

Computer Vision-Based Structural Deformation Monitoring System on Android Smartphones: Design and Implementation

Xiang DONG*, Maokai LAI*, Hui LIANG**, ***, Peng WU*, Chaoxia WANG****, Ting PENG*

* Chang'an University, Xi'an 710064

** Shaanxi Huashan Road and Bridge Group Co., LTD. Xi'an 710016

*** Shaanxi Zhengcheng Road and Bridge Engineering Research Institute Co., LTD. Xi'an 712000

**** Xi'an University of Posts and Telecommunications, Xi'an 710061

1290740787@qq.com, 3412303785@qq.com, 5936001270@qq.com, 1169886830@qq.com, 2102332664@qq.com, t.peng@ieee.org

Abstract— Computer vision displacement monitoring techniques offer a promising alternative to traditional displacement sensors, but most current approaches or systems use high-cost cameras and require limited measurement sites. To facilitate widespread implementation in real-world engineering, simpler systems or approaches are needed. This paper introduces a computer vision-based structural deformation monitoring system, written and developed using OpenCV and Kotlin. The system uses an Android smartphone camera and telescope as the acquisition device and adopts template matching technology based on digital image correlation to realize target displacement monitoring. A real-time display of the offset curve is realized with MPAndroidChart, and socket TCP communication is used to transmit the monitoring data. The detailed operation process of the system is shown as an example of dynamic detection. The test results show that the system runs smoothly, is easy to operate, and has the following advantages: 1) Low cost of hardware composition and simple construction process; 2) High monitoring accuracy (accurate to 0.01 mm); 3) High monitoring frequency (up to 10 frames per second in dynamic detection mode); 4) Visualization of monitoring data, with the monitoring structural offset presented in real time as a curve for easy user comprehension. Overall, this system can provide technical and auxiliary decision support for structural deformation monitoring.

Keywords— Computer Vision, Kotlin, OpenCV, Structural Deformation Monitoring, Socket TCP

I. INTRODUCTION

Structural deformation monitoring plays a very important role in ensuring the long-term safety of transportation infrastructure such as highways, bridges, and tunnels, as well as in their early warning and assessment. The commonly used displacement measurement methods include contact and non-contact measurements. The literature systematically discusses the advantages and disadvantages of the two displacement measurement methods [1-3]. Among them, contact displacement measurement methods usually use accelerometers, linear variable differential pressure transducers (LVDT), and tie-wire displacement sensors.

Accelerometers can directly measure the acceleration response of a structure, but the measurement effect is insufficient in the low-frequency range. Linear variable differential pressure transducers (LVDT) have higher measurement accuracy, but they are not easy to install in practical engineering because they usually need to be mounted between the target point and a fixed reference point. Non-contact displacement measurement methods usually include the Global Positioning System (GPS), Total Station, Laser Doppler Vibrometer (LDV), Computer Vision Displacement Measurement, etc. GPS sensors are relatively easy to install, but their measurement accuracy is limited. Total stations have high accuracy, but the measurement speed is low, and the collection of data is time-consuming, which limits the overall efficiency. The Laser Doppler Vibrometer (LDV) can realize high-resolution, high-accuracy remote displacement measurements, but it needs to be installed close to the object and is limited to a few measurement points and expensive equipment.

In recent years, computer vision-based methods have received extensive research attention due to their advantages of non-contact, long-distance, high accuracy, and multi-point monitoring, and have been applied in civil engineering structural health monitoring, including bridge deflection testing and damage identification. However, most of the current monitoring programs or systems use high-cost cameras, and the measurement sites used to install hardware devices are often limited and affected by external environmental factors, which restricts the widespread application of this technology. To this end, many researchers have made contributions in reducing deployment costs, optimizing target tracking algorithms, and reducing system complexity. Chen [1] proposed an improved visual method for robust multi-point dynamic displacement monitoring of smartphones in interference environments and conducted a series of sinusoidal swept vibration experiments considering different interference factors to investigate the performance of the method. Bai [4] proposed a non-contact visual sensing system for monitoring

structural displacements using the advanced Zernike sub-pixel edge detection technique, which provides the intrinsic frequency and vibration pattern of the target instantaneously and can be used to accurately localize damage. Khan [5] proposed a new low-cost, non-contact displacement measurement system called the high-tech computer-Vive tracking system (HTC-VTS) and achieved favourable results in laboratory-scale free vibration tests and shaker tests on cantilever girders, as well as actual bridge displacement measurements.

To facilitate widespread implementation in real-world engineering, this paper proposes a computer vision-based structural deformation monitoring system on Android smartphones. The computer vision-based structural deformation monitoring system's overall architecture is initially introduced in this study, after which each module's design parameters and implementation tactics are discussed. By using dynamic detection as an example, the basic processes of the computer vision-based structural deformation monitoring system are shown. To a certain extent, the system can offer technical and auxiliary decision support for structural deformation monitoring.

II. DESIGN AND IMPLEMENTATION OF COMPUTER VISION-BASED STRUCTURAL DEFORMATION MONITORING SYSTEM

A. Overall System Design

This paper is based on the Android Studio Arctic Fox |2020.3.1 Patch 2 development environment, which uses OpenCV and Kotlin to set up a structural deformation monitoring program and develop a computer vision-based structural deformation monitoring system. The system uses an Android smartphone camera plus a telescope as the acquisition device and adopts a template matching technique based on digital image correlation to realize target displacement monitoring. The overall architecture of the system is shown in **Figure 1**, which mainly includes four modules: image acquisition, image processing, data visualization, and data transmission. Among them, the image processing module contains two modes: static detection and dynamic detection, which can track the deformation of the structure in real time according to the change in relative offset of multiple markers on the structure and the change in absolute offset of the overall markers and provide an early warning so as to take timely measures to deal with the potentially dangerous structure.

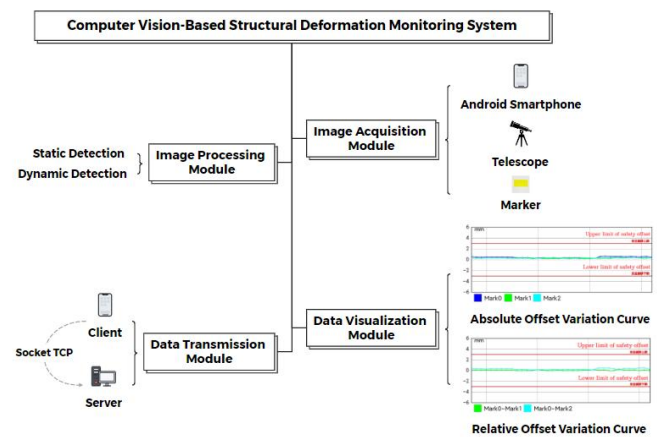


Figure 1. Computer vision-based structural deformation monitoring system architecture

1) Image Acquisition Module: The image acquisition module includes an Android smartphone, a telescope, and markers for the purpose of image acquisition of markers on the structure for template creation and to facilitate subsequent image processing of the markers.

Android smartphones equipped with high-resolution cameras offer the advantages of low cost, portability, and ease of operation, while being able to perform optical sensing under varying conditions [1]. In order to ensure the smooth operation of the system and the high clarity of the captured images, the smartphone used in this paper requires Android 5.0 or higher version.

This paper uses the SAGA Maksutov-Cassegrain II telescope and the accompanying metal mobile phone clip. The telescope's parameters are as shown in **Table 1**. The advantages of the telescope are mainly reflected in three aspects: first is the 70mm large caliber and brighter brightness; second is the combination of the advantages of reflection and refraction; the short-lens body achieves a long focal length, improved resolution, and an effective magnification multiplier; and third is the very short mirror body, which achieves portability and stability.

TABLE 1. TELESCOPE PARAMETERS

No.	Telescope Parameters	Value
1	Size	250×83×135mm
2	Eyepiece Size	20mm
3	Exit Pupil Diameter	2.8~0.93mm
4	Distance of Exit Pupil	15~13mm
5	Magnification Rate	25~75 times
6	Focal Length	780mm
7	Objective Lens Caliber	70mm
8	Near Focal Distance	4.5m

Markers include both artificial markers and natural markers. Among them, artificial markers are markers added to the measured structure to increase the differentiation between the tracking target and the surrounding environment and to improve the tracking accuracy, while natural markers utilize the image features and texture structure on the surface of the structure as markers [3]. As the accuracy of artificial markers

is higher than that of natural markers, this study prioritizes the use of artificial markers to obtain stable measurement results when the installation conditions allow.

The acquisition device consisting of an Android smartphone and a telescope is shown in **Figure 2**.



Figure 2. Acquisition device

2) Image Processing Module: The image processing module includes two modes, static detection and dynamic detection, both of which are realized by switching the monitoring mode through switch code. The image processing is achieved by cropping the acquired image, template creation, conversion of the actual length of the template to the pixel length, target tracking, displacement calculation, and providing a data source for the data visualization module.

Currently the commonly used target tracking method in computer vision structure displacement measurements is based on template matching with digital image correlation. The template matching methods in OpenCV include six [3, 6], as listed in **Table 2**.

TABLE 2. MATCHTEMPLATE () FUNCTION TEMPLATE MATCHING METHOD TO SELECT THE MARK PARAMETERS

No.	Mark Parameters	Function
1	TM_SQDIFF	Sum of Squared Difference
2	TM_SQDIFF_NORMED	Normalized Sum of Squared Difference
3	TM_CORR	Cross Correlation
4	TM_CCORR_NORMED	Normalized Cross Correlation
5	TM_CCOEFF	Zero-mean Cross Correlation
6	TM_CCOEFF_NORMED	Zero-mean Normalized Cross Correlation

Of those indicators listed in **Table 2**, TM_SQDIFF uses the sum of squared differences to match, and TM_SQDIFF_NORMED normalizes TM_SQDIFF so that the result is scaled to a value between 0 and 1. Both methods compute a value of 0 when the template and the sliding window are perfectly matched, and the lower the match between the two, the greater the computed value. TM_CORR uses a multiplication operation between the template and the image; the larger the matching value, the better the matching effect, and 0 means the worst matching result.

TM_CCORR_NORMED normalizes the TM_CORR so that the result is scaled to the range between 0 and 1. When the template matches perfectly with the sliding window, the calculated value is 1, and when the two don't match at all, the calculated result is 0. TM_CCOEFF uses TM_CORR to match the result of the template subtracted from the mean and the result of the original image subtracted from the mean, and this method can be a better solution to the effect between the template image and the original image due to the difference in brightness. In this method, the higher the match between the template and the sliding window, the larger the calculated value is; the lower the match, the smaller the calculated value is; and the calculated result of this method can be negative. TM_CCOEFF_NORMED normalizes the TM_CCOEFF so that the result is scaled down to a value between 1 and -1. When the template matches perfectly with the sliding window, the calculated value is 1, and when the two are not matched at all, the calculated result is -1.

Due to the fact that the sum of squared differences calculates the Euclidean distance between the template image and the overlapping image as a similarity measure, which is the most intuitive indicator and simple to calculate [6], Therefore, the computer vision-based structural deformation monitoring system design implements target tracking by calling the TM_SQDIFF method in OpenCV for template matching. Its corresponding Python code is shown in **Figure 3**.

```

fun match(source: Mat, target: Mat): Point {
    val point: Point
    val resultH: Int
    val resultW: Int
    resultH = source.rows() - target.rows() + 1
    resultW = source.cols() - target.cols() + 1
    val result = Mat(org.opencv.core.Size(resultH.toDouble(), resultW.toDouble()), CvType.CV_32F1)
    Imgproc.matchTemplate(source, target, result, Imgproc.TM_SQDIFF)
    val mnr = Core.minMaxLoc(result)
    point = mnr.minLoc
    return point
}

```

Figure 3. Template matching

The matching algorithm calculation formula is as follows when using TM_SQDIFF from OpenCV:

$$R(x, y) = \sum_{x', y'} [T(x', y') - I(x + x', y + y')]^2 \quad (1)$$

In the formula, T refers to a template image, and I stands for an image to match. x and y represent the coordinates of the element in the upper left corner of the current search box in the I matrix. x', y' represent the element coordinates of the matrix I of the T and the search box out.

3) Data Visualization Module: Based on MPAndroidChart, the visual monitoring system of structural deformation is visualized. The module can record the absolute and relative offsets of each marker in real time and display them in the form of curves, and the visualization function of the system can also be used as an auxiliary means of manual monitoring to ensure the reliability of the data.

4) Data Transmission Module: In order to facilitate further calibration and verification of the data, ExcelUtil is called during the development of the system to realize the function of exporting the monitoring data in the form of an Excel table. When exporting data, you can choose to export

the data to smartphone or PC. If the monitoring data is exported to the smartphone, the system directly stores the monitored data in the path "android/data/com.android.detect" in the file manager by default. If the monitoring data is exported to a PC, it is necessary to transfer the monitoring data through socket communication based on the Transmission Control Protocol (TCP). Zhang [7] mentioned stream sockets use the TCP protocol, and due to their internal flow control settings, they can transmit large amounts of data streams when used. At the same time, it provides a reliable service to ensure that no packet errors occur during transmission. Therefore, when designing the data transmission module, this method is used to achieve data transmission, and the implementation code is shown in **Figure 4** and **Figure 5**.

```
try {
    mSocket = Socket(nIP, mPort)

    mOutputStream = mSocket!!.getOutputStream()
    mInputStream = mSocket!!.getInputStream()
    if (file == null) {
        return
    }
    writeMsgInternal(file)

    val buffer = ByteArray(1024)
    try {
        mInputStream.read(buffer)
        val str = String(buffer, "UTF-8")
    } catch (e: IOException) {
        e.printStackTrace()
    }
    mSocket!!.close()
}
```

Figure 4. Client implementation

```
Socket clientSocket = Socket("192.168.1.100", 8080);
if (clientSocket.isConnected()) {
    OutputStream outputStream = clientSocket.getOutputStream();
    File file = new File("D:\\data\\");
    if (file.exists()) {
        File[] files = file.listFiles();
        for (File f : files) {
            outputStream.write(f.getName().getBytes());
        }
    }
    clientSocket.close();
}

try {
    Socket serverSocket = Socket("192.168.1.100", 8080);
    if (serverSocket.isConnected()) {
        InputStream inputStream = serverSocket.getInputStream();
        byte[] buffer = new byte[1024];
        while (true) {
            int len = inputStream.read(buffer);
            if (len == -1) break;
            String str = new String(buffer, 0, len, "UTF-8");
            System.out.println(str);
        }
        serverSocket.close();
    }
}
```

Figure 5. Server implementation

B. Implementation

When applying the computer vision-based structural deformation monitoring system for displacement monitoring, the static detection is the same as the dynamic detection except that it is not necessary to slide the static detection to the dynamic detection and fill in the time of the dynamic detection after the image acquisition is completed. Take dynamic detection as an example, the process is roughly divided into the following 4 steps:

1) Test Preparation: Attach the telescope to a tripod and secure the Android phone through the phone clip, then aim at artificial targets.

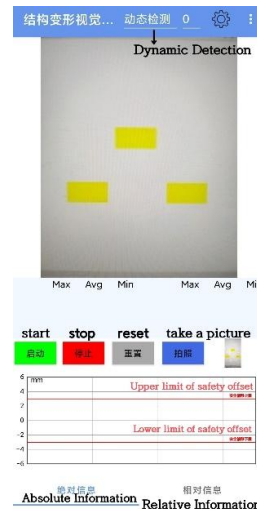
2) Image Acquisition and Processing: The operation procedure of dynamic detection is shown in **Figure 6**, and the specific operation of image acquisition and processing includes the following 4 steps:

First, click the take a picture button to take a picture of the target marker, and then click the photo next to the take a picture button to jump to the image processing interface.

Second, after jumping to the image processing module, slide the static detection to dynamic detection and fill in the dynamic detection time. Then, zoom the image in the image preview interface so that the individual markers are in the template cropping window, click the crop button, and then select the next marker to repeat the above operation until the completion of the cropping of all the markers. The purpose of this step of the operation is to select a sliding window in the image to be matched with the same size as the template and to extract the features from the selected target region for target tracking.

Third, fill in the actual length of the template and click the Calculate Proportion button, then click the Save button to save the cropped image.

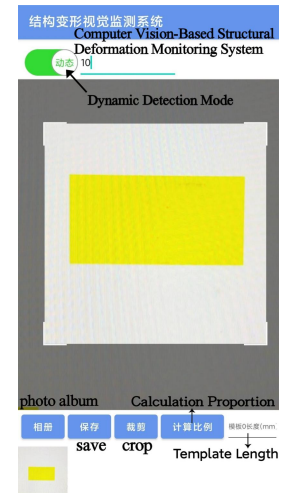
Fourth, click OK in the pop-up interface, and the system will jump to the main interface. Click on the start button to monitor the absolute and relative offsets of the target marker in real time.



a) Image acquisition



c) Calculation proportion



b) Mode switching and image cropping



d) Save

Figure 6. Image acquisition and processing

3) Real-time View of Monitoring Data: In the bottom area of the main interface of the system, the absolute and relative offset variation curves of each marker in the dynamic detection mode during the set time period will be displayed in real time, as shown in **Figure 7** and **Figure 8**.

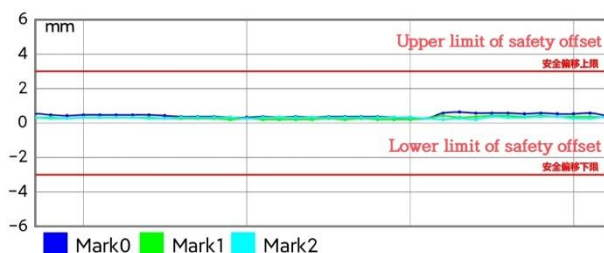


Figure 7. Absolute offset variation curve

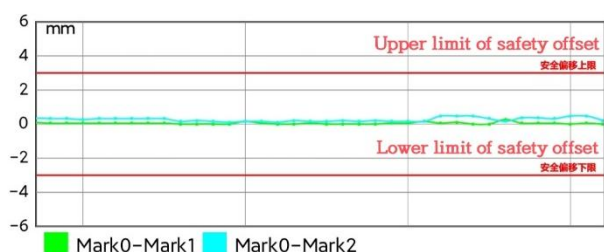


Figure 8. Relative offset variation curve

4) Data Transmission: When the data monitoring is completed, firstly, click on the More Options button located at the top of the main interface to select Export Data to PC; secondly, enter the server IP and port number in the corresponding position of the pop-up interface, whose IP address is in the same address segment as that of the server (PC); and at the same time, enter the server IP and port number on the PC and select the file storage path and click on Start; finally, click on the Export File button on the client (smartphone) to realize the data transfer. The implementation process is shown in **Figure 9**.

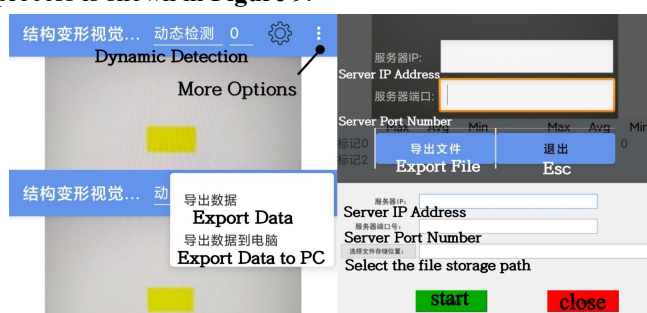


Figure 9. Data transmission

III. CONCLUSIONS

This paper illustrates in detail the overall architecture of the computer vision-based structural deformation monitoring system and the implementation method of each module, and takes dynamic detection as an example to show the operation steps when applying the system, and the test results show that the system has great applicability in the monitoring of structural displacement, and the conclusions are as follows:

- The hardware composition is low cost and simple to construct, which can ensure the accuracy of the data.
- High monitoring precision; for structural offsets, accurate to 0.01 mm.
- High monitoring frequency, the measurement of structural offset in the dynamic detection mode can be up to 10 frames per second.
- Monitoring data visualization, the monitoring of structural offset is presented in the form of curves, which is convenient for users to clearly perceive.

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Xiang DONG is a postgraduate student at the Highway School of Chang'an University. She received her B.S. degree in Transportation Engineering from the City College of Southwest University of Science and Technology in 2022. Her current research interests include intelligent detection technology for infrastructure and engineering data analysis.



Maokai LAI is an undergraduate student at Chang'an Dublin International College of Transportation at Chang'an University. Pursuing a dual undergraduate degree in Transportation Urban Planning and Environmental Policy. His current research interests are in intelligent transportation.



Hui LIANG is working as a researcher with Shaanxi Zhengcheng Road and Bridge Engineering Research Institute Co., Ltd., and Shaanxi Huashan Road & Bridge Group Ltd. She received a master's degree in Materials Science and Engineering from Chang'an University in 2013. Her current research interest is applied research in highway municipal engineering.



Peng WU is a postgraduate student at the Highway School of Chang'an University. He received his B.S. degree in Civil Engineering from Chongqing Jiaotong University in 2022. His current research interests include intelligent detection technology for infrastructure and engineering data analysis.



Chaoxia WANG is a postgraduate student at the Xi'an University of Posts and Telecommunications. She received the bachelor's degree in Software Engineering in Shandong Technology and Business University in 2022. The current research interest is deep learning, and the surface defect detection with industrial products.



Ting PENG is an Associate Professor in the Highway School of Chang'an University. He received his B.S. degree in Highway and Urban Street Engineering from Xi'an Highway University in 1999, his M.S. degree in Road and Railway Engineering from Chang'an University in 2004, and his Ph.D. degree in Computer Science from Xi'an Jiaotong University in 2010. His research interests include infrastructure monitoring, big data mining for engineering, highway assets management systems, and artificial intelligence applications.