Automatic 3D Thermal Modeling Using Thermal Data Obtained from Unknown Viewpoints

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ABSTRACT

There has been an increasing need for diagnostic methods to detect energy leakage in order to reduce energy consumption of buildings. Currently, infrared thermography is used as a preliminary investigation tool because it does not cause physical damage during the exploratory investigation. In practice, diagnosis of the building using infrared thermography requires not only drawings of the building but also the properties of materials and information about the joints and junctions of the building components. However, often, accurate building drawings are not available for existing buildings, and this makes diagnosis of the building using infrared thermography difficult. This study aims to propose a method to automatically map infrared thermographs acquired during periodic diagnosis of the building to its as-built data without fixing the relative position and direction of the infrared camera and a sensor that is used to acquire the as-built 3D point cloud. The preliminary experimental result shows that the proposed method can automatically map an infrared thermograph to an as-built 3D point cloud acquired from different positions and at different times.

Keywords – 3D Thermal Modeling, As-built Data, Energy Leakage, Infrared Thermography, Laser-scan Data

1 Introduction

There has been an increasing need for diagnostic methods to detect energy leakage in order to reduce energy consumption of buildings by heating and cooling, which account for the largest portion of total energy consumption of buildings [1]. Currently, non-destructive testing methods, such as an air leakage test, a co-heating test, infrared thermography, and heat flux measurements, are used to detect the area where energy leakage takes place [2–4]. Among non-destructive testing methods, infrared thermography is used as a preliminary investigation tool because it does not cause physical damage during the exploratory investigation. It also performs quickly and does not incur costly expenses [3,5].

The International Organization for Standardization (ISO) standard 6781-1983 is the most commonly used standard for performing building energy diagnostics [6], and 14 member bodies have approved the standard (Australia, Austria, Belgium, Canada, Denmark, Egypt, Finland, France, Italy, Japan, Norway, Spain, Sweden, and the United States) since 1982 [7]. ISO standard 6781-1983 outlines the general procedure for the interpretation of infrared thermography [8]. First, after acquiring the infrared thermography of a location exhibiting anomalies or that is of special interest, the location is marked on building drawings. Second, the anticipated temperature distribution is determined by using the properties of the materials, like emissivity, which is evaluated based on building drawings and other construction documents. External conditions, such as outdoor air temperature, should also be included. Finally, heat anomalies are defined by comparing the anticipated temperature distribution and the actual temperature distribution. In this way, diagnosis of the building using infrared thermography requires not only building drawings but also information on the properties of the materials and about the joints and junctions of the building components. However, often, accurate building drawings are not available for existing buildings, and this makes diagnosis of the building using infrared thermography difficult.

Previous studies performed as-built data acquisition using spatial survey technologies to obtain geometric information of existing buildings. From the acquired as-built data, these studies proposed methods for mapping an infrared thermograph on a three-dimensional (3D) point cloud [9–13]. In these studies, the infrared thermograph and as-built data have to be acquired at the same time and at the same location (see, for example, [11,13]). However, during repeated periodic diagnosis of the building, it is unnecessary to acquire as-built data whose physical appearance remains unchanged. Although an infrared thermograph can be acquired quickly in camera form, the methods proposed in the previous studies limit the merits of such infrared thermography. In addition, the vertical and horizontal outlines of buildings are used as features when mapping the infrared thermograph on as-built data (see, for example, [12]). In order to acquire an infrared thermograph with a resolution adequate for detecting such features, it needs to be acquired within eight meters from the building façade [14]. However, at eight meters' distance, it is difficult to include such vertical and horizontal outlines of the buildings in the infrared thermograph due to the narrow field of view of the infrared camera.

This study aims to propose a method to automatically map infrared thermographs acquired during periodic diagnosis of a building based on its as-built data. This paper is organized as follows: Section 2 provides a review of previous literature. Section 3 provides an overview of the proposed method and an explanation of the methodology with the results of experiments. Finally, Section 4 provides a summary and recommendations for future research.

2 Literature Review

2.1 Fixed Relative Method

The fixed relative method involves fixing the relative position and the direction of two sensors for mapping infrared thermographs to an as-built 3D point cloud. Ham and Golparvar-Fard [10] proposed using an infrared camera equipped with a built-in digital lens to map an infrared thermograph to a 3D point cloud reconstructed from a number of color images. Prior to acquiring the data, the geometric relationship between the infrared camera and digital camera is measured through a calibration procedure. The infrared thermograph and color image are acquired for the entire building envelope at the same time. Then, the Scale Invariant Feature Transform (SIFT) features are extracted from a number of color images. Based on the extracted features, a structure from a motion algorithm is applied to generate a 3D point cloud. Finally, the infrared thermography is mapped to as-built data by using the geometric relationship between the infrared camera and the digital camera.

Wang et al. [11] proposed a system in which an infrared camera is rigidly mounted onto a laser scanner in order to map an infrared thermograph to an as-built 3D point cloud. The geometric relationship between the laser scanner and the infrared camera attached to the pan and tilt unit is measured through a calibration procedure prior to the data acquisition. The infrared thermograph and as-built data are acquired at the same time according to the movement angle of the pan and tilt. Then, the infrared thermograph is mapped to as-built data by calculating the perspective projection coordinates according to the movement angle of the pan and tilt, as well as the geometric relationship between the infrared camera and laser scanner.

Borrmann et al. [13] proposed a system in which a laser scanner, an infrared camera, and a cam are rigidly attached to a mobile robot in order to map infrared thermography to an as-built 3D point cloud. Prior to the data acquisition, the geometric relationship between the laser scanner and the infrared camera attached to the mobile robot is measured through a calibration procedure. The infrared thermograph and as-built 3D point cloud are acquired at the same time while the mobile robot is moving. From the as-built point cloud, a 3D mesh is generated. Then, the infrared thermograph is mapped to as-built data by using the geometric relationship between the infrared camera and laser scanner.

Using the aforementioned methods, an infrared thermograph can be mapped to as-built data by measuring the geometric relationship between the infrared camera and a sensor that is used to acquire the as-built 3D point cloud. However, as the location of acquiring the infrared thermograph is determined according to the location of the sensor that is used to acquire the as-built 3D point cloud, extra acquisition time is required in order to obtain infrared thermographs of areas needed for diagnosis within the distance limits appropriate to their use.

2.2 Feature-based Method

The feature-based method involves extracting features from the image and as-built 3D point cloud to map the infrared thermograph—acquired from different locations and at different times—to as-built data. To map the infrared thermograph to an as-built 3D point cloud without fixing the relative position and direction of the two sensors, this method extracts features such as points and lines from the image and 3D point cloud. Then, the infrared thermograph is mapped to a 3D point cloud based on the extracted features.

Gonzalez-Aguilera et al. [9] proposed a method that uses the corner that exists in the range image and the color image to map an infrared thermograph that is acquired from different positions and at different times to an as-built 3D point cloud. The infrared thermograph and color image are acquired at the same time by using an infrared camera equipped with a built-in digital lens. An as-built 3D point cloud is acquired from different positions and at different times from the infrared thermograph. The range image is generated from the 3D point cloud, and then the corner that exists on the building envelope is extracted as a feature from the color image as well as the range image. Based on the extracted feature, the color image is matched with the range image, and then the infrared thermograph is mapped to an as-built 3D point cloud using the premeasured geometric relationship between the color image and the infrared thermograph.

Laguela et al. [12] proposed a method that uses a junction between the vertical and horizontal lines of the building exterior to map an infrared thermograph to an as-built 3D point cloud. The infrared thermograph and as-built 3D point cloud are acquired from different positions and at different times. The junction between the vertical line and the horizontal line of the building exterior is extracted as a feature from the infrared thermograph as well as the 3D point cloud. Once the junction between the vertical and horizontal lines has been extracted, the same junction is matched. Then, the infrared thermograph is mapped to as-built data.

The advantage of these methods is that they can automatically map the infrared thermograph acquired from different positions and at different times to as-built data. However, they pose a problem in that the acquisition of an infrared thermograph should ensure the inclusion of a building's façade in order to take advantage of the proposed feature. The feature used in previous studies makes it difficult to extract sufficient numbers for mapping where the infrared thermograph is acquired in terms of its proximity to the building. In order to use this method, the entire façade of a building should be included while acquiring the infrared thermography. However, in this case, the infrared thermograph needs to be acquired at a significant distance away from the building, given the narrow field of view of infrared cameras. In addition, an infrared thermograph taken at a significant distance from the building is not sufficient to identify an object's thermal properties due to its low resolution. In this regard, a method is required that can map an infrared thermograph to an as-built 3D point cloud without regard to position and time restrictions.

3 Methodology

This study uses an infrared camera equipped with a built-in lens to acquire infrared thermographs and visible images at the same time. The infrared camera with a built-in lens is commercially available and it can help users understand the images acquired by infrared camera. To obtain a colored 3D point cloud, a laser scanner equipped with an internal camera is used. The scanner is also commercially available from a laser scanner manufacturer. To acquire the colored 3D point cloud, the correspondence between the 3D point cloud and the pixels of the color image acquired by the internal camera was defined prior to data acquisition.

3.1 Offline Image Database Construction

The laser scanner used in this study provides the color value of each 3D point in addition to spatial information. A database image of a building is generated using the color values of the 3D point cloud. To set the origin of the image plane, the internal camera's parameters and position of the image acquisition are determined. The visible camera equipped with an infrared camera is calibrated in advance to calculate the internal camera's parameters. The position of the image acquisition is then determined by dividing the façade of the building by a certain number, such as 2-by-5 grids. Based on the internal parameters and the divided region, the distance and angle between the façade of the building and the position of the image are identified. The height and width of the image are defined by the resolution of the visible camera. The database image is generated with the same resolution as the visible image acquired through the infrared camera (see Figure 1).

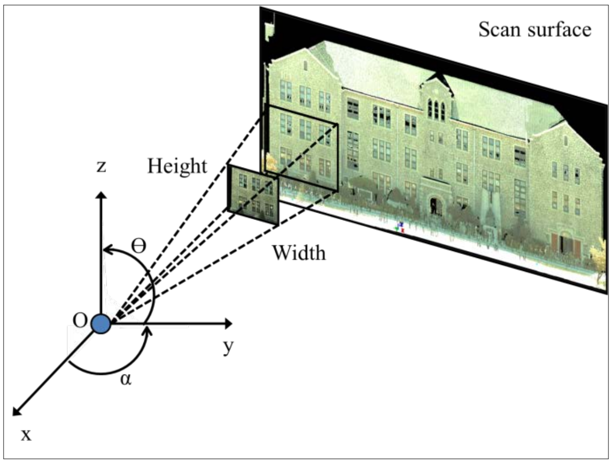


Figure 1. Image databased construction from colored 3D point cloud

After the origin of the image plane is set, the transformation matrix for the projection of the 3D point cloud onto the image plane is calculated. Then, the 3D point cloud is substituted by the projection transformation matrix on the image plane. The color value of each pixel on the image plane is determined by the color value of the nearest point of the 3D cloud projected onto the image plane. This process is repeated until the database image is generated for the entire position of image. Then, the generated database image is pre-processed for matching with the infrared thermograph. The pre-processing consists of color space transformation from RGB color space to YIQ color space as well as histogram equalization using a Y component.

3.2 Pre-processing

The distortion of the digital lens within the infrared camera may cause inaccurate results when matching the features extracted from the database image and the visible image. For this reason, a distortion correction of the visible image is performed to match the features between the visible and database images. The distorted visible image acquired using the infrared camera is corrected based on the internal parameters calibrated prior to data acquisition. Figure 2(a) is the visible image acquired by infrared camera and Figure 2(b) is the database image. In this case, the infrared thermograph and as-built 3D point cloud are acquired at two different times, exposing the database and visible images to different illumination effects. To solve the problem caused by the effects of different illumination, color space transformation and histogram equalization are performed. The YIQ color space, known as the color space invariant to illumination, is used for the color space transformation [15]. In addition, the histogram equalization method that can reduce the effects of illumination is applied [16]. Figures 2(c) and 2(d) show the pre-processed visible and database images.

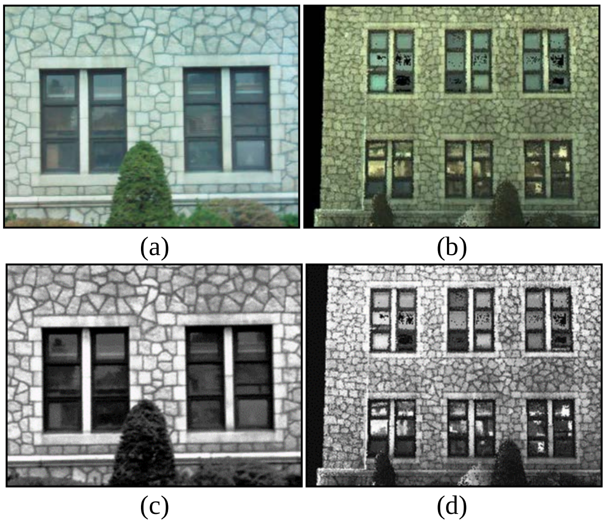


Figure 2. (a) An example of visible image; (b) An example of database image; (c) An example of pre-processed visible image; (d) An example of pre-processed database image

3.3 Feature Extraction and Matching

In this study, the scale-invariant feature transform (SIFT) proposed by Lowe [17] is applied to match the database image and visible image. It has been found in various studies that SIFT is invariant to change due to rotation, translation, or scale [18]. Feature extraction and matching using SIFT consists of four steps—namely, scale-space peak selection, feature point localization, orientation assignment, and feature point descriptor. The first step detects the potential keypoints at diverse positions and scales. For this, a Gaussian pyramid is constructed and the local extrema are detected in the difference of Gaussian image. After the potential keypoints are found, in the second step the keypoints with low contrast are identified and removed from the other potential keypoints. Next, the orientation of each keypoint is defined based on the gradient orientation of the image. Lastly, the local image patch is divided into 4-by-4 sub-blocks around the keypoints. After building the histogram on the gradient orientation and the magnitude of pixels of each sub-block, a 128-dimensional vector is generated, connecting the bin values of the histogram in series.

3.4 Matching Refinement

After matching the keypoints between the database image and the visible image, the matched keypoints are then used to compute the transformation matrix to align the visible image with the database image. Although the SIFT is highly distinctive, a pair of mismatched keypoints may still exist [19]. The pair must be removed because it can affect the calculation of the transformation matrix. In this study, the random sample consensus (RANSAC) algorithm, which uses homography as the geometric constraint model, is applied to remove the pair of mismatched keypoints. Homography is applied to the two images in case of translation, 3D rotation (roll, pitch, and yaw), and zoom transformation [20]. When translation, rotation, and zoom transformation occur in both the visible image and the database image acquired through the infrared camera, homography becomes the most suitable transformation for the geometric constraint model.

The matching refinement applied with homography-based RANSAC is performed as described in the following process. The first step is the random selection of four pairs among the pairs of matched keypoints. Using the four selected pairs, the homography is computed. After transforming the homography, the sum of the squared difference between the matched keypoints is calculated and the inlier of the pair below threshold value is determined. The set that includes the largest inlier is identified as well, and the homography of all inliers is calculated. Afterward, the matching correctness of the calculated homography is computed. If the matching correctness is high, the process ends; otherwise, the entire process is repeated. Figure 3 shows the result of applying homography-based RANSAC.

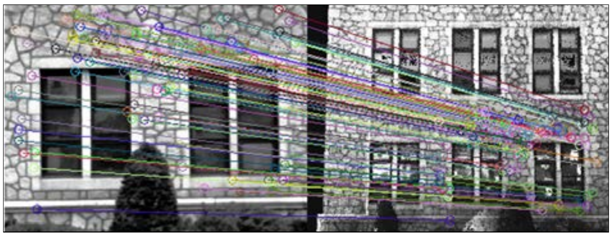
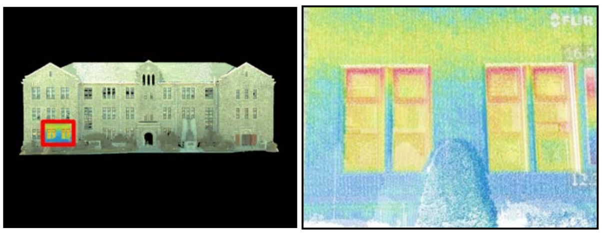


Figure 3. Result of applying homography-based RANSAC

3.5 Image Matching and Mapping

This study proposes a method for measuring image similarity based on the number of matched keypoints. Because the database image is generated by dividing the façade of the building, there is only one piece of the database image that includes a visible image. Once the mismatched features are removed, a large number of matched keypoints exist for the image of the same object, whereas only a very few number of matched keypoints exist for the image of the other object. With regard to the one piece of visible image, matching refinement for all images in the database is performed. Afterward, the number of pairs of matched keypoints is calculated for all images in the database. The database image with the greatest number of keypoint pairs is selected as the image most similar to the visible image.

After finding the best transformation matrix using homography-based RANSAC, the infrared thermograph is mapped to the 3D point cloud. Because the fields of view of the infrared thermograph and the visible image are the same, the region of the infrared thermograph can be confirmed within the database image by applying the transformation matrix of the database and visible images to the infrared thermograph. Then, the infrared thermograph is projected onto 3D space. The thermal value of the pixels corresponding to the 3D points is mapped. Figure 4 shows the results of mapping the infrared thermograph to the colored 3D point cloud.



(a) (b)

Figure 4. (a) Result of infrared thermograph mapping to the colored 3D point cloud; (b) Magnified portion of (a)

4 Conclusion

This study presented a method to automatically map infrared thermographs acquired during periodic diagnosis of a building to its as-built data. Once as-built data of existing building is acquired using laser scanning technology, this study uses the acquired as-built data in every diagnostic step. Thereafter, the acquisition of infrared thermographs using the infrared camera equipped with a built-in lens is only required at desired locations around the building. Pre-processing is proposed to extract features between the database and visible images. Then, a feature extraction and matching refinement method is used to calculate homography according to the transformation between the database and visible images. The preliminary experimental results show that the proposed method can automatically map an infrared thermograph to an as-built 3D point cloud acquired from different positions and at different times. Future research will focus on evaluating the performance of the proposed method.

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