AN OPTICAL SENSOR AND WIRELESS MESH NETWORK FOR RAPID DIRECT MEASUREMENT OF BUILDING INTERSTORY DRIFT

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Abstract

Advancements in sensor technologies and communications networks are generating new opportunities for advanced methods for measuring the earthquake response and associated damage potential in major infrastructure. Motivated by increasingly demanding technology requirements in a number of fields, from autonomous vehicles to robotic manufacturing, optically-based sensor systems have significantly advanced over the past decade. The short latency of the underlying physics, and the ability to perform high resolution measurements across a broad frequency bandwidth are key features that make optical-based measurement systems particularly appealing for applications to infrastructure earthquake response measurement. Concurrently, transformational progress underway in wireless communications and the Internet of Things (IOT) are enabling new paradigms for remote command and control of sensor systems and rapid extraction and analysis of time-critical data.

Building interstory drift is a key earthquake response observable for building structures and is broadly utilized as a response measurement variable in many international engineering codes and standards to define performance-based limit states, maximum allowable story deformations, and quantification of damage in post-earthquake assessments. To date, there has been no widely accepted methodology or technology for reliable and accurate direct measurement of building drift. Historically, drift measurement has been obtained through signal processing and double integration of accelerometer data, which is inherently challenging and typically subject to significant frequency bandwidth limitations, particularly if inelastic, permanent drifts occur.

In this paper, recent advancements in a new optically-based sensor system for direct measurement of interstory drift are presented. The third generation of a *Discrete Diode Position Sensor* (DDPS), which utilizes laser light to directly measure drift, is described and data from recent experimental tests illustrating high-resolution sensor performance is presented. The ability to measure both Transient Interstory Drift (TID(t)) and Residual Interstory Drift (RID) with measurement errors in the sub-millimeter range is demonstrated. To facilitate efficient deployment of the optical sensor systems, a companion activity has focused on the creation of a practical, dedicated mesh network for reliable, rapid extraction of building data in a degraded post-earthquake environment. The mesh network is based on a system of dedicated low-power radio-frequency (RF) nodes that can self-configure and form a dynamic network throughout a building structure. The first field deployment of the optical sensor and mesh communication network are described for a large building, including the practical efficiencies realized from utilization of wireless communication nodes allowing agile deployment and eliminating the need for network communication cables. The proposed optically-based technology provides a pathway to accurate, direct measurement of building drift that will inform building stakeholders for rapid key decision making related to emergency response and continuity of occupancy and operations for critical facilities such as hospitals, financial/data centers, essential operation/business centers and hazardous material repositories. In addition, the ability to use very low-power, eye safe lasers and inexpensive commodity electronics will make system costs attractive in comparison to traditional sensor systems.

Keywords: Building drift, optical sensor, damage detection, wireless network, SHM

1. Introduction

The ability to rapidly respond and execute appropriate post-earthquake mitigation measures is a crucial component of society's overall earthquake resilience and can provide major benefits to both human safety and economic recovery. The ability of infrastructure stakeholders and emergency responders to make key decisions and take appropriate actions in a post-earthquake environment can be greatly assisted by the rapid distribution of actionable data obtained from earthquake monitoring systems. Observables that have traditionally informed the understanding of the damage potential for a particular earthquake event have included both measurements of ground motions, which yield information on the effective forcing function, and measurements of infrastructure response which provide information on earthquake demands for a particular structure. Historically, strong motion accelerometers have been employed to measure both ground motions and structural response, with the limitation that in the case of structural response the accelerometer data must be appropriately processed after an earthquake event to remove drift, instrument noise etc.

A response observable of high interest to the engineering community is a building's interstory drift, measured by the relative displacement between two successive floors of a building as shown in Fig. 1 where Transient Interstory Drift (TID(t)) - the full time-varying drift waveform, Peak Interstory Drift (PID) - the largest magnitude drift observed and Residual Interstory Drift (RID) - the permanent drift due to inelastic action are labeled. Given that structural member stresses are the result of displacement driven deformations in the structural system, displacement drift provides a direct measure of induced stresses and demand on the structure. Many building design and damage inspection standards utilize interstory drift as a key response variable to quantify building limit states, not-to-exceed drifts, and define damage indexes with specific examples provided in Table 1.

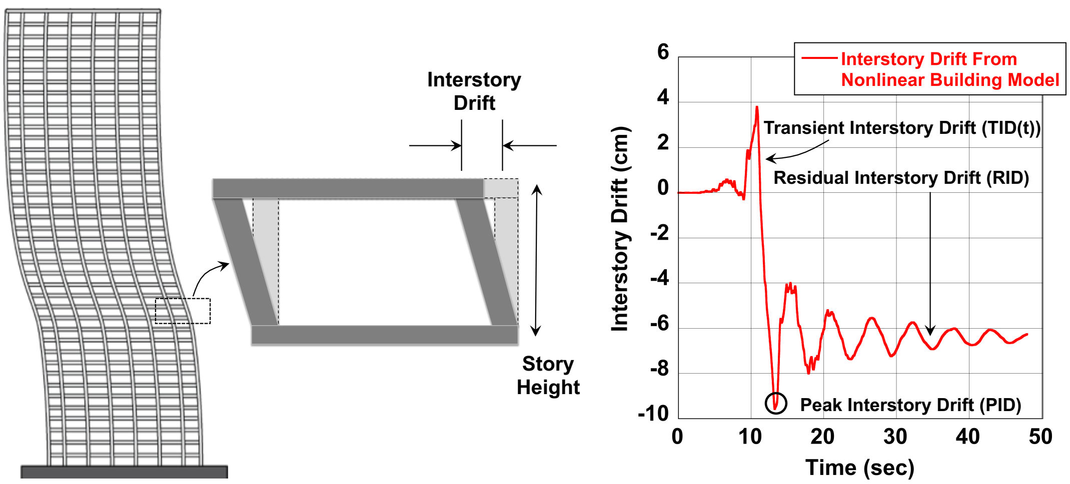

Fig. 1 – Building drift including residual drift due to inelastic response
(representative drift history from a nonlinear building model subjected to strong near-fault motions).

Building floor acceleration measurements obtained from deployed accelerometers have historically been used to compute story drifts through a process of double integration to obtain approximations of floor displacements and subsequent differencing of the computed floor displacements to obtain story drift displacement. This is a challenging process owing to the impacts of accelerometer data processing and the frequency band-limited characteristics of accelerometers and becomes very problematic when inelastic response results in permanent story drifts [1, 2].

The desirability of directly measuring structural displacements as opposed to structural accelerations for evaluation of building earthquake demands and potential damage has been proposed by a number of engineers and researchers for over a decade [3, 4]. In evaluating the ability to detect earthquake damage in a building Rodgers and Celebi [3] noted that; "*post-earthquake condition assessments from instrumental data could be significantly improved by the development of reliable methods for displacement measurement.*" Johnston [4] also proposed the need for displacement measuring technology stating; "*What is needed is a time history of interstory displacements, not accelerations, to properly interpret building displacements because it is interstory displacements which are the principal cause of member stresses.*"

Table 1 - International building standards using building interstory drift as a key response measure.

Standard	**Specification**
U.S. American Society of Civil Engineers Seismic design criteria for structures, systems and components in nuclear facilities (ASCE 43-05)	Definition of structure limit states defined in terms of PID levels
Eurocode (EN1998-1) New Zealand Standard (NZS -1170.5) U.S. Pacific Earthquake Engineering Research Center Guidelines for Performance-Based Seismic Design of Tall Buildings (TBI 2.03)	Definition of system maximum allowable interstory drift in terms of PID
U.S. Federal Emergency Management Agency Seismic Performance Assessment of Buildings (FEMA P58-1)	Definition of system damage states in terms of RID

Some early conceptual work was performed exploring the utilization of optical techniques to measure structural vibrations [5, 6]. McCallen [7] proposed an operational laser-based concept for measurement of interstory drift based on vibration measurement work in the Lawrence Livermore National Laboratory National Ignition Facility (NIF) program. This laser-based concept has subsequently been developed and tested in work supported by the U.S. Department of Energy [8, 9, 10]. The measurement principal of the system as shown in Fig. 2 includes the instantaneous tracking of the position of a laser propagating across a story height with the position of the laser measured by a light sensitive sensor termed a *Discrete Diode Position Sensor* (DDPS). This system directly measures the time history of interstory drift and, due to the ability to measure both dynamic and static displacements, can accurately measure both transient (TID) and residual (RID) drift displacements.

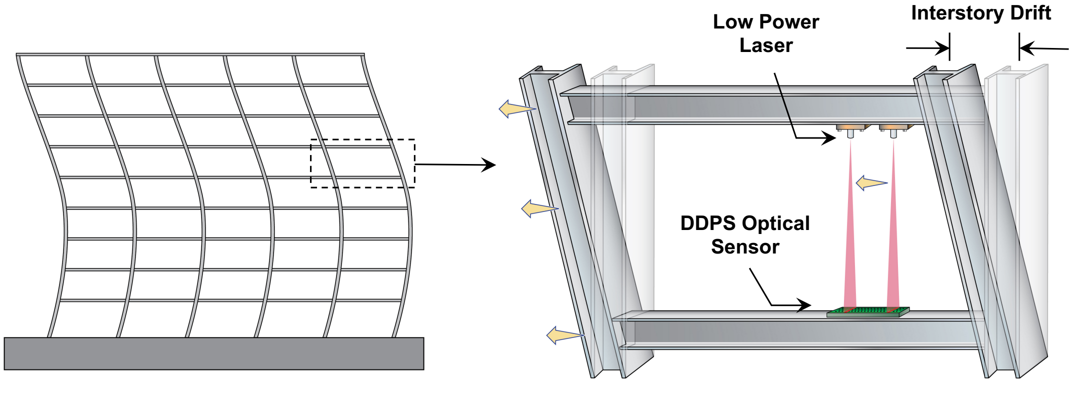

Fig. 2 – Direct measurement of interstory drift with a laser-based optical system, laser beam impinges on a dynamic, light-sensitive optical sensor (DDPS).

In this article the most recent developments in the laser-based technique for direct measurement of interstory drift are summarized and the testing and first field deployment of a third-generation DDPS sensor are described. Recent technology enhancements have resulted in important practical improvements, for example the ability to use a very low-power, eye safe laser, as well as accuracy improvements that can expand the range of applicability of the DDPS system to measure small-amplitude ambient vibrations as well as large earthquake induced building motions. As a result of fundamental improvements in the manner in which the sensor interacts with optical diodes, the DDPS now has a significant dynamic displacement range with an ability to measure drift displacements as small as ~1mm and as large as 10 cm or more as necessary for a particular application.

2. Generation III DDPS developments and testing

The DDPS measures the precise temporal location of an incident laser beam which has been diffracted through a lens to create a line source as indicated in Fig. 3. The diffracted beam is generated with sufficient width transverse to the sensor to prevent the laser from moving off the sensor when orthogonal displacements occur in the structure [8]. The DDPS relies on a staggered grid of simple, inexpensive optical diodes, which register a voltage when hit by laser light, to sense the current location of the impinging laser beam. By very rapidly sampling the voltage in all diodes in the array, the transient location of the incident laser beam is determined by identification of the diodes that are registering a voltage at each instant of time [9]. The sensor has undergone a progressive series of refinements based on lessons-learned from extensive design, evaluation and testing and the sequence and progression of sensor designs are illustrated in Fig. 4. The DDPS has progressed from a set of interconnected components in the first prototype (GENI), to a fully integrated sensor on a single circuit board (GENII), and recently to an enhanced capability integrated sensor/communication system with a small footprint (GENIII). For the current GENIII sensor, key advancements include:

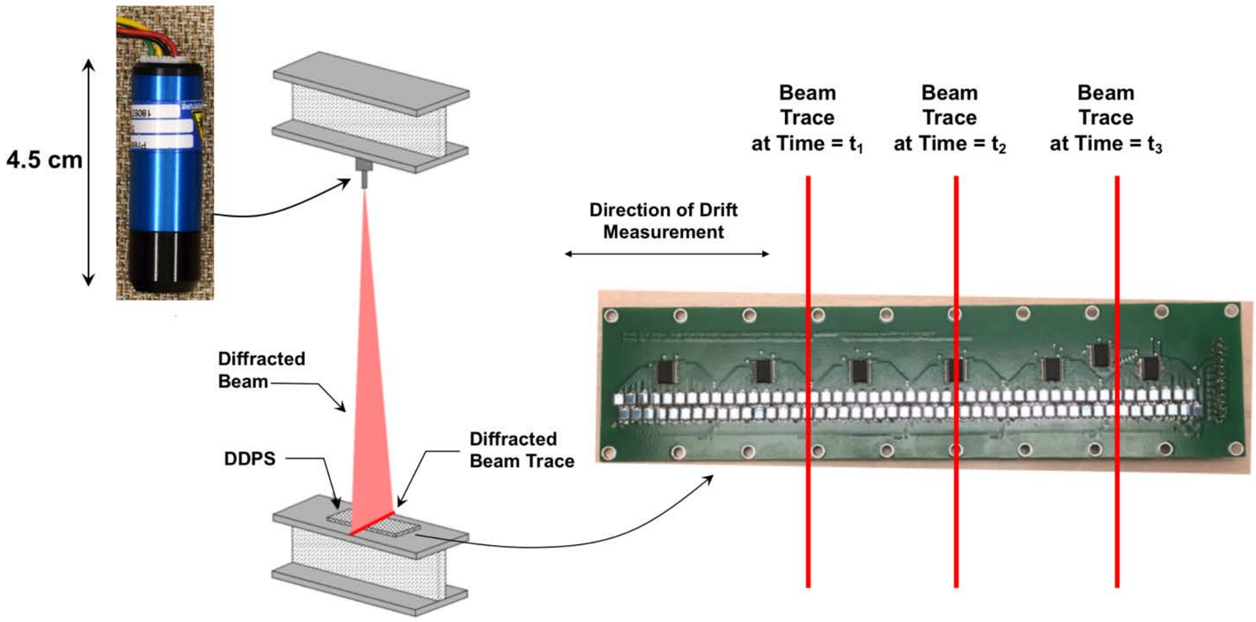

Fig. 3 – Diffracted laser beam trace impinging on the DDPS diode array, low power commercially available small laser used in the GENIII DDPS system shown.

- Modification of the form and conditioning of the laser beam to enhance the manner in which the laser interacts with the individual diodes in the diode grid, this resulted in a reduction in the sensor displacement measurement error by a factor of 2. This error reduction results in drift displacement measurements with an accuracy of +/-0.5mm, and increases the ability of the DDPS to measure environmental vibrations of building structures due to wind or other low-amplitude excitations. This increases the sensor application space to include system identification and structural change detection from small amplitude environmental vibrations, and the new approach also readily enables the extension of the current uniaxial drift sensor to a biaxial sensor for multi-direction drift measurements;

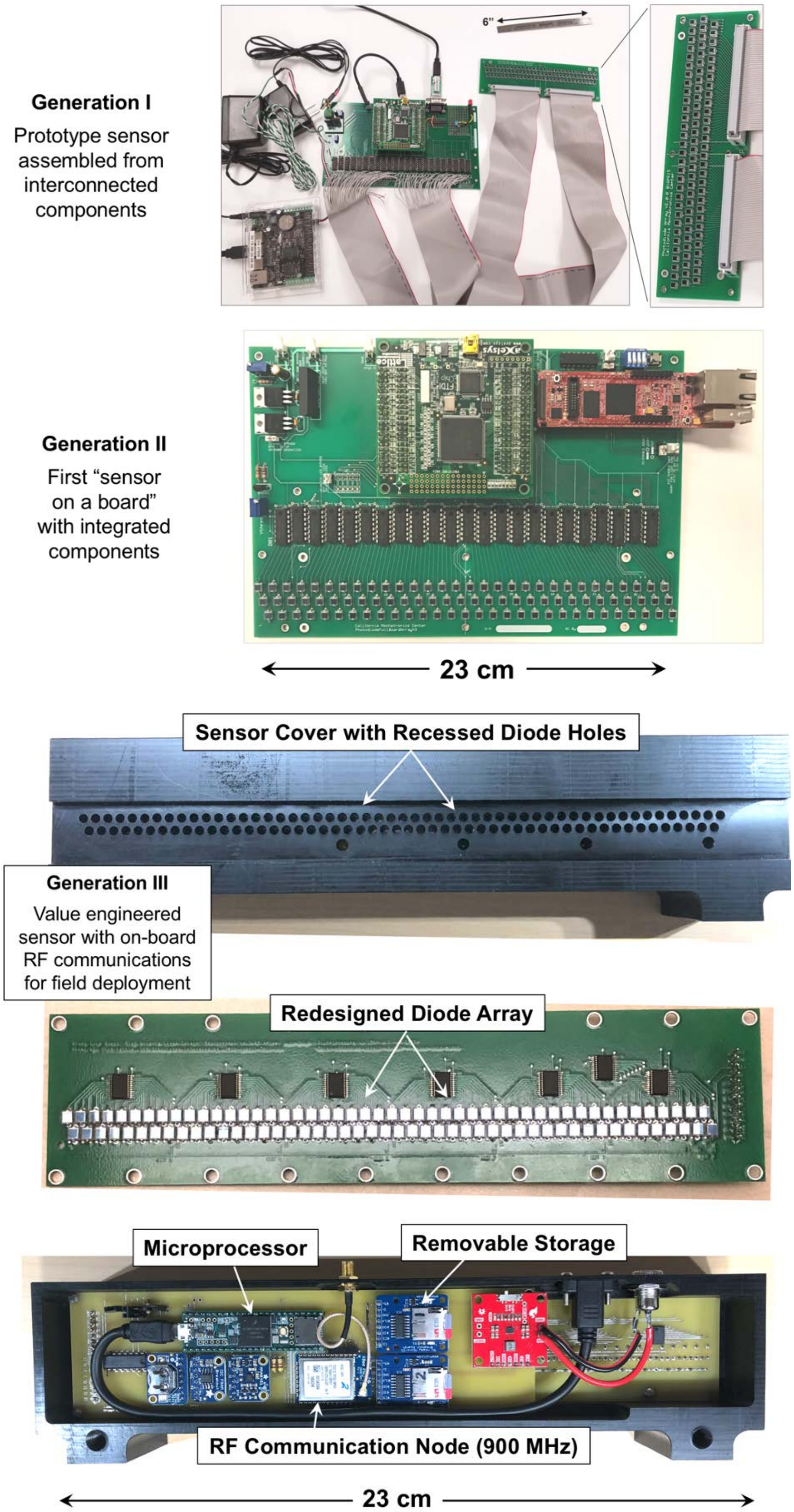

Fig. 4 – Progression of DDPS sensor design phases from Generation I to Generation III.

- Optimization and control of the light environment of the sensor design and packaging in order to allow the use of a much lower power eye-safe laser, which is crucial to eliminating many operational safety considerations. This important practical result was obtained by design detailing which included placing the sensor diodes at-depth in recessed holes that resemble a natural honeycomb structure;
- The inclusion of commercially available wireless communication nodes on-board each sensor with an ability for a distributed network of sensors to form a self-configuring, self-healing network for agile and efficient deployment and data transmission and collection.

A key modification for the GENIII sensor includes the conditioning of the incident laser beam. In previous DDPS designs the laser beam was tightly focused to provide a thin, sharp profile in the direction of measurement, i.e. creating a thin line source. An alternative approach, which proved to support higher accuracy drift measurements, is to make the laser line more defuse – essentially defocusing the laser beam to have a broader "blurred" footprint that engages more diodes as shown in Figure 5. With this approach the centroid of the laser light can be quickly calculated from the voltage profile to provide a better determination of the laser location. This design feature was key to achieving a 2x reduction in measurement error and also making the sensor more robust by reducing the sensitivity to individual diode manufacture and fabrication variability such as imprecise placement and location of the diode or the small diode-to-diode variability in light sensitive surface area.

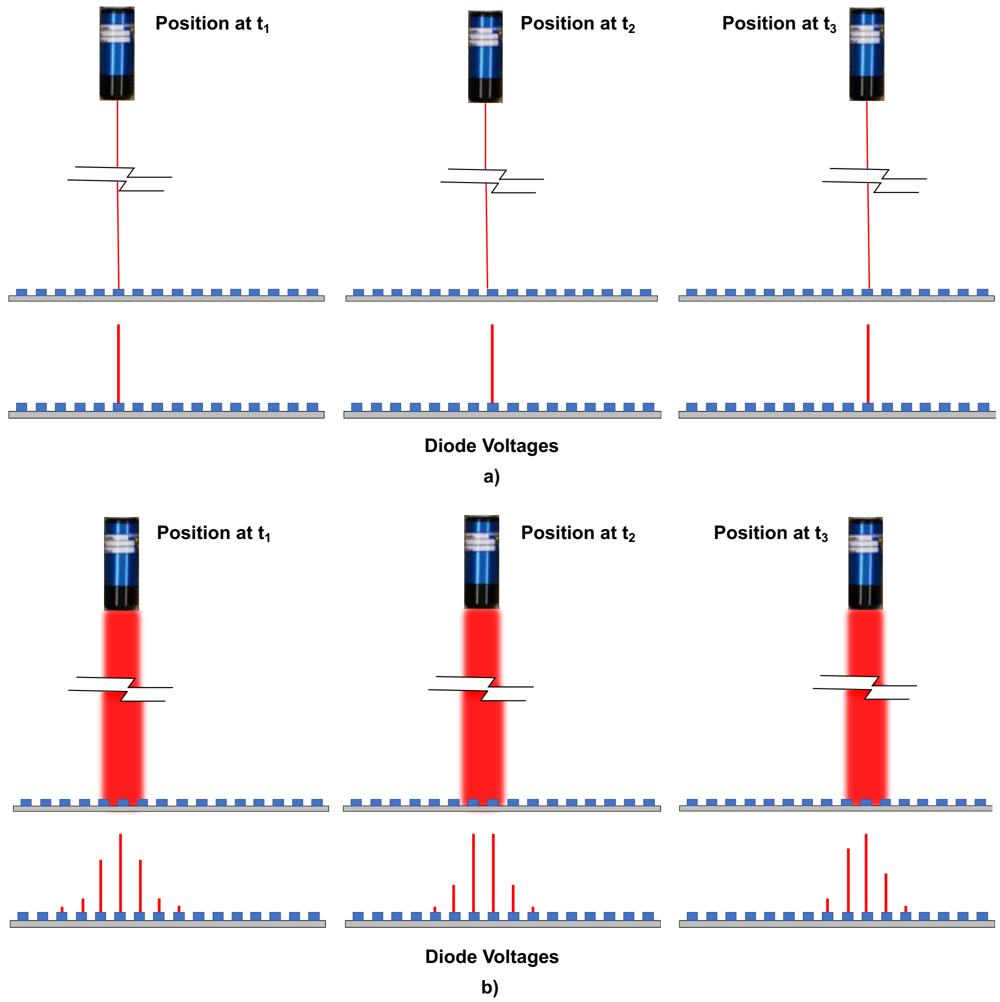

Fig. 5 – Conditioning of the incident laser beam. a) Sharp focused beam of the GENI and GENII DDPS designs; b) diffuse beam of the GENIII DDPS design.

The GENIII DDPS has undergone testing at the University of Nevada's Center for Civil Engineering Earthquake Research. A test bench was constructed using a precision-controlled air table that can be programmed to produce prescribed motions as shown in Fig. 6. To assess the displacement measurement performance, the GENIII sensor was subjected to sinusoidal motions at a selected range of frequencies including 0.2, 0.5, 1.0, 5.0 and 10Hz. The prescribed displacement of the air table, taken as measurement ground truth due to the high accuracy of the controlled displacements, were compared to the DDPS measurement of transient displacement at each frequency and selected comparisons are shown in Fig. 7. Across all frequencies tested, the DDPS displacement measurement was in excellent agreement with the imposed motion of the air table and the error in the DDPS displacement values were on the order of 0.5mm or less across the full range of frequencies.

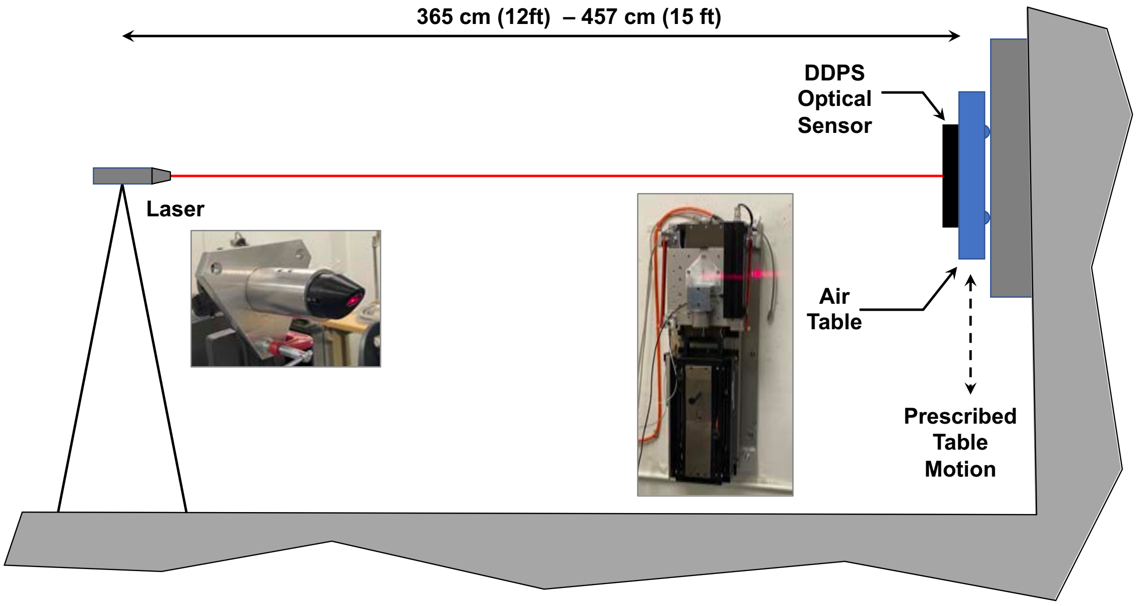

Fig. 6 – Optical sensor test bench configuration.

In addition to the sinusoidal test motions, the GENIII DDPS was tested for representative building interstory drifts. For this set of tests two representative building drifts were previously developed as part of the DDPS testing protocol [9, 10]. The drifts were developed from nonlinear finite element models of steel moment frame buildings subjected to strong near-fault earthquake motions. To span a range of building types, one drift was generated for a three-story steel frame building subjected to near-fault records from the Izmit Turkey earthquake, and one drift was generated for a forty-story steel frame building subjected to the Landers California earthquake (with the record corrected to include near-fault ground displacements). In both cases the buildings experienced large drifts and inelastic response leading to significant residual drifts in the building.

The drift displacement measured by the GENIII DDPS for each building is compared to the air table-imposed drifts in Fig. 8. As with the case of the sinusoidal motions, the DDPS measured motions exhibited excellent agreement with the imposed story drifts, including the ability to measure permanent drifts, and the amplitude of the measurement error was approximately 0.5mm for both buildings.

3. Sensor system field deployment

For any new monitoring system it is essential to gain field application experience to assess how technologies tested in a laboratory setting translate to actual deployment from the standpoint of deployed system performance and long-term reliability. The first field deployment of the GENIII DDPS was completed In September 2019 at Wang Hall, a modern steel frame building on the campus of the Lawrence Berkeley

National Laboratory in Berkeley California as shown in Fig. 9. Wang Hall resides in very close proximity to the Hayward earthquake fault, a major fault running along the eastern portion of the San Francisco Bay Area, and is thus in a zone of very high seismic hazard. The deployment included four sensors at selected locations in the building and with the objectives of:

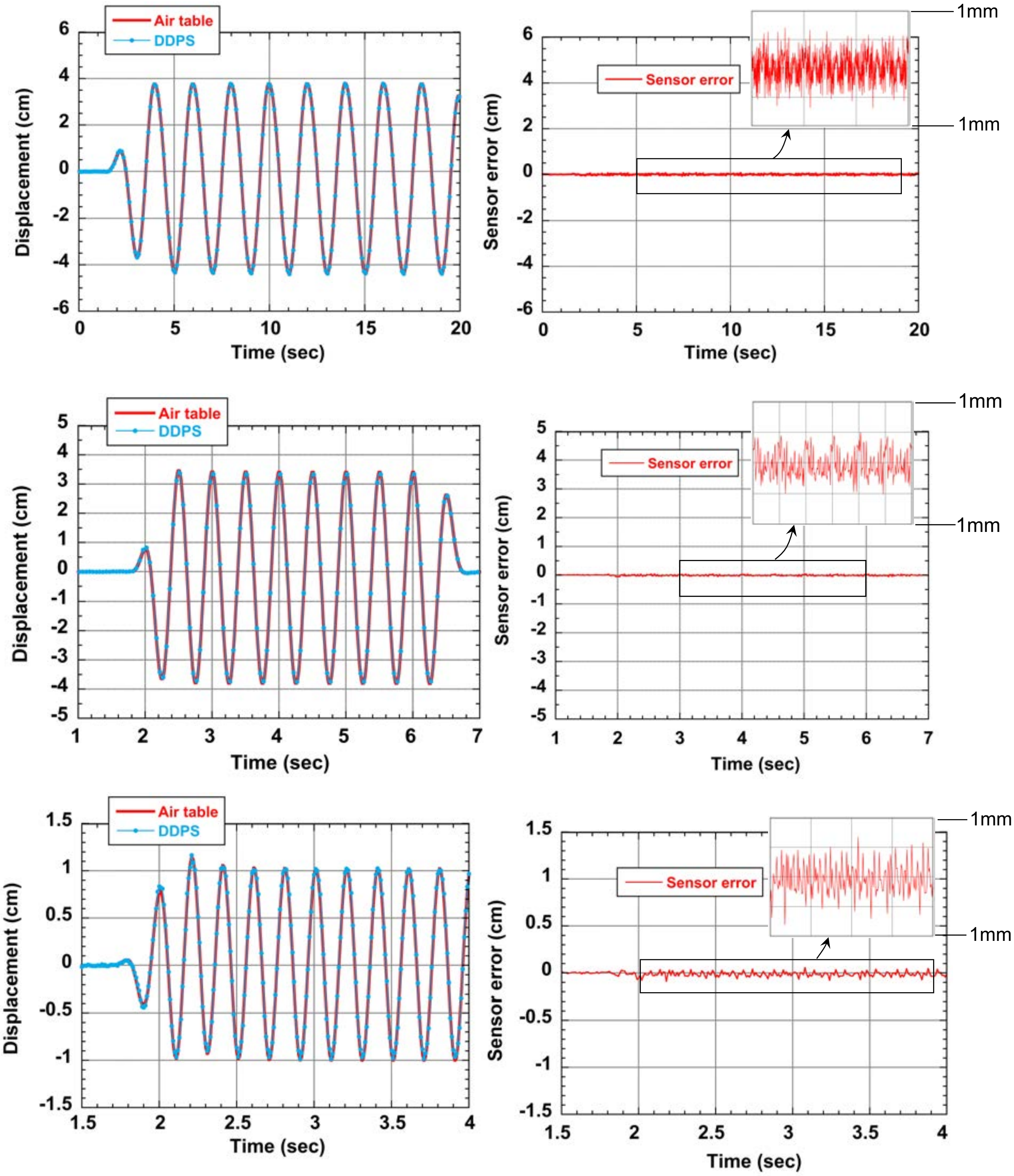

Fig. 7 – DDPS displacement measurement and measurement error for selected applied sinusoidal displacement histories of 0.5Hz, 2.0Hz and 5.0Hz (top to bottom).

- Evaluating the deployment strategy for a sensor system consisting of independent sensors with reliable back-up power systems and an RF communication system;

- Monitoring of the long-term functionality and reliability of the current sensor system design and components;
- Being prepared to capture the building response to frequently occurring small magnitude earthquakes in the San Francisco Bay Area as a first data acquisition for the sensors system;
- Testing and enhancing as necessary the wireless communication network to ensure remote access to both sensor health and operational status and any sensor data.

The deployment of the sensors on this existing building went very smoothly. With appropriate planning and preparation by Berkeley Laboratory staff, consisting principally of electric power drops, the four sensors were fully deployed in less than two days. The wireless communication nodes have been checked and the sensors can “see” each other throughout the building. Additional programming is in process to enable remote access through the Berkeley Laboratory guest computer network. The sensor system has been operational for approximately four months and the sensors are periodically manually triggered, simply by moving the centroid of each laser beam, to ensure the sensors are operational and ready to record. The only fault encountered during this early deployment period was a commercial power charger that prematurely failed and required replacement. This early operational success is encouraging in terms of the early inherent reliability of the monitoring system.

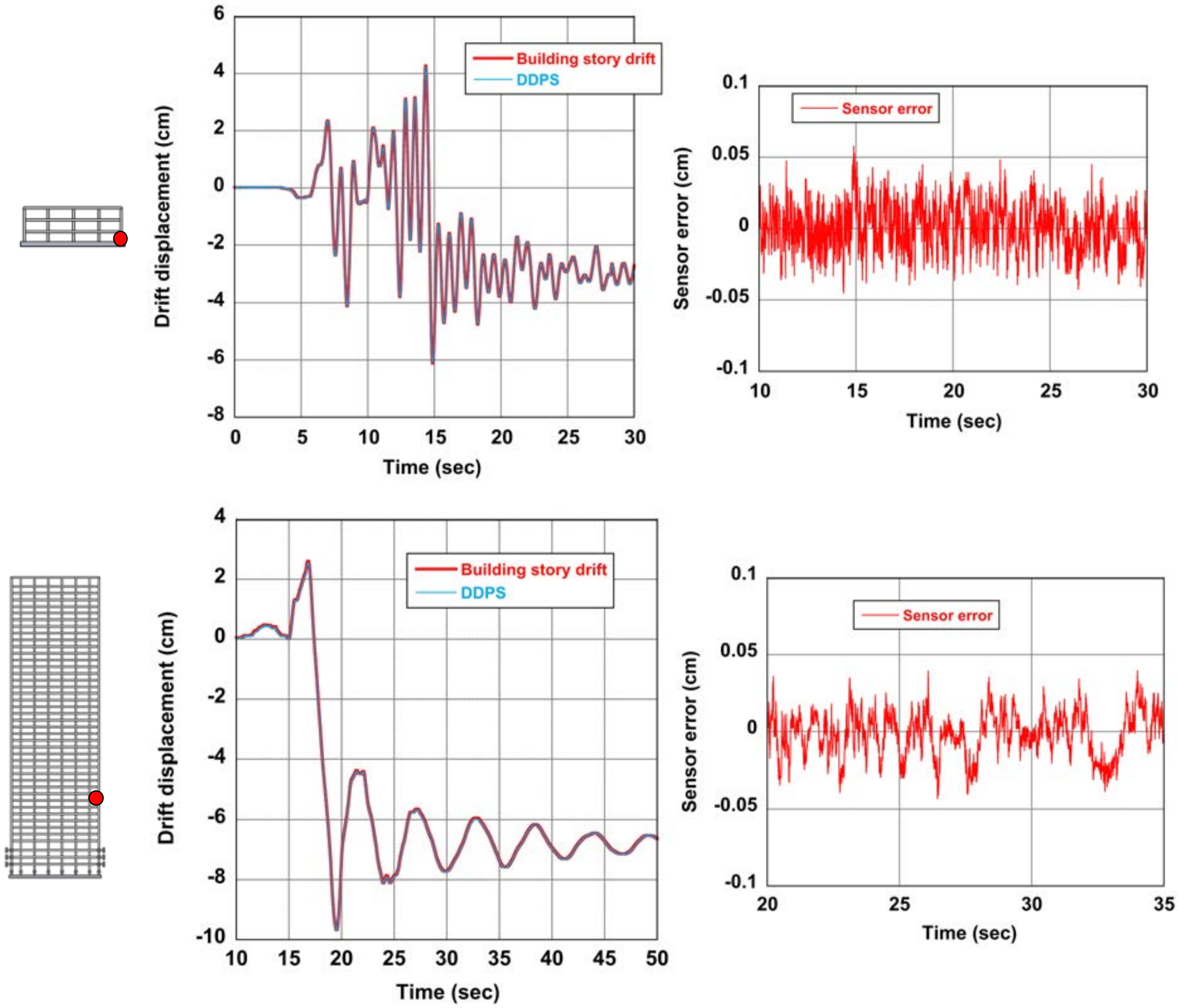

Fig.8 – DDPS displacement measurement and measurement error for representative earthquake induced building drifts.

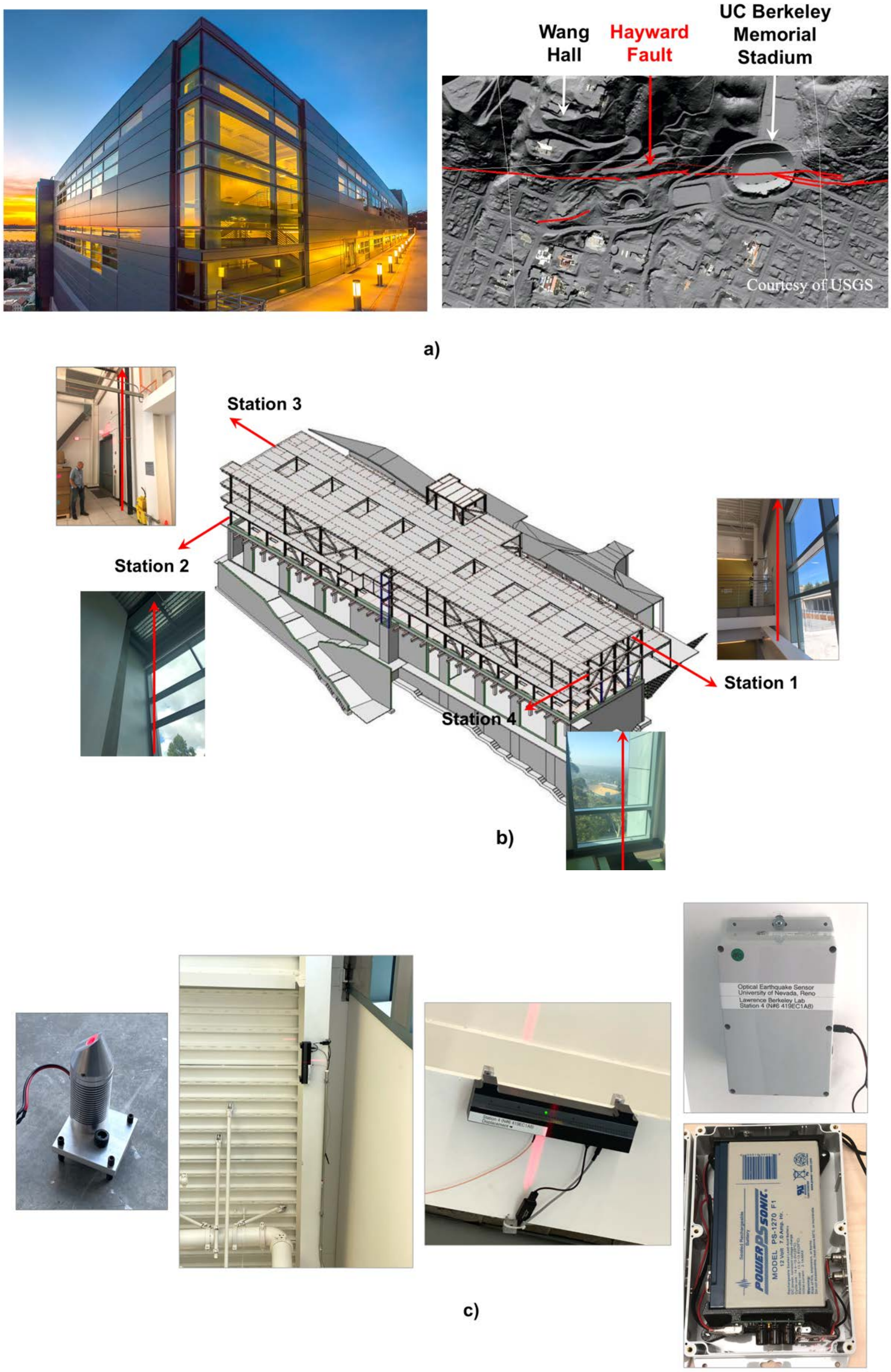

Fig. 9 – Sensor system deployment at Wang Hall on the Lawrence Berkeley National Laboratory campus. a) Wang Hall and proximity to the Hayward fault; b) sensor deployment locations; c) deployed sensor components – laser mount, DDPS, backup power system.

4. Conclusions

A technology that delivers, for the first time, the ability to directly measure structural displacements reliably and economically will provide entirely new pathways for effective, real-time Structural Health Monitoring (SHM). The potential for immediate, reliable information for post-earthquake decisions and actions can provide facility owners and stakeholders with new, crucial data for informed decision making and actions. The optical sensor technology embodied in the DDPS has matured and the performance and reliability of this technology has been established through an extensive series of laboratory experimental testing in combination with computational simulations [8, 9].

The next step is the full transition to practice and the systems engineering necessary to achieve a high reliability, high performance operational monitoring system. The research and development work performed to-date is providing the technology base and performance validation necessary to support a full building deployment with laser sensors and wireless communication. Full system design concepts, that rely on DDPSs and wireless communications, including a satellite node uplink for back-up data transmission in a communication degraded environment, are under development and will provide the next step towards broad application and deployment for real-time building monitoring (Fig. 10).

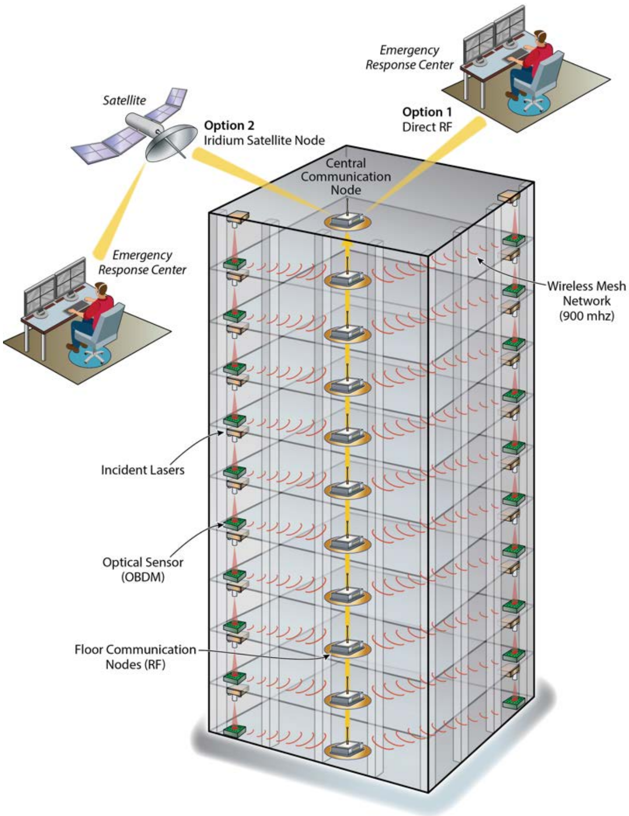

Fig. 10 – Building monitoring network design based on DDPS and a wireless communication network, a satellite uplink provides backup data distribution in the event of a post-earthquake degraded communication environment.

5. Acknowledgements

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