Multiview Vision-based Displacement Measurement of Full-Scale Miter Gate

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ABSTRACT

Miter gates are critical components of locks and dams of inland waterways for facilitating movement of vessels between different water elevations. Closure of locks and dams due to gate failure or unexpected maintenance stalls barge traffic, leading to goods hardly reaching the market as well as huge economic loss. Therefore, continuous condition monitoring of miter gates while not affecting their operation is especially important for the stakeholders. Measured displacements of the gates under load are known to be informative of their condition, as well as for the updating of numerical models of the structure. Considering the need for remaining operational, as well as inaccessibility of contact-type sensors, this study proposes a multiview vision-based displacement measurement strategy tailored for full-scale miter gates. A displacement measurement strategy using multiple cameras is developed specialized for the miter gate under harsh field conditions such as non-negligible camera motion induced by strong wind and lack of reliable reference points. The proposed method will be demonstrated on the full-scale miter gate at The Dalles Lock and Dam by collecting displacements of the gate during the water-fill of the lock chamber. The measured displacements can be compared to the corresponding numerical analysis outputs to inform the updating of the model, thus providing the potential to improve the condition monitoring of the miter gates on inland waterways.

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INTRODUCTION

Miter gates are critical components of locks and dams in inland waterways, facilitating the movement of vessels between different water elevations. However, the failure or unexpected maintenance of these gates can lead to the closure of locks and dams, resulting in disruptions to barge traffic and significant economic losses. Furthermore, the Infrastructure Report Card released by the American Society of Civil Engineers (ASCE) in 2021 [1] gave the condition of the nation's inland waterways a grade of "D +", highlighting the urgency for asset operators to understand the condition of their infrastructure. Therefore, ensuring the continuous monitoring and uninterrupted operation of miter gates is crucial for stakeholders.

The displacements of miter gates induced by hydraulic pressure are known to be informative of their current structural condition. Traditional methods for measuring displacement in civil infrastructure involve the use of contact devices such as linear variable differential transformers (LVDTs) or ring-type displacement transducers. However, these sensors require a stationary reference point for installation and direct access to the structures, which can be challenging in the field [2]. Alternatively, remote cameras positioned at a distance from the structure are widely adopted for displacement measurements due to their high-resolution acquisition and cost-effectiveness. Nevertheless, the subtle movement of these cameras can introduce significant measurement errors [3], making it challenging to accurately measure displacement, especially for large civil infrastructure where complete fixation of the device in the field is not feasible. An advanced measurement method is demanded that can acquire the deformation of the full-scale miter gate even with sensor movement.

This study proposes a non-rigid body deformation measurement method using stereo-typed cameras. The method involves capturing the three-dimensional (3D) displacement field of the miter gate before and after the water chamber is filled. By neglecting rigid body motions induced by either camera motion or structural movement, the proposed algorithm extracts the non-rigid body deformation of the miter gate. A Matlab simulation is then conducted, which validates the effectiveness of the proposed non-rigid body deformation measurement method.

CONVENTIONAL METHOD

Stereo vision has been widely studied for the application of 3D displacement measurement in full-scale engineering structures using multiple cameras. Given camera intrinsic parameters and the relative positions of the cameras, 3D deformation of the structure can be obtained using the images captured from different camera positions. Previous studies have demonstrated the practical application of stereo vision in measuring displacement of full-scale structures [4]. These applications typically assume that the cameras are completely fixed in the field because the camera ego-motion would falsely manifest as additional rigid body motion in the resulting displacement measurements. However, the miter gate is typically situated in an open field where controlling wind-induced camera vibrations is challenging. Therefore, advanced camera ego-motion compensation techniques are necessary to mitigate the effects of camera motion and ensure accurate deformation measurements of the miter gates.

Camera ego-motion is indistinguishable from the true structural rigid body motion if reference points are not available in the field. Consider the measurement scenario shown in Figure 1, where stereo vision is assumed as a 3D displacement measurement device for simplicity. The camera coordinate systems at time 0 and 1 are denoted as $C(0)$ and $C(1)$, respectively. The 3D coordinates of the corner point of the miter gate are measured using the stereo-typed computer vision, which are represented as $\{X(0)\}_{C(0)}$ and $\{X(1)\}_{C(1)}$ for the points at time 0 and 1 with respect to $C(0)$ and $C(1)$ coordinate systems, respectively. The reference coordinate system E is defined by reference points in the field. $W(0)$ represents the coordinate system defined by the miter gate to represent its rigid body motion. Then, the structural displacement of the miter gate can be expressed as:

$$\begin{aligned} X(1)_{W(0)} - X(0)_{W(0)} &= \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)} X(1)_{C(0)} - \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)} X(0)_{C(0)} \\ &= \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{E\to C(0)} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(1)\to E} X(1)_{C(1)} - \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)} X(0)_{C(0)} \end{aligned} \quad (1)$$

where the left-hand term is the deformation of the miter gate represented in W(0), $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)}$, $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{E\to C(0)}$, and $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(1)\to E}$ are respectively the coordinate transform from $C(0)$ to $W(0)$, E to $C(0)$, and $C(1)$ to E. All the right-hand terms in the Equation (1) are known from the measurement, allowing for the computation of structural deformation without the need for additional. However, in the absence of reference points, $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{E\to C(0)}$ and $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(1)\to E}$ cannot be obtained, making it impossible to determine the structural deformation. Since the presence of the reference coordinate system E is not guaranteed in the field, advanced algorithms are required to reliably measure the deformation of the miter gate.

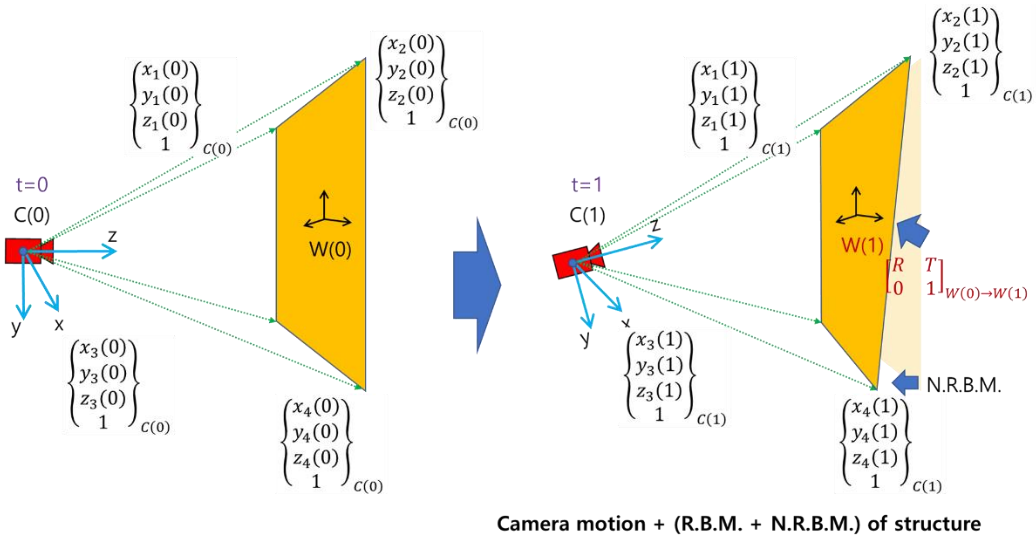

Figure 1. Measurement scenario with camera ego-motion.

METHODOLOGY

This study presents a 3D deformation measurement strategy tailored to full-scale miter gate structure by utilizing multiple cameras while disregarding camera motion. Firstly, the computer vision algorithm for computing the 3D coordinates from multiple cameras is presented, treating the cameras as a 3D sensor in the following formulation. Subsequently, the 3D coordinates acquired by the cameras are used to compute the non-rigid body deformation of the miter gate, naturally neglecting the camera motions. The computer vision algorithm and the formulation for the non-rigid body deformation are presented in the subsequent paragraphs.

As for the algorithm for computing the 3D coordinates from multiple cameras, the "structure from motion from two views" algorithm provided by Matlab [5] is adopted. Structure from motion (SfM) is the process of estimating the 3-D structure of a scene from a set of 2-D images. The basic steps when 2 cameras are used are as follows. 1) Calibrate the 2 cameras to get their intrinsic parameters such as focal length, principal point, image size, lens distortion coefficients, etc., by using for example, Matlab Camera Calibrator app [6]. 2) Set up the cameras at certain locations and orientations to capture 2 images of the scene of interest from different perspectives. 3) Match a set of points between the two images. There are multiple ways of finding point correspondences between two images. If the perspectives of the images are close, then feature detection and tracking can be applied; alternatively, when the 2 cameras are far apart, feature extraction followed by feature matching may be more appropriate. 4) From the point correspondences between two images, together with the known intrinsic parameters, the essential matrix between the two cameras can be obtained, from which the translation and orientation of the second camera relative to the first one can be calculated. Note that the translation can only be computed up to scale. 5) Recover the actual scale factor by detecting an object of a known size. 6) Then the 3D coordinates corresponding to the matched points can be estimated using the triangulate function [7]. Note that the 3D coordinates obtained are in the coordinate system of the first camera, which is $C(t)$ at time t in the previous section.

The formulation of the non-rigid body deformation of the miter gate is designed to neglect the false displacement induced by the camera ego-motion. The non-rigid body deformation expressed in $C(1)$ coordinate system, denoted by $NRB_{C(1)}$, can be decomposed into $X(1)_{C(1)}$, $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)}$, $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)}$, and $X(0)_{C(0)}$ as

$$NRB_{C(1)} = X(1)_{C(1)} - \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)} \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{C(0)\to W(0)} X(0)_{C(0)} \tag{2}$$

Here, every term except $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)}$ is known from the measurement. $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)}$ can be obtained by solving the minimization problem given as:

$$\min_{W(1)} \left\| \begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)} X(0)_{W(0)} - X(1)_{C(1)} \right\| \tag{3}$$

Thus, the non-rigid body deformation of the miter gate can be computed by Equation (2) with the $\begin{bmatrix} R & T \\ 0 & 1 \end{bmatrix}_{W(1)\to C(1)}$ determined by Equation (3).

VALIDATION

To verify the formulation for the non-rigid body deformation, the following Matlab simulation is conducted. First, the following steps are carried out to create synthetic data used for verification.

1) The locations and orientations of the "3D sensor", i.e., a camera, at time 0 and time 1, which have small difference to simulate the inevitable camera motion during the displacement measurement for a water-fill event, are assumed and given in the reference coordinate system. 2) A thin plate that represents the miter gate leaf is defined and 8 points are picked from the thin plate and their coordinates in the reference coordinate system are given. 3) Let the miter gate go through rigid body motion and record the coordinates of those 8 points in the reference coordinate system. 4) On the basis of rigid body motion, let the miter gate go through also non-rigid body motion and record the coordinates of those 8 points in the reference coordinate system. 5) Through coordinate system transformation, obtain the coordinates of the 8 points on the undeformed gate leaf with respect to camera 0; and obtain the coordinates of the 8 points on the deformed (both rigid and non-rigid body motion) gate leaf with respect to camera 1. And those will be the input into the non-rigid body deformation formulation derived in the Methodology section.

An effective way to validate the proposed non-rigid body deformation formulation is that, if the assumed non-rigid body motions in step 4) are all zero, then the non-rigid body motions given by the proposed algorithm should also be zero, which is the case with tolerable accuracy as shown in the following figure.

A_NRB_C1

4x8 double

	1	2	3	4	5	6	7	8
1	-3.9968e-15	-1.7764e-15	2.6645e-15	1.7764e-15	-3.1086e-15	-3.1086e-15	8.8818e-16	-1.5543e-15
2	3.9968e-15	3.1086e-15	2.6645e-15	3.9968e-15	3.5527e-15	3.5527e-15	2.1649e-15	3.3307e-15
3	1.0658e-14	1.4211e-14	1.7764e-14	1.4211e-14	2.1316e-14	1.4211e-14	1.7764e-14	1.4211e-14
4	0	0	0	0	0	0	0	0

Figure 2. Matlab simulation results.

CONCLUSION

In this study, a multiview vision-based non-rigid body deformation measurement method tailored for full-scale miter gates has been proposed. The method is developed specialized for the miter gate under harsh field conditions such as non-negligible camera motion induced by strong wind and lack of reliable reference points. A Matlab simulation has been conducted, verifying the effectiveness of the proposed method. The method involves capturing the three-dimensional (3D) displacement field of the miter gate during the water-fill of the lock chamber and will be demonstrated on the full-scale miter gate at The Dalles Lock and Dam. The measured displacements can be compared to the corresponding numerical analysis outputs to inform the updating of the model, thus providing the potential to improve the condition monitoring of the miter gates on inland waterways.

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