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Project Title

Development of a New Airborne Portable Sensing System to Investigate Bridge Response

University

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Research Needs

Analyzing the structural response to special vehicles with large size and weight is critical for load rating and safe operation of bridges. The current AASHTO codes and formulas used to examine the Live-Load Distribution Factors (LLDFs) that are functions of bridge geometries and deck thickness are either too conservative or too permissive due to insufficient understanding of the bridge response to special vehicles (such as agricultural vehicles). Full-scale long-term structural health monitoring (SHM) provides a unique means to understand the bridge response to special vehicles by collecting authentic data on bridge response without modeling errors, however, the instrumentation of SHM systems is very expensive, which limits its use to only a few long-span bridges. Moreover, once sensors in these SHM systems are installed, they are not easily able to be relocated if a different, critical location is found. Therefore, this project proposes an alternative low-cost portable sensing system to measure the displacement response of bridges, which can be more useful in the management of a large number of bridges by state DOTs. The proposed portable sensing system will be developed based on emerging technology in remote sensing, imagery and unmanned aerial vehicles (UAVs).

There is some existing research on using UAVs to track the displacement response of a structure in either the 2D planar directions (the plane that is perpendicular to the camera) or the out-of-plane direction (the distance from the camera to the structure). With the assumption that the out-of-plane displacement of civil infrastructure is minimal, 2D planar displacements of structures can be measured [1,2]. Hoskere et al. used high-pass filtering to remove noise imposed by the UAV's drift and a scale-factor was calculated to relate real-world measurements to pixels to measure 2D planar displacement [1]. Kalaitzakis et al. implemented a painted speckle pattern on a concrete beam to measure the strain during a four-point loading test with an additional painted speckle pattern on a stationary reference [2]. Other studies measured only the out-of-plane displacement of structures [3,4]. Catt et al. implemented passive stereo vision by mounting two cameras at a known distance apart to measure the out-of-plane deformations of a deformable board [3]. The proposed algorithm processes the speckled pattern placed on the board to accurately measure the deformation and movement of the speckles; however, the drift of the UAV was not compensated. As a result, the speckle points were manually identified and matched, creating a challenge for implementation, especially with longer signals. Garg et al. used a laser Doppler vibrometer, which measures the reflection of a high-frequency wave, to calculate the out-of-plane displacement of an object. Using a high-pass filter, the drifts of the UAV were removed and accurate displacement data was achieved [4]. UAVs have also been used to identify the vibration modes of a structure without correcting for the movement of the UAV [5]. Although aforementioned techniques using painted speckle pattern can provide accurate measurements within the speckled area (such as[2] or [3]), they do not take advantage of the entire field of view of the camera and implementing these techniques in the real-world might be challenging due to the large-scale of the structures and workforce required to install the detailed patterns. Yoon et al. proposed a 2D planar UAV measurement methodology without a speckle pattern by identifying, matching, and tracking feature points in the background of the video to estimate the camera's pose and recover the 3D translation and rotation of the UAV; however, the proof of concept still required LED lights as targets [5].

These existing studies have not attempted to measure the full three-dimensional (3D) movements of a structure, which can be critical for certain types of structures such as bridges or cables. In this context, the proposed portable sensing system aims to enable the measurement of 3D dynamic displacements of bridges through the integration of optical and infrared (IR) sensors with UAVs and the development of a double faceted computer vision technique based on feature extraction, direct linear transformation (DLT), and active stereo vision. This novel system presents a unique advantage compared to the existing UAV-based techniques that allow the measurements in only one or two dimensions.

Research Objectives

The research objectives of this study are to:

Objective 1: Develop a prototype sensing system by integrating UAVs with optical and infrared sensors. The feasibility of the system will be evaluated for different applications.

Objective 2: Develop a double faceted computer vision technique to measure the 3D displacement of a structure and test the proposed algorithms in both the laboratory and field.

Research Methods

In the proposed system, a two-UAV sensing system will be developed, with one UAV equipped with integrated optical and infrared (IR) cameras and the other UAV equipped with one IR projector and one IR camera. The two UAVs will hover adjacent to a bridge to take videos of its response. Although UAVs can hover in the air stably and allow for high-quality image capturing, there is slight drifting and movement of the UAV itself (and the sensors), which may introduce significant errors in dynamically sensitive applications, such as dynamic/static displacement measurement. Thus, this study aims to develop a self-aware UAV-enabled displacement measurement methodology. To measure the planar displacement, the downward-facing camera on UAV # 1 will be used to capture image frames that contain the features of both the region of interest (ROI) on the vibrating object (e.g. a bridge under traffic excitation) and that of the stationary reference target (Fig. 1a). The motion of the UAV is recovered by tracking the relative movement of the features in the stationary reference target with respect to the UAV; while the relative motion between the UAV and the ROI is extracted by tracking the movement of the ROI on the object. By adding the movement of the object with respect to the UAV, to the movement of the UAV with respect to the ground, the true movement of the ROI is found. Extracting the 2D planar motion of the ROI or stationary target using the optical/IR sensor requires simultaneously tracking the features on the object of interest and those on the stationary reference target and transforming the pixels of extracted features into real-world measurements within each image frame of a video over time. To this end, a robust feature extraction algorithm will be developed based on color filtering in conjunction with object tracking techniques, such as a MOSSE filter ([6]). After the features are successfully tracked in the reference target, the actual amplitude of the displacement will be recovered by mapping the pixels on image to the real-world dimensions using a direct linear transformation (DLT). The DLT will ensure that 1) the optical axis of the camera is perpendicular to the 2D plane (i.e. correct the image distortion caused by the inclined angles of the camera), and 2) each pixel is scaled to a real-world measurement (i.e. one pixel could get transformed into one millimeter or another relevant dimension). To begin DLT, the relationship (or perspective transformation matrix) between a known reference point in the real-world in space coordinates and its location in pixel points in image coordinates must be known. By knowing both image and space coordinates, the DLT will be implemented to solve for the perspective transformation matrix with respect to the linear system. In addition to DLT, the radial distortion due to the lens curvature and tangential distortion caused by imperfections in lens centering will be corrected through a rigorous camera calibration process [7,8]. After the raw images are transformed through the process of camera calibration and DLT, the distances between points on the image faithfully represent the real-world dimensions, and the amplitude of the displacement in the real-world is finally recovered.

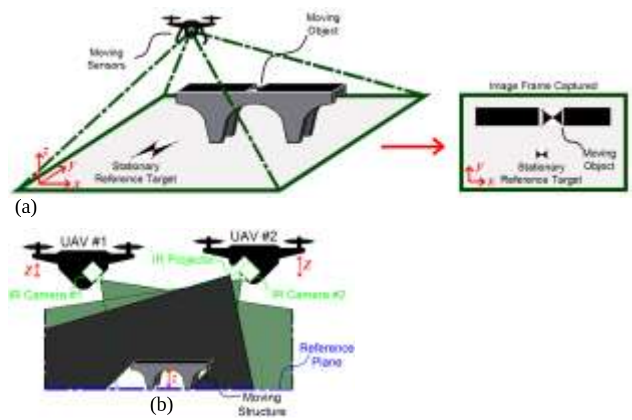

Fig. 1. Schematic plot for measurement concept: (a) 2D planar measurement, (b) 1D depth measurement

To measure the 1D depth displacement, an IR laser projector installed on UAV # 2 will project virtual speckle patterns on the structure, as well as the surrounding background. Then two IR cameras installed on two UAVs respectively will be used to capture stereoscopic videos of the movement of the virtual speckle (Fig. 1b) from the same height through programmed autopiloting. A wireless communication scheme will be developed to enable time synchronization of sensors from two UAVs [9]. A computer vision algorithm based on stereoscopic photogrammetry will be developed to measure the structural displacement in the depth direction. Specifically, the baseline between two IR cameras on the two UAVs will be firstly recovered by subtracting the motion of UAV #1 from the motion of UAV #2, where the UAV motions will be measured using the approach discussed in the previous paragraph. Then each virtual speckle will be matched between the two IR cameras. With the matched speckles and a known baseline between the two IR cameras, the angle from each camera to the speckle will be calculated and the distance from the speckle to the cameras will be found. Since the IR projector can cover the entire field of view of the camera, the depth throughout the entire image can be solved, allowing the full-field displacement measurement. Note that both the object and the UAV might be moving in the two horizontal directions (x and y-directions), thus the ROI and the stationary reference must also be tracked in the IR video to allow for the same point measurement. To accomplish this, a MOSSE filter ([6]) will be used to track the areas of interest in the x- and y-directions. Then, a small group of pixels (within a one cm range) on the tracked ROI will be selected. The averaged depth measurements of the group of pixels will represent the depth motion of one measurement point in ROI. This averaging will help enhance the measurement accuracy and reduce the measurement noise. After obtaining the measurement of ROI, the small motions of UAVs in the depth direction with respect to the stationary background will also be measured in the same way and compensated to achieve the true structural displacement.

Expected Outcomes

This research is expected to develop a portable sensing system that does not need field instrumentation of sensors, cables, data acquisition unit, power supply, etc., thus greatly reducing the cost and effort required for load testing. By leveraging its airborne nature, the developed system can access difficult to reach areas, and provide critical angles from desired key locations, offering greater flexibility compared to ground-based remote sensing techniques. The data acquired by the proposed portable system can be used to build accurate structural models and enable a more reasonable estimation of LLDF and load ratings for bridges with a minimal cost, thus effectively promoting longevity of bridges and cost-effective inspection/operation. The proposed portable sensing system also has the potential to be extended to track changes in displacements of other structures, such as walls, landslides, dams, etc., which is expected to positively impact the safety and maintenance of a variety of structures. The tangible products expected to result from this project include:

1) A prototype sensing platform and algorithms for displacement measurement.
2) A demonstration example of using the proposed system to measure structural response.
3) An assessment of the advantages and limitations of the developed system when used in asset management of bridges and its potential applicability to other transportation structures.

Relevance to Strategic Goals

This study is most closely related to the strategic goal: Safety. This project will develop a portable sensing system to measure the structural response of bridges due to special vehicles and enable a more reasonable estimation of LLDF and load ratings for bridges, which will ensure the safe operation of bridges.

Educational Benefits

One graduate student will participate in the project including writing several papers and a report, which will result in part of his/her dissertation. He/She will gain valuable experience in the field of computer vision, structural dynamics, and asset management.

Technology Transfer

The PI and co-PI have already established collaborations with industry partners in the infrastructure inspection field, including ARE and Stantec. The developed prototype system and algorithms will first be validated in the field and then commercialized for future inspection practice by the industry collaborators. Also, as part of the work plan, we will demonstrate to local transportation agencies (CDOT, Larimer County, local municipalities) the application of the proposed sensing system through full-scale field testing. Through this process, we will continue to build relationships with engineers at these agencies and keep them informed of how the new system could be applied in the context of their decision-making on bridge management. In addition, we will present the project outcome at TRB conferences and prepare journal article(s) about the findings and methods.

Work Plan

The work plan includes four major tasks, each with an interim deliverable/milestone:

Task 1: Development of the portable sensing system
This task identifies the appropriate sensors and UAVs and develops an integrated sensing system that enables the wireless communication of sensors and precise pilot control (1st-4th months).

Task 2: Development of the computer vision algorithms for 3D displacement measurement
This task develops the algorithms to extract the displacement information from videos taken by IR and optical sensors (5th-14th months).

Task 3: Experimental testing
This task tests the efficacy of the developed algorithms in the laboratory and identifies the application areas for the developed system (16th-20th moths).

Task 4: Demonstration of application of the proposed system though field testing
This task demonstrates the use of the proposed system in a full-scale bridge. (20th-24th months).

Project Cost

Total Project Costs:	$123,000
MPC Funds Requested:	$ 63,000
Matching Funds:	$ 60,000
Source of Matching Funds:	Colorado State University, faculty time and effort

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