A Brief Overview of Structure Health Management and How Emerging GPS Technologies Can Augment the Process In Ensuring Proper Structure Management

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I. Abstract

There exists a large movement within the U.S among policymakers and infrastructure professionals to improve the current state of U.S infrastructure. Structures within under both federal and state maintenance received long term; continuous scrutiny due to poor maintenance schedules and underfunding of structural health monitoring efforts. This work will provide a review of basics of structural health management, a general survey of existing legacy systems, and how emerging technologies in GPS allows for millimeter level precision among measurements needed to provide accurate analysis for determining structural health. High precision is desirable, especially in large scale structures such as bridges, dams, and skyscrapers. The drawbacks that are present in current research is also discussed and qualitatively compared with existing measurement systems. Future consideration into further research for GPS based structural health systems is considered as concluding remarks of the topical review. Final synthesis of the topic lead to the culminating statement that GPS receiver technology, with additional testing and research, provide a cost-effective and convenient system to either discreetly apply or augment exiting health monitoring system.

II. Variable Convention

ρ	=	Pseudorange
S_i	=	Geometric Range
R_i	=	Geometric Range Minus Clock Bias
x_i, y_i, z_i	=	Satellite Position
x, y, z	=	Receiver Position
b	=	Clock Bias
N	=	Integer Ambiguity
λ Wavelength	=	
DD	=	Double Difference c
Speed of Light	=	
P	=	Corrected Pseudorange
I	=	Ionospheric Delay
T_r	=	Tropospheric Delay
ε_P	=	Random Error

III. Introduction

When taking into consideration all items required for public municipalities and the federal government to provide adequate structures for civilian use (Such as bridges, dams, and buildings), it requires considerable amount of engineering for the structures themselves to be built up to consistent, regular, and even anticipating an increase in its respective use. Such conditions may lead to adverse characteristics of stress, strain, and fatigue that the structure may not have been designed to withstand, even with the usual safety factor engineering in place. That has been a major problem in the U.S road infrastructure system for the last several decades. An example would be the over-land and over-water bridges. About 1 in 4 bridges currently operational in the US are conditionally deficient. Of all the bridges in operation, 10 percent of the bridges are structurally deficient, where stress, strain, and fatigue parameters no longer meet design and load conditions. In addition, of all the bridges in operation, 14 percent are deemed to be functionally obsolete, where not only do the maintenance subsystems no longer function properly, but some have not been regularly maintained in a very long time and would require significant capital and labor investments [1]. Such investments may not be justifiable as similar investments could be made to create new structures that can better maintain safety and regulatory codes with lower maintenance inputs due to improvements in construction process and materials being used. Recently, the policymakers saw the advantage of overhauling such infrastructure systems instead of retrofitting existing ones. A significant portion of the U.S Infrastructure bill that was passed in November 2021 is attributed to construction of bridges in large traffic flow areas. With construction plans of new structures being developed, methods of maintenance are also being explored with similar scrutiny. A standard that is currently being developed is called Structural Health Monitoring (SHM). It is a process of assessing the health of structures through an automated system while the structure is still in service [2]. Several methods are available for automatic data collection. These systems include but are not limited to inertial accelerometers, laser scanners, fiber optics, etc. [3]. The analysis will focus on GPS receiver systems used in SHM protocols and their levels of precision and accuracy of data. A brief overview of GPS fundamentals will be introduced to provide context behind the techniques used to derive displacement measurements of structures for SHM. The advantages and drawbacks of GPS receiver-based measurement systems are considered which is shortly followed by analysis of the measurements derived by the GPS receiver technologies. Parallels are made between accelerometer data measurements to identify key areas that may have inconsistencies between differential patterns or magnitude of displacement. Prospects of GPS receiver-based deflection measurements are briefly discussed and their potential large-scale viability in applying SHM principles.

IV. Brief Overview of Structural Health Monitoring (SHM)

The design methodology used to ensure structures can withstand stresses imparted on it. Such structures will deteriorate with time. The long life-cycle degradation of such structures are a result of cyclic load and environmental factors that may be difficult to account for in design conditions (e.g corrosion, carbonation of concrete). In addition, structures can also be adversely affected by black swan events such as earthquakes, tornadoes, hurricanes, and floods. Often, these events can significantly alter the structural definition and behavior respectively. An example of a structure under such conditions are waterway bridges. They undergo significant cyclical loading as the entry and exit traffic flow various with speed and mass. In addition, earthquakes and hurricanes can significantly affect structural integrity of bridges due to the structure experiencing magnitudes of loading in direction where loading is not optimized for [2]. An example of such loadings leading to failure is the I-35 Highway bridge collapse. Most maintenance programs beside SHM are comprised of visual inspection campaigns undertaken by experts to evaluate structural conditions. However, these observations prove it difficult to accurately provide sound evaluation on the status of structural health.

A standardized process to implement damage identification and health evaluation for structures has been under study for some time. As a result, the concept of SHM, the use of sensing systems involving hardware and software to provide a host of services while the structure is in service. They include, but are not limited to, rapid condition assessments through sampled measurements, data analysis involving SHM output for current structure capability and forecasting future structure capability and degradation and using periodically sampled data to obtain current performance conditions.

A. SHM System:

Two factors are important in developing a successful SHM system: Measurement technology and a workflow process for data analysis and interpretation algorithms. As different structures call for unique SHM system architecture. The basic categories involving collection and analysis of the data is as follows [2]:

1) Observation: collection, processing, analysis and reporting of all observed (measured or derived) data from the sensory systems
2) Evaluation: real time structural performance analysis coupled with off time prognosis analysis during regular operation or black swan events
3) Rating: Prioritizing structural components for scheduling inspection/maintenance activities
4) Management: Systematic storage and usage of data for optimizing analysis and archival workflow

An example of the categorical application can be seen in a bridge monitoring SHM strategy. The strategy is broken into two sections: Global monitoring, and Local monitoring. Global monitoring approach involves instrumentation and measurement technologies are used to identify if there are ANY damage or structural anomalies present in the whole structure. These instrumentation can include accelerometers, camera deflection systems, or laser vibrometers. Local monitoring approach involves localizing the damage areas. Such measurement technologies include guided ultrasonic waves and eddy currents. Combination of global and local measurements are acquired to satisfy the above mentioned four basic categories.

B. SHM Strategy Example- Damage Information

Damage to a structure is defined as changes in materials and geometric properties that is not part of the design language which can adversely affect the structures current and future performance. SHM identifies the damage by identifying and evaluating levels of data acquired. SHM strategy used is outlined by the following levels [4]

• Level 1: Detect Damage: Qualitative information on whether damage is present (Visual Inspection) • Level 2: Damage Location: Information on probable position of the damage • Level 3: Damage Classification: Information on damage type • Level 4: Damage Assessment: Information on magnitude of damage • Level 5: Damage Assessment: Prognosis of structural safety

With increasing levels, there is a requirement for increase fidelity of data and knowledge of damage state being collected. Level 1 and Level 2 data can be acquired from structure deflection and dynamic response measurement methods. For Level 3, correlation of previously measured data must be available for adequate classification of damage type. Level 4 and Level 5 require analytical models of damage occurred to provide accurate prognosis of structural integrity. Efficiency of the SHM system responsible for such data collection can be outlined by proper implementation of the following strategies: Monitoring of operational environment, monitoring integrity of material, monitoring structure shape (usually for large structure such as high-rise buildings and vehicle bridges).

For monitoring operational conditions, parameters such as ambient temperature, localized temperature, and localized loading data is collected. It is important to have the capability to collect as many operational parameters as possible as structural anomalies can result from a multitude of sources [4]. Material integrity data acquisition is difficult as it requires use of specialized sensors located close to inspection sections. Reliability and calibration of such sensors must be monitored carefully to assure the SHM can provide accurate data. Shape deformities can be monitored with a visual inspection protocol in place by the structure management team. A simple example could be a tolerance limit being placed on a localized section for average deflections. A violation of the tolerance could mean failure of structure subcomponent or usage of structure beyond working limits.

C. Technical Challenges

Technical challenges to SHM deployment are a significant proponent preventing industry from widespread SHM adoption. The complexity of SHM data collection requires used of different technologies that may have inter compatibility issues (differing sensors, communication systems, data processors). This can lead to reliability issues with both acquiring measurements and within the analysis workflow. Beside data acquisition challenges, issues with limited processing resources on site, such as limited energy storage, data transmission capabilities, and processing power available pose tangible resistance to widespread use. Since accuracy and abundance of data are key factors in establishing a prognosis, standardization, and certification of SHM technologies and strategies may be required before widespread adoption can be seen.

V. Global Measurements Using GPS Technology

A. Global Measurement: Intuition Behind Deflection Measurement

One of the most important global measurements acquired for SHM use for vehicle bridges are deflection measurements. General inspection of bridge behavior consists of considering static and dynamic loading. Although dynamic loading investigations have been performed for quite some time, the protocols are not standardized. Each structure management and maintenance team must derive their own protocol for the respective. Theoretical analysis of structural behaviors under dynamic loading is extremely complicated and is not practical for use in the field. As a result, such methods are rarely used. Most structures are heavily designed around static analysis and predicted behavior. However, since vehicle bridges are constantly experiencing dynamic loading with varying levels of traffic flow and total structure mass including vehicles. In addition, there is increasing pressure on the use of more sophisticated and frequent execution of dynamic loading because of increasing vehicle axial pressures and speeds, along with the use of lighter materials for construction, which is susceptible to dynamic action [9].

Evaluation of bridge dynamic characteristics consists of the following parameters: forced/free oscillations, amplitudes of oscillations, and frequencies of respective oscillations. Most displacement measuring systems will try to have sensors at midspan of the bridge. Generally, a bridge is the least supported near midspan and most supported near traffic entry points. This provides the basis for the assumption that midspan deflections will yield highest amplitudes and possibly, varying frequencies. However, most deflection measurement systems will collect a combination of points to identify regions of operations to help the SHM system narrow down on localization of structural damage. For example, instead of having strain gages on just the mid span, there will be strain gages located at each base, quarter-span, and mid span. Width wise section sensor placement may vary as the section cross-sections themselves may change over the course of the structure start to end. It need not necessarily be symmetrical. Rarely is it so as the base of each bridge is located at different location. Each location has its own surface gradient, elevation, and material needs to maintain structural integrity.

B. Legacy Systems and Drawbacks:

Legacy deflection measurement systems involved use of inertial/inductive measurement systems. Such sensors include but are not limited to inductive displacement transducers, strain gages, and accelerometers. However, there are some logistical considerations to examine. Most of these sensors require access to the area under the investigated structure. These sensors are then connected to each other through a series of data link wires. This means the area under the investigated structures must be always available for proper sensor setup and maintenance that may be required. [9]. Accelerometers do not require reference points. However, the low frequency vibration of bridges cannot be acquired. As a result, it is mostly used in static loading measurements. Commercialized photogrammetric methods address both concerns of the lack of bridge underside space and collecting dynamic loading measurements from the inductive sensors and the accelerometers respectively [8]. However, supplemental camera and survey equipment is necessary to increase accuracy of displacement measurements. Since camera systems are susceptible to quality defects from environmental factors (includes but is not limited to ambient inclement weather, surface vibrations, and vehicular vibrations), they require additional reference cameras, survey sensors, and instrumentation to provide the level of measurement precision required for accurate displacement observations.

The GPS displacement measurement system addresses both issues of dynamic loading sensitivities and minimizing equipment overhead needed. In addition, GPS technology exhibits several unique advantages such as ease of obtaining absolute displacements, ambient climate independence, autonomous operation, and not requiring a line of sight between target attributed to signal propagation [1]. In the following sections, the basics of GPS technology will be described and a review of how this technology is applied to bridge deflection reading will be provided.

C. Principles of GPS Positioning

The GPS system is made of 3 subsystems: satellites orbiting the Earth, satellite monitoring stations on Earth, and the individual GPS receiver in operation. The true range between a given satellite is given by the following formula:

$$S_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{1}$$

Where ith subscript term is the individual satellite in the GPS satellite constellation where (xi, yi, zi) is the position of the ith satellite, and (x, y, z) is the unknown position of the receiver. In an ideal environment, three satellites would be necessary to solve for receiver position. However, due to clock differences between each satellite, and the receiver, there is an additional clock bias term that must be added to account for the clock error corrections (Note: b is the clock bias term) [7].

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b \tag{2}$$

In addition to the clock bias correction, path delay between the Earth's ionosphere and troposphere also needs to be taken into consideration as signals do not propagate the same way through the atmosphere as they do in vacuum of space. Furthermore, there is an additional noise component that attributes for miscellaneous errors such as hardware noise, multipath error, etc. As a result, the true range equation is corrected to obtain the pseudorange.

$$P = \rho + I + T_r + c(b_{R_x} - b_{Sat}) + \varepsilon_p \tag{3}$$

General satellite C/A code position resolution yields results that are within meter magnitude accuracy. Such level of accuracy is adequate for general navigation and positioning applications such as vehicle positioning. However, measuring deflection of rigid structures require accuracy level down to millimeter standard. This requires application of techniques that will increase the accuracy of the position solution to millimeter standards. As a result, RTK-GPS technology is used, which can maintain the accuracy specification previously discussed [5].

D. RTK-GPS and Application of Double Difference Technique

Instead of using pseudocode measurement for measuring pseudo range, the carrier signal is used to derive measurements, aptly named carrier phase measurements. The typical error measured from pseudo range measurements, as previously discussed as C/A code position resolution, is in the magnitude of meters. On the other hand, the carrier phase measurement error is observed to be in the magnitude of millimeters. This is possible as the propagation frequency for carrier phase is in the order of gigahertz while the propagation frequency for C/A code is in the order of megahertz [6]. However, the carrier phase measurement includes an integer ambiguity, an unknown number multiplied wavelength that offsets the actual value of range measurements.

The measurement for carrier phase is given by the following equation:

$$\phi = \rho - I + T_r + c(b_{R_x} - b_{Sat}) + (N\lambda + \varepsilon) \tag{4}$$

To solve for the integer ambiguity, a double difference technique on relevant observables must be used to eliminate delay terms related to atmospheric corrections, satellite and receiver biases, and random error [11].

$$\phi_a^{12} - \phi_b^{12} = \rho_a^{12} - \rho_b^{12} - I_a^{12} + I_b^{12} + Tr_a^{12} - Tr_b^{12} + \lambda(N_a^{12} - N_b^{12}) + \varepsilon_a^{12} - \varepsilon_b^{12}$$

The difference of the double difference of carrier phase and pseudo range measurements will yield the integer value.

$$N_{L1} = (DD_{CPL1} - \frac{1}{\lambda_{L1}} DD_{PRL1}) \tag{5}$$

The hardware implementation is based of two GPS receiver, one being the rover and the other being the base station. The location of the base station is fixed while the rover station is the receiver that will be placed on the specific points of the structure that is of interest for measuring deflection. The fixed base station will provide the correction information necessary to the rover station to achieve the accuracy level discussed previously. Usually, to maintain adequate accuracy, the rover and base station must maintain a relatively short baseline at approximately 20 km. The following section will provide an overview of an application of RTK-Carrier Phase receiver technology as part of a study to verify and demonstrate millimeter level capability of measuring deflection using GPS receivers.

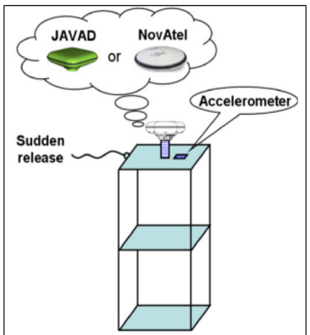
VI. Application of RTK-Carrier Phase Receiver for Deflection Measurement

An experiment conducted by researchers from Dalian University of Technology explored what accuracy a carrier-phase GPS receiver can achieve [10]. In addition, two different receivers with varying sampling rates were used to find how much it will have an impact in displacement accuracy. Two commercially available receivers were used: NovAtel (50Hz Sample) receiver and the JAVAD (100Hz Sample) receiver. The noise characteristics of both were taken into consideration with a static experiment of rover and base station data acquisition 5 meters apart. Both rover and reference receivers were positioned in a manner where the assumptions for no deflection during data acquisition was valid. The statistical study conveyed presumptive notions that not only are such RTK-GPS system appropriate for high precision application for general deflection measurement of large structures (eg. Bridges, High Rise), but dynamic measurement of the respective structures should also be plausible. The only caveat to the previous statement is the noise characteristics makes acquiring accurate motion data at or less than 1.5 Hz problematic and should be carefully considered.

Statistical result of different receivers in static experiments.

	Minimum	Maximum	Mean	Standard deviation	Skewness	Kurtosis
NovAtel GPS receiver	−0.0193	0.0189	0.0014	0.0057	0.0385	2.9737
JAVAD GPS receiver	−0.0148	0.1470	0.0017	0.0040	−0.0723	2.9789

The dynamic measurement accuracy was conducted on a similar manner, except the rover receiver was affixed to an apparatus subject to forces causing deflection while the reference station position was fixed about 10m away from the rover receiver. The apparatus was anchored at the reference surface with reinforced concrete beams. The following figure below is a schematic diagram of the experiments.



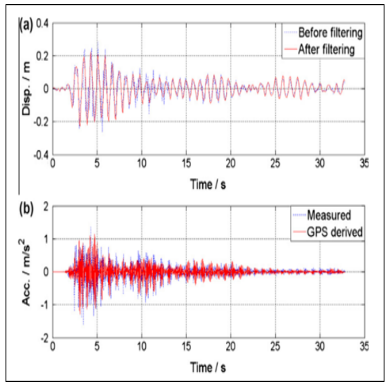
(b) Schematic diagram of the kinematic experiments

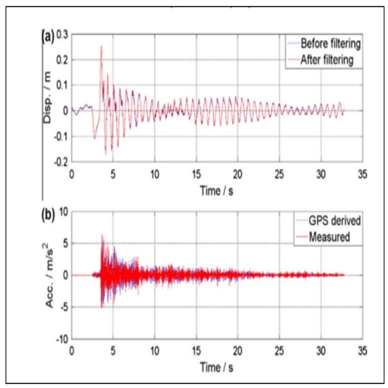
An initial displacement was provided to the model to set it into free vibration. Near the same area, an accelerometer in set in place to record the deflection along with the GPS receiver.

A. Results:

The data acquired by the researchers showed that both units can provide signal data with high signal to noise ratio. This allows for sensitive displacement response recordings. When compared to the accelerometer data in both acceleration and deflection measurements, the magnitudes are much larger for the accelerometer than the GPS receiver data. This could be attributed to the double integration techniques used to acquire deflection data from the accelerometer. The integration constants introduced along with drift error caused by numerical integration caused there to be a bias in deflection data. The data collected from the GPS receivers is promising as double integration generally creates very noisy data. The lower oscillations in the amplitudes could be an indication to higher quality data being acquired [10].

The first deflection and acceleration figure is for the NovAtel receiver and the second figure is for the JAVAD receiver





B. Limitations:

One significant known limitations of GPS based deflection measurements is the quality of the data and the type of data that can be acquired is heavily based on the receiver sampling rate. Until recently, the sampling rate for commercially available receivers were around 20Hz. Per Nyquist theorem, the highest modal frequencies that can be captures is 10Hz. As a result, high frequency receiver sampling rate is necessary to cover all, if not most modal frequencies experienced by application structures. In addition, such receivers can be subjected to modal frequency dependence if the displacement of the structures affixed to, are not high enough, depending on manufacturer of receiver [7].

C. Future Experimentation Opportunities:

Another method to verifying the results obtained from the dynamic test performed by the researchers is to recreate the dynamic testing environment to match the researcher specification. The data will be then obtained from both the JAVAD and NovAtel receivers and the same post-processing Wavelet Packet de-noising algorithm will be applied as previously done by the researchers. However, in conjunction with the recreation of the experiment. A simulation in ANSYS Mechanical will be performed where the geometry will be recreated, and the same deflection boundary conditions that was applied on the experiment will be applied in the ANSYS simulation. The deflection and acceleration values of the specified points (where the receiver location is on the structure), will be compared to the experimental values to provide an insight to how close to theoretical deflections and acceleration the GPS receiver is.

VII. Conclusion

With structural maintenance becoming a topic of critical discussion in the engineering and construction management community, as critical infrastructure ages without adequate maintenance, the need for adequate and standardized management is necessary. This is where the concept of SHM allows for better structural management and damage analysis, prognosis. One of the factors of SHM is calculating deflections and accelerations of structure. GPS technology shows promise on providing such information not compromised from infrastructure and computational power limitations. Such technology is highly sought after in dynamic vibrations and deflection measurements and have slowly been introduced into practice over a series of large infrastructure projects.

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