SmartSync: An Integrated Real-Time Structural Health Monitoring and Structural Identification System for Tall Buildings

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Abstract: This study introduces a unique prototype system for structural health monitoring (SHM), SmartSync, which uses the building’s existing Internet backbone as a system of virtual instrumentation cables to permit modular and largely plug-and-play deployments. Within this framework, data streams from distributed heterogeneous sensors are pushed through network interfaces in real time and seamlessly synchronized and aggregated by a centralized server, which performs basic data acquisition, event triggering, and database management while also providing an interface for data visualization and analysis that can be securely accessed. The system enables a scalable approach to monitoring tall and complex structures that can readily interface a variety of sensors and data formats (analog and digital) and can even accommodate variable sampling rates. This study overviews the SmartSync system, its installation/operation in the world’s tallest building, Burj Khalifa, and proof-of-concept in triggering under dual excitations (wind and earthquake). DOI: 10.1061/(ASCE)ST.1943-541X.0000560. © 2013 American Society of Civil Engineers.

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Introduction

Long before the term structural health monitoring (SHM) was coined, buildings were instrumented and monitored in situations where their performance was suspect, e.g., the John Hancock Tower in Boston (Durgin 1990). These unsavory origins made the concept of proactive monitoring, particularly for buildings, quite foreign, as owners were naturally reluctant to install instrumentation systems for fear that this may tarnish the reputation of their buildings. With growing need to assure life safety and rapid reoccupation in regions of high seismicity, full-scale monitoring applications began to flourish in the western United States as part of coordinated strong motion instrumentation programs. With such exposure, these early perceptions and attitudes have gradually changed with the advent and acceptance of smart building systems, which rely on instrumentation to assure and optimize the performance of elevators, various mechanical systems, and, in some cases, auxiliary dampers installed to limit building movements. In addition to some owners embracing the feedback from real-time monitoring, a number of research efforts have sought to validate structural performance and various design principles in full scale, not only for earthquakes but also wind events, as summarized in Kijewski-Correa and Cycon (2007).

One class of structure that is especially well suited to benefit from continuous monitoring is tall buildings. These structures affect the safety and comfort of a large number of people in both residential and office environments, and as state-of-the-art structural analysis software and wind tunnel testing used in the design of these structures are advancing rapidly, the accuracy and validity of their results need to be calibrated with respect to actual performance. This becomes particularly important to insure the economy and efficiency of future designs with increased complexity and height generally governed by serviceability and habitability limit states under wind that are especially sensitive to the amount of inherent damping in these systems. Unfortunately, only limited studies have pursued full-scale investigations related to habitability performance of structures (Ohkuma 1991, 1996; Denumon et al. 1999) and validation of their design practice (Littler 1991; Li et al. 2004), whereas most published full-scale damping observations under service conditions are derived from midrise buildings, associated largely with the well-known Japanese database (Satake et al. 2003). For this reason, the authors initiated the Chicago Full-Scale Monitoring Program in 2002 to...
permit the response of three tall buildings in Chicago to be compared against design predictions, including their levels of inherent damping (Kijewski-Correa et al. 2006a).

The SHM system historically used in many buildings, including the Chicago Full-Scale Monitoring Program, has been a wired system, often termed hub and spoke because of the fact that the sensors are located throughout the structure and then wired to a central data acquisition unit (datalogger). This is a proven technology that has been applied to a wide range of structures, but suffers from two significant issues associated with its cables: (1) instrument cables are very costly and difficult to deploy and maintain and (2) lengthy cables essentially serve as antennas, allowing noise to infiltrate the system. In the aforementioned applications to tall buildings, where response at the highest floor is generally the sole observed quantity, the wired hub-and-spoke systems have proven to be exceptionally reliable, e.g., have performed very well in nearly a decade of continuous monitoring in the aforementioned project in Chicago (Kijewski-Correa et al. 2006a); however, because this type of system originates from the small-scale laboratory setting, it becomes increasingly less practical in full scale when sensors are distributed over large, complex structures. Perhaps more importantly, the use of cables inherently creates a rigid system that cannot be easily reconfigured or expanded.

Thanks to a number of technology advancements recognizing these limitations and taking advantage of wireless communications, multihop radio or cellular relays have replaced cables in some recent applications to ease installation, relocation, and maintenance burdens (Kijewski-Correa et al. 2008). However, the passage of large amounts of data wirelessly increases the likelihood of packets being lost or other radio frequencies interfering. Further, although these radios may perform well in outdoor environments with line of sight, like bridges, communications within buildings have proven especially challenging, particularly on mechanical floors where these sensors are often placed. Moreover, the distributed nature of these systems requires some form of network synchronization.

In response to this need, this study presents a unique system the authors termed SmartSync, which leverages the strengths of the aforementioned architectures while minimizing their limitations, as summarized in Fig. 1. The SmartSync system uses the building’s existing Internet backbone as a system of virtual instrumentation cables. Given the reliability of modern local area networks (LANs), the issues of packet loss and synchronization are nullified, without the need for lengthy instrumentation cables that increase cost and noise. Furthermore, because this modular system is packaged to be plug-and-play, the units can be moved to any location with access to power and an Internet connection, removing an important technology adoption barrier to put SHM hardware directly in the hands of those best suited to advocate for it (building owners and management). Within this framework, data streams from distributed sensors are pushed through network interfaces in real time and seamlessly synchronized and aggregated by a centralized server, which performs basic data acquisition, event triggering, and databasing while also providing a powerful interface for data visualization. This enables a completely modular and scalable approach to structural health monitoring and can readily interface a wide variety of sensors, data formats (digital and analog), and even variable sampling rates. Furthermore, hardware costs are reduced because all acquisition functions are centralized at the server, and only basic network interfacing is required at the location of each sensor. Also, the flexibility of this modular system and the fact that all of its configuration and triggering operations are software enabled uniquely allows the system to be used concurrently for wind or seismic monitoring, with dual triggering mechanisms (top down versus bottom up) designed to activate the sensor arrays in case of either hazard. This paper will present the hardware and software used to realize the SmartSync concept in the context of its prototype application in the world’s tallest building, Burj Khalifa (formerly Burj Dubai), whose basic structural details will be first presented.

**Structural Overview**

Burj Khalifa, located in Dubai, United Arab Emirates, and known formerly as Burj Dubai, was completed in 2010 and crowned the world’s tallest building, measuring 828 m in height (Abdelrazaq 2010). The primary structural system, as described in Baker et al. (2007), is a 606-m buttressed RC core topped by a >200-m diagonally braced steel structure supporting the tower’s spire/pinnacle. The building’s Y-shaped plan consists of three wings,
each connected to the central hexagonal core to achieve this buttress effect. Walls extend from the central core through these wings to form hammer head walls that provide lateral resistance and create a torsionally stiff structure. In addition, outriggers connect the interior concrete core to the perimeter columns in each wing at the mechanical levels to decrease the overturning moment at the base.

As further discussed in Baker et al. (2007), extensive iterative wind tunnel testing was used in the design stage to achieve an aerodynamic profile that reduced the wind loads significantly. This included a setback scheme in a spiraling pattern to not only effectively modify the structural cross section with height in an effort to disorganize vortex shedding, but also achieve a desired aesthetic effect. This was enabled by the choice of structural system that provides a seamless means to transition to these reduced floor plates while maintaining a continuous load path to the foundation. Fig. 2 shows the site, including the main tower with its three wings, as well as pool and office annexes. The inset image provides further detail of the main tower’s cross section and its variation with height according to the continuous setback scheme, as well as the orientation of primary structural axes.

Given the unprecedented nature of this project, a real-time monitoring program capable of integrating measurements from a variety of sensors was requested by the owners, engineers, and construction team (Abdelrazaq 2010). Because the monitoring program was to be initiated during the later stages of construction and then be extended into a permanent system on commissioning of the building, a robust and rugged yet flexible and scalable system was required that would allow units to be deployed, redeployed, and augmented with ease to meet evolving monitoring needs. The following sections discuss the SmartSync modular hardware and software that were developed and deployed on this structure in two stages in response to this need.

Hardware and System Architecture

In SmartSync, sensor options are presented in a modular format that permits the customization of a monitoring package uniquely suited for the target application, which was particularly important given the evolving needs of building ownership from construction-stage to permanent monitoring in the case of Burj Khalifa. Each sensor module is housed in a ventilated, National Electrical Manufacturers Association (NEMA)-certified enclosure, which can be wall mounted at any location with access to building power and Internet. Within each enclosure, there are various supporting electronics, including uninterruptible power supplies (UPSs) and remote power regulators to provide control of power and reboot functions in event of a system failure to mitigate the need for on-site interventions following installation [Figs. 3(a–d, and f and g)]. The following sections discuss a number of sensing modules developed in this research that use sensors previously vetted in other tall building monitoring programs (Kijewski-Correa et al. 2006a, b) and discuss their physical deployment on Burj Khalifa.

**Acceleration Module**

Basic dynamic response measurements are achieved using an analog accelerometer module [Figs. 3(a and b)] featuring low-noise, force-balance analog accelerometers from Columbia Research Laboratories. These devices are highly sensitive to even the slightest motions, which are ideal for capturing the low-amplitude, low-frequency responses of a tall building. In the case of a torsionally stiff structure like Burj Khalifa, measurements are generally focused on the two lateral directions, and the biaxial sensors are mounted within the enclosure and installed in the service core, insuring accessibility for maintenance and installation, with the power cord and network line being the only external cabling. To provide a stable interface for long-term monitoring in especially harsh desert environments, in lieu of a lower-cost data acquisition over LAN interface, the accelerometers and their supporting programmable antialiasing filters interface with a Campbell Scientific Datalogger that samples data at 20 Hz. The acceleration module is suitable not only for monitoring the response of the structure, but by incorporating the triaxial version of these sensors, can serve as a seismograph to detect potential ground motions.

**Displacement Module**

The displacement response of any structure can be characterized by three components: mean, background (quasi-static), and resonant. When monitoring the wind-induced response of structures, all three components are present and quite important. In fact, studies have shown that the background response contributions can be as high as 20–80% for some structures in certain wind events (Williams and Kareem 2003). The only way to recover these components is by directly measuring displacements in full scale, a task that proved difficult until the advancement of global positioning systems (GPSs). This is an important addition to any monitoring program for tall flexible structures that exhibit significant mean and quasi-static deflections under winds, which cannot be recovered by

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**Fig. 2.** Site plan of Burj Khalifa with inset detail of cross-sectional shape setting back with height

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accelerometers alone (Kijewski-Correa et al. 2006b). It should be noted that GPS is not an off-the-shelf technology, as often perceived. In fact, the continuous variation in satellite visibility and orientation, as well as the potential for multipath distortions, requires considerable signal processing and compensation to achieve consistently reliable measurements (Kijewski-Correa and Kochly 2007). For this module, the Leica AT504 GG choke ring GPS antenna [Fig. 3(e)] must be placed external to the enclosure and connected by a short length of coaxial cabling with in-line surge protection to the Leica GRX1200 GG receiver within the displacement module enclosure [Figs. 3(c and d)], acquiring data at 10 Hz. Additionally, the need to produce high accuracy displacement measurements (subcentimeter accuracy) requires a second displacement module to be installed on a stationary nearby structure (termed the reference site). Measurements taken at this location as well as on the primary structure being monitored are processed against one another on a dedicated GPS server to reduce atmospheric interferences that degrade the accuracy of GPS displacements. The corrected displacements are then streamed from this server at 10 Hz in near real time.

**Meteorology Module**

This module offers a direct measurement of on-site weather conditions, with wind speed and direction being the most relevant to...
evaluate dynamic responses of tall buildings against wind tunnel predictions. In this case, the sensor again must be external to its electronics enclosure, requiring a relatively short cable run with in-line lightning protection. The instrumentation should have sufficient durability to withstand the harsh extreme winds; thus, it is desirable for the anemometer to be as compact as possible with no moving parts, which makes ultrasonic devices like the Vaisala WXT520 Met Station [Fig. 3(h)] a viable option even in tenant-occupied areas. This digital technology streams data, including temperature, humidity, and barometric pressure, at a rate of 1 Hz through the same Campbell Scientific Datalogger [Figs. 3(f and g)] used in the acceleration module.

**Construction Stage Module Deployment**

The first SmartSync prototype was deployed in Burj Khalifa during the final stages of its construction in July 2008. As discussed in Abdelrazaq (2011), this system included one analog accelerometer module, a pair of GPS modules (reference and rover), and a meteorological module to monitor the structure’s responses and environmental conditions at Level 138. In addition, a digital accelerometer module was included at the prototype stage for the purposes of validating the stability and sensitivity of a Summit Industries digital sensor with direct-LAN interfacing capabilities. Fig. 4 shows the GPS antenna and meteorological station on the balcony at Level 138 of the tower, as well as the internally installed enclosures anchored to the core wall at that level. Because of the negligible torsional response anticipated, the biaxial accelerometers are installed only at the core to monitor lateral response in the building’s two primary axes, denoted previously in Fig. 2. At this stage, the reference GPS was installed on the roof of the adjacent pool annex, also shown as deployed in Fig. 4.

**Permanent Module Deployment**

This system was later expanded in the summer of 2010, with re-location of these units (with the exception of the prototype digital accelerometer) and addition of other hardware as part of the permanent building movement monitoring system (BMMS) (Abdelrazaq 2010). As further described in Abdelrazaq (2011), this

*Fig. 4. Construction stage SmartSync deployment in Burj Khalifa at single level defined in Abdelrazaq (2011); note: object linking and embedding for process control (OPC) is used for communication between the data loggers and the server.*
Fig. 5. Screenshots of user selection of real-time data display (inset) and resulting interface to view (a) real-time data streams and (b) power spectral densities of accelerations based on current buffered data at multiple levels defined in Abdelrazaq (2011)
expansion was executed in partnership with Cermak Peterka Petersen (CPP), Inc. and included acceleration monitoring at six points along the height of the tower: Levels 73, 123, 155 and 160M2, Tier 23A, and the top of the Pinnacle—all focused near the building centerline to capture only lateral responses in the primary axes of the structure and including displacement and meteorological monitoring on the balcony of Level 160M3. These locations represent readily accessible levels that still had significance for the dynamics of the structure or mark transition points between various aspects of the lateral system. In addition, triaxial accelerations are monitored in each of the wings at the base of the structure. The GPS reference station was also relocated to the roof of the Office Annex as part of this final phase of deployment.

Software-Enabled Data Delivery and Management

The realization of a LAN-based architecture significantly depends on the software development operating on the system’s centralized server housed within the building being monitored. In the case of Burj Khalifa, the adoption of a software-enabled data delivery and management system was essential to not only effectively integrate distributed, heterogeneous sensors belonging to the authors but also to effectively integrate the uniquely formatted data streaming from a completely different set of hardware installed by the CPP team. The server is responsible for coordinating five essential functions: (1) data receipt and processing, (2) statistical analysis and archiving, (3) triggering and archiving, (4) real-time display, and (5) online data analysis, with the robustness to integrate both analog and digital sensing elements with variable data formats and sampling rates, to provide an efficient means to archive and retrieve the large volumes of data anticipated over the life of the deployment, and to support real-time, secure remote access, and visualization of data streams. The extent to which these processes, as well as basic data curation and analyses, could be automated to minimize human interventions was an equally important design parameter.

All data acquisition operations in SmartSync are programmed in LabVIEW at the central server, whereas the higher-level processing and analyses are facilitated by web-based online modules running on an additional analysis server with results pushed to web-accessible user interfaces that are streamlinied using the authors’ e-technology scheme (Kwon et al. 2008). This allows an automated system that collects data in various formats, transforms all voltages to physical engineering units, adjusts all inclined sensors to yield results on the primary building axes (shown previously in Fig. 2), and corrects for any bias or drift in the sensor outputs. In the case of GPS

![Fig. 6. Screenshots of user selection of real-time statistics (inset) and resulting interface to view the latest 10-min statistics from sensors at multiple levels defined in Abdelrazaq (2011)](image-url)
measurements, this includes removal of the GPS baseline position as locked down by international positioning services using multiple regional reference stations. One challenge that arises when using distributed sensor modules, similar to the situation in wireless sensor networks, is the challenge of synchronization. Each module has a different clock with its own accuracy, and the precision of these clocks would make strict synchronization across devices a challenging and ongoing concern. SmartSync makes this issue irrelevant by not relying on the clocks and time stamps at individual devices but instead ties everything to the clock of the server. When the LabVIEW code executes a call for sampling data, it is collected simultaneously across all the distributed devices. All data captured at the time of this request are thereby tied to the same time stamp, that of the central server itself. Certainly there exists some potential network latency, usually less than 1 ms in a reliable LAN environment, but this has been observed to affect more the data delivery to the server and not the call to transmit data. Because the unified time stamping occurs at the moment when data delivery is requested across the network, even if the data are slightly delayed in its arrival at the server, this is of no consequence. To insure reliability of this data delivery, transmission control protocol/internet protocol (TCP/IP) is invoked as a stable stream delivery service that guarantees transmission of data sent from one host to another without duplication or loss, ideally suited for data from variable sensors coordinated over LAN. It is noted that the Nagle algorithm is used by default in TCP communications in most operating systems, such as Windows, as one of the basic algorithms that helps reduce internet traffic by combining several small packets into a single large one. However, the algorithm can introduce some latency for situations where small amounts of information are being sent back and forth, such as in instrument handshaking. Accordingly, in SmartSync, the Nagle algorithm is forcibly turned off to remove a potential TCP delay, which can be controlled in the LabVIEW code.

As the data are received from each module, at variable sampling rates, buffers accumulate the data over predefined intervals (10 min) for real-time dissemination to authorized users, and statistics from all sensing modules are stored in terms of a database management system (DBMS), e.g., MySQL (MySQL AB). Even though large volumes of data storage are relatively inexpensive nowadays, for long-term monitoring programs such archiving of statistics, proves

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**Fig. 7.** Screenshot of user selection of archived statistics (inset) at multiple levels described in Abdelrazaq (2011) and resulting interface to query statistical archive by date; pop-up inset depicts calendar date selection tool

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to be far more efficient than continuously storing time histories that often are nothing more than low-level ambient vibration and then having the burden of mining those massive stores of data later.

However, detailed analysis must be conducted using data from significant events. For this reason, a server-level triggering methodology is incorporated using a moving windows analysis of the buffered data to determine whether the response has exceeded a predefined threshold at a master module in the network, in which case continuous time histories would be archived synchronously for all the sensing modules. For wind events, this master module would generally be the accelerometer at the uppermost floor, whereas in seismic events, the accelerometers at the ground level or free field would be queried. It should be emphasized that because triggering is handled by the server, which is based only on the response of a particular master accelerometer module and not designed a priori into the hardware, the system can be easily expanded and readily triggered for either excitation source, as the trigger level and even data stream used as the master feed for triggering can be regulated with ease, including reducing it to zero to create continuous recording of data. Both the running 10-min statistics and triggered time histories collected by the central server are also backed up daily on the off-site server via file transfer protocol to mitigate potential data losses caused by a system failure.

In addition to data acquisition and triggering, SmartSync also supports various data visualization and analysis features through a secure web portal: real-time modules such as streaming data visualization and the latest 10-min statistical display, and on-demand modules such as triggered data archive, daily statistical archive query, and spectral analysis. By selecting the real-time data stream option (Fig. 5), authorized users are capable of viewing data in two formats. The first tab accesses the time histories [Fig. 5(a)], with the right two panels providing real-time feeds of accelerations and displacements at the highest levels of the building as a function of time or plotted spatially in the x,y-plane. The left top panel of the interface has dials to display the real-time wind speed, direction, humidity, and temperature, whereas the bottom left panel displays the statistics of the acceleration and displacement responses. The second tab allows users to view the latest buffered 10-min data as a power spectral density at multiple levels [Fig. 5(b)]. On the other hand, selecting the real-time 10-min statistics interface (Fig. 6) outputs a quick summary of the most current wind field and response statistics at all locations in the instrumented building, including the three wings at the base of the structure. Similarly, the daily statistics can be accessed (Fig. 7) on demand such that the values (maximum, minimum, SD) at each level are mined from the archival statistics, using a calendar tool to select the date of interest. In addition, triggered data sets can be viewed and downloaded by authorized users through a web library as shown in Fig. 8.

In addition to the basic spectral information available from 10-min records in real time [Fig. 5(b)], a higher-quality spectral analysis can be requested by selecting a triggered 1-h time history. This results in a multitab web display [Fig. 9(a)], whose first tab shows the overview of all upper level accelerometers with the time

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**Fig. 8.** Screenshots of user selection of archived triggered data (inset) and resulting interface to show lists of triggered data to date
histories and the power spectra for the selected triggered data. Subsequent tabs allow users to select a specific location along the building height and view the time history, corresponding power spectra, and basic system identification (natural frequency and damping estimates) for each accelerometer from a triggered event [Fig. 9(b)]. The final tab on the interface provides wind velocity time histories and wind roses for the selected event [Fig. 9(c)].

To automate the basic system identification provided by this module, a reliable method to identify the peaks corresponding to the actual modes of the structure was required. Because of the variance

Fig. 9. Screenshots of user selection of on-demand spectral analysis (inset): (a) user interface to select a triggered file to analyze; (b) example of selected accelerometer time history, power spectral density, estimated properties; (c) wind speed and direction
of power spectra from limited amounts of data, more than a hundred peaks (local maxima) can be identified in a given spectrum, many of which are a cluster of several local maxima. Particularly in the case of Burj Khalifa, this phenomenon is even more complicated because of the number of closely spaced modes in the structure. Therefore, an algorithm was developed that first identifies all local maxima in the spectrum [Fig. 10(a)] and then executes the average linkage method (Morse 1980) to classify all potential clusters among the identified peaks [Fig. 10(b)]. To then determine whether the clustered spectral values are physically meaningful, a repeatability check is executed to verify that an identified cluster frequency recurs in other spectra in the array, which one would expect for any physical modes. The result of this process causes all nonrecurring spectral values within a given cluster to be averaged together.

Even after this process, some spurious peaks with nonnegligible amplitude persist and are then eliminated by a subsequent thresholding operation based on the statistics of the peak distribution over a moving window of 0.1 Hz, to adjust the threshold accordingly for the relative participation of various modes in the spectrum. In some cases, coupled modes will display a pair of peaks with one having relatively larger amplitude in a given axis of the building. The companion mode (with smaller spectral value in that direction) may be eliminated during the thresholding process. Thus, a final repeatability check is conducted to reinstate any of these companion peaks in coupled modes that were erroneously removed in the thresholding process. The end result, shown in Fig. 10(c), is displayed in the user interface in Fig. 9(b). Each of the identified clustered peaks is used to estimate of the frequency and damping of that mode using the half-power bandwidth approach for simplicity, although any other approach can be implemented in the future. This result is displayed on the right side of Fig. 9(b). Even with these measures, the level of variance in the spectra generated from a single hour of ambient vibration data are far too significant to be used for any reliable system identification, as only one raw low-bias spectra can be generated from an hour of data for this very flexible structure. Accordingly, more accurate data processing requires the use of a series of triggered time histories (Kijewski et al. 2006a), downloaded via the triggered data archive as shown previously in Fig. 8.

Proof of Concept
SmartSync has been deployed on Burj Khalifa since late 2008. Given its unique software-enabled triggering functions, a verification of the system’s ability to effectively trigger under either earthquake or wind excitations is now presented as proof of concept. Since 2008, a number of earthquakes have originated from southern Iran and sufficiently excited the building to trigger the system, one of those being the September 10, 2008, magnitude 6.1 earthquake that struck the region of Bandar Abbas, approximately 1,368 km (850 mi) south of Tehran. Fig. 11 displays the acceleration responses along the two primary axes of the structure as measured by the construction stage accelerometer module. The variations of the modal participation with time are explored using the wavelet analysis framework discussed in Kijewski and Kareem (2003) and confirmed the participation of approximately five modes in each of the response axes. The results affirm the dominance and persistence of the fundamental mode in the x-axis responses, with intermittent content at higher frequencies during the strongest shaking between 250 and 350 s. Two of these contributions correspond to the predicted third and fifth sway modes in that direction. The y-direction response does not show the same dominance of the fundamental mode, with the most significant energy again being associated with the frequency of 0.6 Hz, although for only about 1 min. Two of the higher modes participating correspond to the predicted second and fourth sway modes in that direction. Fig. 11 also shows the resonant component of the GPS displacements during this event, dominated by the fundamental modes, reasonably agreeing with the wavelet analyses of the accelerations during this event. Additional system identification results verified that the observed frequencies were within 2–3% of finite-element model predictions (Abdelrazaq 2011).

The first substantial triggers of the system under wind occurred in March 2009; a sequence of triggered records from March 30, 2009, is provided in Fig. 12. This figure displays the wind speed and direction over a 24-h period. Inset images provide snapshots of the triggered building responses correlated to their time of occurrence on the wind speed plot. The peak accelerations associated with each inset plot are reported in the figures, as the axis scales can be hard to view given the image size. During the most sustained response, the wind speed intensifies to a mean value of 37 km/h (23 mi/h), primarily from the east-southeast. Airport records indicate that thunderstorms were in the area at this time, which have been shown in other studies to produce noteworthy responses in similar structural systems (Bentz and Kijewski 2011b), particularly because this wind direction is known to be one of the higher-impact angles from wind tunnel testing of Burj Khalifa (Baker et al. 2007).

Concluding Remarks
This paper presented a modular structural health monitoring framework interlinked by SmartSync technology that enabled the flexibility to tailor a customized global monitoring system that can be expanded and deployed with plug-and-play ease in the world’s

Fig. 10. Three-stage peak identification algorithm by clustering analysis: (a) all identified peaks; (b) all peaks identified by cluster analysis; (c) identified dominant modes of vibration

Fig. 11. Measured acceleration and displacement responses in September 10, 2008, earthquake.

Fig. 12. Measured wind-induced accelerations on March 30, 2009: inset accelerations are shown indicating on the wind speed and direction plots the times at which they were triggered with peak accelerations reported for each axis; inset cross section of building indicates the angle of attack for the triggered wind events and the primary axes against which responses are measured.
tallest building, Burj Khalifa. In particular, because the SmartSync communications infrastructure is local area network based, it can adapt easily to the evolving needs of building use without hardware redesign and the need for lengthy cable runs, which would not only be costly but incredibly inefficient in tall and complex buildings. This proved particularly important in the application case study herein, where monitoring both during construction and after commissioning by a heterogeneous array of sensors was required. This paper overviewed three different hardware modules, as well as the automated data acquisition, curation, and archiving functionalities of the system. Various web-based online modules were presented to demonstrate the range of data mining, postprocessing, and system identification capabilities available through a combination of real-time and on-demand services. Two proof-of-concept demonstrations are provided to verify the ability of a software-enabled triggering framework to effectively monitor both seismic and wind events from different master modules to offer a truly multihazard platform for monitoring of Burj Khalifa.

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References

LabVIEW 8.0.1 [Computer software]. Austin, TX, National Instruments.