

Flexible camera series network for deformation measurement of large scale structures

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Abstract. Deformation measurement of large scale structures, such as the ground beds of high-rise buildings, tunnels, bridge, and railways, are important for insuring service quality and safety. The pose-relay videometrics method and displacement-relay videometrics method have already presented to measure the pose of non-intervisible objects and vertical subsidence of unstable areas, respectively. Both methods combine the cameras and cooperative markers to form the camera series networks. Based on these two networks, we propose two novel videometrics methods with closed-loop camera series network for deformation measurement of large scale structures. The closed-loop camera series network offers “closed-loop constraints” for the camera series network: the deformation of the reference points observed by different measurement stations is identical. The closed-loop constraints improve the measurement accuracy using camera series network. Furthermore, multiple closed-loops and the flexible combination of camera series network are introduced to facilitate more complex deformation measurement tasks. Simulated results show that the closed-loop constraints can enhance the measurement accuracy of camera series network effectively.

Keywords: videometrics; deformation measurement; large scale structure; closed-loop; camera series network

1. Introduction

Large scale structures, such as high-rise buildings, tunnels, bridge and railways, are the fundamental elements of our modern life (Ye *et al.* 2013, Ye *et al.* 2016a). Tiny deformation of large scale structure may lead to serious property damage and cause unexpected casualties (Sirivachiraporn and Phienwej 2012, Ozcoban *et al.* 2007). Therefore, the quality monitoring is required to measure the deformation of large scale structures dynamically with high accuracy.

Deformation measurement techniques can be broadly divided into three categories: conventional land surveying techniques, space geodetic techniques, and traditional optical measurement techniques. Conventional land surveying techniques such as leveling, theodolites, total stations and laser range finders have been routinely employed to gather deformation information (Eyers and Mills 2004). However, this technique is time consuming, especially for setting up the system. Moreover, it is not suitable for long-term measurement. Space geodetic techniques, particularly the Global Positioning System (GPS) (Hiroshi *et al.* 2003, Engelkemeir *et al.* 2010), have been widely used in monitoring ground deformations

caused by earthquakes, volcanoes and land subsidence. But the measurement accuracy of GPS in the vertical direction is insufficient for engineering applications. Besides, space geodetic techniques are limited by the period and frequency of observations. Traditional optical measurement techniques are quite mature for deformation measurement. It offers real time operation and dynamic measurement along with little impacted by circumstances. Several vision-based systems have been proposed for dynamic displacement measurement of civil structures (Ye *et al.* 2015a, b, Ye *et al.* 2016b). However, the stability of the camera installations is crucial for this method and it can only be guaranteed under stringent conditions (Luhmann *et al.* 2006).

Compared with abovementioned methods, videometrics has a lot of advantages in the deformation measurement of large scale structures. It can conduct non-contact dynamic measurement with high accuracy, and can handle large set of points simultaneously. In recent years, we proposed two kinds of camera series networks for the deformation measurement of large scale structures. The camera series networks connected all cameras in a relayed fashion (see Figs. 1 and 2). The camera series network differs from the camera parallel network in both principle and detail.

Pose-relay videometrics with camera series network (Chao *et al.* 2010, Yu *et al.* 2015a) was proposed by us to measure the 6 degrees-of-freedom (DOF) of the pose by relaying the position and attitude. This method is the extension of broken-ray videometrics method (Yu *et al.* 2007, Yu *et al.* 2008a, Yu *et al.* 2008b) and the fold-ray videometrics method (Yu *et al.* 2009). A large number of experiments showed that this method can be used to measure 6 DOF deformations of large scale structures, even when the cameras are located on unstable areas. We also

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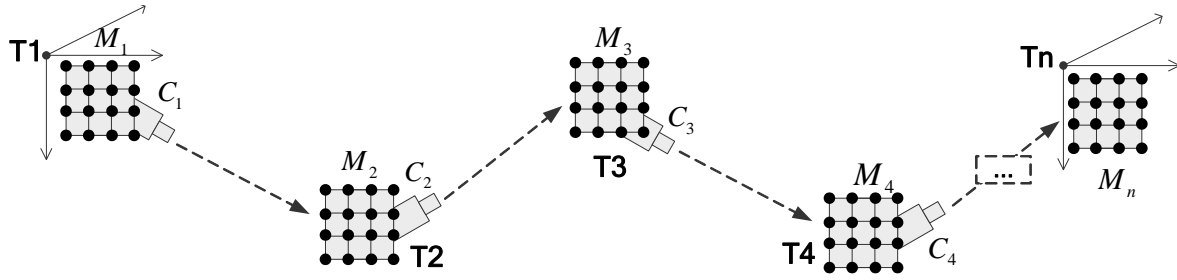


Fig. 1 Pose-relay videometrics with camera series network

proposed the displacement-relay videometrics with camera series network for surface subsidence surveillance (Yu *et al.* 2015b). Different from the pose-relay videometrics, this method only focuses on the vertical subsidence measurement of surface under the condition that cameras are located on unstable areas and thus, tilting and/or subsiding of the cameras may happen. The camera series network is usually calibrated before performing the deformation measurement and a number of calibration methods have been developed (Guan *et al.* 2015, Guan *et al.* 2017a, Guan *et al.* 2017b).

For many deformation measurement tasks, we need install the camera series network around the targets. For example, when we measure the subsidence deformation of the ground bed of a high-rise building, the cameras and cooperative markers are installed around the high-rise building. This type of camera series network is called closed-loop network. The closed-loop camera series network offers “closed-loop constraints” for the camera series network: the subsidence of the reference points observed by different measurement stations is identical. In this paper, we incorporate the closed-loop constraints to our two videometrics methods with camera series network to improve the measurement accuracy. In addition, our videometrics methods with camera series network are quite flexible. Different camera series networks can be combined into a hybrid camera network. We have proposed the combination of the pose-relay videometrics with camera series network and the displacement-relay videometrics with camera series network in this paper. Besides, the camera series network can also be combined with the camera parallel network for deformation measurement of large scale structures.

The remainder of this paper is organized as follows: Section 2 describes the basic principle of pose-relay videometrics with camera series network. Section 3 describes the basic principle of displacement-relay videometrics with camera series network. Section 4 describes the pose-relay videometrics and the displacement-relay videometrics with closed-loop camera series network. Section 5 describes camera series network with multiple closed-loops. The combinations of camera networks are presented in Section 6. Section 7 describes simulation experiments that are carried out to prove the correctness and validity of the proposed methods. Conclusions are presented in Section 8.

2. Pose-relay videometrics with camera series network

The pose-relay videometrics with camera series network is capable of measuring the pose of both non-intervisible targets and targets that are far from their reference point. The method is outlined as follows: (a) construct a pose-relay path using multiple measurement relay stations, each of which comprises cameras and cooperative markers; (b) obtain the position and attitude of each camera on the path relative to the corresponding marker in its neighboring relay station; and (c) transmit and calculate the position and attitude of the final measurement target relative to the reference point.

Here we provide a brief introduction to the principle of the pose-relay videometrics with camera series network, using the pose-relay form shown in Fig. 1 as an example. The pose-relay videometrics with camera series network consists of three parts: T1, a reference station; Tn, a target to be measured, and Ti ($i = 2, 3, \dots, n-1$), which denotes measurement relay stations. The stations can be built by combining a pose measuring camera C and an artificial cooperative marker M. The artificial cooperative markers can be constructed by any objects with known structure, such as a calibration cube, and a flat checkerboard. The transformation between the camera C and the cooperative marker M are fixed and can be obtained by calibration beforehand (Shiu and Ahmad 1989, Park and Martin 1994).

In light of our fundamental knowledge of videometrics and computer vision, the position and attitude relationship between the cooperative marker and the neighboring camera can be obtained in real time by a camera based on the monocular measurement principle according to images obtained by the cooperative markers (Lu *et al.* 2000, Ansar and Daniilidistc 2003). Thus for $1 \leq i \leq n$, the following equation can represent the rotation matrix $\mathbf{R}_{T1, Tn}$ and the translation vector $\mathbf{t}_{T1, Tn}$ from the reference point T1 to the target Tn

$$\begin{cases} \mathbf{R}_{T1, Tn} = \prod_{i=1}^{n-1} \mathbf{R}_{n-i, n-i+1} = \mathbf{R}_{n-1, n} \mathbf{R}_{n-2, n-1} \cdots \mathbf{R}_{1, 2} \\ \mathbf{t}_{T1, Tn} = \sum_{i=1}^{n-2} \left[\left(\prod_{j=0}^{n-2-i} \mathbf{R}_{n-j-1, n-j} \right) \mathbf{t}_{i, i+1} \right] + \mathbf{t}_{n-1, n} \end{cases} \quad (1)$$

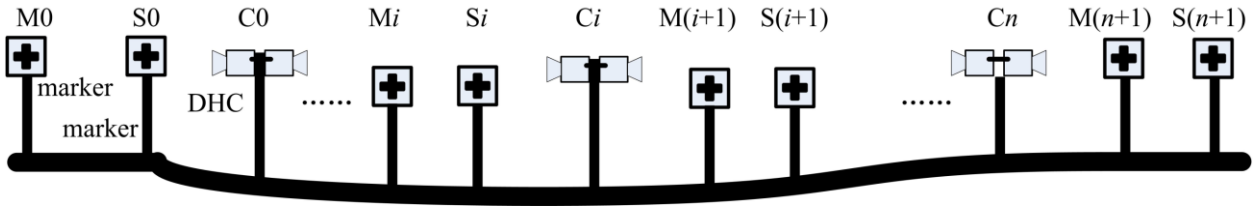


Fig. 2 Displacement-relay videometrics with camera series network

Pose-relay videometrics with camera series network is suitable for the measurement of 6 DOF deformation in real-time for the long term. A large number of experiments conducted both ship deformation measurement (Yu *et al.* 2007, Yu *et al.* 2008a, Yu *et al.* 2009) and tunnel rocks monitoring (Yu *et al.* 2008b) have shown that this method is an effective solution to the problem of deformation measurement between non-intervisible objects in a large structure or between objects in a large viewing field.

3. Displacement-relay videometrics with camera series network

The displacement-relay videometrics with camera series network is designed to measure the vertical subsidence of unstable areas of interests (Yu *et al.* 2015b), which differs from the pose-relay videometrics with camera series network. The displacement-relay videometrics with camera series network is formed by mounting double-headed cameras (DHCs) and cooperative markers either into a line. The number of DHC and cooperative markers can be selected according to the application requirement, as shown in Fig. 2. The notation C_i represents the DHCs. The notations M_i and S_i represent the cooperative markers.

In practice, vertical subsidence is the major deformation of roadbed and the deformation of other directions is quite small. Thus, we suppose that there is only subsidence deformation for cooperative markers and as for the DHC, it just exists subsidence and pitch angles. The fixation constraint between double-headed cameras and the homologous constraint between images of the same cooperative marker are established to formulate the displacement-relay measurement equations as follow (Yu *et al.* 2015b)

$$\begin{cases} h_{M_i}^{C_i} = k_{M_i}^{C_i} (\Delta y_{M_i} - \Delta y_{C_i} - d_{M_i}^{C_i} \cdot \sin \theta_{C_i}) \\ h_{S_i}^{C_i} = k_{S_i}^{C_i} (\Delta y_{S_i} - \Delta y_{C_i} - d_{S_i}^{C_i} \cdot \sin \theta_{C_i}) \\ h_{M(i+1)}^{C_i} = k_{M(i+1)}^{C_i} (\Delta y_{M(i+1)} - \Delta y_{C_i} + d_{M(i+1)}^{C_i} \cdot \sin \theta_{C_i}) \\ h_{S(i+1)}^{C_i} = k_{S(i+1)}^{C_i} (\Delta y_{S(i+1)} - \Delta y_{C_i} + d_{S(i+1)}^{C_i} \cdot \sin \theta_{C_i}) \end{cases} \quad (2)$$

Where C_i is the DHC, M_i , S_i , $M(i+1)$, and $S(i+1)$ are the corresponding cooperative markers, Δy_{M_i} , Δy_{S_i} , $\Delta y_{M(i+1)}$ and $\Delta y_{S(i+1)}$ are the subsidence of the cooperative markers, Δy_{C_i} is the subsidence of the DHC, θ_{C_i} is the pitch angle

of the camera's optical axis, $d_{M_i}^{C_i}$, $d_{S_i}^{C_i}$, $d_{M(i+1)}^{C_i}$ and $d_{S(i+1)}^{C_i}$ are the distances between the camera and the corresponding markers. The vertical displacements of the cooperative markers on the images are $h_{M_i}^{C_i}$, $h_{S_i}^{C_i}$, $h_{M(i+1)}^{C_i}$ and $h_{S(i+1)}^{C_i}$ respectively, and the magnifications are $k_{M_i}^{C_i}$, $k_{S_i}^{C_i}$, $k_{M(i+1)}^{C_i}$ and $k_{S(i+1)}^{C_i}$ respectively. Eq. (2) contains 4 sub-equations and 6 unknown parameters, Δy_{C_i} , θ_{C_i} , Δy_{M_i} , Δy_{S_i} , $\Delta y_{M(i+1)}$ and $\Delta y_{S(i+1)}$.

When there are two DHCs, two unknown parameters, i.e., the subsidence of two markers between them, are repeated. Hence, when there are n DHCs as shown in Fig. 2, the number of unknown parameters is $4n+2$, and the number of sub-equations is $4n$. In order to have unique solutions of Eq. (2), one of the following conditions should be guaranteed: (1) the subsidence of two or more reference points must be known; (2) the subsidence and pitch angle of one or more DHC must be known. Principal components analysis (PCA) (Gao *et al.* 2011) is adopted to obtain the robust solutions.

Both the simulations and the laboratory experiments validate that this method could obtain the vertical subsidence of measurement points even when the subsidence and tilts happened for the DHCs themselves (Yu *et al.* 2015b).

4. Closed-loop camera series network

Closed-loop camera series network exhibits that the cameras and the cooperative markers are installed around the large scale structures, which is the common setup for deformation measurements. For example, when we measure the subsidence deformation of the ground beds of a high-rise building, the cameras and cooperative markers are installed around the high-rise building, so that the camera series network is a closed network. The closed-loop camera series network provides "closed-loop constraints" of the camera series network: the subsidence of the reference points observed by different measurement stations is identical. The reference point can be chosen from any measurement stations in the closed-loop camera series network. The reference points are required to be either stable or with known subsidence. This section explores the possibility of taking full advantage of the closed-loop constraints of camera series network for both the pose-relay videometrics method and the displacement-relay

videometrics method.

4.1 Pose-relay videometrics with closed-loop camera series network

The pose-relay videometrics with closed-loop camera series network is designed for measuring the 6 DOF deformation of large scale structures, see Fig. 3. It is formed by mounting the measurement stations around the large scale structures. Please refer to the Section 2 for the principle of measurement.

We use the closed-loop constraints of the closed-loop camera series network. The closed-loop constraints are established at the reference point T1. Thus the closed-loop constraints of pose-relay videometrics with camera series network can be represented as follows

$$\begin{cases} \mathbf{R}_{T1,T1} = \mathbf{R}_{n,1} \prod_{i=1}^{n-1} \mathbf{R}_{n-i,n-i+1} = \mathbf{R}_{n,1} \mathbf{R}_{n-1,n} \mathbf{R}_{n-2,n-1} \cdots \mathbf{R}_{1,2} = \mathbf{I} \\ \mathbf{t}_{T1,T1} = \mathbf{R}_{n,1} \left(\sum_{i=1}^{n-2} \left[\left(\prod_{j=0}^{n-2-i} \mathbf{R}_{n-j-1,n-j} \right) \mathbf{t}_{i,i+1} \right] + \mathbf{t}_{n-1,n} \right) + \mathbf{t}_{n,1} = \mathbf{0} \end{cases} \quad (3)$$

Typically, the closed-loop constraints provide constraint conditions for non-linear optimization. We perform the optimization process by adjusting the measurement data in the pose-relay videometrics with closed-loop camera series network, the cost function minimizes the re-projection error of all the cooperative markers.

4.2 Displacement-relay videometrics with closed-loop camera series network

As shown in Fig. 4, the displacement-relay videometrics with closed-loop camera series network is designed for measuring the vertical subsidence of large scale structures. It is formed by mounting DHCs and cooperative markers alternately around the large scale structures. Assuming the optical axes of the DHCs are approximately parallel, we only need to install the cooperative markers at the turning points of closed-loop. Please refer to the Section 3 for the principle of measurement.

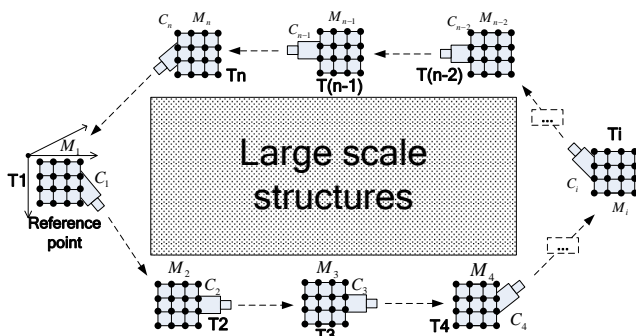


Fig. 3 System configuration of pose-relay videometrics with closed-loop camera series network

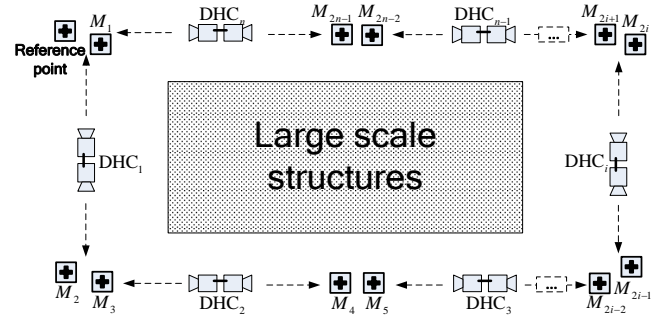


Fig. 4 System configuration of displacement-relay videometrics with closed-loop camera series network

In the displacement-relay videometrics with closed-loop camera series network, there is a reference point which is strictly stable or have known subsidence. The images of reference point are captured by different cameras in DHC_1 and DHC_n . This is equivalent to that there are two reference points are distributed at both ends of camera series network. There are n double-headed cameras, and we obtain $4n$ equations based on Eq. (2). The number of unknown parameters is only $4n-1$, which consists of $2n-1$ subsidence of the cooperative markers, n subsidence of the cameras, and n pitch angles of the camera's optical axis. The measurement equations of displacement-relay videometrics with closed-loop camera series network can be written in the following matrix form

$$\mathbf{A}_{4n \times (4n-1)} \cdot \mathbf{X}_{(4n-1) \times 1} = \mathbf{H}_{4n \times 1} \quad (4)$$

where the vector \mathbf{X} consists of the unknown parameters. \mathbf{A} is a $4n \times (4n-1)$ coefficient matrix which consists of the magnifications and the distances between the camera and the corresponding markers. \mathbf{H} is a $4n \times 1$ vector which consists of the vertical displacements of the cooperative markers on the images. Finally, the PCA is adopted to obtain the solutions for the subsidence of positions where the cameras and markers are attached to. Furthermore, the tilt angles of cameras are computed at the same time.

5. Camera series network with multiple closed-loops

In some deformation measurement applications, camera series network with multiple closed-loops are required, for example, simultaneously monitoring the ground beds of multiple high-rise buildings or the deformation around multiple mines. Camera series network with multiple closed-loops can be transformed into a variety of configurations based on the different structures of measurement stations. Since some cooperation markers are observed by several measurement stations at different locations, these cooperation signs can be set as spherical markers. Compared with multiple independent closed-loop camera series networks, camera series network with

multiple closed-loops provides more constraints for the measurement stations. This network is flexible in designing different structures of measurement stations, so we introduce the multiple closed-loops through typical designing structures.

5.1 Pose-relay videometrics with multiple closed-loops

As shown in Fig. 5, the pose-relay videometrics with multiple closed-loops is designed for measuring the 6 DOF deformation of multiple areas. It is formed by mounting the different structures of measurement stations rounding A, B, C and D areas.

There are four closed-loops which contain four closed-loop constraints of the camera series network

$$\begin{aligned}
 \text{Closed-loop1: } & \mathbf{T}_A^1 \longrightarrow \mathbf{T}_A^i \longrightarrow \mathbf{T}_A^j \longrightarrow \mathbf{T}_A^n \longrightarrow \mathbf{T}_A^1 \\
 \text{Closed-loop2: } & \mathbf{T}_A^1 \longrightarrow \mathbf{T}_A^i \longrightarrow \mathbf{T}_B^j \longrightarrow \mathbf{T}_B^n \longrightarrow \mathbf{T}_A^1 \\
 \text{Closed-loop3: } & \mathbf{T}_A^1 \longrightarrow \mathbf{T}_C^i \longrightarrow \mathbf{T}_C^j \longrightarrow \mathbf{T}_A^n \longrightarrow \mathbf{T}_A^1 \\
 \text{Closed-loop4: } & \mathbf{T}_A^1 \longrightarrow \mathbf{T}_C^i \longrightarrow \mathbf{T}_D^j \longrightarrow \mathbf{T}_B^n \longrightarrow \mathbf{T}_A^1
 \end{aligned} \quad (5)$$

The closed-loop constraints of four closed-loops can be represented by Eq. (3). These closed-loop constraints provide the constraint conditions for non-linear optimization, then the optimization process is performed by adjusting all the measurement data in the camera series networks.

5.2 Displacement-relay videometrics with multiple closed-loops

The displacement-relay videometrics with multiple closed-loops is designed for measuring the vertical subsidence of multiple areas. As shown in Fig. 5, the DHCs and cooperative markers are mounted alternately rounding A, B, C and D areas.

In Fig. 6, there is a reference point which is strictly stable or has known subsidence. Assuming there are n double-headed cameras, so we can obtain $4n$ equations based on Eq. (2).

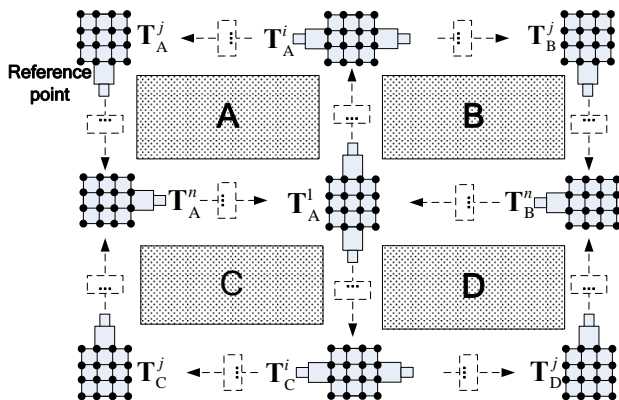


Fig. 5 System configuration of pose-relay videometrics with multiple closed-loops

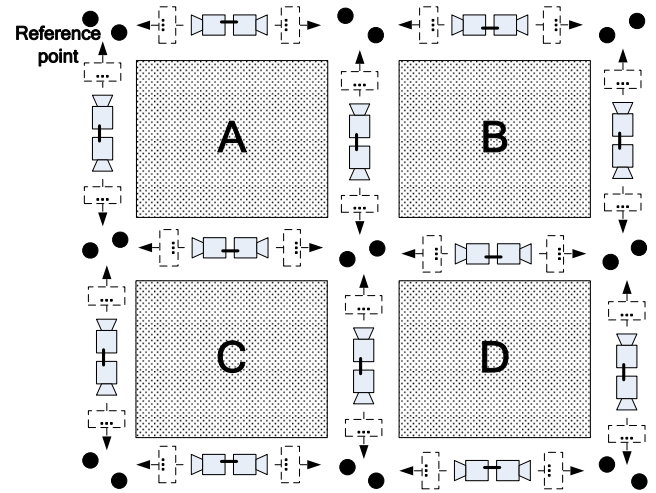


Fig. 6 System configuration of displacement-relay videometrics with multiple closed-loops

Since six markers are repeatedly measured by several cameras, the number of unknown parameters is only $4n-7$, which consists of $2n-7$ subsidence of the cooperative markers, n subsidence of the cameras, and n pitch angles of the camera's optical axis. The measurement equations of displacement-relay videometrics with multiple closed-loops can be written in the following matrix form

$$\mathbf{A}_{4n \times (4n-7)} \cdot \mathbf{X}_{(4n-7) \times 1} = \mathbf{H}_{4n \times 1} \quad (6)$$

where the matrix \mathbf{A} , the vector \mathbf{X} and the vector \mathbf{H} are similar to Eq. (4). The robust solutions for the above equation are also obtained based on the PCA.

6. Combination of camera networks

The establishment of videometrics methods with camera series network are quite flexible for the deformation measurement of large scale structures. The different forms of camera series networks can be combined into a hybrid camera network. As mentioned above, the pose-relay videometrics with camera series network is capable of measuring the pose of measurement stations, and the displacement-relay videometrics with camera series network only focuses on measuring the vertical subsidence. Thus, any one of the measurement stations in the pose-relay videometrics can also be used to measure the vertical subsidence of unstable areas of interests. Besides, we can install more than two cooperative markers between the DHCs, the subsidence of all cooperative markers, the subsidence of the cameras, and the pitch angle of the camera's optical axis can be also solved simultaneously. The displacement-relay videometrics with camera series network will become the pose-relay videometrics with camera series network if more than three cooperative markers between the DHCs and the fixed spatial relationship between the cooperative markers is known.

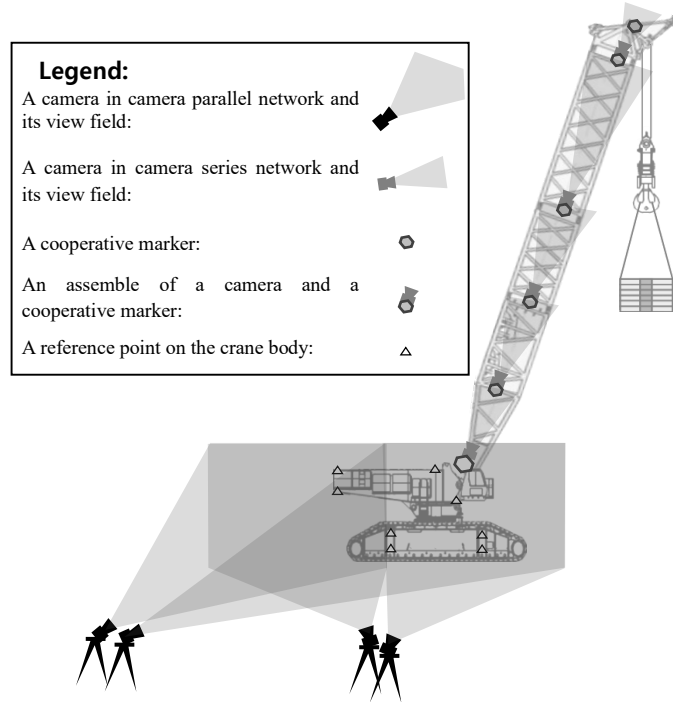


Fig. 7 The illustration of dynamic monitoring of large scale crane

Moreover, we can combine the advantages of the camera parallel network and the camera series network. The pose-relay videometrics with camera series network combined with the camera parallel network has been applied for the dynamic monitoring of a large scale crane in lifting operation (Shang *et al.* 2014). As shown in Fig. 7, the camera parallel network is designed to measure the motion of the crane body in a small range while the pose-relay videometrics with camera series network is designed to measure the motion of the crane arm in a large range and the deformation of the arm. The camera parallel network is mounted on the ground adjacent to the crane, aiming at the crane body and the reference points of the camera series network. The measurement stations of the camera series network are mounted from the root to the end of the crane arm, where the reference station (first station) is on the root of the arm and the last station is on the end. The last station is installed with a cooperative marker. The others measurement stations are equipped with an assemble of a camera and a cooperative marker. The results obtained by the camera parallel network and the camera series network are in the same coordinate system.

In the dynamic monitoring of large scale crane, the camera parallel network which is mounted at stable points is used to measure the deformation of the reference points for the camera series network. The camera series network is then used to measure the large range deformation of the large scale structures. However, there is no stable point for mounting the camera in some situations. The deformation measurement data at different times cannot be unified to a global coordinate system, so that the deformation of the large structure over time cannot be analysed. To overcome these situations, we have proposed another method of

combining the camera parallel network and the camera series network. As shown in Fig. 8, C indicates the camera, M indicates the artificial cooperative marker, W indicates the object to be measured. The camera series network is composed of $C_{S0}, M_1-C_{S1}, \dots, M_i-C_{Si}$ and M_n . The camera parallel network can be divided into two groups: one is $C_{P0}, C_{P1}, \dots, C_{Pi}, \dots, C_{Pn}$, and the other is $C_{D0}, C_{D1}, \dots, C_{Di}, \dots, C_{Dn}$. The measured objects W_{Pi} and W_{Di} are observed by more than two cameras of the camera parallel network. We assume that the camera coordinate system of C_{S0} is set as the global coordinate system.

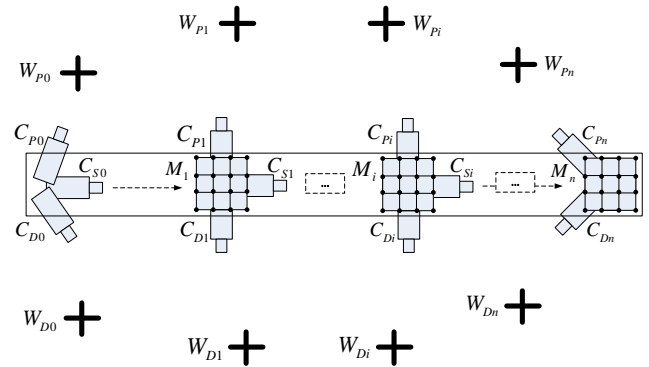


Fig. 8 Another combination of camera series network and camera parallel network

Table 1 RMS of errors made by ten-level pose-relay videometrics with camera series network

Measurement errors	Previous camera series network	Closed-loop camera series network
Ax (angular second)	27.9774	20.8423
Ay (angular second)	20.6109	15.8905
Az (angular second)	28.6320	21.3209
Tx (mm)	2.4312	1.3385
Ty (mm)	3.4492	2.3876
Tz (mm)	2.5885	1.8828

The camera series network is used to determine the poses of the cameras in the camera parallel network, and these cameras is then used to measure the deformation of the markers in the large scale structures. Thus the measurement results obtained by the camera parallel network and the camera series network can be unified to the global coordinate system. Note that the configuration of the cameras and lens can be flexibly determined according to the actual measurement object. Compared with the measurement method by a camera parallel network or a camera series network, the camera series network combined with the camera parallel network accomplish the measurement with low cost by designing the measurement system intelligently.

7. Experimental results and analysis

The simulated data is used to test the feasibility of the pose-relay videometrics method and the displacement-relay videometrics method with closed-loop camera series network. Same data is used to compare previous camera series network and the closed-loop camera series network for the deformation measurement of large scale structures.

7.1 Numerical simulations for pose-relay videometrics with closed-loop camera series network

A closed-loop camera series network with 10 measurement stations is used in our experiment, i.e. $n=10$ in Fig. 3. Around the large scale structures, the measurement stations are uniformly installed on a circle with a radius of 25 meters. The image size of camera is 2000×2000 pixels. The cooperative marker, is composed of 8 non-coplanar cross control points, along with the local coordinate information. The transformation between the camera and the cooperative marker is fixed and set to be known in each measurement station.

Gaussian noise with standard deviation 0.1 pixels is added to the image feature observations of all cameras. T_1 is set as the reference station in camera series network. The relative pose between the measurement station T_i and the reference station T_1 , i.e., $\mathbf{R}_i^{T_1}(Ax_i^{T_1}, Ay_i^{T_1}, Az_i^{T_1})$ and $\mathbf{T}_i^{T_1}(Tx_i^{T_1}, Ty_i^{T_1}, Tz_i^{T_1})$ are solved according to the previous camera series network method and the closed-loop camera

series network method, respectively. The only difference between two methods is whether to use the closed-loop constraints of the camera series network.

The simulation process is repeated 100 times to calculate the standard deviation of the pose errors between the measured values and the true values. Table 1 reports the standard deviation of measuring errors made by a ten-level pose-relay videometrics with camera series network.

One can see from the Table.1 that the pose-relay videometrics with closed-loop camera series network gives considerably higher accuracy, when the closed-loop constraints are adopted. The closed-loop structure implies that there are two reference which points are distributed at both ends of camera series network. Compared to only one stable point in previous camera series network, the closed-loop camera series network gives better measurement results.

7.2 Numerical simulations for displacement-relay videometrics with closed-loop camera series network

The displacement-relay videometrics system with closed-loop camera series network containing 10 DHCs in the simulation is similar to that in Fig. 4. Around the large scale structures, the DHCs and cooperative markers are uniformly installed on a circle with a radius of 25 meters. The simulation conditions are:

(c1) Each distance between adjacent DHCs is assumed as about 16 meters, and all magnification factors (k) in Eq. (1) are set to 1 pixel/mm by adjusting markers' size, lens focal length.

(c2) Random subsidences in the range of $[-50, 50]$ mm is added to the mediate markers and DHCs, and random tilt angles in the range of $[-10', 10']$ are added to each DHC.

(c3) The subsidence of only one reference point is set to be known for the closed-loop camera series network. However, two reference points distributed at both ends of camera series network are required to have known subsidence for the previous camera series network.

(c4) The ideal marker changes in the image coordinates are calculated from Eq. (2). Then, image location errors between $[-0.1, 0.1]$ pixel are added to the changes in the ideal coordinates.

The simulation process has been repeated 100 times. The root mean square (RMS) of the subsidence error of each marker and each DHC is chosen as the output error, which is illustrated in Table 2.

Table 2 RMS of errors made by ten-level displacement-relay videometrics with camera series network

	Previous camera series network	Closed-loop camera series network
Subsidence measurement errors (mm)	1.2947	1.0653

Compared with the previous camera series network, the closed-loop camera series network improves measuring accuracy. It should be noted, only one reference point is required for the closed-loop camera series network and the previous camera series network has solution only in the case of two reference points.

8. Conclusions

In this paper, we first give an overview of our research work in the camera series network for the deformation measurement of large scale structures, including the pose-relay videometrics with camera series network and the displacement-relay videometrics with camera series network. Then we propose two kinds of videometrics with closed-loop camera series network for deformation measurement of large scale structures. The closed-loop camera series network provides the closed-loop constraints for the camera series network. The closed-loop constraints improve the measurement accuracy in camera series network. The simulated results show that the closed-loop camera series network enhances the measurement accuracy achieved with the previous camera series network owing to its use of the closed-loop constraints. The camera series networks with multiple closed-loops are also proposed for the complex deformation measurement applications. Furthermore, we propose several flexible combinations of camera series networks to facilitate more measurement tasks.

A number of factors are needed to consider in the practical application of camera series network, like high and low temperature tolerance, preventing damp and dust, system power, synchronization of multiple cameras, etc. We will solve these factors in the future work for the popularization of camera series network.

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