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Local positioning systems versus structural monitoring: a review

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SUMMARY

Structural monitoring and structural health monitoring could take advantage from different devices to record the static or dynamic response of a structure. A positioning system provides displacement information on the location of moving objects, which is assumed to be the basic support to calibrate any structural mechanics model. The global positioning system could provide satisfactory accuracy in absolute displacement measurements. But the requirements of an open area position for the antennas and a roofed room for its data storage and power supply limit its flexibility and its applications. Several efforts are done to extend its field of application. The alternative is local positioning system. Non-contact sensors can be easily installed on existing infrastructure in different locations without changing their properties: several technological approaches have been exploited: laser-based, radar-based, vision-based, etc. In this paper, a number of existing options, together with their performances, are reviewed. Copyright © 2014 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The final goals of structural health monitoring (SHM) are to detect and quantify damage within a structural system, to promote a residual lifetime prognosis of the structure and to guide the management in planning optimal cost-effective strategies for system maintenance, inspection, repair, or rehabilitation. Structural monitoring technologies utilize different types of sensors which are installed on the structure to be monitored. The purpose is to record its static deflection or its dynamic responses during forced vibration or natural excitation. The static deflection can be used for damage detection, while the dynamic responses can be analyzed to identify the current status of the structure [1], which will be compared with its behaviors in the healthy condition. Thus, a health diagnosis of the structure can be performed to detect and quantify damage as well as to update its effects on the remaining integrity. All these results will assist the structure and system manager toward the residual lifetime prognosis and guide the management in planning optimal cost-effective strategies for system maintenance, inspection, repair, or rehabilitation. By analyzing vibration data (caused by environmental interactions such as wind and traffic loads) or severe vibration data (caused by earthquakes and strong winds), appropriate actuation can also be imposed on the structure in order to counteract the effect of severe loading events. In this way, the effective damage can be significant reduced [2,3].

Uncertainties play an important role in the prediction of the safety of an infrastructure. The load and response uncertainties are quantified by adopting suitable sensor networks. As a key implementation issue to link the models with real world structures, the sensor network plays an important role in the usability and

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performance of any SHM system. Among several possible directions of SHM sensor network, wireless [4,5], non-contact [6], and positioning [7] are three endearing directions, and they are analyzed in this work.

Sometimes the experimental analysis of properly reduced scale models is adopted to obtain a better understanding of the behavior of large-scale structures. Conventional sensors often are not feasible for this application because the introduction of the sensor masses can affect the behavior of the models. Thus, there is growing interest in developing alternative techniques for measuring movement without any contact with the structure. Furthermore, because non-contact sensors do not undergo the same force or deformation as the structure does, they should result more durable.

2. POSITIONING SENSOR

Traditional (relative) displacements measurement methodologies, such as linear variable differential transformer, require a reference point, creating significant challenges for the field application in large-scale structures. Absolute acceleration measurements, which do not require a reference point on the structure, are traditionally used to determine the dynamic characteristics of structures. The displacement is then obtained through double integration of acceleration data, but the result may not be stable due to a bias in low-frequency contents. Therefore, non-contact displacement measurement sensors are sometimes desirable.

Global positioning systems (GPS) positioning devices represent one of this kind of sensors (see the pioneering papers by Celebi and Kijewsji-Correa [8,9]). Indeed, it has been adopted in the structural monitoring of very flexible structures, such as suspended bridges or tall buildings, and offers a mm-level accuracy, which is sufficient for accurate deformation measurements in the structural monitoring [10,11]. To reduce the cost, the potential of using off-the-shelf low-cost GPS receivers into SHM were also investigated [12,13], but the accuracy of low-cost GPS is still to be improved.

From a technological point of view, the main difficulties encountered in field applications are related to the cabling system: due to the high cost of the cables, their difficulty of installation, their invasive effect on the monitored structure, their vulnerability to mechanical damage, and their high cost of maintenance. For these reasons, the adoption of wireless connections is regarded as a fundamental aspect for the spread of permanent monitoring solutions. Its feasibility is supported by the improving performance and declining cost of electronics and wireless communication technologies. Similar problems are encountered in the application of GPS receiver.

Global positioning systems is only effective in open area, and therefore, it requires a visible sky position to place its antenna, and a roofed position to place its processor and the power supply. At times, it is difficult to route cables due to the building structure constraint. Therefore, a wireless data logger can greatly facilitate the setup and use of GPS receivers. Indeed, there are several products of wireless GPS data logger [14–18]. But these products focus on providing data logger for the vehicle tracking and therefore low-accuracy GPS receiver is built-in. In addition, either general packet radio service or WiFi is adopted in those ready-made data logger, and this means high power consumption. Therefore, a low-power-consumption wireless cable replacement was recently implemented to transmit the data back to the center in real time for a GPS receiver [19].

Another deficiency of high-accuracy GPS is that the system is only effective in open area with a satisfactory number of the available satellites and a suitable geometric distribution. Therefore, continuous monitoring with equal precision in all position components at any time is a challenge for GPS sensor. Hence, various methods were proposed to enable robust indoor positioning.

First, inertial systems, which include all the techniques that take advantage of the inertial properties of any movement, were proposed to improve the robustness of a GPS system. This system can bridge global navigation satellite system outages as well as provide accurate short-term data with very high rate to interpolate a GPS trajectory while the GPS provides bound data for inertial sensors. Few coupled integrations were employed to share information between the GPS and the inertial navigation system (INS) system [20,21]. Currently, Trimble provides a serial of global navigation satellite system-inertial system, which provides centimeter level mobile positioning accuracy [22], but for structural health monitoring, this accuracy cannot be regarded as sufficient.

Another way to provide indoor positioning measurement could be the pseudolite local positioning system (LPS) whose main idea is to deploy pseudolites around the measuring sensor unit to assure the sensor can measure its distances to each pseudolite at any time through which the sensor position then is obtained, as shown in Figure 1. The distance is obtained by multiplying the signal propagation time by the speed of the electromagnetic wave. Providing the sensor is synchronized with the pseudolites, several technologies can help assessing the propagation time more accurately: chirp spread spectrum, ultra wide band, frequency modulated continuous wave (FMCW), and carrier phase shift measurement. Chirp spread spectrum and ultra wide band are adopted by 802.15.4a standard and offer accuracies of meter-level and decimeter-level, respectively [23–25]. FMCW and carrier phase shift are utilized in laser radar-based LPS [26], which provides accuracy of the centimeter level [27] and of the millimeter level or even better [28], respectively. Carrier phase shift is also used in dual-frequency high performance GPS, which provides positioning accuracy of mm-levels [10,11], and it is also employed in the pseudolite-based LPSs, which provides cm-level accuracy [29].

As one of the few successful pseudolite LPS systems, Locata created terrestrial networks that serve as a 'local ground-based replica' of the GPS-style positioning. The Locata system includes three or more transceivers, called LocataLites, which provide signals that enable highly accurate range measurements, and some standalone receivers, called Rovers, which track LocataLite signals and calculate latitude, longitude, and elevation. This system works on the free-license 2.4G radio frequency. Different from GPS satellite, which uses high-cost atomic clock to keep the accurate time, the Locatalite employs a low-cost temperature-compensated crystal oscillator clock [30]. The main difficulties of this system are how to synchronize all of the base stations accurately and how to mitigate the multipath error, which is dominant in the positioning accuracy [31]. A direct digital synthesis technology is used in the time-synchronization procedure within the LocataNet, known as TimeLoc [32,33]. Currently, TimeLoc synchronizes Locata transmitters and receivers to an accuracy of 1nanosecond, which is a level substantially more accurate than that which can be attained using the multiple atomic clocks on board GPS satellites [29]. Locata utilized an antenna array, called TimeTenna, to mitigate the multipath signal under indoor environment [34]. The resulting position standard deviation of outdoor test of this system is approximately 2 mm and there are no long term drifts [32]. For most points measured under indoor static test, the mean error is less than 2 cm, while during the dynamic test, the error is no more than 3 cm after the algorithm has converged [35].

A further proposed cheap solution to indoor pseudolite LPS is to import satellite signals in a satellite un-visible area through repeater [36], which consists of an amplifier with two kinds of antennas: one, external, has full visibility of the satellites; the other kind of antenna irradiates the amplified signal

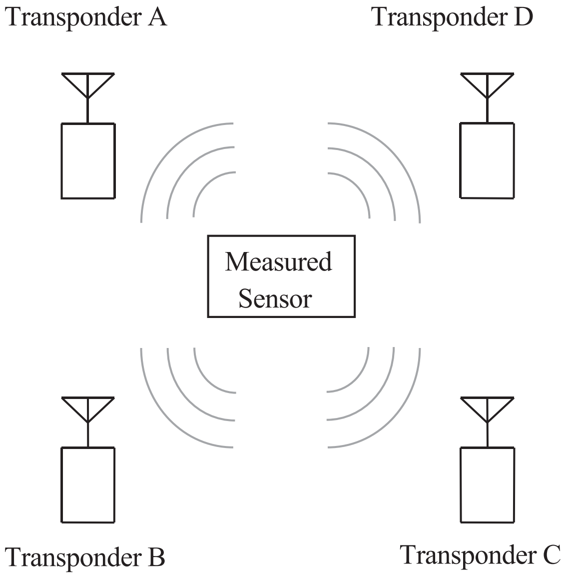

Figure 1. Local positioning system.

toward the measurement environment (Figure 2). Four irradiating antennas are generally required. Different latency steps were introduced in different irradiating antennas in order to avoid signal conflicting because the signals are reproduced by the same external signal. If the latency step is big enough for the wished cover range, the signals from different irradiating antennas become uncorrelated inside the covered range and can be simultaneously demodulated by the receiver, namely, received simultaneously. Theoretically, using a minimum of four antennas appended in different positions, the repeater can reproduce the situation of an open sky measurement node even with just a single visible satellite (provided the signal from it is good enough). Experiments were performed on which SPIRENT GSS 6560 L1 generator was use to simulate the signals, which were supposed to be received by the receiver [37]. Experiment results confirmed the feasibility of this conception. So far, there is no off-the-shelf latency device that can provide precise time-delay for such a pseudolite LPS.

The positioning accuracies of these two pseudolite methodologies are yet to be improved in view of SHM.

As a third option, laser-based LPS is a good (thanks to its monochromatic feature) alternative for indoor displacement measurements. The emitted laser light possesses high degree of spatial coherence which assures narrow output beam with limited diffraction. Therefore, there is no multipath error and large distance that can be reached because the power is concentrated. These special features let laser distance measurement sensors be universally applied. There are a variety of techniques utilized for laser distance measurement [28,38]: time-of-flight (TOF), triangulation, phase shift, FMCW, and displacement measuring interferometry. In the TOF distance measurement, a short laser pulse is projected to a target. The time the pulse takes to travel forward and backward is measured. The distance to the target is calculated from the TOF and the speed of the light in the medium. Laser positioning system could provide displacement measurement accuracy as high as from pm to nm when using displacement measuring interferometry technology, such as the modular vibrometer system OFV-5000 from Polytec. But the maximum full scale displacement measurement range of this system is relatively small: ±82 mm even though the working distance is configurable up to 10 m [39]. Laser-based systems have been used to measure the displacement of structures. A wireless laser-based displacement measurement system, which incorporates a friendly graphical user interfaces, was constructed by University of Pavia to measure the one-dimensional displacement of a structure in the laboratory [7,40]. In this system, data from different sensors can be sent back to the data center simultaneously due to the adoption of the frequency division multiple access mechanism [4]. A second laser sensor is utilized as a reference sensor to reduce the noise floor introduced by the laser sensor. Another wireless laser-based displacement measurement system was also constructed, which adopts the code division multiple access mechanism to increase the wireless communication distance [41]. This system is used to real time monitor the vertical deflections occurring at the free end of the mega-trusses and edge truss of a real structure during the construction process. Driven by the progress in sensor technology, computer methods and data processing capabilities, 3D laser scanning, such as Terrestrial Laser Scanner (TLS), have found its application in monitoring the static and dynamic behavior of large infrastructures and provide high accuracy [42].

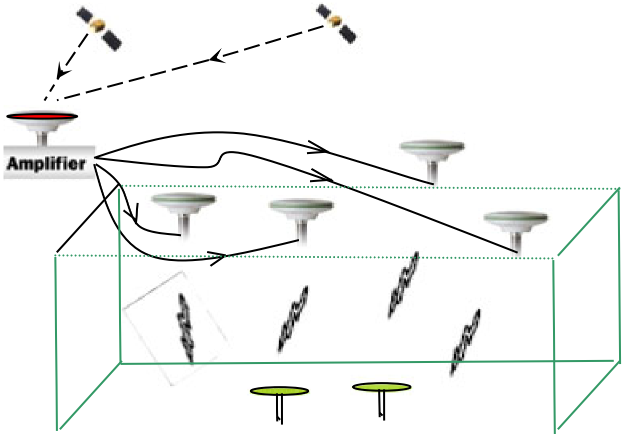

Figure 2. Schematic representation of the adoption of repeaters toward local positioning system.

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As a forth option, the precise displacement measurement based on Radar, which is the acronym of radio detection and ranging, has been possible. The radar dish or antenna transmits pulses of radio waves or microwaves, which bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna, which is usually located at the same site as the transmitter. The distance between the transmitter and the target is determined by measuring the time for the radar signal to propagate to the target and back. By comparing the carrier phase difference between the transmitted signal and the received signal, the distance measurement precision can be fairly high. A wireless radar-based sensor was developed to measure the bridge displacement [43]. According to the laboratory experiment results, the performance of the radar does not degrade proportionally to the target distance but rather reaches a limit beyond which the signal is rapidly overcome by measurement noise. The signal collected by the wireless radar sensor match well with the ones collected by the linear variable differential transformer and accelerometer. There are also some commercial radar-based sensors. For example, IBIS-S[*] is an interferometric radar displacement sensor, which can provide with an accuracy between 1/100 and 1/10 of a millimeter through comparing the phase difference between the transmitted signal and the received signal [6,44]. Specially, this radar sensor achieves a spatial resolution dense to 0.5 m via a technology called step frequency continuous wave [45]. On the basis of IBIS-S, a multi bistatic interferometric radar sensor was realized to measure the three dimensional displacement of structures [46]. In this system, only one IBIS-S (called main radar unit) is required. Another two remote radar transmitters, which have only transmitting antenna, were connected to the main radar unit through cables at RF level. The experiment results demonstrate that the standard deviation of this sensor is better than submillimeter when the working distance is 30 m.

A summary of the wireless positioning system alternatives is reported in Table I. Table II lists several displacement measurement systems based on laser and radar.

3. VISION-BASED LOCAL POSITIONING SYSTEM

In this section, vision-based LPS is discussed. Velocity and displacement measurements using images are based upon tracking the object motion between sequences of images. As illustrated in Figure 3, four markers are sticked on four interested positions on the front plane of a frame model. When the frame model moves, the motions of markers can be obtained by identifying the positions of markers in the image sequences. This system, although it requires a 'sight-of-line scene', enables accurate dense measurements of both dynamic processes and, especially, static deformations. Consider damage detection for instance: data for damage detection can be either dynamic, (i.e., vibration-based properties) or static deformation profiles. It is usually more convenient to obtain dynamic types of data because they contain more information regarding a given structure [47,48]. However, devices required in order to collect dynamic data are normally expensive to set up, maintain and automate. Moreover, it can be very difficult (or even impossible) to excite a large structure to vibrate at high frequencies which characterize the high order vibration mode shapes. The static deformation profile requires much less effort, and therefore using the static deflection for damage detection is sometimes more attractive [49].

Vision-based displacement measurement systems have been installed on large-scale structures: six video cameras were included in the health monitoring system of the cable-stayed bridge in Shenzhen Western Corridor, 18 video cameras were embodied in the SHM system of the Stonecutter Bridge [50], and three video cameras were incorporated in the SHM system of GuangZhou TV Tower [51,52]. The vertical displacement influence lines of Stonecutters Bridge were successful figured out through using vision-based displacement system [53]. The motion of the top of main tower recorded by the vision-based system and GPS system agrees each with the other very well [51]. In those vision systems, the space coordinates of the object are reconstructed through multiplying the image coordinates by a scale factor [51]. During the experiment, it was found that the precision of this approach greatly depends on the orientation of camera, which reduces the repeatability and flexibility

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[*] IBIS-S is an interferometric radar of INGEGNERIA DEI SISTEMI s.p.A.(https://www.idscorporation.com/) for the remote static and dynamic monitoring of structures.

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Table I. Wireless positioning system alternatives.

				LPS				
Features	GNSS inertial system	Pseudolite LPS	Satellite repeater	CSS	UWB	FMCW	Laser	Radar
Company	Trimble	Locata	N/A	Nanotron	Decawave	Abatec AG	Polytec	INGEGNERIA DEI SISTEMI s.p.A
Product type	AP50	Leica Jps receiver	N/A	nanoPAL RTLS toolbox	ScenSor	LPM	PSV-500	IBIS-S
Coverage	Global	Local	Local	Local	Local	Local	Local	Local
Accuracy	cm-level	cm-level	Sub-meter accuracy (simulation)	1–3 m	cm-level	2–50 cm	mm-level	0.01 –0.1 mm
Sampling rate	1–200 Hz	10 Hz	N/A	>200 Hz	N/A	1000 Hz	100 kHz	<200 Hz
Availability	Available	Available	N/A	Available	Available	Available	Available	Available

GNSS, global navigation satellite system; LPS, local positioning system; CSS, chirp spread spectrum; UWB, ultra wide band; FMCW, frequency modulated continuous wave.

Table II. Laser-based and radar-based displacement measurement systems.

	Author	Dimension	Measured parameter	Real time	Accuracy	Sample rate (Hz)	Sensor model	Sensor number	Measurement range
Laser-based	Casciati F. 2012	1D	Displacement	No	Submilli-meter	100 Hz	YT89MGV80	2	0.5–3.5 m
	Park HS, 2013	1D	Displacement	Yes	±2 mm	≤50 Hz	LLD-0100	1	0.2–35 m
	González-Aguilera D 2008	3D	Displacement	No	6.5 mm at 200 m	N/A	Trimble GX200	1 station	≤350 m
Radar-based	Rice JA, 2012	1D	Displacement	Yes	Submillimeter	100 Hz	N/A	1	≤6 m
	Gentile, 2010	1D	Displacement	Yes	≤Submillimeter	200 Hz	IBIS-S	1	~400 m at 200 Hz
	Mecatti, 2011	3D	Displacement	N/A	≤Submillimeter	N/A	IBIS-S	1	100 m

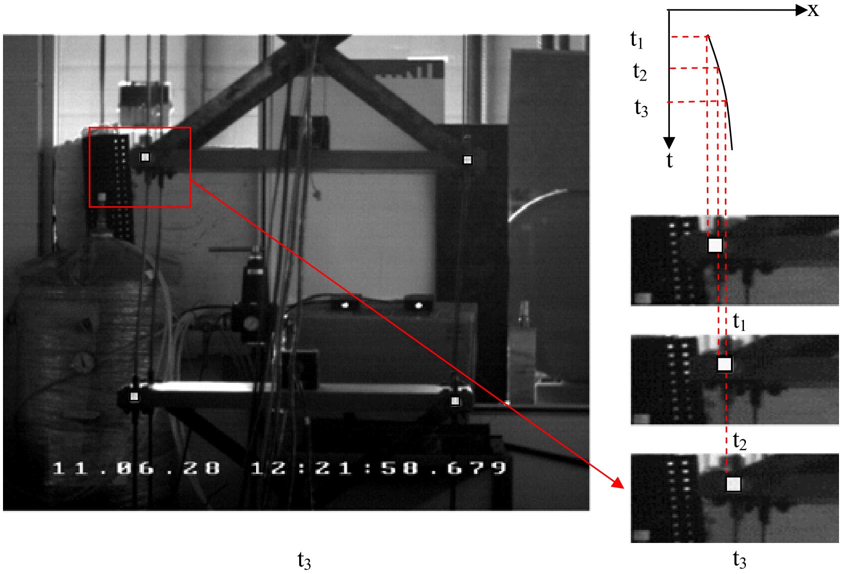

Figure 3. The idea of displacement measurement through tracking the object motion between sequences of images.

of experiment. It is because the scale factor approach does not take the projective distortion into consideration. More robust space coordinates reconstruction approaches are required.

A tailor-made two-channel camera system, which provides sample rate at 25 frames per second (fps), was utilized to monitor the two-dimension motion of a bridge in the work of Olaszek [54]. The camera calibration was based on coefficient calculation through measuring a known size of cross axis and the errors sources in vision system were discussed. Lee and Shinozuka [55] constructed a vision system based on a commercial camera with a sample rate at 30 fps. It was used to monitor a bridge for getting its influence line. Similarly, the scale factor camera calibration was adopted. It was calculated through two pairs of known-distance white spots, which are perpendicular to each other [55]. On the work of Uhl [49], vision-based measuring apparatuses, which adopting Canon EOS 450D digital camera and Canon EOS 5D Mark II, were used to measure the in-planer static deformation of a steel frame loaded by a point force in a laboratory experiment. They took the projective distortion into consideration and therefore introduced a procedure called image registration to rectify the distorted image. Then, a circular intensity pattern with a known diameter was used to obtain the scale factor [49]. The image registration asks for a reference image that is taken when the optic axis of camera is perpendicular to object plane to register the distortion images. That could be a limitation in field application. In the laboratory experiment carried out by Jurjo [56,57], a vision system, which includes a camera (with an adjustable sample rate at 30fps or 60fps) and an associated image processing program, was used to study the 2D non-linear dynamic behavior of a clamped-free slender metallic column subjected to its own weight and large displacements and rotations under both tension and compression. In this work, direct linear transformation (DLT) was utilized to calibrate the camera. DLT approach relieves the orientation limitation of digital camera and therefore greatly increases the flexibility of the vision system. In this approach, the relations between image coordinates and their respective space coordinates are expressed by a set of co-linearity equations [58]. For two-dimension DLT transformation, at least four known-position-non-collinear points are required. The calibration was performed following an interpolation way [56], which means to put the reference markers in a region around the structure thus ensuring that any configuration of the structure will always be within the calibration region, and therefore, provides precise results when compared with those obtained by following an extrapolation way. The experiment results corroborate the precision of this system.

There are little vision systems that support simultaneously multipoint measurement. Lee [59] proposed an extendable architecture for multipoint measurement vision system, which groups each two synchronized camera into a subsystem. Synchronization all over the network was achieved by synchronizing different subsystems with the assistant of wireless links.

The vision-based systems can also monitor 3D dynamic responses of structures when two or more synchronized cameras are utilized. The 3D space coordinates of objects can be reconstructed from the

Table III. Vision-based displacement measurement systems.

Author	Dimension	Measured parameter	On/offline	Calibration	Accuracy/resolution	Sample rate (Hz)	Camera number	Camera type	Camera resolution
Olaszek 1999	2D	Vibration/deflection	On	Scale factor	0.1–1.0 mm for l = 10–100 m	25	One	—	512 × 512
Lee 2006	2D	Vibration	On	Scale factor	0.021 mm/pixel	30	One	—	720 × 480
Jurjo 2010	2D	Vibration	On	DLT	0.5 mm/pixel	60	One/two	Analog camera	811 × 508
Uhl 2011	2D	Deflection	On/off	Registration + scale factor	Difference <0.5% with a laser sensor (0.008 mm resolution)	—	One	Canon EOS 450D	4272 × 2848
Lee 2012	2D	Vibration	On	Scale factor	0.053 mm/pixel	30	2/subsystem	JVC GZ-MS120& PV-GS35	640 × 480
Ye 2013	2D	Vibration	On	Scale factor	Comparable with GPS receiver	5–25	One	GigE GC2450	2456 × 2058
Wieger 2009	3D	Position and orientation of points	Off	Camera and DRS calibration	mm-level	—	One	—	640 × 480
Kohut 2009	3D	Vibration	Off	Bouguet and Perona [66], Heikkila [67]	0.08–1.00 mm	0.1–150	One	X-stream vision	—
Park 2012	3D	Track construction entities	On	Heikkilä and Silvén [68], Zhang [69], Bouguet [70]	The errors of 3D position are at maximum 0.658 m with 95%	30	Two	Canon VISXIA HF S100	1920 × 1080
Myung 2010 Jeon 2011 2013	6D	Static and dynamic displacement	—	Translation and rotation matrix	RMSEs < 0.084 mm	—	2/subsystem	—	—

RMSE, root mean square error; GPS, global positioning systems; DRS, displacement recording station.

image coordinates based on two-view-geometry or multiple-view-geometry [58]. One 3D vision-based system was developed by Kohut to support the modal analysis method [48]. An automated 3D vision-based system was also constructed by Park to track the motion of constructions [60].

To further extend the cover range of vision-based system, several elaborated systems, which integrate camera, laser, and even screens and servos, were proposed. Wieger and Caicedo [61] proposed a system which utilizes two lasers located in each measuring point on the structure and directed to a displacement recording station (DRS). A camera located inside the DRS was used to record the location of the laser marks. Displacements and rotations of measuring points were obtained according to the changes in positions and orientations of the lasers with respect to the camera reference frame. In this way, synchronization between measurements is not necessary given that only one camera is used for several measurements and changing lighting conditions have minimal effects on the methodology. Additionally, the size of the structure is not a factor in the displacement calculations. The vision-based system requires a clear line-of-sight path between the camera and the interested target. This could be a difficulty when the high-rise building is monitored. To overcome this problem, another elaborated system was proposed [59,62] utilizing partitioning approach which used a multiple synchronized vision-based displacement measurement system to successively estimate the relative displacements and rotational angles at several floors. A further complicated designed system is proposed by KIAST [63–65], so called a paired structured light system, which is compose of two cameras, three laser lights driven by servos and two screens. This system can measure the 6-DOF displacement of structure, i.e., the translational and the rotational displacement each in 3-DOF between two sides [65].

Vision system is also used to detect the cracks of structure. Iyer utilized the vision system to detect cracks in underground pipeline images [66]. An automatic multi-image stitching and scene reconstruction vision system was proposed by Jahanshahi [67] for evaluating defect evolution in structures. This system adopts a camera that can zoom or rotate in three directions. An image database was managed for reconstructing the history scenes when defects are observed. Based on these scenes, the deficiency evolution can be learned. Similarly, scene reconstruction was used to detect cracks for assessing the structural conditions [68].

A summary of the aspects discussed in this section is reported in Table III [69–73]. Basically, the aforementioned systems are constructed on the basis of a self-developed program, which requires a well-understanding of both the program language (such as Visual C++) and the digital image processing methodologies, and those requirements limit the utilization of vision-based displacement system. A vision-based system was also constructed in University of Pavia [19,74] for monitoring the two-dimension displacements of a laboratory structure on which markers were simply glued. In this system, the image sequences recorded by the camera are processed by a commercial software to obtain the image coordinates of the markers. The real coordinates of the markers are reconstructed by algorithms, including DLT and registration, which were programed in Matlab. Thus, one can quickly construct his own vision-based displacement measurement system and perform experiments.

4. CONCLUSIONS

Thanks to the fast electronic technology developing, a direct displacement measurement is becoming possible. GPS represents a mature technology, but, on the basis of GPS, more and more displacement measurement solutions have been proposed. Efforts were made to increase the flexibility and the usability of displacement sensor, including the wireless links for GPS, the indoor pseudolite positioning system, the laser-based positioning system, the radar-based positioning system, the vision-based positioning system, etc. Especially, the non-contact sensors could be easily installed on existing infrastructure or existing modules in different locations without altering the structure properties. Thus, they can provide both direct displacement measurements and flexibility of application, which make them favorite innovative devices in the area of structural monitoring. This work targets to provide an overview of the proposed non-contact sensor systems concept and the existing non-contact sensor products. Those systems are reviewed considering the technologies they utilized, the accuracies or resolution they achieved, and the system parameters etc. On the basis of this study, one can find out that the GPS, indoor pseudolite positioning system do not ask for a thoroughly clear line-of-sight. On the contrary, it is necessary for the normal operation of a laser-based, a radar-based, or a vision-based system, which, however, can provide a better accuracy: from submillimeter to millimeter. The laser-based and radar-based systems can only measure the displacement of a single point at each time stamp. For this reason, to measure multiple points simultaneously, scanning approach is adopted in laser-based and radar-based systems. For the vision-based system, they can measure the displacements of multiple points simultaneously providing those points are inside its cover range.

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