SURVEY OF CONSTRUCTION METROLOGY OPTIONS FOR AEC INDUSTRY

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ABSTRACT: Techniques for measuring distances, relative heights, and angles have improved significantly during the last decades. Some of these techniques can be used in the Architecture, Engineering, and Construction industry to improve the precision of measurements being made currently using traditional equipment. Other techniques can be used to record information that could not be obtained practically using the traditional equipment. Cost comparisons are made for different scenarios to show that the substantial initial cost of the new hardware can be compensated for by lower labor cost and shorter duration. This paper also points out some of the salient features of the new metrology options. For example, locating the three-dimensional coordinates of a point is necessary for robotic control. In this case, new equipment must be used if the traditional equipment cannot obtain the coordinates at a rate that is useful to control the movement of the robot.

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry today relies heavily on the use of automatic levels and electronic theodolites to perform measurements at construction sites. In the last decades, a variety of metrology instruments like the robotic total station, RTK-DGP differential global position, fanning laser, LIDAR, LADAR, and real-time photogrammetry have been produced to facilitate the traditional jobs associated with the AEC industry. These innovations may present many potential money-saving opportunities in spite of the higher initial cost and the learning period necessary to use these new technologies.

In this paper, we will attempt to describe the salient features of the new metrology instruments available today. We will compare the performance characteristics of these instruments against the automatic level and theodolites. A cost comparison will be made for these instruments by considering their initial cost, labor cost, maintenance cost, and potential timesaving. Although their initial costs are considerable, these comparisons show that, for large projects, the new metrology systems have the potential to reduce both cost and duration of the project, while improving the quality of measurements, work environment, quality control, and documentation of the as-built structure.

Additional important factors in determining the life-cycle cost are the tax benefits and discounts provided by many companies eager to have their equipment adopted. These factors can lower the life-cycle cost substantially.

BACKGROUND

While tapes and transits are still used today in construction to measure distances and angles, these tasks have been made simpler by combining the distance measuring capability into the theodolite to produce the total station. Further development of the total stations made them possible to be handled single handedly (Henstridge 1994). Such an instrument is typically called the robotic total station. The robotic total station has the potential of reducing both labor cost and activity duration that are associated with point stakeouts and other surveying tasks. The initial cost of acquiring the instrument and the initial learning time, however, have kept many users from taking advantage of this instrument.

In certain construction activities, traditional surveying equipment such as the total station is not well suited. For example, automatic dredging operation and virtual reality representation of construction tasks require the feedback of equipment location. The global positioning system (GPS) has been used in automatic dredging operations for the past decade (Jacobs 1992; Jordan 1993; MacLeod 1995). Similarly, a recent demonstration of a virtual reality representation of a robotic crane at the Institute of Standards and Technology (NIST) suggests that a laser positional device could be used to provide feedback positioning information to the virtual reality application in "real time" (Stone 1998). These techniques have already found practical uses in the construction industry in Japan (Sada 1994).

In the early 1990's the Consortium for Advanced Positioning Systems (CAPS 1995) was formed by Bechtel, Jacobus Technology, SPSI (now Arc-Second) and others to study the possible use of advanced positioning systems in the AEC industry. The CAPS report described some of the systems and their capabilities, but it did not compare the relative cost of using these technologies. Moreover, advances in the GPS technology, LIDAR, LADAR, and Photogrammetry merit another look at the state of the art of metrology in the AEC industry. NIST is continuing the spirit of the CAPS program to develop an industry-consensus standard for the wireless transmission of metrology data at construction sites.

SURVEYING INSTRUMENTS

In this section the instruments, their performance, limitations, and salient features are described. The information for Tables 1–5 are obtained from manufacturers' published data. These data are obtained under different conditions. In addition to different testing conditions, some companies are more conservative with their claims, while others may be more optimistic in their assessment. The authors used their judgment in making the comparisons. In the comparisons that follow, the authors used manufacturers' published data without corrections; therefore, some inconsistencies in reported accuracy are to be expected.

Levels

Levels are probably the most commonly used instruments in construction-related surveys today. These instruments can be divided into three categories: automatic compensator levels, digital levels, and laser levels. Digital levels use an Invar staff that works like the bar codes. It is capable of estimating dis-

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tances as well as elevation. Laser levels are useful where a continuous elevation is important (de Sousa 1995; Malisch 1996). Some applications include tunnel drilling and footing drilling. A summary of the performance data for levels is shown in Table 1.

For precise elevation measurements, the level excels. For small companies or at small construction sites, a level and measuring tape are all the tools needed to layout the construction site. At large construction sites, the use of a level alone is perhaps slower than many other techniques. In these situations, the level should be complemented by other equipment to expedite the measurement process.

Theodolites and Total Stations

Theodolites have been in use for over 150 years. The term *optical theodolite* was originally only used in Europe to describe instruments similar to the transit. Later, the term theodolite became synonymous with instruments that included a shell which encloses a telescope that can read angles about a vertical and a horizontal plane, an optical plummet, and a leveling system. An electronic distance measuring (EDM) device is often added on the theodolite (Obaidat 1996). These devices are usually called digital theodolites.

Total stations are electrical digital theodolites. Total stations typically have an accuracy of 0.16–4.7 mm over a distance of 100 m. Traditional theodolites, in comparison, have a corresponding accuracy of 0.35–7.9 mm. Some total stations are equipped with electronics that allow remote operations and automatic fine adjustments. Remote operations eliminate the need for a rodman; thereby labor cost associated with a worker is saved. Automatic fine adjustments expedite the work and relieve the worker of the tedious tasks associated with instrument adjustment. It also increases productivity by allowing work to proceed in poor-sight conditions such as fog or darkness. A summary of the performance data for theodolites and total stations is shown in Table 2.

Although the total station has been available for over a decade, its use is not widespread in the AEC industry. Unfamiliarity and initial purchase cost are probably the two main reasons this equipment is not widely used.

Laser Metrology Instruments

In the mid 1960s, electronic distance measurement (EDM) lasers became the first application of laser technology in the construction industry. More recently, laser levels have been made by attaching a rotating prism to the laser to generate a horizontal or vertical sheet of light. Two types of lasers exist for the construction industry: gas lasers with visible light and semiconductor lasers with invisible infrared light. Four categories are used to classify the safety of the laser. They are

Type I. No need for safety precautions. Most EDM instruments are Type I lasers.
Type II. Warning against exposure of laser to eyes required.
Type III. Warning signs against possible damage to eyes and skin.
Type IV. Damages to eyes and skin are likely.

TABLE 1. Performance Data for Levels

Performance data (1)	Automatic levels (2)	Laser level (3)	Digital levels (4)
Accuracy			
Visual measurement (standard deviation for 1 km double leveling)	0.7–3.0 mm/km (with parallel-plate micrometer down to 0.3 mm)	5–15 mm (standard deviation for a distance of 100 m)	1.5–2.0 mm/km (with metric scale staff)
Electronic measurement (standard deviation for 1 km double leveling)	NA	NA	0.3 mm/km–0.7 mm/km (with precision Invar staff) 1.3 mm/km–1.0 mm/km (with foldable Invar staff)
Height accuracy (at 100 m of free sight)	0.5 mm–3.0 mm	5–15 mm	0.5 mm
Distance accuracy			
Visual measurement (measurement at 20 m)	200 mm–300 mm	NA	200 mm–300 mm
Electronic measurement (measurement at 20 m)	NA	NA	20 mm–30 mm
Measuring range (min–max)	0.5/1.5–80/120 m	0–50/300 m	1.5 m–100 m (starts at 1.3 m for visual measurement)
Measuring time	5–10 s (depending on operators experience of using a level)	1–2 s	2–4 s

TABLE 2. Performance Data for Theodolites (EDM) and Total Stations

Performance data (1)	Digital theodolite (2)	Digital theodolite + EDM (3)	Total station (4)
Accuracy (standard deviation for 100 m of measurement)			
Horizontal angle, Hz	0.35–7.9 mm	0.35–7.9 mm	0.16–4.7 mm
Vertical angle, V	0.35–7.9 mm	0.35–7.9 mm	0.16–4.7 mm
Measuring time	0.5 sec	0.5 sec–1.5 sec	0.5 sec–1.5 sec
Measuring range (min–max)	0.5 m–100 m	0.5 m–100 m (EDM with prism 3,000 m with gray card 100 m)	0.2/1.9 m–700/500 m (range is dependent on prisms used)
Distance accuracy	0.2 m–0.3 m	3 mm + 3 ppm	1–10 mm + 1–5 ppm
Operation (number of persons needed to operate the instrument)	2	2	1*–2

*Robotic or automatic lock total station with remote control from roving prism pole.

Laser-based metrology for the AEC industry can be divided into the following categories: (1) Pulsed lasers used for EDM, laser plummets, and laser levels; (2) fanning laser used for spatial coordinate capture; (3) pulsed laser rangers in scan mode using Light Detection and Ranging (LIDAR) to capture high volume spatial coordinates at very high rates; and (4) continuous wave laser rangers to capture high volume spatial coordinates. A summary of the performance data for the different types of laser-based metrology instruments is shown in Table 3.

The simplest form of LIDAR is the range finder (Wagener 1995; Fouilloy 1995; Gimmestad 1994). More sophisticated systems use the method of triangulation to locate a target in three dimensions accurately. LADAR-based systems, similarly, measure spatial coordinates. A current long-range LADAR ranging instrument available on the market is capable of generating 2,000 measurements per second at a distance of 200 m (Salisbury 1993; Yura 1994; Kovacs 1996). Research instruments using continuous wave lasers are currently available with 100 KHz scan rates.

The rotating laser is a well-established piece of equipment in the construction industry today. Excavation companies use it to control excavation depth. Tunneling operations use it for direction and depth control. Frequency modulated lasers and LIDAR systems are better suited for capturing positions of objects after they are built. This type of laser-based equipment is better used to document as-built information. Laser-based positioning systems, although based on similar principles, are typically used to give feedback information of equipment positions.

The drawbacks of laser-based instruments are the sensitivity to disturbances of light such as air fluctuation, and the sensitivity to the reflection of the target. LIDAR and frequency-modulated lasers also have a maximum range of 100 m at present.

Global Positioning System

Global positioning systems (GPS) was originally designed for navigational purposes. Typical accuracy for code solution GPS coordinates is ±50 m. The U.S. Department of Defense, however, limits civilian uses to an accuracy of 100 m horizontally and 156 m vertically by adding errors to the satellite signals. While this level of accuracy is acceptable for navigational use, it is inadequate for surveying needs, which requires accuracy to several millimeters. Adaptations of GPS have been made to produce useful construction tools (Kikuta 1994; Gefsrud 1995; Borchardt 1996; Wu 1996).

One method to increase the accuracy of the GPS system is differential point positioning (DGPS), or relative positioning. Currently, DGPS has an accuracy range of 0.01 m to 2.0 m (Alber 1997). DGPS can be carried out by using either static or kinematic positioning. Static positioning uses one or more stationary receivers, and the kinematic method typically uses one stationary and one mobile unit.

Static DGPS uses one or more receivers positioned at known point(s) at some distance from each other (Mathes 1994; Wu 1995). GPS coordinates are then received simultaneously over a period of time at the survey points and the stationary or reference receivers. Measurement data are then corrected for bias errors by using corrections determined at the known locations. The corrections are done after the measurements are made. The need for postprocessing makes this method unsuitable for some surveying tasks, such as coordinate stake-out, where instantaneous location of a point is required. This method is often used to measure national or international networks and tectonic plate movements.

In the kinematic DGPS method, correction is made by using the position at one known point (reference receiver) (Jiyu 1996; Leach 1997; Satalich 1998). The mobile unit, also called the roving station, is used like the GPS unit. Corrections are made "on the fly." The measurement rate is typically 1–2 s per point. Some kinematic DGPS systems require a 5–10 min initiation time before measurements can be made. Because only one known point is used to correct the measurements, the range is limited to approximately 10 km of the reference point. Moreover, the results are less accurate than static DGPS. In spite of the superior accuracy, static DGPS is not suitable for

TABLE 3. Performance Data for Laster Metrology Instruments

Performance data (1)	Laser levels (by SOKKIA) (2)	Frequency modulated laser (CLR-100 Metric Vision) (3)	Laser-based positioning system (Odyssey™ from Arc Second) (4)	LIDAR (Cryax from Cyra Technologies Inc.) (5)	RIEGL (6)	K^2T (Seeme Modelar 6000) (7)
Accuracy in plane $\perp$ to laser beam (Standard deviation for a distance of 100 m)	5–15 mm	3 mm	2–10 mm	6 mm	20 mm	13 mm @ 57 m 2.9 @ 13 m
Update rate	NA	NA	10–20 Hz	800 Hz	8,000 Hz	100,000 Hz
Measuring range (min–max)	0–50/300 m	0–60 m	+ 200 m	0–100 m	2–300 m	60 m
Distance accuracy parallel to laser beam	NA	0.25 mm	2–10 mm	6 mm	20 mm	13 mm @ 57 m 2.9 @ 13 m
Laser class	Class I and II	Class I and II	NA	Class II	Class II	Class IIIb
Operation (number of persons needed)	1	1	1	1	1	1

TABLE 4. Performance Data for GPS and DGPS

Receiver (1)	GPS (SPS) (2)	DGPS (kinematic) (3)	DGPS (static) (4)
Satellites	≥5	≥5	≥5
DOP-value	PDOP ≤ 4	PDOP ≤ 4	PDOP ≤ 4
Measuring range (min–max)	No limit	0–10 km	0–20 km
Accuracy (when SA is turned on)	20 (100) m horizontal 30 (156) m vertical	10–20 mm + 2 ppm	5–10 mm + 2 ppm (horizontal) 5–10 mm + 2 ppm (vertical)
Delay (time it takes from measuring until position is calculated)	1.5 s	1.5 s	1.5 s without field memory 1.0 s with field memory
Operation (number of persons needed to operate instrument)	1	1	1

TABLE 5. Measurement Error Comparison for Stakeout Instruments

Performance data (1)	RtPM (Odyssey) (2)	Robotic total station (3)	Regular total station (including servomechanism) (4)	Theodolite with EDM (5)	RTK-DGPS (6)
Measurement range	+200 m	700 m Robotic tracking 0–5,000 m (with 3 prisms)	700/5,000 m	100/3,000 m	10–20 km
Accuracy (standard deviation over 100 m)	2–10 mm	0.16–4.7 mm	0.16–4.7 mm	0.35–7.9 mm	5–10 mm + 2 ppm
Distance accuracy	2–10 mm	1–10 mm + 1–5 ppm	1–10 mm + 1–5 ppm	3 mm + 3 ppm	5–10 mm + 2 ppm
Number of operators	1	1	2	2	1
Sensitivity to natural disturbances	none	none	air fluctuations	air fluctuations	multipath reflections
Price range	≅$50,000	$35,000–$40,000	$8,850–$18,790	$5,190–$8,314	$30,000–$40,000
Measurement delay	0.1 s	0.5–1.5 s	0.5–1.5 s	0.5 s	0.1–0.5 s
Data transfer format	proprietary	proprietary	proprietary	proprietary	proprietary or RTCM 2.1
Data output	open format RS 232C	open format RS 232C	open format RS 232C	open format RS 232C	RS 232C, RINEX, NMEA, RTK/O, TF
Are field calculations of measurement points possible to execute?	Yes	Yes	Yes	Yes	Yes
Need line-of-sight	Yes	Yes	Yes	Yes	No (needs line-of-sight to satellites)
Number of receivers that can be used concurrently from a transmitter	1 or more	1	1	1	1 or more
Measurement areas	Where line-of-sight can be established	Where line-of-sight can be established	Where line-of-sight can be established	Where line-of-sight can be established	Where there is line-of-sight to satellites

AEC applications. A summary of the performance data for the different types of GPS systems is shown in Table 4.

Real-time kinematic (RTK) GPS is a kinematic DGPS method in which the coordinates are corrected in real time. In this method, the reference station broadcasts the correction message to the roving receivers. The roving receivers process this information and make the correction in real time. RTK-GPS is effective only in relatively open terrain. Phase differential lock can be lost in a number of common situations, including foliage cover, reflection from nearby structures, refraction of ionized particles in the ionosphere, and poor satellite geometry. When this occurs, the position accuracy will first drop to code-differential (3–5 m) and then to pure code accuracy (±50 m) if the radio modem link is lost with the reference station. Sometimes weather conditions may affect the accuracy of the GPS measurement (Walker 1997). DGPS has the widest range of application. It can be used to stake out construction sites, measure as-built construction, and position feedback for remote machine control.

Table 5 shows the comparison of measurement errors for an instrument from each of the categories cited for the reader's convenience.

COST COMPARISONS

The cost comparisons are made by considering initial cost of the instrument, maintenance cost, and productivity. Interest rate is assumed to be zero in the cost comparisons that follow. The reader is encouraged to use a different rate to reflect the local economy. Table 6 shows price ranges for the different categories of instruments discussed in the previous section. Prices were gathered from dealers, personal quotes, and the World Wide Web.

Table 7 shows average setup time of the instrument, time required to stake out one point, and other important background information for different surveying instruments. The figures used in Table 7 reflect the first author's experience as a professional surveyor. The reader may wish to use other figures that may reflect the local labor productivity and instrument cost, for a comparison that reflects the local conditions more realistically.

TABLE 6. Price List for Metrology Instruments

Instrument (1)	Diverse notes (2)	Price range (in U.S. dollars) (3)
Automatic levels (instrument only)	Price addition of $615 for leveling rod and tripod	650–2,490
Digital levels (instrument only)	Price addition of $615 for leveling rod and tripod	3,190–6,314
Laser plummet	Price addition of $615 for rod and tripod	1,495
Digital Theodolites (instrument only)	Price addition of $864 for rod, tripod, and tribach; $2,000 for EDM	2,590–5,490
Total station (instrument only)	Price addition of $1,508 for rod, tripod, tribach, and prism	8,850–18,790
Robotic total station	Price addition of $1,508 for rod, tripod, tribach, and prism	34,790
RTK GPS system	Top of the line Ashtech, including all accessories for RTK measurements	28,000
RTK GPS system	Prices contain two receivers + all accessories from Spectra precision L1/L2 12 channel	39,974[a]
Laser scanner	K^2T	90,000
Laser 3D point system	25 KHz	75,000
Laser 3D point system	2 KHz	25,000

[a] Leica and Spectra Precision may not be compatible, but it gives a comparative price for this specific technology.

The data for using GPS surveying instruments were gath-

TABLE 7. Time Consumption and Important Background Information for Different Surveying Instruments Performing Same Tasks

Work procedure (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station (5)	RtPM (SPSI) (6)	RTK-DGPS (7)
Erecting the tripod	1 min	1 min	1 min	1 min	2 min (two transmitters)	1 min
Mounting instruments on tripod(s) (including leveling the instrument)	2 min	2 min	2 min	2 min	1 min + 3 min for walking distance (half a minute for each transmitter)	1 min
Establishing instrument position over known point (average time consumption when known points exist close by)	7 min	5 min	5 min	5 min	20 min (has to measure about 6 known points)	2 min (loading point coordinates and measuring height)
Measurement of a point (average time including movement between two points)	6 min	3 min	1.5 min	1 min	1 min	5 min (before getting satellite lock) after that 1 min
Setup time	10 min	8 min	8 min	8 min	26 min	9 min (including getting satellite lock)
Sum of hours used to set out 500 points, if instrument has not to be moved (1 setup included)	50.2 h	25.1 h	12.6 h	8.5 h	8.7 h	8.5 h
Sum of hours used to set out 5,000 points, if instrument has not to be moved	502 h	251 h	126 h	85 h	87 h (time can be divided, by using more than one receiver)	85 h (time can be divided, by using more than one rover)
Learning time	24 h	24 h	24 h	18 h	6 h	6 h
Expected lifetime in measurement points (assumed)	100,000	100,000	100,000	100,000	100,000	100,000
Expected lifetime in years (assumed)	20 years	20 years	20 years	20 years	20 years	20 years
Average number of measurement points per year	5,000	5,000	5,000	5,000	5,000	5,000
Average purchase price	$6,904	$15,328	$20,298	$36,298	≅$50,000	$39,974
Cost per point measurement for assumed lifetime (purchase price divided by lifetime in measurement points)	$0.06	$0.15	$0.20	$0.36	$0.50	$0.40
Yearly maintenance[a] (function control)	$313	$313	$313	$313	$313	$313
Yearly repair cost[a] (repair plus)	$288	$288	$288	$288	$288	$288
Yearly total service[a] (ISO 9000 calibration)	$600	$600	$600	$600	$600	$600

[a] Prices from (Spectra Precision AB 1998).

ered during the summer of 1998 at a construction site. Data related to the use of Odyssey are based on similar experience and data from the literature about the system. Table 7 shows setup time, stakeout time, and lifetime and maintenance costs for different surveying instruments, to perform the same task. The time used for each piece of equipment listed in Table 7 is based on a user or users who are familiar with the tool under normal conditions. Where more than one worker is needed for a task, the time shown is the sum of all workers' time.

To be able to perform a cost comparison for staking out points with different instruments, a fictitious project is created. Instruments included are supposed to be able to conduct stakeouts. Tables 8–12 are constructed based on the data in Tables 6 and 7. The hypothetical project's characteristics are as follows:

- A large project where 5,000 points are to be executed, and a smaller project where 500 points are to be executed. Surveys are to be executed at a 500- and a 5,000-point project, with single or multiple setups.
- Two assumptions are made: one assuming that each 10 points requires a new setup of the instrument, and the

TABLE 8. Measurement Cost for Project of 500 Measurement Points, 1 Setup

Costs (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station 5)	RTK-DGPS (6)	RtPM (SPSI) (7)
Crew cost (one setup is included	$2,259.00	$1,129.50	$567.00	$297.50	$297.50	$304.50
Measurement cost	$30.00	$75.00	$100.00	$180.00	$200.00	$250.00
Maintenance cost (function control)	$31.30	$31.30	$31.30	$31.30	$31.30	$31.30
Repair cost (repair plus)	$28.80	$28.80	$28.80	$28.80	$28.80	$28.80
Sum of costs	**$2,349**	**$1,265**	**$727**	**$538**	**$557**	**$615**

TABLE 9. Measurement Cost for Project of 500 Measurement Points, 10 Setups

Costs (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station 5)	RTK-DGPS (6)	RtPM (SPSI) (7)
Crew cost (one setup is included)	$2,259.00	$1,129.50	$567.00	$297.50	$297.50	$304.50
Measurement cost	$30.00	$75.00	$100.00	$180.00	$200.00	$250.00
Additional setup cost for (10 − 1) = 9 setups	$67.50	$54.00	$54.00	$42.00	0	$136.50
Maintenance cost (function control)	$31.30	$31.30	$31.30	$31.30	$31.30	$31.30
Repair cost (repair plus)	$28.80	$28.80	$28.80	$28.80	$28.80	$28.80
Sum of costs	**$2,417**	**$1,319**	**$781**	**$580**	**$557**	**$751**

TABLE 10. Measurement Cost for Project of 5,000 Measurement Points, 10 Setups

Costs (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station 5)	RTK-DGPS (6)	RtPM (SPSI) (7)
Crew cost (one setup is included)	$22,590.00	$11,295.00	$5,670.00	$2,975.00	$2,975.00	$3,045.00
Measurement cost	$300.00	$750.00	$1,000.00	$1,800.00	$2,000.00	$2,500.00
Additional setup cost for (10 − 1) = 9 setups	$67.50	$54.00	$54.00	$42.00	0	$136.50
Maintenance cost (function control)	$313.00	$313.00	$313.00	$313.00	$313.00	$313.00
Repair cost (repair plus)	$288.00	$288.00	$288.00	$288.00	$288.00	$288.00
Sum of costs	**$23,559**	**$12,700**	**$7,325**	**$5,418**	**$5,576**	**$6,283**

TABLE 11. Measurement Cost for Project of 5,000 Measurement Points, 100 Setups

Costs (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station 5)	RTK-DGPS (6)	RtPM (SPSI) (7)
Crew cost (one setup is included)	$22,590.00	$11,295.00	$5,670.00	$2,975.00	$2,975.00	$3,045.00
Measurement cost	$300.00	$750.00	$1,000.00	$1,800.00	$2,000.00	$2,500.00
Additional setup cost for (100 − 1) = 99 setups	$742.50	$594.00	$594.00	$462.00	0	$1,501.50
Maintenance cost (function control)	$313.00	$313.00	$313.00	$313.00	$313.00	$313.00
Repair cost (repair plus)	$288.00	$288.00	$288.00	$288.00	$288.00	$288.00
Sum of costs	**$24,234**	**$13,240**	**$7,865**	**$5,838**	**$5,576**	**$7,648**

TABLE 12. Life Cycle Cost 100,000 Measurement Points, 200 Setups

Costs (1)	Theodolite with EDM (2)	Regular total station (3)	AutoLock total station (4)	Robotic total station 5)	RTK-DGPS (6)	RtPM (SPSI) (7)
Crew cost	$451,800	$225,900	$113,400	$59,500	$59,500	$60,900
Measurement cost (instrument purchase price)	$6,904	$15,328	$20,298	$36,298	$39,974	≅$50,000
Additional setup cost at 200 − 1 = 199 projects with 500 measurement points	$1,493	$1,194	$1,194	$929	$1,045	$3,018
Maintenance cost (function control)	$6,260	$6,260	$6,260	$6,260	$6,260	$6,260
Repair cost (repair plus)	$5,760	$5,760	$5,760	$5,760	$5,760	$5,760
Sum of costs	**$472,217**	**$254,442**	**$146,912**	**$108,747**	**$112,539**	**$125,938**

other assuming that all points can be obtained from one instrument set up.

- Accuracy of the instrument is assumed to be sufficient to perform stakeouts for all instruments included in this cost study (which is true for most projects).
- Average distance between points is 30 m.
- Lifetime has been assumed to be equal for all instruments in years and number of measured points.
- Maintenance and repair costs are assumed to be equal for all instruments, with a fixed rate per year for maintenance and repair service. This assumption is made because most of the equipment compared is new and has no track record. Readers are encouraged to make another comparison based on different estimates of maintenance cost.

The measurement cost is calculated as (purchase price/100,000) × number of measurement points. Salary for surveyor is assumed to be $35/h, and $10/h for the rod man. Instrument movement is to be included in the calculations as setup time. And the crew cost is assumed to be equal to salary × [setup + (measurement time for a point × number of points)].

This cost comparison shows the proportions that purchase price, crew cost, and duration of setup on the final cost. Some facts have to be taken into consideration, when comparing costs. One is the probability of using several receivers (rovers) for both RtPM (Odyssey) and RTK-DGPS systems. By being able to do that, crew cost can be cut even more dramatically. Cost reductions for new technologies may also alter the overall measurement cost. Another fact is the initialization time for DGPS to lock on to satellites. In the United States, satellite coverage is available 24 hours a day, 12 months a year. At other locations the satellite coverage may be more sporadic, making it hard to do measurements continuously.

Further considerations can be made about accuracy. The need for accuracy better than 5 mm excludes the use of systems with DGPS. The need to cover a large work site (>300 m) excludes the use of systems like the theodolite with EDM, the regular total station, and the RtPM (Arc-Second).

Tables 8–12 have been made to illustrate a cost comparison that justifies the initial cost of the more expensive state-of-the-art metrology instruments made for the AEC industry. Under different circumstances, certain instruments can be more cost effective than others can. There is not a single instrument that is superior in all situations; rather, instruments that are better suited to perform certain tasks.

Tables 8–12 show that savings from less expensive instruments can be offset by the labor cost. At smaller jobs, however, the purchase cost is significant and probably unjustified. A complicated setup will also increase measurement cost notably.

CONCLUSIONS

For small companies or at small construction sites, a level and measuring tape are all the tools needed to layout the construction site. At large construction sites, however, the potential benefits of the new metrology equipment outweighs the initial cost and learning curve needed to use them. Two hypothetical scenarios were created to show that the new equipment can perform the same job as the traditional equipment at about 25% of the cost when labor cost is included. It was also shown that over the life of the instrument, the potential savings is also approximately 75%.

In addition to the potential of cost saving, new metrology equipment can perform tasks the traditional equipment cannot perform. Some of the tasks that the new equipment can perform are the following:

1. The robotic total station can be operated single handedly, thereby reducing the labor associated with the task of laying out the construction site.
2. Laser-based positioning can be used to continuously track points at the construction site, allowing for equipment or material tracking.
3. LIDAR and LADAR technology can detect object positions passively, allowing the capture of as-built information.
4. Differential global positioning system, with its "overhead" reference to satellite, is able to overcome limitations in cluttered construction sites in many situations that would otherwise render ground-based instruments ineffective.

The writers are aware that there is little reliability data on the new hardware discussed in this paper. It should be noted that the new metrology options may result in shorter duration; on some sites the time savings may not translate into cost reductions, since a surveyor might be available full time even though only a portion of his/her time is used for productive work. As a result, faster performance of tasks might not result in cost savings.

APPENDIX. REFERENCES

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