COVER SHEET

Title: *Long Distance Video Camera Measurements of Structures*
Proceedings of the **10th International Workshop on Structural Health Monitoring 2015**

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ABSTRACT

Tall buildings, long-span bridges, and other structures that have physical access issues can be difficult or costly to instrument to measure structural vibrations. Videos cameras offer a potential method for noncontact measurement of structures. Measurements have previously been made over long distances with targets placed on the structure of interest, however this addition removes much of the flexibility of using a camera in the first place. This paper will present a method for measuring displacements of structures from long range with a video camera in an uncontrolled and natural environment. The technique relies on optical flow processing of the video to determine the displacements of structures in the frame. A pilot study of a long range video camera measurement of a structure from a distance of over 500 feet will be shown as an example of the current possibilities of long range measurements. The issues of atmospheric turbulence and camera motion will be discussed and potential efforts in solving these issues will be described along with a discussion of camera requirements.

INTRODUCTION

For the purposes of structural health monitoring (SHM) sensors are necessary to make measurements of structural responses to feed into algorithms and methods that determine if any damage or changes have occurred. Accelerometers are most commonly used, however wired sensors are inconvenient to run over long distances and wireless sensors have only recently become viable but still require development especially with regards to power consumption. Spatially dense measurements are also difficult to obtain as many sensors are necessary, usually more than may be economically feasible. Non-contact measurement methods generally avoid the issue of having to instrument a building by hand and can be convenient to use.

As civil infrastructure and other structures may be relatively large, video cameras are well suited to make non-contact measurements of them. Video cameras measure

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displacements of structures by tracking the motion of pixels or detected features in the image such as edges, circles, or targets using a computer vision algorithm. These techniques have been applied to great effect in laboratory experiments measuring simple and complex structures such as cantilever beams [1-3] and model steel frame buildings [4, 5]. Outdoor measurements have previously been made of a traffic signal structure [6], cables on suspension bridges [4, 7, 8], and bridges among other structures [4, 7, 8]. Some of these previous studies use targets [2, 4, 5] or lights [7] on the structure which gives a better signal because it is easier to determine the displacement from the structure, however this removes some of the advantage of ease of instrumentation the camera has over traditional wired measurement methods. Methods that do not use any additional preparation of the structure use edge detection, digital image correlation, or more general optical flow techniques.

This paper focuses on a phase-based optical flow method derived from motion magnification [9] to measure the displacement of structures [3]. Since it was previously tested in a laboratory setting [3], this paper discusses the transition of the method to displacement measurements of structures in an uncontrolled outdoor environment, specifically the issues involved in long distance video camera measurements of structures. The theory behind the method and the initial laboratory verification measurement comparing it to a laser vibrometer and accelerometer will be presented. A pilot study of a long range video camera measurement of a structure from a distance of over 500 feet will be shown as an example of the current possibilities of long range measurements using the phase-based optical flow methodology. The issues of atmospheric turbulence and platform motion will be discussed and potential efforts in solving these issues will be described and the necessary requirements for camera hardware will be discussed and referenced to commercially available hardware.

THEORY

Our processing consists of taking a video of a vibrating structure and computing the displacement signal everywhere on the structure in the image using a technique related to phase-based motion magnification [3, 9]. The main limitation of the technique is that the displacement signal is only well defined at edges or other high-contrast regions in the video and then only in the direction perpendicular to the edges. This is because the motion of textureless, homogeneous regions is locally ambiguous. Determining the motion at places where it is ambiguous is an open problem in computer vision known as dense optical flow [10, 11]. For the purposes of determining the displacement of structures we can use the edges of the structures against a contrasting background such as the sky, or any features on the structure itself like windows or columns.

To determine the displacement signal, we use a quadrature filter pair that decomposes the signal into the local phase and local amplitude, quantities analogous to the phase and amplitude of Fourier series coefficients [12, 13, 14]. The phase controls the location of the basis function while the amplitude controls its strength. For the G2 and H2 filter steerable filter pair we are using, the local amplitude is proportional to the edge strength, and the local phase gives us local motion [14]. Assuming no variations in illumination, constant contours of the local phase through time correspond to the displacement signal [12, 13]. We can use this assumption to process the phase signal to determine the local displacement signal, and then convert from pixels to physical units by the known size of an object in the video frame. A more detailed derivation of the methodology is located in [3].

EXPERIMENTS

This section will cover experiments with the camera measurement system for measurement of moving objects. The first is a verification measurement where the camera is compared to a piezoelectric accelerometer and a laser vibrometer. The second experiment is a pilot study involving a long range camera measurement of a structure with known resonant frequencies.

Verification Measurements

In order to determine the precision and accuracy of the video camera displacement measurements an experiment was formulated to compare the results against an accelerometer and laser vibrometer [3]. An accelerometer was mounted on the free end of a steel cantilever beam, and the motion of the cantilever beam was simultaneously measured by the accelerometer, a laser vibrometer, and a Phantom v10 high speed camera, as shown in Figure 1(a). A screenshot of the video from the camera is shown in Figure 1(b), and the resolution of the camera was 480 × 288, and the frame rate was 5000 frames per second for a bandwidth of 2500 Hz. In the plane of the accelerometer, the video frame was 104 mm wide and 62 mm tall, with 4.615 pixels per millimeter for a magnification of 1:18.8. The cantilever beam was excited with an impact hammer near the base, and the subsequent response was measured for comparison. A fast Fourier transform (FFT) was performed on the data from the laser vibrometer, accelerometer, and camera derived displacement, and integrated in the frequency domain to obtain the displacement so that the frequency peaks and noise floors could be directly compared.

(a) (b)

Figure 1: (a) Labeled picture of experimental setup and (b) screenshot of scene from camera (artificially brightened for visibility) [3]

The comparison plot is shown in Figure 2. Both the accelerometer and laser vibrometer data show eight resonant frequencies of the cantilever beam above the noise floor from 0 to 2500 Hz, while the camera only shows the first four resonant frequencies of the cantilever beam. The correlation between the camera and laser vibrometer displacement signals is 99.6% so the camera accurately captures the response of the cantilever beam. The noise floor of the camera for this nine second measurement is 40 nanometers, while the laser vibrometer has a noise floor of 0.2 nanometers, and the accelerometer has a noise floor of 0.02 nanometers. Given the conversion factor of 480 pixels for 104 mm, and accounting for the length of the measurement and bandwidth, the noise floor of the camera for this measurement was approximately 10^{-5} pixels per root Hertz. This gives us a basis for determining the pixel resolution necessary for measuring a given magnitude of displacement of a structure.

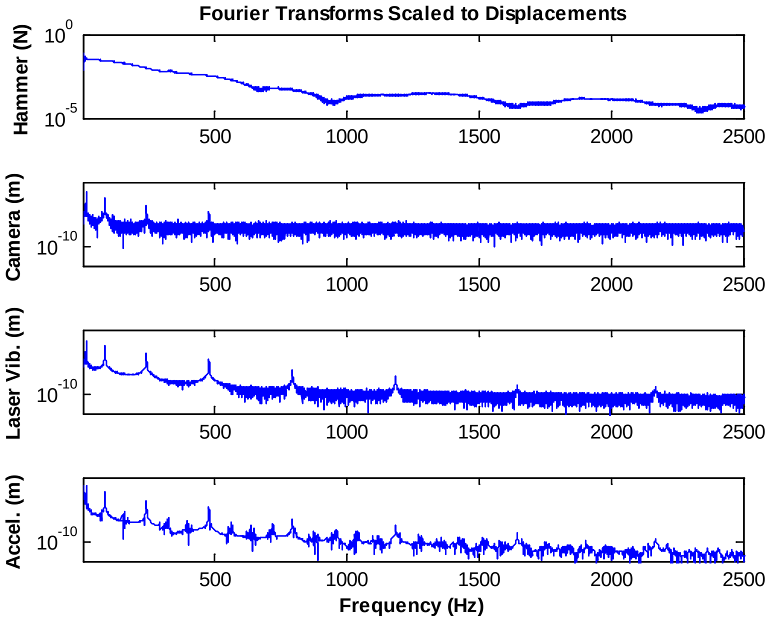
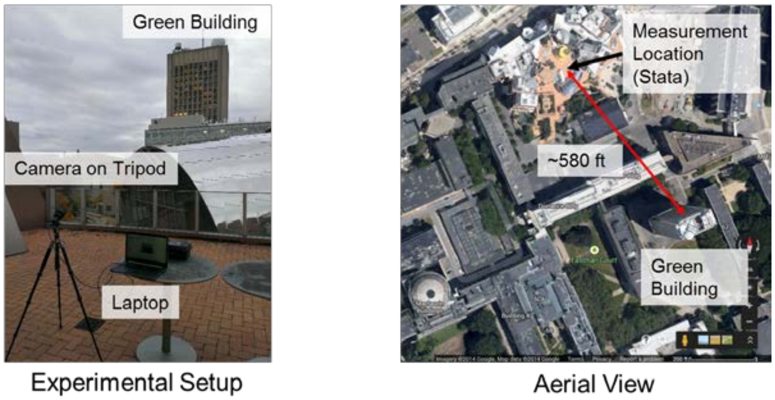


Figure 2: Comparison of displacements extracted from camera video measurement to a laser vibrometer and accelerometer [3]

Long Range Camera Measurement

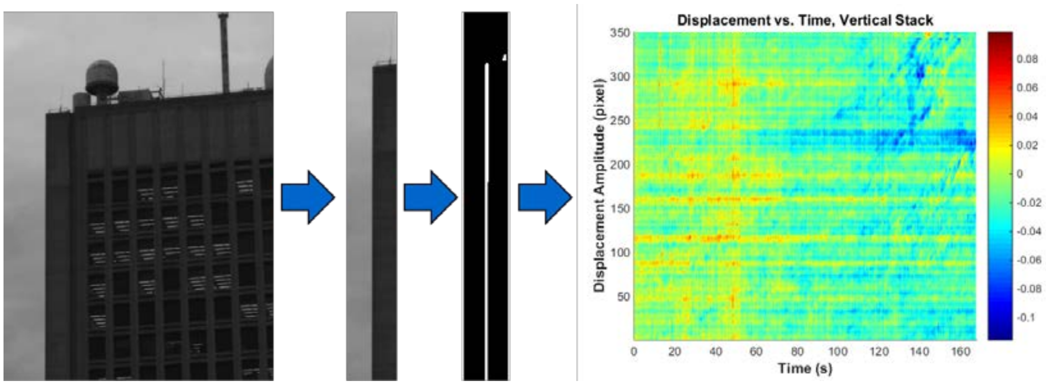
As a pilot study, a long range camera measurement was made of the Green Building on MIT's campus, a 90 meter, 21 story, reinforced concrete building. Figure 3(a) shows the experimental setup and figure 3(b) is a satellite view of the measurement location, which is approximately 580 feet away from the building. A Point Grey Research Grasshopper3 camera was used and 167 seconds of video was taken at 60 frame per second at a resolution of 704 × 960 cropped to 112 × 816 where one pixel is approximately 4.2 centimeters for a magnification of 1:3650.



(a) (b)

Figure 3: Long range camera measurement of MIT's Green Building with (a) the experimental setup and (b) aerial view of the measurement and structure of interest's location

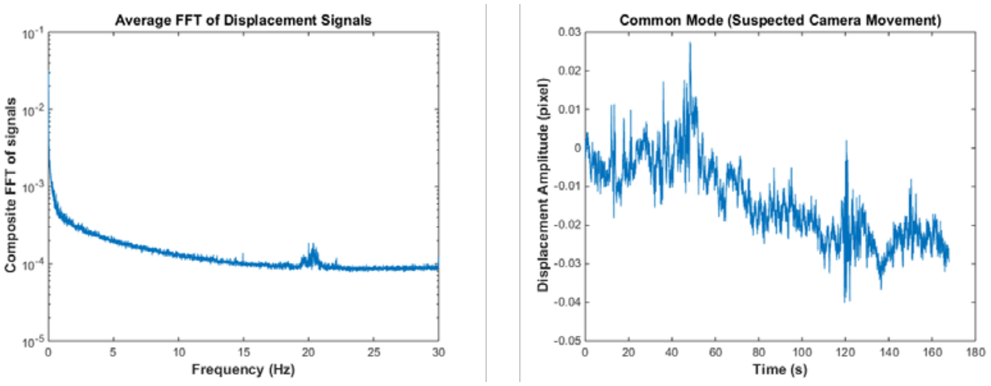
The processing workflow for this experiment is shown in Figure 4. First the source video (a) is cropped to only show the left edge (b) of the building to use the highest contrast textures to determine the displacement and to reduce processing time. After applying the quadrature filter pair, the pixels determined to have good texture are shown in (c), which are the pixels at which the displacement will be calculated. For visualization purposes, pixels which are at the same vertical height are averaged together to produce a displacement signal per vertical position in the video. Then the displacements can be plotted as in (d) where the vertical axis is the vertical position of the displacement signal, the horizontal axis is time, and the color represents amplitude.



(a) (b) (c) (d)

Figure 4: Processing workflow of long range camera measurement from (a) source video to (b) cropped video to (c) pixels with calculated displacements to (d) displacement vs. time plot

Figure 4(d) shows the vertical stack of displacement time series as extracted from the video of the structure. There are some disturbances in the signals, particularly around 22 seconds, 50 seconds, and 135 seconds elapsed. Some of the vertical heights also seem to be more active than the others, however this may be more noise rather than actual signal. For some more simple analysis of the signals we take the FFT of all the displacement signals and average them together to see if any resonant frequencies come out of the measured displacements.



(a) (b)

Figure 5: Average displacement signal from all the pixels for the long range camera measurement, (a) FFT and (b) displacement vs. time representing the suspected common mode motion of the camera

Figure 5(a) shows the average FFT of all the displacement signals from Figure 4(d). The expected first two resonant frequencies of the structure in the East-West direction seen by the camera are 0.68 Hz and 2.49 Hz [15]. These frequencies are not observed in the plot as the absolute displacements of the structure are very small and likely masked by noise. However, there is a resonant frequency at 20 Hz. This resonant frequency is far too high to belong to the structure, so our best guess is that it corresponds to camera motion, especially as it is relatively strong compared to the noise floor. Given the relatively lightweight tripod, and the magnitude of the motion, it is highly likely that this 20 Hz resonant frequency corresponds to a resonant frequency of the tripod causing camera motion. Another reason why we might not see the resonant frequencies of the structure is that atmospheric turbulence is adding random noise to the measurement. This issue of camera motion along with another source of noise unique to outdoor measurements, atmospheric turbulence, will be covered in the discussion section.

DISCUSSION

This discussion section will cover the issues of long range camera measurements as well as some suggestions for camera hardware requirements.

Sources of Noise

Excess noise can easily swamp the small displacements of civil infrastructure under normal operational vibrations. As with any measurements, camera measurements are also about obtaining the best signal to noise ratio. As discovered in the long range camera measurement of the Green Building, some potential sources of noise specific to long range outdoor measurements include camera platform motion and atmospheric turbulence. Camera platform motion is not a major issue for short distance measurements, however with long range measurements where any small rotations of the camera can be multiplied by a large distance to manifest in large motions as seen by the camera. To stabilize the camera a large heavy weighted tripod mounted to the center of mass of the camera lens system will mechanically reduce motion as much as possible. Additionally accelerometers could be mounted to the camera system itself to measure the camera motion or use a known fixed point in the scene for reference [8], to compensate for camera motion in video processing.

Atmospheric turbulence is another source of noise that only manifests itself in long range outdoor measurements. Temperature differentials and random irregular air currents in the atmosphere cause small changes in the index of refraction of the air that over long path lengths distort and blur coherent images. This source of noise is difficult to correct as the distortions in the atmosphere are not only stochastic but also worst in the frequency band typical of civil infrastructure. Possible solutions come from tools such as adaptive optics and guide stars, used in astronomy for telescopes imaging through the atmosphere.

Camera Hardware

Camera hardware for displacement measurements can range from relatively inexpensive cell phone cameras to moderately expensive research cameras to very expensive high-speed video cameras. The cameras used in this study are the Phantom v10 and the Point Grey Grasshopper3, which cost approximately $30k and $1,000 respectively. One feature that they both have is a global shutter, which means that they image off their sensor the whole image at once, rather than a rolling shutter which images line by line, which most consumer cameras have. For high-speed vibrations, this is important because a rolling shutter may cause a shifting effect of the structure, however this can also be used to collect limited data at a higher frame rate than the stated frame rate by taking advantage of this [16]. Given that most civil infrastructure will have relatively low resonant frequencies under 50 Hz, the version of the Point Grey Grasshopper3 used in the long range camera measurement which has a maximum frame rate of 162 frames per second is more than sufficient to satisfy the Nyquist criteria. Given that tall buildings have resonant frequencies under 5 Hz, at least given the frequencies involved, normal video cameras which typically shoot video at 30 frames per second are sufficient. For the pixel resolution, the higher the resolution the better, and lenses with good optics that can provide higher magnifications will allow for smaller displacements to be measured.

CONCLUSION

This paper discussed the use of video cameras to measure the displacements of structures from long distances. A phase-based optical flow method was described and verified in an experiment comparing the camera measured displacements with a laser vibrometer and accelerometer, which was found to have good agreement with a noise floor of 10^{-5} pixels per root Hertz. An initial measurement of MIT's Green Building was made at a range of greater than 500 feet and some displacements were measured, however no resonant frequencies of the structure were identified, but a higher resonant frequency was seen, suggesting vibration of the camera on the tripod. Sources of noise such as camera motion and atmospheric turbulence were discussed along with recommendations for camera hardware for displacement measurements. As digital video cameras have recently come down in cost and high frame rate cameras are being widely included in consumer devices, there are growing opportunities for successful camera measurements of structures.

Acknowledgements

The authors acknowledge the support provided by Royal Dutch Shell through the MIT Energy Initiative, and thank chief scientists Dr. Dirk Smit and Dr. Sergio Kapusta, project manager Dr. Keng Yap, and Shell-MIT liaison Dr. Jonathan Kane for their oversight of this work. At the time of this work, Neal Wadhwa was supported by the MIT Department of Mathematics and the NSF Graduate Research Fellowship Program under Grant No. 1122374.

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