Nondestructive testing and monitoring of stiff large-scale structures by measuring 3-D coordinates of cardinal points using electronic distance measurements in a trilateration architecture

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ABSTRACT

By using three, or more, electronic distance measurement (EDM) instruments, such as commercially available laser trackers, in an unconventional trilateration architecture, 3-D coordinates of specialized retroreflector targets attached to cardinal points on a structure can be measured with absolute uncertainty of less than one part-per-million. For example, 3-D coordinates of a structure within a 100 meter cube can be measured within a volume of a 0.1 mm cube (the thickness of a sheet of paper). Relative dynamic movements, such as vibrations at 30 Hz, are typically measured 10 times better, i.e., within a 0.01 mm cube. Measurements of such accuracy open new areas for nondestructive testing and finite element model confirmation of stiff, large-scale structures, such as: buildings, bridges, cranes, boilers, tank cars, nuclear power plant containment buildings, post-tensioned concrete, and the like by measuring the response to applied loads, changes over the life of the structure, or changes following an accident, fire, earthquake, modification, etc. The sensitivity of these measurements makes it possible to measure parameters such as: linearity, hysteresis, creep, symmetry, damping coefficient, and the like. For example, cracks exhibit a highly non-linear response when strains are reversed from compression to tension. Due to the measurements being 3-D, unexpected movements, such as transverse motion produced by an axial load, could give an indication of an anomaly–such as an asymmetric crack or materials property in a beam, delamination of concrete, or other asymmetry due to failures. Details of the specialized retroreflector are included.

Keywords: Structural Health Monitoring, Nondestructive Testing, Electronic Distance Measurement, Laser Tracker, Total Station, patent, vibration, deflection

1. INTRODUCTION

It is the thesis of this paper that the use of Electronic Distance Measurement for Nondestructive Testing and Structural Health Monitoring has been overlooked, or misapplied, outside of the aerospace and precision manufacturing industries. Significant opportunities are available in the civil, structural, mechanical, and software engineering fields, as well as expanded markets for instrument manufacturers, service providers, and software companies. In order to capitalize on these opportunities, an introduction to what has heretofore been disparate fields may be helpful in expanding communications between the fields.

1.1 An introduction to Electronic Distance Measurement

Electronic Distance Measurement (EDM), also called Electromagnetic Distance Measurement and Electro-optic Distance Measurement, developed along parallel paths from laser interferometers and Fizeau time-of-flight architectures. The fundamental difference being that interferometers work on optical interference principles and count interference fringes as the distance to a retroreflector target changes. If the beam is broken, the count is lost and the distance can not be re-established–in other words, it is a differential distance measurement from initial to final positions of the retroreflector. The Fizeau principle, which was perfected by Froome at the National Physics Laboratory,[1] measures the time-of-flight for a beam of light to travel from the instrument to a

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retroreflector target and return. By knowing the speed of light along the path, the distance is determined. A Fizeau measurement is inherently an absolute distance measurement, i.e., a broken beam measurement is simply repeated when the beam is re-established.

Historically, interferometry was inherently more accurate than the Fizeau method, i.e., sub micron vs several mm. Range for interferometers is limited by the coherence length of the laser, whereas the Fizeau principle is not so limited. Ranges for laser interferometers are typically less than 100 m–whereas measurements have been made to the moon, since 1969, by the Fizeau principle.

The HP 5525A Laser Interferometer,[2–5] introduced in 1971, had a range of 60 m. This instrument was based on a two frequency laser described in US Patent 3,458,259[6] to Bagley et al. Laser interferometers quickly became the length standard for metrology and were used extensively in calibration labs and for calibrating precision machining tools. The requirement that the retroreflector target remain centered on the beam while moving was not a major problem for movements of machine tools, such as milling machines and machine ways.

Hewlett Packard introduced the Model 3810A Total Station in 1976.[7] Technical details are found in US Patent 4,113,381[8] to Epstein. A Total Station combines a Fizeau distance measurement with the sighting telescope and angle measurements of a theodolite, i.e., combines the functions of the steel tape and theodolite into a compact portable instrument that measures 3-D coordinates. Typical distance accuracy of 3 mm and measurement time of several seconds was more than adequate for surveying purposes.

The need for laser interferometer accuracy while moving the retroreflector along non-rectilinear paths gave rise to US Patents 4,457,625[9] to Greenleaf et al. in 1984, 4,621,926[10] to Merry et al. in 1986, 4,714,339[11] to Lau et al. in 1987, and 4,790,651[12] to Brown et al. in 1988. These instruments, which became known as Laser Trackers, incorporated servo systems that automatically track the retroreflector with a laser interferometer and measure the two angles. The automatic tracking negated the need for a sighting telescope, as in a theodolite or Total Station.

Laser Trackers opened up opportunities to make laser interferometer measurements on the shop floor. An operator could simply walk around with a retroreflector in his hand and make measurements at cardinal points on a precision piece of equipment. However, if there were obstructions in the beam path, such as a column, the beam was broken and the measurement had to be repeated, starting at the home position.

There was a long-felt need for a Laser Tracker–without the limitations of a laser interferometer. US Patent 5,764,360[13] to Meier in 1998 and 7,800,758[14] to Bridges et al. in 2010 gave rise to so called Laser Trackers with Absolute Distance Measurement (ADM), i.e., the laser interferometer was replaced by a Fizeau architecture. This enabled the instrument to not only recover from a broken beam, but also switch from one target to another, i.e., much like a Total Station. While not as accurate as a laser interferometer, the accuracy of the ADM systems used in Laser Trackers is very close to a laser interferometer. Unlike customers that went from steel tapes and theodolites to Total Stations, where accuracy of 3 mm was a great improvement, Laser Tracker customers that went from laser interferometers to ADM required comparable high accuracy. While Laser Trackers with interferometers are still available, the market is dominated by ADM type instruments.

At the same time Laser Trackers were moving to ADM, Total Stations were moving to automatic tracking and became known as Robotic Total Stations (RTS). This allowed surveying to be done by the rodman, without an operator at the instrument. Today, Robotic Total Stations and Laser Trackers have become very much alike. The principle distinguishing characteristic being the higher radial accuracy for Laser Trackers, the user market targeted (surveying vs metrology), the annual sales volume (tens of thousands vs hundreds), and the price ($20,000 vs $100,000). It is reasonable to assume that if the market for Laser Tracker accuracy instruments expanded to the thousands per year, the price would approach the present price for high end Total Stations, i.e., in the $20,000 range.

A more detailed history can be found in Ruger,[15] Burnside,[1] Bell,[16] and US Patent 9,354,043[17] to Parker *Methods for measuring and modeling the structural health of pressure vessels based on electronic distance measurements*. A summary of instrument specifications is shown in Table 1. As a point of reference, the thickness of a standard sheet of 20 lb. printer paper is 100 μm, or 0.004 inches.

Note that while the distance limitations of laser interferometers is not a constraint for ADM systems, manufacturers maintain relatively short ranges in their specifications, e.g., the Leica AT960-LR is 160 m, but the

Table 1. Range and accuracy for Laser Trackers

Manufacturer	Model	Range	Accuracy	Data Rate
API Automated Precision	Radian	80 m	10 μm or 0.7 μm/m	?
FARO	Vantage	80 m	16 μm + 0.8 μm/m	?
Kern (no longer available)	ME5000 Mekometer	4,000 m	200 μm + 0.2 μm/m	?
Leica	AT402	160 m	10 μm	?
Leica	AT960-LR	160 m	0.5 μm/m	1,000 points/sec
Nikon	MV351 HS	50 m	10 μm + 2.5 μm/m	2 sec/point
NRAO (no longer available)	PSH97	1,000 m	50 μm + 1 μm/m	1,000 points/sec

remaining instruments available today are between 50 m and 80 m. The physics of the ADM systems does not impose such a limitation. For example, the Kern ME5000* Mekometer range, with a simple retroreflector, is 4,000 m.[15,16]

It is well known in the art that the tracking accuracy is a limitation for Laser Trackers, which focus an image of the return beam of a CCD camera, or an analog position sensitive device (PSD). There is an inherent limitation in pointing a telescope through the atmosphere, due to atmospheric turbulence and the Rayleigh criterion, that limits instruments to around 1 arc second, i.e., the sine of 1 arc second is $\approx 5 \times 10^{-6}$, or 5 parts per million. Distance measurements are about 5 times more accurate that the best possible angle measurement. It is likely that the specified operating range of commercially available instruments are simply limited for marketing reasons, i.e., to keep the published range within the specified angle accuracy.

1.2 An introduction to Large-Scale Dimensional Metrology

Estler et al.,[18] wrote a comprehensive review of Large-Scale Metrology (LSM) in 2002–including sections on: Limitations Imposed by the Atmosphere, The Laser Tracker, Multilateration, and Absolute Distance Metrology. Peggs et al.,[19] wrote a review of LSM in 2009, with a section on Laser Trackers. Franceschini et al.,[20] wrote a review of LSM in 2014. Schmitt et al.,[21] wrote a review of LSM in 2016. Muralikrishnan et al.,[22] wrote a review of Laser Trackers for LSM in 2016–including sections on Principles of Operation and Error Sources, Multi-station Measurements, and Multilateration. Franceschini et al.,[23] discussed Large Volume Metrology (LVM) and the notion of competitive vs cooperative data fusion–which they define as

> *Competitive fusion.* Each system performs an independent measurement of the 3D coordinates of the point of interest and these position measurements are fused into a single one...
>
> *Cooperative fusion* Data provided by two or more independent (non homogeneous) sensors, even from different measuring systems are processed in order to achieve information that otherwise could not be obtained from individual sensors...

For example, in a Laser Tracker, two angle measurements and range measurement are cooperatively fused to determine a 3-D coordinate of the target. Whereas in a trilateration architecture, three Laser Trackers each independently determine a set of three 3-D coordinates of the target, which are then competitively fused, by a process such as a weighted least squares adjustment, to produce a single 3-D coordinate. Another example would be a Laser Tracker measuring coordinates of three non-colinear retroreflectors attached to a beam and competitively fusing the data with an inclinometer attached to the beam.

Peggs[24] and Hughes[25] talk about the notion of a virtual coordinate measurement machine (CMM) using laser distance measurements in a trilateration/multilateration architecture. For example, an entire airplane, bridge, radio telescope, nuclear power plant containment building, boiler, manufacturing facility, construction

*The ME5000 is a distance meter only, i.e., it does not track.

site, railway car, ship, building, amusement park, or the like, can be virtually within the measurement volume of a CMM.

As explained by Brinker and Minnick,[26] Parker,[27] Sandwith and Preadmore,[28] Estler et al.,[18] Muralikrishnan et al.,[22] Camboulives et al.,[29] and others, trilateration measurements are much more accurate than instruments that use angle measurements. To put it in perspective, a micrometer epitomizes precision in a machine shop. A one inch micrometer is accurate to 0.000 050 inch, or 50 parts per million–in one dimension. Moreover, the part must be placed in the micrometer by hand.

A properly configured multilateration based virtual CMM could have an accuracy of 1 part per million–in a volume of a several hundred meter cube, in three dimensions, and measure dynamic motions and vibrations!

Engineers should ask themselves how measurements of this accuracy could be applied to their problems.

One of the impediments to multilateration in LSM is commercially available retroreflector targets that can accept laser beams from multiple directions, with zero Abbe error. While novel wide angle spherical retroreflectors are available,[24,30–32] there are problems with fabrication and cost. There is also a potential problem for amplitude modulated lasers, or dual wavelength interferometers–such as the HP laser interferometer based on US Patent 3,458,259,[6] discussed above. The optical path length through the glass is different for rays off the optical axis. Due to the dispersion of the glass and the group refractive index, this potentially produces different phase shifts for the modulated group, depending on the path. This is called Optical Amplitude Modulation (OAM) Aberration.

OAM Aberration is explained in US Patent 8,630,828[33] to Parker, *Methods for modeling amplitude modulated light through dispersive optical systems and electronic distance measurement instruments.* Note that the US Patent and Trademark Office (USPTO) doesn't always do a good job publishing equations. If anyone actually wants to follow the mathematical derivations, they should download the original application documents, written in LaTeX, from the USPTO via the Public PAIR website.

There is no commercially available optical design software to analyze the group phase delay of temporally modulated light, so it is assumed that none of the spherical retroreflectors have been corrected for OAM Aberrations. However, a simple test is disclosed in the patent, i.e., using a Laser Tracker, with tracking disabled and the beam direction locked, and a narrow collimated beam; translate the spherical retroreflector in the plane normal to the beam and record the measured distances.

A solution to the zero Abbe error retroreflector problem is found in Parker[34] and US Patent RE41877[35] to Parker, *Multidirectional retroreflectors.* The idea is somewhat related to US Patent 5,530,549[36] to Brown, *Probing retroreflector and methods of measuring surfaces therewith*, which is the commercially available probing retroreflector sold by FARO and Leica as an accessory to Laser Trackers, and US Patent 5,861,956[37] to Bridges et al., *Retroreflector for use with tooling ball.* Note that RE41877 is not limited to EDM type instruments. It also teaches how to combine EDM instruments with Total Stations, theodolites, alignment telescopes, and the like. While multidirectional retroreflectors are not commercially available, the patent is available for license in the US from the National Radio Astronomy Observatory, Charlottesville, VA. There are no foreign counterpart patents, so it is dedicated to the public, outside the US.

An impediment to EDM, particularly in an outdoor environment, is the sensitivity of the group refractive index to atmospheric temperature, humidity, and pressure through the measurement beam path. This is explained in detail by Rüeger,[15] Burnside,[1] and others. For example, for a 780 nm wavelength, amplitude modulated laser, at temperature T=20 °C, pressure P=700 mm Hg, and 50% relative humidity, the group refractive index $n_g =$ 1.000 253 24, based on Rüeger.[15] For convenience, the group refractivity, N_g, is defined as $(n_g - 1) \times 10^6$, or 253.24 for the stated conditions.

$$\frac{\partial n_g}{\partial T} = -0.895 \times 10^{-6} / ^\circ C \tag{1}$$

$$\frac{\partial n_g}{\partial p} = 0.272 \times 10^{-6} / mb \tag{2}$$

$$\frac{\partial n_g}{\partial P_w} = -4.09 \times 10^{-8} / mb \tag{3}$$

where P_w is the water vapor pressure.

Several methods for correcting N_g are disclosed by Parker,[38] Pollinger,[39] and others. Temperature is the major problem, because it is likely to be inhomogeneous within the measurement volume. For example, the lower boundary can be dirt, grass, water, snow, concrete, forest, pavement, etc. Volumes can be shaded and in full sun.

The bottom line is that a Laser Tracker measuring to a fixed target, of known baseline length, can be used as a refractometer. The uncorrected distance will drift with bulk changes in the atmosphere–although the bulk atmosphere can change rather fast when the sun goes behind, or moves out of, a cloud. The bulk group index of refraction is calculated, based on the known length of the baseline. Individual measurements will jitter at several Hz due to turbulence, which may require low pass filtering by averaging as much as 1 second to filter out.

A simple measure of the homogeneity is to measure the turbulence. Turbulence in a refractive medium has been studied extensively.[40] Turbulence is quantified by the refractive-index structure parameter C_n^2. The lower the C_n^2, the smaller the standard deviation will be for a series of measurements of the baseline.

Ideal conditions are night with a snow covered ground. Measurements made under ideal conditions would require little averaging, while measurements made in bright daylight may require longer averaging. Experience has shown that C_n^2 is high near interfaces, such as the ground, while it tends to smooth out higher above the ground, e.g., measuring to an elevated retroreflector–such as on a bridge.

Pressure is fairly predictable, e.g.,

$$\frac{\partial p}{\partial h} = 0.11mb/m \tag{4}$$

where h is height. For example, for a 150 m height, $\Delta n_g = 4.5 \times 10^{-6}$.

Water vapor pressure, P_w, is subject to local perturbations. For example, rivers, melting snow, puddles of water, tilled earth, exhaust stacks, etc. can be significant problems and should be avoided. For example, significant changes in the water vapor pressure have been observed near a microwave oven, due to the exhausted steam.

The speed of sound, v, is very sensitive to temperature.

$$\frac{\partial v}{\partial T} \approx 1700 \times 10^{-6}/°C. \tag{5}$$

Acoustic thermometry has been used to measure temperature to correct geodesy EDM measurements. For example, the propagation time delay between the flash and sound for a shotgun blast to travel from one mountain to another has been used. Electronic measurements are described by Kleppe[41] and others. It is important to correct for wind speed when measuring the propagation time, so double path measurements, with and against the wind, are probably required.

2. PRESENT RELATIONSHIP BETWEEN THE NDT, SHM, AND EDM COMMUNITIES

The American Society for Nondestructive Testing (ASNT) originated as The American Industrial Radium and X-Ray Society (AIRXS) in 1941, the history of which is recorded by Jones.[42] The scope of the society was expanded in 1947 by changing the name to the Society for Non-Destructive Testing (SNT), and changed again in 1967 to the present name, American Society for Nondestructive Testing. Despite the fact that the scope of the Society has broadened beyond the roots in radiography, there is no mention of EDM in the ASNT published handbooks or training manuals. There were no exhibitors of Total Stations or Laser Trackers at the 2016 Annual Conference.

There are a lot of publications on Structural Health Monitoring. Aktan et al., published a 290 page report on *Development of a Model Health Monitoring Guide for Major Bridges.*[43] Under the section **Sensors Used in Bridge Monitoring and Testing Applications**, the following were listed: Direct Strain Measurement, Linear Displacement and Position Measurement, Temperature Measurement, Accelerometers, Tilt Measurement, Weight-In-Motion (WIM) Systems, Global Positioning Systems (GPS), Environmental Sensors, and Acoustic Emission Monitoring Systems. There is no mention of Total Stations or Laser Trackers.

Ettouney and Alampalli published a two volume set of books on *Infrastructure Health in Civil Engineering*.[44,45] In Volume I, under section 5.4 **Sensor Measurement in SHM**, they list the following sensors: Strain Sensors, Position, Accelerometers (Angular and Linear), Velocity (Angular and Linear), Displacement (Angular and Linear), Force, Inclinometers, Corrosion, Pressure, Temperature, Other, and Advanced Sensing Technologies. There is no mention of Total Stations or Laser Trackers.

The Transportation Research Board (TRB) is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. They have Standing Committees on Structures Maintenance (AHD30), and Testing and Evaluation of Transportation Structures (AFF40), as well as a Joint Subcommittee on Structural Health Monitoring. The 2016 Annual Conference had 13,700 registered attendees. There was one paper that used a Metris MV224 Laser Radar to eliminate shop assembly of steel bridges by measuring the component girders and do a virtual fit-up, based on the measured hole patterns.[46–48] A presentation on the new FHWA NDE facilities and instrumentation did not mention dimensional metrology. However, in a survey of sixteen railway structural engineers, Moreu[49] shows in Table 1 that deflection measurements was given the highest ranking for proposed research topics. There were no exhibitors of Total Stations or Laser Trackers at the 2016 Annual Conference.

The 2017 SPIE Smart Structures NDE Conference does not include an Exhibition, so no EDM instruments are likely to be seen by the attendees at the Conference.

The Coordinate Metrology Society (CMS) Conference (CMSC) is the premier conference for the Laser Tracker industry. This is where new products are typically introduced. CMS describes itself by the following.

> Founded in 1984, the Coordinate Metrology Society (CMS) is a large membership of users, service providers, and OEM manufacturers of close tolerance, industrial coordinate measurement technology. The metrology systems include inspection software, traditional CMMs, theodolites, GPS, laser projection systems, laser trackers, laser radar, photogrammetry/videogrammetry systems, scanning devices, and articulated arms.

The 2016 Annual Conference was attended by approximately 400 attendees. They were predominately from National Laboratories, aerospace, defense, precision manufacturing, universities, and instrument manufacturers. There was no visible presence of members of the NDT or SHM communities. The Precision Path Consortium (PPC) was announced to expand the CMS knowledge base to other industries. The PPC describes itself by the following.

> On June 2015, the Coordinate Metrology Society (CMS) and UNC Charlotte received an Advanced Manufacturing Technology Consortia (AMTech) Grant from the National Institute of Standards and Technology (NIST), a division of the U.S. Commerce Department. The AMTech Grant is one of 16 awards dedicated to accelerating growth of advanced manufacturing in the United States. The CMS-UNC Charlotte team established the Precision Path Consortium for Large-Scale Manufacturing, an industry-driven group working to identify and prioritize the technology needs of the aerospace, defense, energy, and other industries that manufacture large-scale, high accuracy parts and products.

It is pretty clear that communication between these communities is limited. Based on conversations with engineers at conferences, content of journal articles, and high cost of the instruments, it is a fair assumption that most engineers, or engineering students, have never seen, or know anything about, a Laser Tracker and the capabilities. In fact, a good argument can be made that Laser Trackers are still in the early adopter stage of the technology adoption life cycle.

Despite the fact that these three disciplines apparently operate in isolation, there are examples of EDM being used for SHM–although one could argue that for the most part, it is not being used in the most productive ways.

2.1 Historic use and misuse of EDM for NDT and SHM

Cosser et al.[50] measured dynamic deformation of a bridge using a Total Station. Initial testing was conducted in the lab by moving a retroreflector by known distances and taking static measurements. A dynamic test of the servo system was conducted by attaching a "small sticky retro target" to a metronome to produce low frequency oscillations. It is not clear if this was a true retroreflector, with a true vertex that the servo could lock onto, or if this was a reflective tape that produces a blob for the servo to lock onto. In any case, the instrument servo system could not track at 0.5 Hz, in the lab. No lab tests were conducted on the EDM system in the radial direction. They used a single Leica TCA2003 instrument to measure a retroreflector attached to the bridge, from a location on the river bank. The vertical deflection of the bridge was mainly determined by the servo system tracking the elevation angle, i.e., the accuracy of the EDM system was not a factor. Measurements were hampered by a 1 Hz nonuniform data rate.

The Center for Infrastructure Engineering Studies at the University of Missouri-Rolla (now Missouri S&T) did a series of measurements using a single Leica TCA2003 Total Station.[51–56] They conducted static measurements, so the data rate was not a limitation. The TCA2003 range specifications are 1 mm + 1 ppm for a 3 second measurement. The geometry was such that the vertical deflections were determined by the elevation angle, i.e., the accuracy of the EDM system was not a factor. They commented

> Because the instrument was extremely sensitive to vibration and movement, automation helped eliminate human error associated with physical contact during instrument operation.

This illustrates the sensitivity of the instrument mounting. For example, if the instrument mounting is 2 meters tall, and it tilts by 1 arc second, and the target is 50 meters away, the error in the measured deflection would be about $50\ \text{m} \times 5 \times 10^{-6}$, or 250 μm. However, the error in distance would only be $2\ \text{m} \times 5 \times 10^{-6}$, or 10 μm.

The report on *In-situ load testing of Bridge A6358 Osage Beach, MO*[52] is particularly interesting. Section 2.3.2 **Test Results** noted an asymmetry of 28% in the test results between two sides of the bridge. It was determined that a girder on the higher deflection side was damaged during construction, but had been straightened and used. This suggest that such measurements could be made as part of a final acceptance program for bridges.

Four Leica TCA1800 Total Stations were used for deformation monitoring during the Dulles Airport underground train tunneling project.[57] The article does not mention that the instruments worked together, or that the data were combined in an adjustment, so it is assumed they operated independently to cover the large area. The TCA1800 range specifications are 1 mm + 2 ppm for a 3 second measurement. Movements of an overhead walkway were detected, which required additional lateral support.

Gikas and Daskalakis[58] reported dynamic measurements of a Leica TCA1800 Total Station with a retroreflector mounted on a shaker at 100 m. The directions of motion were parallel to the laser, perpendicular to the laser, and two intermediate angles. In other words, the EDM system was tested alone in the parallel configuration, the servo system was tested alone in the perpendicular configuration, and both combined in the intermediate angles. Unfortunately, the report does not break the results down by direction. However, it is clear, from Figure 5, that the combined results are significantly deteriorated above 0.2 Hz.

Palazzo et al.,[59] measured 3-D deformations of a bridge from 180 meters, with a Leica TCRA 1205 Total Station. Preliminary measurements were made in the lab using a motor driven linear scale to oscillate the retroreflector. For the bridge measurements, the geometry was such that the vertical deflections were determined by the elevation angle, i.e., the accuracy of the EDM system was not a factor for the vertical and transverse directions, but it was sensitive to the longitudinal direction. Unfortunately, the coordinate system is not clear. However, in addition to movement of 26 mm in the vertical direction, there were movements of 11 mm north and 11 mm east, which would seem to be significant.

Umemoto et al.,[60] used a single laser ranging instrument built by TOHOKU University to measure dynamic deflections of a bridge. The instrument was placed directly under the bridge, as shown in Figures 11 and 12. The geometry was such that the measurements were purely due to the EDM system. Measurements were made at 200 measurements/second with good results.

Kopáčik et al.,[61] used a single Total Station to measure 3D motions of the Danube Bridge Apollo.

Attanayake et al.,[62] measured deflection of a bridge using a single Laser Tracker and a Laser Scanner. Neither the geometry of the Laser Tracker, nor the measurement results are clear.

Psimoulis and Stiros[63] used a single Leica TCA1201 Total Station to measure deflections of a railway bridge. The TCA1201 range specifications are 2 mm + 2 ppm for a 1.5 second measurement. The vertical deflection of the bridge was mainly determined by the servo system tracking the elevation angle, i.e., the accuracy of the EDM system was not a factor.

Barazzetti et al.,[64] conducted a series of measurements using Leica AT901 and AT401 Laser Trackers. Below Figure 2, they state

> In fact, the direct measurement from a single [total] station is often insufficient for high precision monitoring applications requiring precisions better than ±1 mm. The laser tracker overcomes this limitations since the distance is measured by means of a laser interferometer. High accuracy coordinates can be obtained by combining distances with horizontal and vertical angles (polar coordinates) and can be therefore considered as an instrument able to provide precise target coordinates from a single station.

This is a common misconception! Consider an instrument measuring in the horizontal plane. The vertical (or horizontal) deflection of the target is

$$z = r\theta \tag{6}$$

where z is the vertical deflection, r is the radial distance, and θ is the vertical angle.

$$\frac{\partial z}{\partial \theta} = r \tag{7}$$

or

$$\Delta z = r\Delta\theta \tag{8}$$

so, if r= 50 m and $\Delta\theta$ is one arc second, $\Delta z \approx 0.250$ mm. It is common for an instrument to tilt by as much as a few arc seconds by someone walking around an instrument resting on an 8 inch thick concrete ground floor.

On the other hand

$$\frac{\partial z}{\partial r} = \theta \tag{9}$$

or

$$\Delta z = \theta\Delta r \tag{10}$$

so if $\Delta r = 5$ mm, $\Delta z < 1\mu$m.

The net result is that angle measurements with a laser tracker are no better than a theodolite or Total Station, and the high accuracy EDM of a Laser Tracker is of little value in the plane perpendicular to the beam–as is the case in the examples given in Barazzetti et al.[64] (and all of the other papers reviewed in this section–except Umemoto et al.[60]).

Note that the accuracy of surveying measurements is easily predicted by commercially available survey planning software, such as MicroSurvey STAR*NET. Given instrument accuracy assumptions, and geometric instrument and target locations, the software produces 3-D error models for the measurements.

Psimoulis et al.,[65] measured a bridge using Leica TS30 and TS50 Total Stations. The TS30 and TS50 range specifications are 0.6 mm + 1 ppm, with a measurement time of 7 seconds for the TS30 and 2.4 seconds for the TS50. The geometry was such that the vertical deflections were determined by the elevation angle, i.e., the accuracy of the EDM system was not a factor.

Marendić et al.,[66] measured a railway bridge at 21 locations using a Leica TPS1201 Total Station, with a sampling frequency specification up to 10 Hz, and a Trimble S8 Total Station, with a sampling frequency specification up to 20 Hz. They reported that the Leica TPS1201 only achieved around 7 Hz, but that the Trimble S8 achieved the specified 20 Hz. The vertical deflection of the bridge was mainly determined by the servo system tracking the elevation angle, i.e., the accuracy of the EDM system was not a factor. The two instruments were located adjacent to each other, thus there was nothing to be gained by combining the data in a least squares adjustment, e.g., had the instruments been on opposite sides of the river, or the bridge, the combined distance measurements would have strengthened the lateral and longitudinal measurements significantly, and the vertical measurements somewhat. It is interesting that they did report the clearly detectable lateral and longitudinal displacements, in addition to the vertical displacements. One could argue that from a structural health monitoring perspective, abnormal longitudinal or lateral displacements could be strong indicators of structural problems.

While results obtained by these examples are mixed, they do illustrate the potential utility of augmenting the standard sensor based instrumentation used for SHM to include EDM. There are common problems among these examples.

- The instrument manufacturers do not provide enough useful specification information for dynamic applications.
- The short range specifications for Laser Trackers may be discouraging possible novel applications.
- Laser Trackers should be considered vs Total Stations in the initial planning stages.
- The measurement architecture and geometry should exploit the high accuracy of the distance measurements.
- An error analysis should be done before conducting the experiment.
- Depending on the desired accuracy, multilateration may be necessary.

3. OPPORTUNITIES FOR EDM IN NDT AND SHM

3.1 Proof of principle demonstration

The Green Bank Telescope (GBT) is a 100 meter, offset paraboloid, radio telescope, built by the National Radio Astronomy Observatory (NRAO) for the National Science Foundation (NSF). Because of the unique offset paraboloid design, 100 GHz operating requirements (3 mm wavelength), one arc second pointing requirement, and 2004 active surface reflector panels, an ambitious metrology system was incorporated in the plans, as described by Hall et al.[67] The author was the Group leader for Antenna Metrology, working under John M. Payne, who was the inventor and Chief Engineer for the EDM system–along with the full-time job of being Head of Electronics for NRAO in Tucson, and about four other jobs. In 1990, there were no suitable ADM instruments available, so the model PSH97 prototype instruments, designed by John and the NRAO Central Development Lab, were built and tested by NRAO.[27,34,35,38,68–71]

Fortunately, the GBT performed better than expected, e.g., the pointing is very repeatable–which can be corrected by simple fitting algorithms as a function of elevation angle and astronomical observations by the telescope.

Unfortunately, astronomers interested in observing at 100 GHz were in the minority, and the radio astronomy community decided, through the GBT Advisory Committee, that the EDM was not needed, the budget was reallocated, and the project was not implemented in the commissioning of the telescope. However, Bob Bridges designed the FARO Laser Tracker ADM along the lines of John's original 1992 paper,[68] and perfected huge improvements over the original PSH97 prototype instruments.[14,72,73] Most notably, the Bridges design retained the digital phase measurement architecture, which is a very robust, low noise, continuous measurement, that can follow dynamic changes in distance at very fast rates.

At the outset of the GBT project, the conventional wisdom was that outdoor measurements of 100-200 meters by EDM was not practical. Early experimental results confirmed that in fact it is practical. A vast number of outdoor experiments were conducted at ranges from several meters to over one kilometer to a nearby mountain top. Experiments were conducted year round through day/night, hot/cold, static/dynamic, indoor/outdoor conditions. A wealth of experience and data was gained.

Figure 1 shows measurements of the deflection of a derrick mounted on top of a 180 foot tower while lifting a 89 500 pound load for the GBT main reflector, from a distance of approximately 725 meters. Details are in Petticrew,[71] which is available under the NRAO GBT Memo series on the internet, and described in US Patent 7,895,015[74] to Parker and Payne, *Method for measuring the structural health of a civil structure.* Note that the vertical scale is 3 mm/division at 725 meters, or about 4 parts per million, and the time scale is 10 minutes/division.

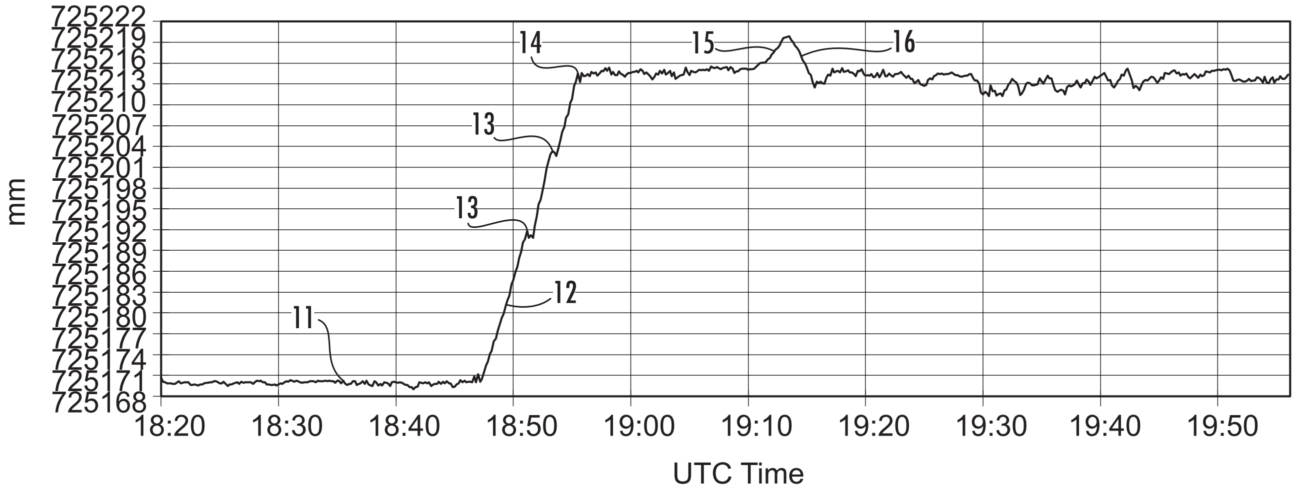

Figure 1. Measurements of the deflection of a derrick from 725 meters.

Figure 2 shows measurements of the offset feed arm of the telescope from 162 meters. Details are available in Parker,[75] and Parker and Payne.[74] Note that the time scale is one second/division and the vertical scale is 10 microns/division. The natural frequency vibrations of about 60 microns with a period of about 1.5 s are shown.

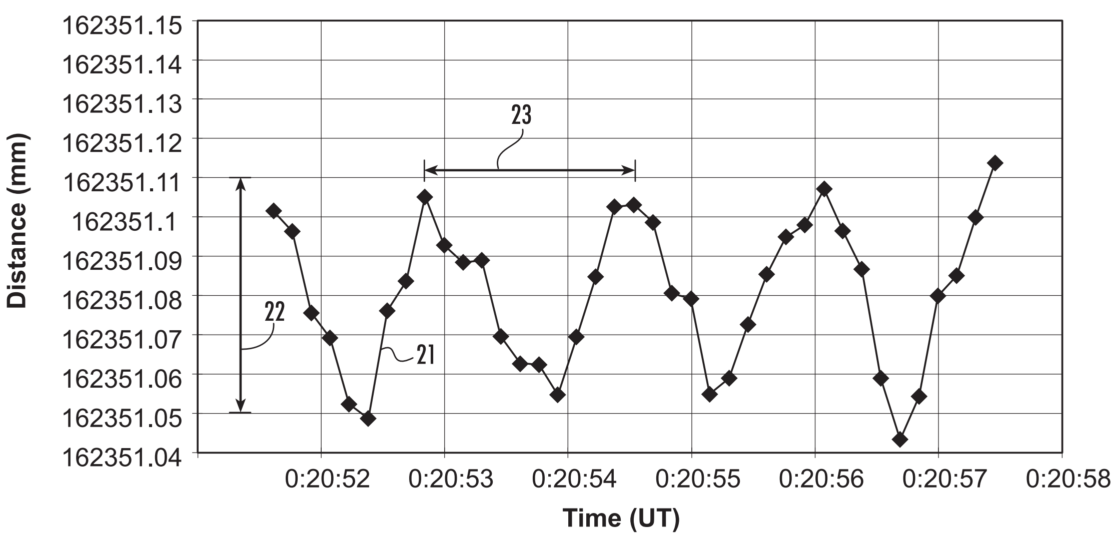

Figure 2. Vibration measurements from 162 meters.

3.2 Example applications in aerospace and precision manufacturing industries

The aerospace industry was an early adopter of Laser Trackers. US Patents 7,672,817 and 8,688,408[76,77] to Marsh et. al., *Flight in factory* disclose how the wings of an airplane are nondestructively tested in the factory by measuring points on the structure with Laser Trackers while subjecting the wings to a simulated lift pressure distribution.

US Patent 7,978,322[78] to Marsh, *Calibrating aircraft surfaces* discloses how Laser Trackers are used to measure the location and orientation of wings, horizontal stabilizers, vertical stabilizers, and control surfaces. The net result is that the as-built airplane is optimized to reduce drag and fuel consumption.

US Patent Application Publication 2015/0316649[79] to Marsh et al., *Aircraft Enhanced Reference System and Method* discloses how Laser Trackers are used to establish, and recover, cardinal reference points on an airplane, i.e., so called "golden rivets". These points are recoverable for the life of the airplane and can be used to confirm the structural health of the airplane, i.e., things have not moved with age or hard service.

Precision manufacturing and fabrication has also been an early adopter of Laser Trackers. US Patent Application Publication 2015/0254376[80] to Pettersson, *Method and system for virtual assembly of a structure* discloses how a structure can be virtually assembled before delivery to the construction site. Necessary adjustments are worked out before actual assembly by making modifications to the components before actual assembly. This is similar to the virtual fit-up problem with bridge girders and retrofit problem addressed by Fuchs.[46–48]

3.3 Example proposed applications of EDM for NDT and SHM

Parker and Payne disclosed a number of applications of EDM for NDT and SHM in a family of US Patents:

- US Patent 7,895,015[74] ('015) *Method for measuring the structural health of a civil structure*
- US Patent 8,209,134[81] ('134) *Methods for modeling the structural health of a civil structure based on electronic distance measurements*
- US Patent 9,354,043[17] ('043) *Methods for measuring and modeling the structural health of pressure vessels based on electronic distance measurements*
- US Patent Application Publication 2016/0274001[82] ('001) *Methods for measuring and modeling the process of prestressing concrete during tensioning/detensioning based on electronic distance measurements*

New bridges and buildings undergo extensive Finite Element Model (FEM) analysis in the design phase. However, a number of assumptions are made. A modern FEM may approximate the joint as a pin connection and not bother with the details of the gusset. It is common to assume symmetry in a FEM and only model half of a structure with assumptions that the centerline is constrained to only move in a vertical plane. In reality there may be significant asymmetries, such as utility pipes and electrical distribution cables, substations, access ladders and catwalks, access hatches, penetrations, and the like on one side of a bridge or containment building. The mesh size and number of the elements is selected in a trade-off between accuracy and computing time. It is assumed that material properties are homogeneous. All of such factors may be part of the engineering experience.

Finite Element Models can predict deflections and natural frequency modes of a structure in stages as it is being built. By actually measuring the deflections and vibrational modes as the structure is built, errors in the model can be detected when the predicted coordinates do not match the experimental data. Moreover, by providing the designer with feedback, confidence will be gained in the design. It will be understood that movements and deflections are resolved into three axes (x, y, z).

It will be recognized by those skilled in the art–such as experienced engineers–that in the absence of a Finite Element Model, there are general characteristics indicative of a healthy structure. Deviations from these general characteristics will be recognized by those skilled in the art as a harbinger to a structural health problem. For example:

1. Deflections should be linear, i.e., they should follow Hooke's law $f = kx$ where f is force, k is a spring constant, and x is the displacement. For example, the deflection of a bridge deck under a 2 ton load should be twice the deflection under a 1 ton load. The deflections of a tower crane should be linear as the load is translated out the arm.

2. Cracks are one source of nonlinearity that will be identifiable. For example, a crack is stiff in compression and weak in tension. Loading that cycles a cracked element between tension and compression shows strong nonlinearities in the movements of points on the structure. For example, a tower crane with no load typically has a net moment produced by the counterweight. This results in elements of the tower on one side being in tension and elements on the opposite side being in compression. By rotating in azimuth, the loads reverse. A structurally sound tower should produce symmetric deflections as a function of azimuth. However, a cracked weld or member will exhibit different properties for compression and tension.

3. Elements operating near their elastic limit will produce nonlinearities in the movements of points.

4. There should be no hysteresis, e.g., a structure should return to the initial position after a load is removed. By measuring a plurality of points, such things as slipping joints are detectable.

5. Movements should be a smooth function. For example, as the temperature goes through a diurnal cycle, a bridge will expand and contract. Typically one end is supported on a bearing to accommodate these movements. If the bearing is not functioning properly, excessive forces may develop until they reach a point of producing slip. This will be easily detectable by accurate coordinate measurements.

6. Plots of the deflections in (x,y,z) of a cardinal point as a vehicle travels over a bridge at uniform velocity should be capable of being expressed as the first few harmonics in a harmonic series, i.e., there should not be any sharp bumps in the plots, and there should be no hysteresis.

7. Long-term creep should be well understood, such as concrete curing or seasonal moisture absorption.

8. Changes in the damping coefficient, or Q, of the structure should be well understood, such as changes in weight due to rain.

It will also be recognized by those skilled in the art that even in the absence of a Finite Element Model, symmetry of a bridge may be exploited in the analysis. For example, most bridges have left-right symmetry about the direction of traffic and one would expect the deflections of a test load on the left side to produce symmetric deflections for the same load applied to the right side. There can also be symmetry between ends, spans, support columns, and even between other bridges of similar design. Prestress or post-tensioned tendon failure could be detected by asymmetry. Internal corrosion of concrete embedded rebar could be detectable–particularly as a long term drift over years.

It is often the case that the highest loads may be experienced during construction. For example, a load may be cantilevered out producing loading on columns that they will not experience under normal operating conditions. By measuring a plurality of points routinely, problem areas can be detected when experimental data does not match predictions, or something creeps.

As will be recognized by those skilled in the art, the integrity of a bridge may come into question as a result of an accident, flood, earthquake, etc. For example, an accident producing a fire on, or under, a bridge my weaken structural members. Bridges over waterways are often hit by ships, flood debris, ice, etc. Simply by knowing that cardinal points on the bridge are not within the seasonal limits could quickly identify problem areas to an experienced engineer.

Due to the expense of conventional transducers, it is not common to instrument a structure for unexpected conditions. For example, if a member fails or deforms, the loads will shift to a new equilibrium condition. This may require twisting or shifting of members in directions that they would not normally move. By making strong measurements in all 3 dimensions, such unexpected movements of a fraction of a mm would be easily detected. For example, in the case of the I-35W bridge gusset plate, the forces reached a new equilibrium condition. This probably produced slight movements in unexpected directions which propagated to points that may have been measured by EDM, and thus investigated as to the cause of the unexpected movements.

It will be recognized that the analysis can be extended to vibration and modal analysis. For example, the stiffness of a structure is directly related to the lowest natural frequency. The stiffer the structure is, the higher the lowest natural frequency. For example, the Green Bank Telescope weighs 16,727,000 lbf and has a lowest natural frequency of around 0.9 Hz. The entire structure is welded steel construction, i.e., there are no bolts or rivets which can slip. As a result, the damping coefficient is very small, or the quality factor Q is very high, where

$$Q = 2\pi \frac{\text{energy stored}}{\text{energy dissipated per cycle}}. \tag{11}$$

For this reason, the structure rings for a long time after a disturbance. Any change in the natural frequency or Q of the structure would be a sure sign of a problem. For example, a crack would result in a less stiff structure, which would lower the natural frequency. It would also dissipate energy faster, and thus the Q would go down.

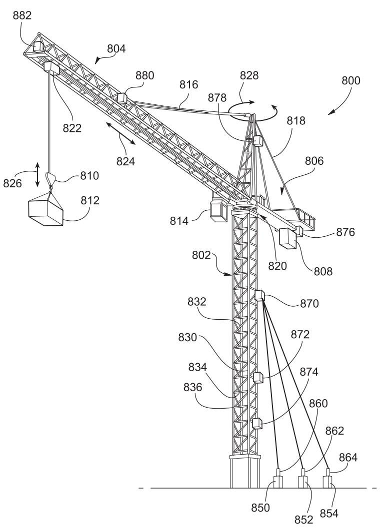

Figure 3. Measuring deflections of a tower crane.

An example of a tower crane **800**, as shown in Figure 3, and explained in greater detail in ’015, will serve to illustrate the method. The tower crane **800** has a rigid tower **802** supporting a load boom **804** and a counterweight boom **806** and counterweight **808**. The load boom lifts the load hook **810** and load **812**. The operator typically operates the crane **800** from a cab **814** that moves with the load boom **804** for optimal visibility. The load boom **804** is supported by a cable **816** which counters the load **812** by the counterweight **808** and another cable **818**. The load boom **804** rotates on the tower **802** via a bearing and drive system **820**. The load hook **810** travels along the load boom **804** via a trolley **822** in a radial direction **824**, and in the vertical direction **826**. By rotating about the tower axis **828**, the load **812** can be positioned by the operator. The tower **802** is typically constructed of vertical members **830** with diagonal braces **832** and horizontal braces **834** with welded joints **836**. Sections are typically bolted or pinned together in the field.

Electronic distance measurements are made from at least 3 stable instrument locations **850, 852, 854** by EDM instruments **860, 862, 864**. Targets are located at a plurality of cardinal points **870, 872, 874, 876, 878, 880, 882**. For example, cardinal points **870, 872, 874** on the tower **802** would be good indicators of bending of the tower under load. Ideally, the tower should bend linearly with load **812**, and the points on the tower should deflect as a beam fixed at one end, as is well known in the art. For a load balanced by the counterweight, the tower should be straight and in pure compression. Any deviation may be an indication of buckling, which can result in a dramatic failure.

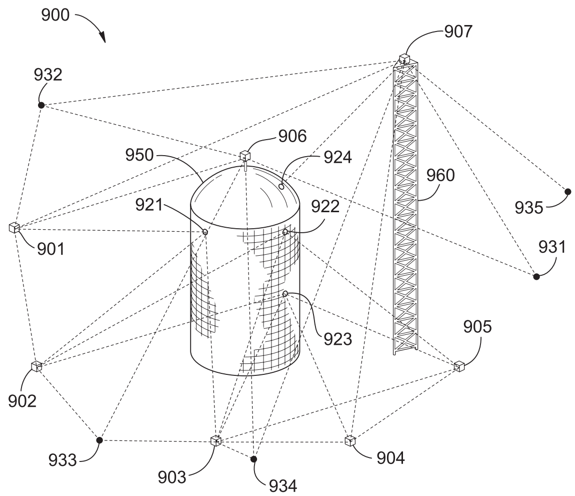

Figure 4. Measuring deformations of a nuclear power plant containment building undergoing a pressure test.

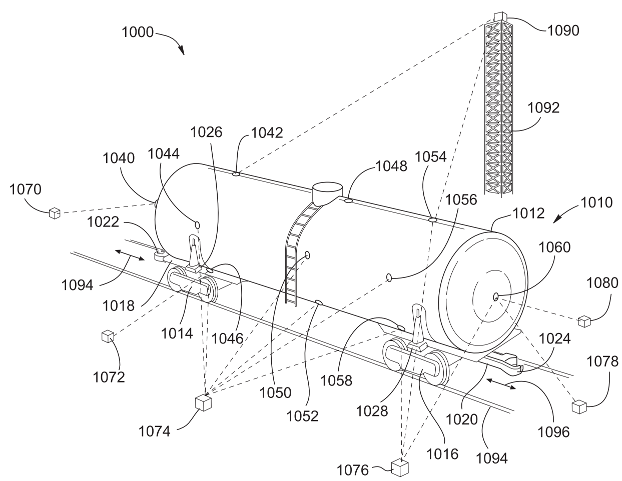

Figure 5. Measuring deformations of a railway tank car undergoing a pressure test.

The torque on the tower should be linear with the radial distance of the load **812** from the center of the tower **802**. As the boom is rotated about the axis of the tower **828**, the moment on the tower will shift directions and vertical members **830** that are in compression will shift to tension, in a sinusoidal function, as the boom **804** is rotated in a complete circle. However, if a joint **836** has a crack, the behavior will not be linear when the load shifts from compression to tension, i.e., the tower will exhibit a non-linear characteristic.

If there is a slippage of the joint, or the crack grows, the tower will exhibit hysteresis, i.e., when the boom **804** returns to the original orientation, the tower will not return to the original coordinates. Using trilateration with three instruments, or multilateration with additional instruments, the coordinates of the cardinal points can be resolved to a fraction of a mm, which will enable engineers to make very good assessments as to the structural health of the tower crane.

As shown in Figure 3 the top cord of the load boom **804** will be in tension, and the bottom cord will be in compression, due to the cable **816** and tower **802** supporting the load **812**. If the trolley **822** is moved inside the cable **816** support point, the loads on the load boom **804** will reverse, i.e., the bottom cord will be in tension. By

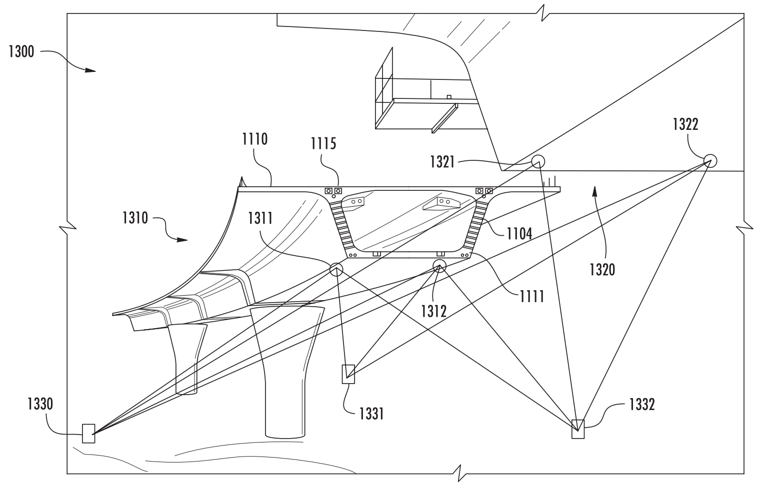

Figure 6. Measuring deformations of a bridge segment undergoing tensioning.

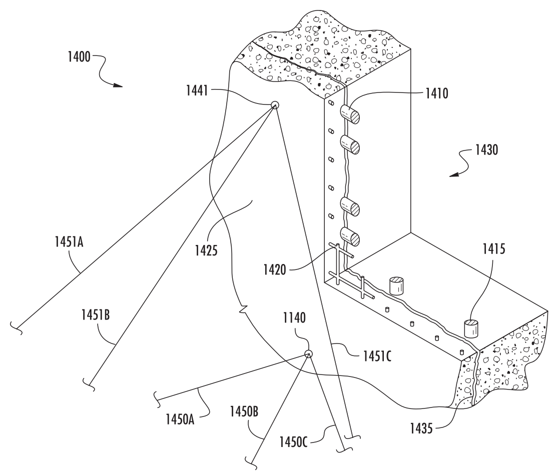

Figure 7. Measuring deformations of a nuclear power plant containment building undergoing detensioning.

watching the behavior of targets **882, 880** on the load boom **804**, an engineer could make an educated judgment as to the health of the load boom **804**.

Figure 4 shows measurements of a nuclear power plant containment building, as explained in greater detail in '043.

Figure 5 shows measurement of a railway tank car undergoing nondestructive testing, as explained in greater detail in '043.

Figure 6 shows measurement of a bridge segment undergoing tensioning, as explained in greater detail in '001.

Figure 7 shows measurement of a nuclear power plant undergoing detensioning, as explained in greater detail in '001.

4. WHAT IS NEEDED

4.1 Instrument specifications

It is clear that the instrument manufacturers need to provide better specifications that meet the needs of the NDT and SHM industries. There is an industry standard for static performance of Laser Trackers. ASME B89.4.19-2006 *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems.*[83] However, there are no standards for dynamic performance. Hence you see the common problem of testing the instruments, and using them in ways that were not intended, in the example articles above.

US Patent 7,856,334,[84] to Parker *Method for calibrating a laser-based spherical coordinate measurement system by a mechanical harmonic oscillator* disclosed a simple method for generating an oscillating target and testing the dynamic performance of EDM instruments. For example, a 2-D plane pendulum and a 3-D Foucault pendulum.

Welty[85] wrote a Masters Thesis on *Dynamic Evaluation of Laser Trackers*. She used a rotating ball bar as a moving retroreflector standard.

4.2 Communication

There needs to be communication between ASNT, TRB, CMSC, FIG, IAG, NGS, NIST and the instrument manufacturers to facilitate better understanding of each other's measurement problems and capabilities.

REFERENCES

[1] Burnside, C. D., [*Electromagnetic Distance Measurement*], BSP Professional Books, third ed. (1991).

[2] Dukes, J. N. and Gordon, G. B., "A two-hundred-foot yardstick with graduations every microinch," *Hewlett-Packard Journal* , 1–8 (Aug. 1970).

[3] Rudé, A. F. and Wayne, K. J., "A new tool for old measurements–and new ones too," *Hewlett-Packard Journal* , 9 (Aug. 1970).

[4] Burgwald, G. M. and Kruger, W. P., "An instant-on laser for length measurement," *Hewlett-Packard Journal* , 12–14 (Aug. 1970).

[5] Meier, D., *Dave Meier's HP Laser Interferometer Evolution Page.* `http://www.n4mw.com/hp5526/hple.htm`.

[6] Bagley, A. S., Cutler, L. S., and Rando, J. F., *Interferometric System* (1969). US Patent 3,458,259.

[7] Bullock, M. L. and Warren, R. E., "Electronic total station speeds survey operations," *Hewlett-Packard Journal* , 2–12 (Apr. 1976).

[8] Epstein, J. S., *Surveying Instrument and Method* (1978). US Patent 4,113,381.

[9] Greenleaf, A. H. and Watson, J. T., *Self calibrating contour measuring system using fringe counting interferometer* (1984). US Patent 4,457,625.

[10] Merry, J. B. and Brown, L. B., *Interferometer system for controlling non-rectilinear movement of an object* (1986). US Patent 4,621,926.

[11] Lau, K. C. and Hocken, R. J., *Three and five axis laser tracking systems* (1987). US Patent 4,714,339.

[12] Brown, L. B., Wells, D. N., and Merry, B., *Tracking laser interferometer* (1988). US Patent 4,790,651.

[13] Meier, D., *Electro-optical measuring device for absolute distances* (1998). US Patent 5,764,360.

[14] Bridges, R. E., Brown, L. B., West, J. K., and Ackerson, D. S., *Laser-based coordinate measuring device and laser-based method for measuring coordinates* (2010). US Patent 7,800,758.

[15] J.M.Rüeger, [*Electronic Distance Measurement*], Springer-Verlag, third ed. (1990).

[16] Bell, B., ed., [*Proceedings of the workshop on the use and calibration of the Kern ME5000 Mekometer*], Stanford Linear Accelerator Center (June 1992). Prepared for the Department of Energy under contract number DE-AC03-76F00515.

[17] Parker, D. H. and Payne, J. M., *Methods for measuring and modeling the structural health of pressure vessels based on electronic distance measurements* (2016). US Patent 9,354,043.

[18] Estler, W. T., Edmundson, K., Peggs, G., and Parker, D. H., "Large-scale metrology—an update," *Annals of the CIRP* **51**(2), 587–609 (2002). Keynote Paper.

[19] Peggs, G. N., Maropoulos, P. G., Hughes, E. B., Forbes, A. B., Robson, S., Ziebart, M., and Muralikrishnan, B., "Recent developments in large-scale dimensional metrology," *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture* (June 2009).

[20] Franceschini, F., Galetto, M., Maisano, D., and Mastrogiacomo, L., "Large-scale dimensional metrology (LSDM): From tapes and theodolites to multi-sensor systems," *International Journal of Precision Engineering and Manufacturing* **15**, 1739–1758 (Aug. 2014).

[21] Schmitt, R. H., Peterek, M., Morse, E., Knapp, W., Galetto, M., Härtig, F., Goch, G., Hughes, B., Forbes, A., and Estler, W. T., "Advances in large-scale metrology–review and future trends," *CIRP Annals Manufacturing Technology* **65**, 643–665 (2016).

[22] Muralikrishnan, B., Phillips, S., and Sawyer, D., "Laser trackers for large-scale dimensional metrology: A review," *Precision Engineering* **44**, 13–28 (2016).

[23] Franceschini, F., Galetto, M., Maisano, D., and Mastrogiacomo, L., "Combining multiple large volume metrology systems: Competitive versus cooperative data fusion," *Precision Engineering* **43**, 514–524 (2016).

[24] Peggs, G. N., "Virtual technologies for advanced manufacturing and metrology," *International Journal of Computer Integrated Manufacturing* **16**(7-8), 485–490 (2003).

[25] Hughes, E. B., Wilson, A., and Peggs, G. N., "Design of a high-accuracy CMM based on multilateration techniques," *Ann. CIRP* **49**(1), 391–394 (2000).

[26] Brinker, R. C. and Minnick, R., eds., [*The Surveying Handbook*], Chapman & Hall, second ed. (1995).

[27] Parker, D. H. and Payne, J. M., "Metrology system for the Green Bank Telescope," in [*Proceedings ASPE 1999 Annual Meeting*], 21–24, American Society for Precision Engineering (1999).

[28] Sandwith, S. and Predmore, R., "Real-time 5-micron uncertainty with laser tracking interferometer systems using weighted trilateration," 2001 Boeing Large-Scale Metrology Conference, St. Louis, MO (2001).

[29] Camboulives, M., Lartigue, C., Bourdet, P., and Salgado, J., "Calibration of a 3D working space by multilateration," *Precision Engineering* **44**, 163–170 (2016).

[30] Atcheson, P. D., *Hemispherical Retroreflector* (1989). US Patent 4,889,409.

[31] Zürcher, W., Loser, R., and Kyle, S. A., "Improved reflector for interferometric tracking in three dimensions," *Optical Engineering* **34**, 2740–2743 (September 1995).

[32] Oakley, J. P., *Retroreflector* (2009). US Patent Application Publication 2009/0303592.

[33] Parker, D. H., *Methods for modeling amplitude modulated light through dispersive optical systems and electronic distance measurement instruments* (2014). US Patent 8,630,828.

[34] Parker, D. H., "Multidirectional retroreflector assembly with a common virtual reflection point using four-mirror retroreflectors," *Precision Engineering* **29**, 361–366 (2005).

[35] Parker, D. H., *Multidirectional retroreflectors* (2010). US Patent RE41877.

[36] Brown, L. B., *Probing retroreflector and methods of measuring surfaces therewith* (1996). United States Patent 5,530,549.

[37] Bridges, R. E., Brown, L. B., and Ackerson, D. S., *Retroreflector for use with tooling ball* (1999). United States Patent 5,861,956.

[38] Parker, D. H., "Methods for correcting the group index of refraction at the ppm level for outdoor electronic distance measurement," in [*Proceedings ASPE 2001 Annual Meeting*], 86–87, American Society for Precision Engineering (2001). Full presentation is available from The National Radio Astronomy Observatory (NRAO) Library, GBT Archive L0680.

[39] Pollinger, F. and et al., "JRP SIB60 Metrology for long distance surveying–a concise survey on major project results," in [*Proceedings of 3rd Joint International Symposium on Deformation Monitoring, Vienna, Austria*], The International Federation of Surveyors (FIG) Working Group 6.1, Deformation Measurement and Analysis and The International Association of Geodesy (IAG) Sub-Commission 4.2, Applications of Geodesy in Engineering, FIG (2016).

[40] Andreas, E. L., ed., [*Selected Papers on Turbulence in a refractive medium*], *SPIE Milestone Series* **MS 25**, SPIE (1990).

[41] Kleppe, J. A., [*Engineering Applications of Acoustics*], Artech House, first ed. (1989).

[42] Jones, T. E., ed., [*From Vision to Mission, ASNT 1941 to 2016*], ASNT (2016).

[43] Aktan, A. E., Catbas, F. N., Grimmelsman, K. A., and Pervizpour, M., "Development of a model health monitoring guide for major bridges," Tech. Rep. Contract/Order No. DTFH61-01-P-00347, Drexel Intelligent Infrastructure and Transportation Safety Institute (2003). Report Submitted to Federal Highway Administration Research and Development.

[44] Ettouney, M. M. and Alampalli, S., [*Infrastructure Health in Civil Engineering: Volume 1, Theory and Components*], CRC (2012).

[45] Ettouney, M. M. and Alampalli, S., [*Infrastructure Health in Civil Engineering: Volume 2, Applications and Management*], CRC (2012).

[46] Fuchs, P. A., *Instrument to Aid in Steel Bridge Fabrication, Final Report of Highway IDEA Project 127.* Transportation Research Board (Mar. 2009).

[47] Fuchs, P. A., *Bridge Retrofit Laser System, Final Report for Highway IDEA Project 153.* Transportation Research Board (Sept. 2012).

[48] Fuchs, P. A., *Apparatus and method for bridge assembly* (2014). US Patent Application Publication 2014/0207410.

[49] Moreu, F., LaFave, J. M., and Spencer, B. F., "New regulations on railroad bridge safety: Opportunities and challenges for railroad bridge monitoring," in [*Proceedings of SPIE, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2012*], **8345**, 834540–1 through 11 (2012).

[50] Cosser, E., Roberts, G. W., Meng, X., and Dodson, A. H., "Measuring the dynamic deformation of bridges using a total station," in [*Proceedings of 11th FIG Symposium on Deformation Measurements, Santorini, Greece*], The International Federation of Surveyors (FIG), FIG (2003).

[51] Merkle, W. and Myers, J. J., "Use of the total station for serviceability monitoring of bridges," in [*Proceedings of 16th WCNDT 2004–World Conference on NDT, Montreal, Canada*], (2004).

[52] Matta, F., Bastianini, F., Galati, N., Casadei, P., and Nanni, A., "In-situ load testing of Bridge A6358 Osage Beach, MO," Tech. Rep. UTC R124-3, University Transportation Center Program at The University of Missouri-Rolla (Jan. 2005).

[53] Galati, N., Casadei, P., and Nanni, A., "In-situ load testing of Bridge A6101 Lexington, MO," Tech. Rep. UTC R124-1, University Transportation Center Program at The University of Missouri-Rolla (Jan. 2005).

[54] Hernandez, E., Galati, N., and Nanni, A., "Assessment of bridge technologies through field testing: In-situ load testing of Bridges B-20-133 and B-20-134, Fond du Lac, WI," Tech. Rep. UTC R133A, University Transportation Center Program at The University of Missouri-Rolla (Dec. 2005).

[55] Hernandez, E., Galati, N., and Nanni, A., "Assessment of bridge technologies through field testing: In-situ load testing of Bridges B-20-148 and B-20-149, Fond du Lac, WI," Tech. Rep. UTC R133B, University Transportation Center Program at The University of Missouri-Rolla (Dec. 2005).

[56] Galati, N., Casadei, P., and Nanni, A., "In-situ load testing of Bridge A6102 Lexington, MO," Tech. Rep. UTC R124-2, University Transportation Center Program at The University of Missouri-Rolla (Jan. 2005).

[57] James, H., "Automatic deformation monitoring," *The American Surveyor* (March/April 2006).

[58] Gikas, V. and Daskalakis, S., "Full scale validation of Tracking Total Stations using a long stroke electrodynamic shaker," in [*Proceedings of 23th International FIG Congress, Munich, Germany*], (2006).

[59] Palazzo, D., Friedmann, R., Nadal, C., Filho, M. S., Veiga, L., and Faggion, P., "Dynamic monitoring of structures using robotic total station," in [*Proceedings of 23th International FIG Congress, Munich, Germany*], (Oct. 2006).

[60] Umemoto, S., Hara, T., Kubota, K., Miyamoto, N., Fujino, Y., and Okamoto, T., "Verification of high-accuracy and contact measurement system using FSF laser optical coordinate," in [*Proceedings of The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure, Vancover, British Columbia, Canada*], (Nov. 2007).

[61] Kopáčik, A., Kyrinovič, P., Lipták, I., and Erdély, J., "Automated monitoring of the Danube Bridge Apollo in Bratislava," in [*Proceedings of the FIG Working Week 2011, Bridging the Gap between Cultures, Marrakech, Morocco*], (May 2011).

[62] Attanayake, U., Tang, P., Servi, A., and Aktan, H., "Non-contact bridge deflection measurement: Application of laser technology," in [*Proceedings of the International Conference Structural Engineering Construction and Management, ICSEM 2011, Peradeniya, Sri Lanka*], (2011).

[63] Psimoulis, P. and Stiros, S., "Using robotic theodolites (RTS) in structural health monitoring of short-span railway bridges," in [*Proceedings of 1st Joint International Symposium on Deformation Monitoring, Hong Kong, China*], The International Federation of Surveyors (FIG) Working Group 6.1, Deformation Measurement and Analysis and The International Association of Geodesy (IAG) Sub-Commission 4.2, Applications of Geodesy in Engineering, FIG (2011).

[64] Barazzetti, L., Giussani, A., Roncoroni, F., and Previtali, M., "Monitoring structure movement with laser tracking technology," in [*Proceedings of SPIE, Videometrics, Range Imaging, and Applications XII; and Automated Visual Inspection*], **8791**, 879106–1 through 12, SPIE (2013).

[65] Psimoulis, P. A., Peppa, I., Bonenberg, L., Ince, S., and Meng, X., "Combination of GPS and RTS measurements for the monitoring of semi-static and dynamic motion of pedestrian bridge," in [*Proceedings of 3rd Joint International Symposium on Deformation Monitoring, Vienna, Austria*], The International Federation of Surveyors (FIG) Working Group 6.1, Deformation Measurement and Analysis and The International Association of Geodesy (IAG) Sub-Commission 4.2, Applications of Geodesy in Engineering, FIG (2016).

[66] Marendić, A., Paar, R., Grgac, I., and Damjanović, D., "Monitoring of oscillations and frequency analysis of the railway bridge "Sava" using robotic total station," in [*Proceedings of 3rd Joint International Symposium on Deformation Monitoring, Vienna, Austria*], The International Federation of Surveyors (FIG) Working Group 6.1, Deformation Measurement and Analysis and The International Association of Geodesy (IAG) Sub-Commission 4.2, Applications of Geodesy in Engineering, FIG (2016).

[67] Hall, R., Goldman, M., Parker, D. H., and Payne, J. M., "Measurement program for the Green Bank Telescope," in [*Proceedings of SPIE*], **3357**, 265–276 (1998).

[68] Payne, J., Parker, D., and Bradley, R., "Rangefinder with fast multiple range capability," *Rev. Sci. Instrum.* **63**, 3311–3316 (June 1992).

[69] Payne, J., Parker, D., and Bradley, R., "Rangefinder with fast multiple range capability," in [*Selected Papers on Laser Distance Measurements, SPIE Milestone Series MS 115*], Bosch, T. and Lescure, M., eds., 257–262, SPIE Optical Engineering Press (1995). reprint of Review of Scientific Instruments article.

[70] Payne, J. M., Parker, D. H., and Bradley, R. F., *Optical Electronic Distance Measurement Apparatus with Movable Mirror* (1995). United States Patent 5,455,670.

[71] Petticrew, A. L., "Laser rangefinder deflection measurements of the gbt derrick," Tech. Rep. GBT Memo 160, The National Radio Astronomy Observatory (NRAO) (Nov. 1996). Available from the NRAO Library.

[72] Bridges, R. E. and Hoffer, J. M., *Absolute distance meter that measures a moving retroreflector* (2008). US Patent 7,352,446.

[73] Bridges, R. E. and Hoffer, J. M., *Absolute distance meter that measures a moving retroreflector* (2010). US Patent 7,701,559.

[74] Parker, D. H. and Payne, J. M., *Method for measuring the structural health of a civil structure* (2011). US Patent 7,895,015.

[75] Parker, D. H., *First measurements of the GBT feed arm* (1999). GBT Archive L0535, Available from NRAO Library.

[76] Marsh, B. and VanScotter, K., *Flight in Factory* (2010). US Patent 7,672,817.

[77] Marsh, B. J. and VanScotter, K., *Flight in Factory* (2014). US Patent 8,688,408.

[78] Marsh, B. J. and Lazar, M. A., *Calibrating Aircraft Surfaces* (2011). US Patent 7,978,322.

[79] Marsh, B. J., Lazar, M. A., Vanscotter, K. D., Cooke, B. T., Bodziony, L. S., Coleman, R. M., Wel, M. M. V., Olson, A. S., Dorsey, D. V., and Nobles, O. M., *Aircraft Enhanced Reference System and Method* (2015). US Patent Application Publication 2015/0316649.

[80] Pettersson, B., *Method and system for virtual assembly of a structure* (2015). US Patent Application Publication 2015/0254376.

[81] Parker, D. H. and Payne, J. M., *Methods for modeling the structural health of a civil structure based on electronic distance measurements* (2012). US Patent 8,209,134.

[82] Parker, D. H. and Payne, J. M., *Methods for measuring and modeling the process of prestressing concrete during tensioning/detensioning based on electronic distance measurements* (2016). US Patent Application Publication 2016/0274001.

[83] The American Society of Mechanical Engineers, *ASME B89.4.19-2006 Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems* (2006).

[84] Parker, D. H., *Method for calibrating a laser-based spherical coordinate measurement system by a mechanical harmonic oscillator* (2010). US Patent 7,856,334.

[85] Welty, V., *Dynamic Evaluation of Laser Trackers*, mathesis, University of North Carolina at Charlotte (2015).