 (Aujoulat *et al.* 2005; Bandiera *et al.* 2011).

The photgraphs above are of the oldest CH based mid-range TLS scans still known to exist at time of publication. Shown in 3Dipsos – point cloud software developed by Mensi – the .ips (above) files demonstrate that laser based triangulaton systems like the SOISIC paved the way for mid-range TLS as a site documentation and inspection tool. This is especially the case for the Cosquer Cave example, as it was only accessible by entering the cave from under water. The author would like to thank Ken Shain – former CEO of Mensi USA – for use of the photographs and data above.

(b) The Coignard family used structured light scanning to create digital molds in their early work. This eventually led to the collaboration with Mensi. (Courtesy of Coignard Family, email to author, June 12th, 2015).

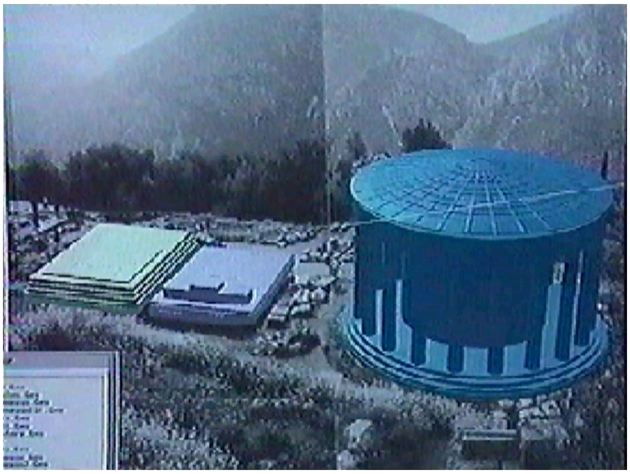


Figure 12. Mensi showcased a virtual reconstruction of Delphi at SIGGRAPH 2000, which included scans of the sculptural decorations of a circular tholos temple carried out in association with the French School at Athens in 1996. The video presentation produced by the company's Chief Executive Officer, Ken Shain, was one outcome of the high-profile cultural-heritage projects discussed in this article they were carried out by EDF and Mensi between 1993 and 1999 (Shain 2009).

There was also a document prepared by the French School at Athens called *Marmaria*. It outlined the point cloud-based work carried out at Delphi with the Mensi SOISIC scanner (Bommelaer and Albouy 1997). All information was used as attribute data, which were then fed into a vector-based modeling workflow (Albouy *et al.* 1989; Albouy 1990; Dekeyser *et al.* 2003; Vergnieux and Delevoie 2008; Homann n.d.). The latter had already been demonstrated through the Digital Karnak project (Figure 13). Architectural fragments were collected, meshed, and then introduced into the model. The Delphi video also demonstrates this, when premodeled sections of the tholos are draped onto a photograph of the site.

Trends and Influences on Development Cycles in the Fourth Phase

Lower-cost commodity sensors began to emerge because companies like Velodyne entered the midrange TLS market ("Breaking Through the Price Barrier" 2014; Ackerman 2016a; Ohnsman 2020; "Velodyne Lidar Introduces Velabit" 2020). The development cycle linked to their multibeam ToF systems made an impact within five years of having a working sensor in place (Halterman and Bruch 2010; Velodyne Lidar 2017). However, high-fidelity object documentation was not the primary driver for applied development, which is the case for most of the scanners outlined in this article. Instead, a return to autonomous vehicle development began the process of making sensors that are more affordable (Figure 5; Ohnsman 2020; "Velodyne Lidar Introduces Velabit" 2020).

For example, Velodyne entered into a partnership with Google for its self-driving car initiative (seen in Figure 6) in 2010 (Ackerman 2016a; Velodyne Lidar 2017). From this point, a development cycle began to emerge around vehicle safety applications for all sensors developed. This ultimately led to a $150 million investment in Velodyne from Ford and Baidu in 2016 (Ackerman 2016a)—that is, after the Velodyne Puck (VLP-16) was released in 2014 ("Breaking Through the Price Barrier" 2014). This sensor was priced at $7,999 and had an almost immediate impact on midrange TLS systems designed for as-built surveys.

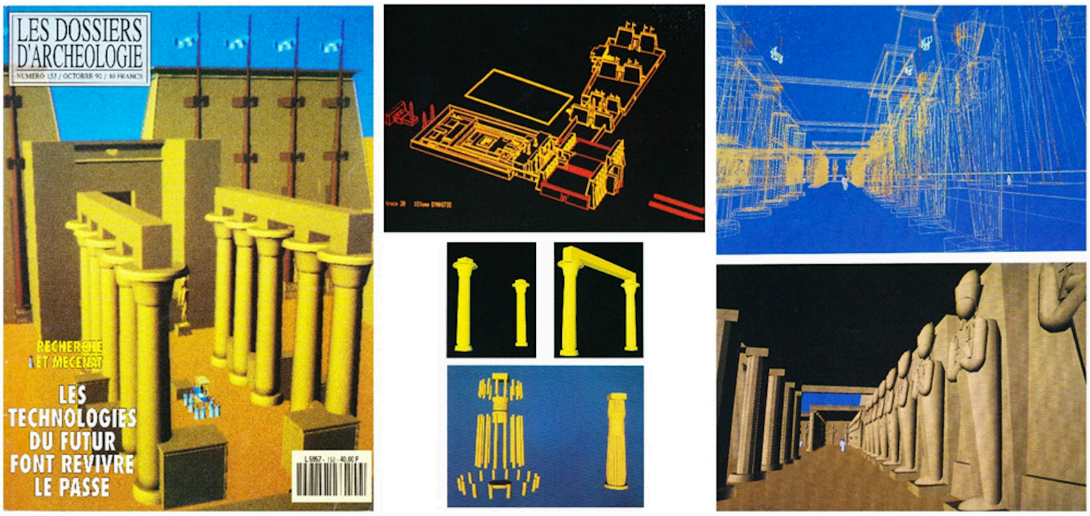


Figure 13. Mensi-based cultural-heritage applications were influenced by the computer-aided design approach developed by EDF for a digital recreation of Karnak in 1987. Henri Boccon-Gibod and Jean-Claude Golvin wrote a detailed article for the French publication *Les Dossiers d'Archéologie* in 1990. It outlined how computer-aided design models were generated–as well as informed by–the site information that was accessible to modelers at the time.

Designed for Documentation and Inspection

The Velodyne Puck was integrated into the NCTech LASiris VR and Effortless 3D laser scanners around the same time that Leica Geosystems released the more affordable BLK360 scanner, in 2016 (Tompkinson 2017). Even sensors developed by manufacturers of the first commercially available tripod-based systems repurposed their flagship hardware to include the Puck unit—a more affordable multibeam sensor, developed by Velodyne, designed to plug into a system architecture ("Breaking Through the Price Barrier" 2014). This meant that scanners could be more easily incorporated into vehicle-based applications. Primarily, for mapping based on SLAM, as seen via later midrange systems like the Leica Geosystems Pegasus, which was based on P-series scanners. Vehicle-based and wearable instruments are expanded upon in the "Building upon Navigation-Based Initiatives—Who and What?" and "Waves of Development Driven by Its Users—How and Why?" boxes.

Application to Cultural Heritage (Second and Third Phases)

The first CH applications of midrange TLS came out of France. They were supported by EDF, which was a state-owned company. University connections with EDF also encouraged the adoption of new technologies within the organization (Paramythioti and d'Aligny 1989; Bandiera *et al.* 2011). It was its corporate foundation, however, that offered up the means to legitimately support CH work. For example, philanthropic acts became more clearly defined activities in French corporate environments after a philanthropic law was passed in 1987 ("Sur le développement du mécénat et le Code général des impôts (CGI)": "On the development of philanthropy and the general code of imports"; Gautier *et al.* 2013). This law was soon followed by another, in 1990, that encouraged the creation of corporate foundations ("Sur portant création du statut de fondation d'entreprise": "On establishing the status of a corporate foundation". Both pieces of legislation came about because ADMICAL was created in 1979.

Three business students who had observed philanthropic corporations in the USA created ADMICAL to bring about similar conditions in France (Gautier *et al.* 2013). The turning point came when Jacques Rigaud—a former Chief of Staff in the Ministry of Arts and Culture—became the chairman of its board in 1980 (Guerrin and de Roux 2008). It was his passion for the arts and culture that helped make it possible for new technologies used in industry to immediately be applied to CH. In this instance, his framework for corporate philanthropy enabled midrange TLS to make the transition from industrial applications to CH from within EDF. It legitimized activities on a bureaucratic level within the organization. Industrial engineers were exposed to sites like Cosquer Cave and Delphi, and they were able to exchange their knowledge with heritage professionals (Brillault *et al.* 1995; Brunet and Vouvé 1996; Clottes *et al.* 1997; Moulin *et al.* 1998; Thibault 2001). With them came workflows geared toward as-built information—something EDF engineers had been exposed to on a daily basis.

Once access to technologies was in place, conservation professionals and geologists took an interest in midrange TLS for the documentation of in situ remains and museum collections (Schmitt 1993; Schmitt *et al.* 1993; O. Coignard *et al.* 1998; Moulin *et al.* 1998; B. Coignard 1999; Thibault 2001). They saw the potential for accurate reconstructions of an artifact or environment: reconstruction based on real-world data. Point clouds could be used to represent actual surface conditions, as well as provide more detailed overall measurements than tape measures, still cameras, and survey instruments like theodolites (Levoy and Whitted 1985; Levoy 2007). Because this early work was closely tied to the École Nationale Supérieure des Télécommunications, Paris (now Télécom Paris), ideas quickly spread to French-speaking Canada via a professor at Telecom Paris called Francis Schmitt (Baribeau, Rioux and Godin 1995; Beraldin *et al.* 2011). Schmitt's connections extended on the one hand to the École Polytechnique de Montréal in Canada (Hurtut *et al.* 2011). On the other hand, he had also published research with Xin Chen, the Chief Technology Officer at Mensi, who had obtained his PhD at the École Nationale Supérieure des Télécommunications, Paris (X. Chen and Schmitt 1992). EDF was more than large enough to support its own research and development efforts; it also worked with a network of collaborators which could disseminate its activities to a variety of professional communities all over the world.

Proof of concept for the value of technology like midrange TLS came in 1987, when EDF research and development funded the Digital Karnak project (Albouy *et al.* 1989; Albouy 1990; Dekeyser *et al.* 2003; Vergnieux and Delevoie 2008; Homann n.d.). The models produced for the project demonstrated that

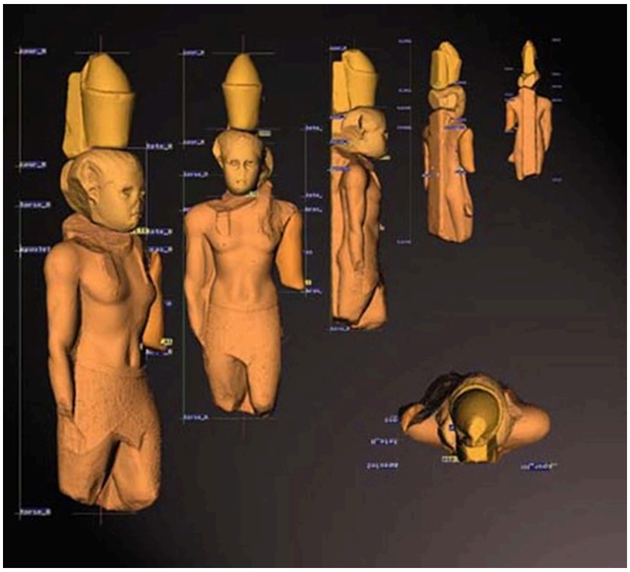


Figure 14. The Mensi SOISIC scanner quickly established that laser-based 3D point clouds could be used as an efficient way to document cultural heritage. Examples like the Colossus of Ramses II provided a more accessible way to create a digital mold or surrogate of an artifact or scene. Prior to scanning, a tape measure and the perspective of the conservator were used to preserve site and artifact information. The introduction of 3D imaging solutions like the Mensi SOISIC scanner improved any issues related to subjectivity or human error that stemmed from this process.

attribute data and primitive shapes could be created from all forms of information, including photographs and documentary evidence. It laid the groundwork for Mensi solutions to enter into CH workflows as another source of data. Marc Albouy, Deputy Director of Studies and Research at EDF, partially supported this effort in 1987 (Bommelaer and Albouy 1997). By the end of the 1990s, CH case studies also took center stage as marketing material. They were used by companies like Cyra Technologies and Riegl because of their mass appeal.

The first example of midrange scanning in CH was with a Mensi SOISIC scanner in France (Figure 11a; O. Coignard *et al.* 1998; Lavigne 1998; R. Coignard *et al.* 1999). EDF engineer Guillaume Thibault used it to document the Pont Neuf Bridge, Pont Marie Bridge and Henri IV Statue in Paris in 1993, and in 1994 it was also used at the Cosquer Cave in the Calanque de Morgiou at Marseille (Brillault *et al.* 1995; Brunet and Vouvé 1996; Clottes *et al.* 1997; Thibault, email to author, July 4th, 2020; Thibault and d'Aligny 1994; Thibault 2001). These later scans were inspired by natural relief drawings done by prehistoric artists, as well as the practical need for a realistic visitor display to compensate for waterlogged conditions inside the Cosquer Cave. Note: the Coignard family had become aware of Mensi's technology in prototype form in 1991 (Coignard Family, email to author, June 12th, 2015)

From 1993 to 1999, several CH case studies were generated through a collaboration between the Coignard family and the EDF team headed by engineer Guillaume Thibault (Schmitt 1993; Schmitt *et al.* 1993; O. Coignard *et al.* 1998; Moulin *et al.* 1998; B. Coignard 1999). These included a statue of a Gallic warrior, the Hindu god Harihara from Cambodia, a centaur, the Colossus of Ptolemy II from Alexandria, Egypt, an epigraphy-based example from the Louvre in Paris, and a statue of the Emperor Augustus. The Emperor Augustus statute was used as the first attempt at creating a digital surrogate of a scene with computer-based technologies—or, as Benoit Coignard described it, “clones numériques” (B. Coignard 1999). Prior to scanning, tape measure and the perspective of the conservator were used to preserve site and artifact information. The introduction of 3D imaging solutions like the Mensi SOISIC scanner resolved any issues related to subjectivity or human error that stemmed from this process.

Cultural Heritage as Marketing (Second and Third Phases)

Kevin Cain, who is discussed in more detail later under “Nonprofit Corporations (Third Phase),” had used a prototype Field Digital Vision machine developed by Cyra Technologies by 1995 (Kevin Cain, email to author, August 23, 2015; “Reimagining Maybeck’s Palace,” 2002), on the Palace of Fine Arts in San Francisco (Kacyra *et al.* 1997; Loedeman 1999). Samples of the modeling work produced from this data are seen in Figure 15. Unlike the Mensi system, the FDV used a ToF-based solution, which had increased accuracy and range based on specifications for improvement identified through the JPL Laser Rangefinder project (see part one of this article). A time-interval interpolation integrated circuit, which had been developed for underground blast monitoring at the Los Alamos National Laboratory, was linked to a Q-switched or pulsed laser developed by the MIT Lincoln Laboratory (Howe and Auchampaugh 1992; Kacyra *et al.* 1997; Wilson *et al.* 1999; Shan and Toth 2009; Spring *et al.* 2010). The increased pulse rate created from this solution meant that a data resolution of 2–6 mm could be achieved over distances of 0.5–50 m (Gaiani *et al.* 2000). Solutions based on Field Digital Vision and CGP (Computer Graphics Perception)—the first point-cloud registration and modeling software, created by Cyra Technologies—were also strategically marketed to sectors such as architecture, engineering, and construction. They were positioned around pre-existing 2D CAD and 3D visualization pipelines (Kacyra *et al.* 1997).

In the spring of 1997, Cyra Technologies carried out more historic building work by scanning the facade of the Hearst Memorial Mining Building at the University of California, Berkeley (Addison and Gaiani 2000; Addison *et al.* n.d.). The scans were conducted as part of an earthquake-proofing retrofit of the building, which would subsequently involve dismantling parts of the historic facade to add structural reinforcements. A similar retrofitting project occurred at San Francisco City Hall in February 1998 (“Renovation of Historic

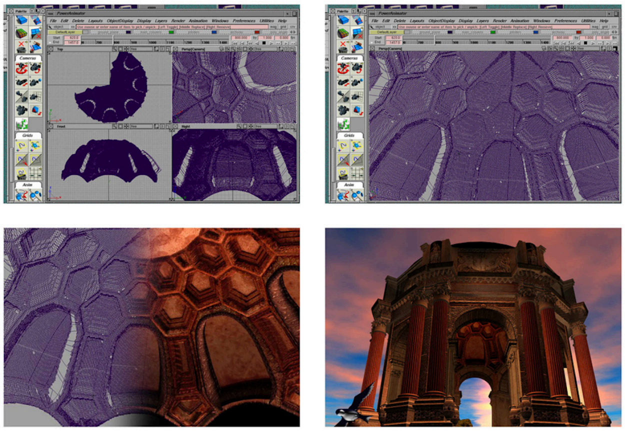


Figure 15. The Palace of Fine Arts in San Francisco was used by Cyra Technologies to market early midrange laser scanners like the HDS 2400. Modeling work of the point-cloud data was carried out by Kevin Cain and his team at the Academy of Art University in San Francisco. All photographs were kindly provided to the author by Kevin Cain (Email to author, September 17th, 2013).

Building" 1998). Marc Levoy followed on from this in 1999 by using a Cyrax HDS 2400 for in situ scans of Michelangelo's David as part of the Digital Michelangelo Project in Rome (Levoy *et al.* 2009).

From 1998 to 2001, several examples were presented by Riegl using data from the LMS-Z160/Z210 (Ullrich and Studnicka 1999; "3D Imaging Sensor LMS-Z210" 2001; Pfeifer and Rottensteiner 2001). These included the Assemblée Nationale in Paris; the ruins of Burg Kollmitz in Lower Austria; the Kirche am Hof in Vienna (the inside vaulting and outside facade of the church); and Schönbrunn Palace and the State Opera in Vienna. The Riegl system was explained by using polychromatic scales for the representation of height data, with grayscale used to represent surface reflectance (Nitzan *et al.* 1977; Pfeifer and Rottensteiner 2001; Riegl 2001; Ullrich and Studnicka 1999). These CH examples were also used to explain the relationship of the laser echo returned to the scanner and the point cloud generated, and to emphasize the difference between a depth image, a conventional 2D photograph, and basic 3D models (Ullrich and Studnicka 1999; Pfeifer and Rottensteiner 2001). Case studies were disseminated using VRML 3D interactive vector models displayed on the Riegl website (Ullrich and Studnicka 1999; Riegl 2001; Pfeifer and Rottensteiner 2001). As with the EDF Digital Karnak project, CAD modeling played an important role in the data-processing workflow adopted for early Riegl CH examples.

Nonprofit Corporations (Third Phase)

Having acquired a Mensi scanner in 2000, Kevin Cain turned the California nonprofit Egyptian Cultural Heritage Organisation into the Institute for the Study and Integration of Graphical Heritage Techniques (INSIGHT) and continued to enlist the skills of Philippe Martinez (Cain 2000; P. Martinez 2001; Cain, Martinez and Munn 2002; Cain and Martinez 2003; Cain *et al.* 2003; P. Martinez and Cain 2011). Martinez was an archaeologist who had been part of the Mensi-based Delphi project seen in Figure 12. He would also go on to work with Paul Debevec at the Parthenon using a SceneModeler scanner in 2003 (Debevec *et al.* 2005).

Mensi also showcased this virtual reconstruction of Delphi at SIGGRAPH 2000, including scans of the sculptural decorations of a circular tholos temple done in association with the French School at Athens in 1996 (Bommelaer and Albouy 1997; Flaten and Gill 2007; Thibault and Martinez 2007; J. L. Martinez and Thibault 2012). The video presentation produced by the company's Chief Executive Officer, Ken Shain, was one outcome of the high-profile CH projects already discussed that were carried out by EDF and Mensi between 1993 and1999 (Saint-Aubin 1995; Brillault *et al.* 1995; Brunet and Vouvé 1996; Bommelaer and Albouy 1997; Clottes *et al.* 1997; O. Coignard *et al.* 1998; Lavigne 1998; Moulin *et al.* 1998; B. Coignard 1999; Thibault 2001). Meanwhile, after selling Cyra Technologies to Leica Geosystems in 2001, Ben Kacyra turned from commercial applications to CH by forming his own nonprofit corporation, CyArk, in 2003 (Dawson *et al.* 2013). This San Francisco-based archive for scan data was his response to the destruction of the Bamiyan Buddhas in Afghanistan in 2001.

Both INSIGHT and CyArk went on to achieve success in the 2000s. For example, Cain worked with members of the EDF team on the omphalos in the museum at Delphi discussed in part one of this article. INSIGHT helped with the development of the registration process in CloudCompare, which in 2009 became an open-source platform for working with point-cloud

Waves of Development Driven by Its Users—How and Why?

Developments in midrange TLS now follow general consumer trends and markets. Two waves of development have taken place under these conditions, both driven by how much laser scanning solutions cost and in reaction to developments in other technology-driven markets. Included in this melee is the adaptation of business models used to monetize personal computing. For example, the same iTunes service-as-a-solution (SaaS) model used by Apple for MP3 files was applied to point-cloud data by 2013 (Spring 2015). The ReCap range of software packages from Autodesk were the first to adopt and promote this form of content management (Spring 2015). One of their pricing options even included a credit-based system to process point-cloud and mesh data via their distributed computing-based services.

It is, however, the commoditization of sensor technologies—the process of turning products of value into objects of trade—that ultimately created the second, third, and fourth waves of sensor development. For example, the Velodyne Puck has been used across both mobile and terrestrial mapping solutions. It was incorporated into hardware like the Pegasus mobile mapping unit from Leica Geosystems as well as tripod-based products like the NCTech LASiris VR and Effortless 3D seen in figure 1b of the first part of this article. Leica Geosystems also announced the BLK360 solution, which, along with the Puck-based LASiris VR and Effortless 3D, created another layer to the TLS market that was promoting midrange TLS solutions for professional uses at prices below $15,000 (Tompkinson 2017).

Arguably, the fourth wave of development—signaled by plug-and-use sensors and low-cost kit-based solutions—had fully emerged by 2016. ToF-based kits like the Scanse unit, for example, incorporated low-cost computers like the Raspberry Pi into their system architecture, making them easier for nontechnical users to build (Ackerman 2016b). Velodyne released a $100 sensor called the Velabit in January 2020 (Ohnsman 2020). It was introduced at the Consumer Electronics Show, immediately positioned for clash detection in cars, and was described as "designed to be easy to manufacture at mass production level" ("Velodyne Lidar Introduces Velabit" 2020). This kind of development in hardware is similar to kits seen in the period building up to the mass adoption of the personal computer, such as the Altair 8800 kit or Sinclair kits.

FARO Technologies, Inc

In terms of sensors and software, the FARO Focus^{3D} scanner and Scene software are the prime example of the way the technology is shaped or packaged in the commercial era of laser scanning. FARO packages midrange TLS along similar lines to tablets or smartphones—smaller, powerful, and yet easy to use (Spring 2012). The FARO Focus^{3D} was designed to be like other all-in-one systems. Midrange TLS scanners had contained all the components required of a solution—sensors, onboard computer, data storage, and power supply—since the Z+F 5006 was released in 2006 (Shan and Toth 2009). The Focus^{3D} was, however, miniaturized to fall in line with consumer technologies such as handheld computing devices like the iPhone. Software variations like Scenect—an Xbox Kinect-capable version of Scene—and the creation of a FARO app store in 2012 were also developments geared to broader "prosumer" markets (Kotler 1986). These are markets that are composed of user communities working with 3D imaging technologies, whether laser scanner or app-equipped smartphone, in their personal and professional lives (Spring 2015). Midrange TLS had entered a stage of development where more socially driven business models were being considered by the time this article was published. Technologies shaped by user experiences were the next big thing.

information (Duguet *et al.* 2004; Thibault and Martinez 2007). CyArk quickly refined its business model for heritage documentation around the same time. It was predominately geared toward capitalizing on the points of synergy between private- and public-sector entities. In fact, the turning point for CyArk came in 2010, when Mount Rushmore was scanned in collaboration with the Scottish government using five midrange TLS scanners (Lee 2010; "New Lanark, Scotland" n.d.). Point clouds that were generated fed into both the Scottish Ten and CyArk 500 projects. Mass media exposure from the scanning of Mount Rushmore helped corporate partners like Leica Geosystems, as well as the US National Park Service and the CyArk 500 initiative—a reflection of Ben Kacyra's ambition to document 500 heritage sites over a five-year period (Kacyra 2009). FARO was listed as the main contributing midrange TLS partner on CyArk's website by 2020 ("Partners" 2020). There was also an ongoing collaboration between CyArk and Google Arts & Culture via the Open Heritage initiative (Watkin 2018; "Open Heritage" n.d.).

Commercialization in the Late 1990s (Third Phase)

Developments in personal computing enabled TLS to make the transition from applied research communities like robotics into applied markets, such as design, engineering, and as-built survey (Kacyra *et al.* 1997; Roland and Shiman 2002; Markoff 2005; "Project Development Plan" n.d.). This link is a fundamental reason why 1997 and 1998 were turning-point years for a broader commercialization of laser scanning: years when personal computers finally became ubiquitous technology. In fact, the miniaturization and increased efficacy of both computers and TLS are intertwined. This is because integrated circuits are one of the key components driving their development.

For example, microelectronics and microchip-based timing were fundamental in the development of both Riegl and Cyra Technologies laser scanning hardware (Wilson *et al.* 1999; Studnicka n.d.). Riegl optimized its preexisting LD90-3 laser distance meter to create its early ToF scanners, whereas Cyra Technologies combined a passively Q-switched microchip green laser—which stemmed from a collaboration with John Zayhowski from the MIT Lincoln Laboratory—with a time-interval interpolator integrated circuit that was originally designed to monitor nuclear blasts (Kacyra *et al.* 1997; Zayhowski 2010, 2018; Wilson *et al.* 1999). That was in order to create a ToF system specified to accuracy and resolution in millimeters, with a range of up to 100 m.

Even throughout the 1990s, the main computers used to develop point cloud-enabled software like CGP were specialist graphics machines. Silicon Graphics or Sun Microsystems hardware was used to create point-based software capable of running on Windows NT microcomputers (Kacyra *et al.* 1997). It was not until the advent of dedicated graphics processing unit (GPU) cards—which led the way to affordable high-performance computer graphics—that processor-intensive point-cloud and polygon-based rendering became accessible to a wider consumer base (Tarini, *et al.* 2003). As seen in the "CloudCompare" box in part one of this article, for example, GPU-based computation made it easier to perform otherwise processing-intensive tasks, such as light-field simulation. This development was in favor of faster GPU-based functions like the Poisson shading of the Tristan Stone photograph in that box (Spring and Peters 2014). Users outside of large corporations, government agencies, and research institutions were relatively small in number before dedicated GPUs (Palacios and Triska 2011). They would have needed a clear application for the use of such technologies to justify absorbing the costs associated with information processing and development requirements (Kotler 1986).

Expanding the User Community

Once TLS started to emerge as a coherent solution in this way, different types of users began to take the technology in a diverse range of applied directions. In industrial sectors like automotive engineering, for instance, CAD and computer-aided manufacture presented clearly defined incentives for the continued development of TLS in general (see the use of computer numeric control and rapid prototypers by Besl and McKay mentioned earlier under "Automotive Industry"). Along with close-range scanners, which were made popular by companies such as Cyberware, industrial applications like machine-part design bridged a gap in terms of awareness. New users and skill sets were brought into communities where point-cloud information would change the way they approached a


(a)

(b)

Figure 16. (a) Dan Collins started to incorporate full-body scanning into his sculptures as the technology developed. (b) *Twister* was the most successful piece of art to come out of Collins's collaboration with Cyberware. The point clouds generated provided a level of detail not seen before. Collins had to wait for an affordable computer to be released before he could work with his point clouds in the way he had originally intended.

project (Lavigne 1998). Early adopters like sculptor Dan Collins, who outlined his scan to computer-aided manufacture creations in *The Challenge of Digital Sculpture* in 1997, serve as good examples (Figure 16a and 16b; Collins 1994, 1997; "ISC Web Special" n.d.).

By 1998, midrange TLS and digital photogrammetry solutions began to unlock the potential of point cloud-driven workflows (Pot *et al.* 1997). Software like 3Dipsos (Mensi), Architect (K^{2}T/Quantapoint), CGP (Cyra Technologies), and RiScan (Riegl) worked with point-cloud information from midrange TLS systems (Kacyra *et al.* 1997; Debevec *et al.* 2005; X. N. Chen *et al.* 2005; Ullrich and Pfennigbauer 2011). They used the information provided to solve real-world problems. In industrial applications, for example, the as-built condition of a structure could now be compared to the as-designed specifications from which it was constructed in order to look for variation between the two. 3D point clouds were used to inform and refine future projects as well as help formulate management strategies for existing structures (Addison *et al.* n.d.). This was touched upon earlier in this article, when Cyra Technologies used its midrange TLS solutions on buildings that were retrofitted to withstand the effects of earthquakes in San Francisco ("Renovation of Historic Building" 1998).

The ability to easily connect individual point clouds together was also a key selling point for laser scanning. ICP-based registration took stitching from a three-point process to an actual all-point process (Besl and McKay 1992; Y. Chen and Medioni 1992). It gave users the ability to connect overlapping scenes by picking common points of overlap, which would inform any statistical analysis performed by the software used. It also led the way for other point cloud-based processes to take on a more user-friendly form. These included solid meshing for processes like volume analysis, georeferencing scan data to real-world coordinate systems, and packaging files in ways that were more compatible with CAD solutions like AutoCAD (Kacyra *et al.* 1997). For the first time, data were repackaged to be accessible to users whose skill sets were not overtly linked to otherwise specialist computer practices.

Parallels to the Personal-Computing Market

Cheaper systems like the Scanse Sweep also started to emerge around the period of 2014–2016 (Ackerman 2016b). The $349 Sweep unit was also available in kit form, so that users could build their own laser scanners. This kit-based approach—along with the plug-in integration with an individual's own systems and own practices—as validated by Velodyne, parallel's activities seen in the early days of the personal-computer market (Markoff 2005). It suggests that midrange TLS sensors will continue to make a transition to become commodity items, much like microchips and semiconductors did after the mass adoption of personal computers (Figure 17).

Similarities to Personal-Computer Markets

The midrange TLS systems outlined in parts one and two of this article would not be possible without the microcomputer revolution started by the Intel 8080 microprocessor. In fact, midrange TLS currently feeds into the infrastructures built up around smartphones, tablets, and powerful desktop- or carry case-sized computers (as outlined in the section "Trends and Influences on Development Cycles in the Fourth Phase" and the "Waves of Development Driven by its Users—How and Why?" box). The development of markets around midrange TLS hardware and software presents its own examples of hybridization and commoditization as well—patterns of development related to repurposing or adding value to objects, which was fundamental to the creation of a user community and market based around early examples like personal computers.

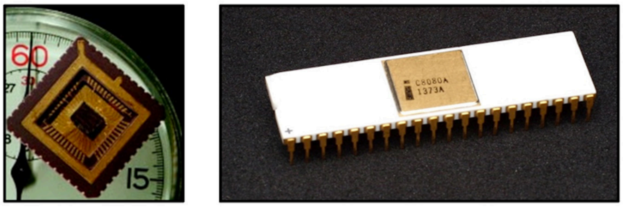


Figure 17. (Left) The time-interval interpolator integrated circuit created by Los Alamos National Laboratory for its nuclear-weapons program. It was later repurposed for the Cyrax scanners produced by Cyra Technologies to reach the millimeter and centimeter levels of accuracy they required. (Right) The Intel 8080 8-bit microprocessor, originally used in calculators, cash registers, computer terminals, and industrial robots. It was more famously repurposed for the Altair 8800, the first successful personal or microcomputer.

For example, the first wave of Cyra Technologies (later Leica Geosystems) scanners were developed by repurposing the time-interval interpolator integrated circuit created by Los Alamos National Laboratory (Figure 17). It was used alongside a green eye-safe laser from MIT's Lincoln Laboratory to create what was initially called the Field Digital Vision machine. Its associated software, CGP, was designed on specialist graphics workstations from Silicon Graphics (Kacyra *et al.* 1997; Wilson *et al.* 1999). But the software was developed to run on Windows NT workstations of the time, so that a wider user community had access to the scanner and its data. This act of commoditization came in the added value brought by a growing user base. Having a working product and proven value would later help establish a midrange TLS market—especially when coupled with the dot-com boom in the mid to late 1990s, first when Leica Geosystems acquired Cyra Technologies in 2000 ("Leica Geosystems Acquires Oakland-Based Cyra Technologies" 2000), and then when Trimble acquired Mensi in 2003 ("Trimble Navigation Acquires Mensi S.A." n.d.).

This type of activity around the technology is similar to what happened during the formative years of the personal-computer market (Markoff 2005). That is, once the Altair 8800 provided the proof of concept required to make personal computers a reality to a broader spectrum of people—like the Homebrew Computer Club in the San Francisco Bay Area, and Microsoft's co-founders Bill Gates and Paul Allen.

The Altair 8800 computer proved to be a nexus for both hybridization and commoditization to take place around personal-computing technologies (Rustad and Onufrio 2012). Hybridization via the way its 8080 microprocessor had been repurposed–taking the idea of the computer from room-size mainframes to a desktop box (Markoff 2005). Commoditization via the scale and cost at which the hardware could be produced. This and the fact that people could afford access to the Altair 8800 grew the market that formed around it by adding layers, such as discovering ways to add hardware via software. Well-known examples where the latter occurred include the Homebrew Computer Club and what went on to become Microsoft.

The first proven use for the Altair 8800—which began to demonstrate its potential through hobbyist users—came from the Homebrew Computer Club (Markoff 2005). Steve Dompier programmed it to play "The Fool on the Hill" by the Beatles using static from a radio next to it. Gates and Allen then extended its use further by creating Altair Basic, an interpreter that essentially enabled users to add a keyboard and monitor to the system. This made the Altair 8800 easier to use and usable for a broader range of applications, such as word processing and gaming. Prior to Altair Basic, the 8800 had no display monitor or keyboard and could execute commands only via a number of switches on the front of its box—hence why a radio had to be put next to it to play music. Altair Basic was also the foundation upon which Gates and Allen formed Microsoft.

Parallel example in mid-range TLS: the multibeam system architecture developed by Velodyne for self-driving vehicles in the Grand Challenge quickly got repurposed for tripod-based and mapping systems (Halterman and Bruch 2010; Tompkinson 2017). Its success as a platform to integrate into or build new system architectures on led to a new wave of sensor companies as well, including Cepton, Hella, Innoluce, Ouster, and many more (Davies 2020). These happenings—the development of a sensor for one purpose getting used for another, then a market forming around it to the point where other companies are formed to produce similar technologies—mirror events that played out around the Intel 8080 microchip in the 1970s (Markoff 2005).

Components like the 8080 microchip were repurposed from use in sequencing in hardware like traffic lights and calculators to create the Altair 8800—the first personal computer (Markoff 2005). This same process of hybridization, repurposing existing materials to create something new, can also be seen in the years building up to midrange TLS becoming a commercially viable product (Rustad and Onufrio 2012). Cyra Technologies is a prime example of this process in action. A laser system from MIT's Lincoln Laboratory and a time-interpolation circuit from Los Alamos National Laboratory were core components for all Cyra-based laser scanners up to 2009 (Kacyra *et al.* 1997; Zayhowski 2010, 2018; Wilson *et al.* 1999). This and other examples have already been outlined in more detail in the section "Commercialization in the Late 1990s (Third Phase)."

On the business side, the formation of K^{2}T also follows the template set out by Ivan Sutherland and David Evans at the University of Utah in the 1960s ("Evans & Sutherland" n.d.; "Project Development Plan" n.d.). Evans and Sutherland formed a company of the same name as part of their agreed-upon move to Salt Lake City (Gaboury 2016). This not only commercialized their research in computer graphics at the university—where they made one of the main nodes for ARPA/DARPA's research in computing—but set out the template most universities now use in commercializing their research in the USA: finding a commercial niche for research, then using the application to develop the technology out and expand a market. Ed Catmull, one of the founders of Pixar, is even on record as saying that his time as a student at the University of Utah School of Computing helped inform how he structured Pixar Animation Studios (Catmull 2014). Companies formed by former students of Evans and Sutherland include Adobe, Netscape, Pixar, and Silicon Graphics (Gaboury 2016). Nolan Bushnell, founder of Atari, was also a student at the University of Utah when Evans and Sutherland were there (Gaboury 2016).

Summary

This history of midrange TLS was born out of curiosity and crafted via perseverance. It stemmed from questions about what was largely a black-box technology when the author started working with it in 2006. Putting together all the pieces of the puzzle grew into a project that evolved for well over a decade. A multilingual literature review was part of the process—comprising media written or produced in Chinese, English, French, German, Japanese, Italian, and Russian—as were many lessons learned in network literacy and cultures.

It is a history defined by constant change that is, at certain times, forged from what superficially appear to be otherwise disjointed threads or happenings—events that are woven together at turning-point moments in intricate and incidental ways. Take the ICP algorithm as an example: Besl had just gotten some success (if slow) with the Nelder–Mead downhill simplex algorithm from *Numerical Recipes in C*. He stopped by McKay's office to chat about it, and McKay said it would be interesting to try matching with the closest point for each model point and then repeat that iteratively. Besl modified his existing code by the next day, found he was getting monotonic convergence, and then proved the local convergence theorem. This is just one of many examples of the importance of having the personalities in the appropriate—usually applied—research settings for major breakthroughs to happen in the long term. It also highlights that the technologies and solutions which will continue to evolve beyond this publication were forged out of a rich and complex web of events.

Events that shaped technologies also feed into a history born out of applied research—from space and defense guidance systems to site documentation and inspection. The funding sources that fueled this research and work environments are equally as important as how technologies were being applied, because funding helped frame the progress being made, whether it was DARPA, the ESA, corporate funds or grants, via ADMICAL, or business models based on consumer uptake from the late 1990s onward.

Funding sources have a fundamental impact on how further changes to both hardware and software are shaped. For example, companies like Velodyne demonstrate that funding sources remain one of the constant agents of change in the commercial period of use and development of midrange TLS. The volume of commentary about the lidar market around the time this history was published supports this idea as well.

The term *lidar*—light detection and ranging—was avoided in both parts of this article due to the broad and sometimes vague ways in which it can be used. This was especially the case around the time of publication: a period when a gold rush was playing out in the sensor market. Lidar had become an all-encompassing term in the automotive industry and in associated media output tethered to events like the Consumer Electronics Show. This was, in part, largely due to the impact that sensors from companies such as Velodyne were having on collision detection and driver safety–and, in bringing the cost of technologies down so that a larger community of developers now had access to them. Marketing and associated press related to the iPad Pro from Apple (released around the time this article was published) emphasize this further as well. A central element to the iPad Pro announcement—which came in March 2020, shortly after the Consumer Electronics Show and during the COVID-19 pandemic—highlighted that a lidar sensor was included in this new tablet.

Overall, the term *midrange* TLS was used to be more specific to the subject matter at hand—that is, to focus on the intricacies linked to devices of measurement tethered to dynamic range and ranging. Or, in other words, the retrieval of entire surfaces of varying sizes in a scene as clouds of measurable points as opposed to just single points of measurement. As a term, *midrange* firmly cemented where the technologies sat as a method of data collection: those designed for building-scale documentation, sitting between small to medium-size object scanners and landscape-scale scanning instruments that can collect data from over a kilometer away.

The act of scanning was also considered an active imaging process, where a point cloud was generated by a laser beam making contact with a surface. Accuracy, repeatability, and resolution were seen as overarching variables to consider in working with point-cloud information. Accuracy pertained to the perceived scale of measurement (within centimeters over a distance up to a kilometer away); repeatability (examples include the ability to rescan a site with the same instrument and workflow to compare to previous results and / or baseline, or features of the system architecture of the instrument, such as number of times the signal of points returned are sampled to help improve data quality); and resolution was considered in terms of data quality or the visual level of detail represented in the 3D image generated via the point cloud.

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The articles are dedicated to Rebecca, Fonzie, Harvey, Poppy and Willow. This article was made open access by Remotely Interested LLC.

Note: The author discovered the JPL Research Robot–which had the scanning laser rangefinder on it–had been mislabeled as the 'Stanford Refined Cart Robot' at the Computer History Museum (CHM) in Mountain View, California. This discovery came in between the final edits for part one and part two. Its starting point are in part one though: 'This took a similar form to the JPL Laser Rangefinder by 1979.' Dr Spring contacted the CHM and the catalogue was corrected to 'Jet Propulsion Laboratory (JPL) Research Robot' on June 22nd, 2020.

The author would also like to correct a typo made in the melee of final edits for part one. The Amiga based Scannerless Range Imager was an early example of a phase shift system.

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