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AN IMAGE-BASED FRAMEWORK FOR AUTOMATED DISCREPANCY QUANTIFICATION AND REALIGNMENT OF INDUSTRIAL ASSEMBLIES

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Abstract: Image-based frameworks for automated as-built modeling and infrastructure 3D reconstruction are increasingly being used in the construction industry. The increasing use of image-based technologies in the construction processes is due to the ease of application, cheap cost of enhancement, time effectiveness and high level of accuracy and automation. Automating the tasks involved in the inspection, quality control and quality assurance (QA/QC) processes are the potential avenues for utilizing such frameworks. This paper presents an image-based approach for acquiring the built status of fabricated assemblies and describes a framework for realigning the defective segments by borrowing concepts from robotics and forward kinematics. A laboratory set of experiments is then conducted to measure the accuracy and performance of the proposed framework for realignment of industrial facilities, in general, and pipe spools, in particular. Results demonstrate that it can be utilized in real cases providing the required level of accuracy as well.

1 INTRODUCTION

Inspecting and monitoring of civil infrastructure is a critical challenge that has to be performed in various construction and maintenance phases. Inspection processes guarantee that construction segments and components are reliably fabricated, transported, and erected. They also provide the determination of as-built status and dimensions required for potential considerations needed to be given to defective segments. These tasks are difficult to perform on construction sites. Inspection processes to perform quality control and quality assurance (QA/QC) process become more critical in staged fabrication that requires sequential fabrication and installation. In the construction industry, in particular, staged fabrication includes but is not limited to prefabricated steel columns, concrete segments and huge pipe spools/modules. Although construction segments are typically correctly fabricated considering recent advances in the fabrication industry, they still require continuous inspection as dimensional errors are introduced during transportation and shipment. As-built status acquisition is therefore necessary to assess the current state of construction elements and determine the potential considerations for repair and realignment.

Manual and conventional approaches to acquire the as-built status are inherently prone to error and therefore often ineffective and inaccurate. Craft workers use tape measuring and paper-based methods to inspect and control the fabrication quality. The as-built status acquired is therefore often unreliable and may cause profound unfavorable effects on construction sites such as schedule delays and rework. For example, in the case a defective segment is erected on site and discrepancies are not detected in a timely and accurate manner, the segment is going to be either repaired or replaced whereby both cases are associated with rework. Therefore, as-built status of construction elements must be acquired in a timely manner and electronically transferred to various interfaces involved in order to provide managers and decision makers with an effective framework. In the last couple of decades, adequate accuracy and speed for as-built status acquisition and assessment has become possible utilizing various sensing technologies including Ultra Wide Band (UWB) tags, Global Positioning System (GPS), Radio Frequency Identification (RFID), and 3D imaging techniques. Among these sensing technologies, 3D imaging that provides spatial and detailed geometric information of objects is a reliable method for detailed and geometric as-built status acquisition. 3D imaging is the general name for the process used to generate three dimensional images, also called point clouds, that includes LADAR (Laser and Distance Ranging), range imaging, videogrammetry, traditional photogrammetry, and modern photogrammetry which is also known as image-based sensing technology. Among these technologies, laser scanning is the most common technique in the related industry because of the ease of use and the level of accuracy provided. However, there are major limitations involved with laser-based methods that make it less applicable under some conditions. These conditions may include the time required for setting up, data preprocessing, and occlusion occurrences in busy construction environments. Cost of purchasing is an additional barrier for laser scanners that makes them less accessible by all contractors and project managers. Developing a cheaper framework, commonly affordable, with a high rate of accuracy that can address the mentioned deficiencies of laser scanners is therefore necessary.

In recent years, some research efforts have attempted to address these limitations of laser scanners. Image and video based techniques that have been developed during the past several years are the emerging solutions that are significantly less expensive than laser scanning. It has been stated that image-based methods can provide the desirable level of accuracy and automation if well applied. According to (Dai et al. 2013; Golparvar-Fard et al. 2011; Zhu and Brilakis 2009) image-based 3D reconstruction has provided a comparable level of accuracy to laser-based methods without the previously discussed limitations of laser scanners.

One of the key advantages of utilizing the image-based techniques to assess the as-built status of construction elements is that it does not require any further consideration or procedure on construction sites as images are taken on a regular basis by inspectors (Golparvar-Fard et al. 2011). Such random and unordered images can be imported to a cloud server on a daily or weekly basis for further processing in order to generate 3D images for assessing the as-built status. This paper presents an image-based framework in order to accurately detect, characterize, and identify the discrepancies between the as-built status and as-designed data (Figure 1). Most research to date is relatively limited in its approach to the automated detection of visible damage and defects. There is still a significant lack of knowledge in civil infrastructure aimed at effectively and efficiently assessing the construction processes in different phases in order to realign defective assemblies in a timely manner.

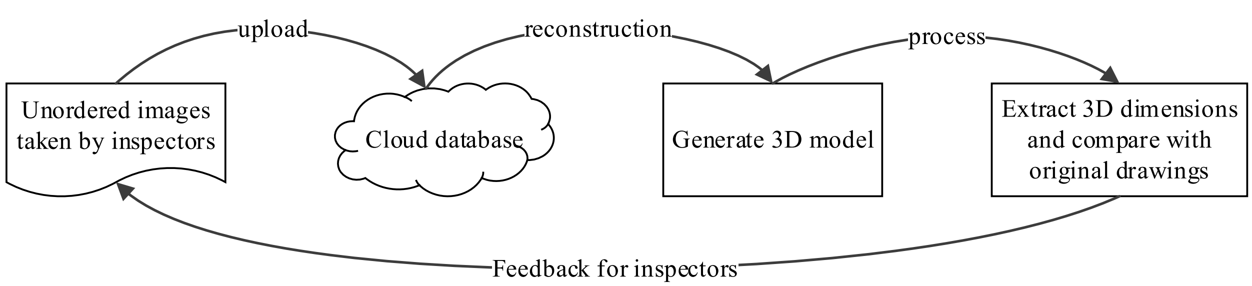

Figure 1: Proposed framework for image-based 3D model generation and realignment strategy

This research is directed toward damage prevention by localizing and quantifying fabrication errors and generating a potential solution for repair and rehabilitation in a systematic way. In order to comprehensively determine the knowledge gap and the need in the construction industry, the related background is extensively investigated. The research methodology to develop the proposed framework is then presented, and required functions and metrics are formed. A set of experiments are then designed in order to validate the proposed framework and evaluate its accuracy by comparing the results with previously acquired laser-based data.

2 RESEARCH BACKGROUND

The key contribution of the framework presented in this work is an image-based reconstruction technique for the as-built status assessment of industrial facilities compared with laser-based status acquisition. Recent studies attempted for inspecting, monitoring, and assessing the built status of civil infrastructure, in general, are also briefly reviewed. The related background is extensively investigated in order to determine the current state of these methods, and the knowledge gap is therefore comprehensively identified.

2.1 Monitoring and Inspecting Civil Infrastructure for the Built Status Assessment

Using automated tools for monitoring and inspection purposes in construction provides a superior level of accuracy. The automated tools and techniques for reliable and accurate 3D measurement are also being increasingly used because of electronic communication and integration with other interfaces in the construction management system. 3D spatial locating devices such as ultra-wide band (UWB) and radio frequency identification (RFID) tags have been used for automated material location on heavy industrial construction facilities (Razavi and Haas 2010). They have been found to improve productivity and to reduce risk substantially.

Additionally, 3D sensing and imaging technologies such as laser scanning, image/video-based reconstruction methods, and range imaging are used for a wide range of applications in construction. Laser scanning was first introduced as a tool for structural health monitoring (Park et al. 2007). Automating the tasks involved in the processing step to use the point clouds generated by laser scanners improved the applicability of laser-based techniques in real-sized and complex construction sites. Bosche et al. (2009) developed a method for automated recognition of CAD objects in cluttered point clouds that was later employed for automated progress tracking of construction components (Turkan et al. 2012). Laser scanning can be employed for compliance control used for QA/QC purposes. An automated framework was used for compliance control of industrial assemblies using laser-scanned point clouds (Nahangi and Haas 2014). A video-based 3D point cloud generation technique (videogrammetry), was also employed to acquire the as-built status (Brilakis et al. 2011; Koch et al. 2013), to be used for various purposes such as progress tracking and status assessment discussed earlier. Recently, 3D sensing technologies have been actively employed for tracking the progress of the industrial construction or Mechanical Electrical and Piping (MEP) components (Ahmed et al. 2012; Dimitrov and Golparvar-Fard 2015; Lee et al. 2013; Son et al. 2014). The use of image-based techniques and their application in the construction industry are discussed in the following section.

2.2 Image-Based 3D Reconstruction State-Of-The-Art in the Construction Industry

Photogrammetry is well known as a 3D reconstruction technique. It was originally developed for generating the stereo elevation from aerial photos (Mikhail et al. 2001). In recent decades, advances in the camera production industry have provided the required accuracy for close-range applications such as industrial inspection and architectural documentation. The challenge associated with traditional photogrammetry techniques is the manual labour and computationally intensive processing involved. When high accuracy is desired for further investigations, computational cost and time also increased. This drawback of traditional photogrammetry has been a challenging factor over the years that makes it limited and currently not applicable for near-real-time modeling. Later advancements in the processing unit and related industry significantly improved the preprocessing time involved for common feature detection; however, it was still time consuming to achieve the required accuracy (Mikhail et al. 2001).

With the rise of digital images and digital photos, traditional techniques were replaced with modern and digital photogrammetry, which resulted in profound improvements in accuracy considering the required processing time (Brilakis et al. 2012; Jahanshahi et al. 2009; Liu et al. 2014). In the construction industry, the use of modern photogrammetry thus became more significant as it was much less expensive than laser scanning, the most common technique in AEC industry for as-built status acquisition, mentioned earlier. A study by (El-Omari and Moselhi 2008) showed the enhancement of integrating photogrammetry and laser scanning for progress tracking, which was proven to be more time effective. Researchers enhanced the use of close range photogrammetry for pavement pothole localization and progress tracking in pipe-works construction (Ahmed et al. 2011; Ahmed et al. 2012). Most of this research showed the time effectiveness of the application of photogrammetry in the related industry, however, some major limitations such as the desired accuracy and required intensive preprocessing, such as camera calibration, severely diminished the method’s practical utility compared to its competitor, laser scanning.

New and innovative techniques have emerged, however for the detection of common features of the desired accuracy without requiring camera calibration. Such automated feature detection techniques include scale the invariant feature transform (SIFT) and speeded up robust features (SURF). (Golparvar-Fard et al. 2009) introduced as automated reconstruction techniques that use time-lapsed photographs to generate the as-built status of construction projects in order to measure the progress on construction sites. (Zhu and Brilakis 2009) investigated the accuracy of the optical-based methods compared to laser-based techniques for the reconstruction of the built status of civil infrastructure. They concluded that laser scanning has larger range for data collection with a higher level of accuracy that makes it more reliable though also more costly. They have suggested the efficient optical-based technique for different applications in the construction industry under various circumstances. These methods include videogrammetry and 3D range imaging that can be employed based on the level of accuracy required and the application used.

The construction industry, several research efforts have been attempted to evaluate the accuracy and investigate time and cost effectiveness of the image-based methods compared to laser scanning. Golparvar-Fard et al. (2011) evaluated the accuracy of an image-based 3D point cloud for determining the as-built status of construction elements compared to a laser-based 3D point cloud. They concluded that the accuracy provided by laser scanning is slightly higher than image-based techniques, however, image-based reconstruction is quicker and less costly.

Bhatla et al. (2012) evaluated the accuracy of an image-based reconstruction framework for assessing the built status of bridge girders. According to this study, image-based 3D reconstruction using free, promising commercial software packages provided the desired level of accuracy; however, their study also revealed that for highly accurate modeling purposes, laser scanning is more appropriate. (Dai et al. 2013) comprehensively compared the image-based techniques with time-of-flight in various civil infrastructure. Such a comparison includes the accuracy of reconstruction, density of the point cloud generated, cost of purchasing and utilizing, and the required time for setting up and processing. Their study revealed that both photogrammetry and videogrammetry can provide sufficiently dense and accurate point clouds to be employed for different applications such as visualization. It was stated that photogrammetry is sufficiently accurate to be used for as-built quality control on construction sites. In summary, image-based 3D reconstruction, which is originally known as photogrammetry, has provided the desired accuracy within a reasonable processing time due to the recent advances in the related industry that are previously discussed. Such improvements in image-based reconstruction provide the opportunity to employ related techniques in different inspection phases of civil infrastructure.

Despite the significant impact of automated tools, in general, and image-based techniques, in particular, in the construction industry, their uses are mostly directed toward object recognition for status assessment. A preventive approach to measure the discrepancies in a time effective way that can avoid rework is needed. Nahangi et al. (2015a) showed the effectiveness of laser-based point clouds for discrepancy detection and a realignment strategy. This paper is aimed to generalize the previous developments by employing an image-based framework for the as-built status acquisition and to measure the performances of the resulted realignment strategies. The detailed methodology along with the required functions and metrics are explained in the following section.

3 PROPOSED METHODOLOGY

For generating the 3D model required for performing the as-built status identification and discrepancy quantification, an image-based framework is used. As shown in Figure 2, the image-based algorithm for automated discrepancy detection and quantification has two primary steps: (1) Image-based 3D point cloud generation that provides the as-built status with a reasonable level of accuracy, and (2) processing that enables detection, localization, and quantification of incurred discrepancies based on the original drawings. The primary steps and the required components are extensively explained in the following section.

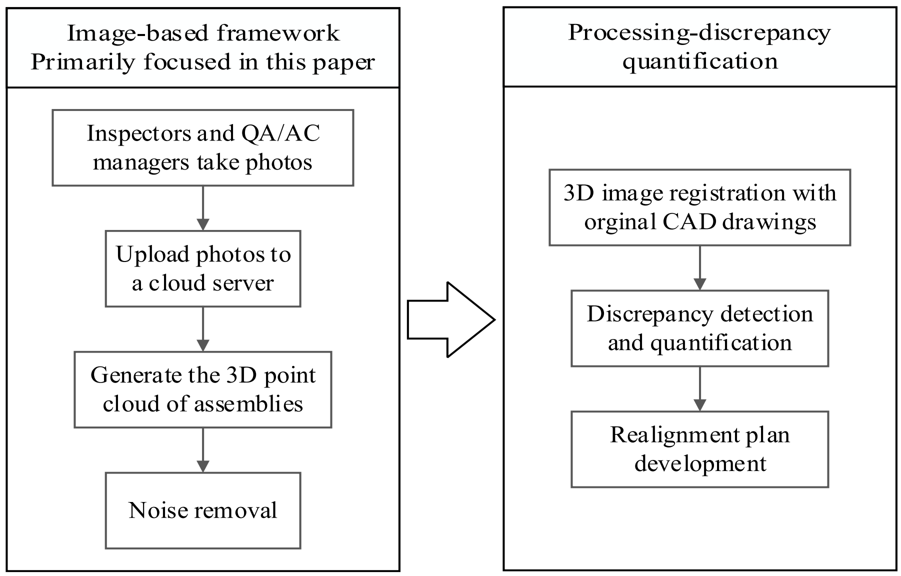

Figure 2: Algorithm for automated discrepancy quantification using an image-based framework

3.1 Image-Based 3D Point Cloud Generation

Inspectors and QA/QC managers use off-the-shelf digital cameras. Cellphone and tablet cameras can also be used to acquire the required images. Once sufficient numbers of images with sufficient overlap are captured they are imported to a cloud server/database for point cloud generation. The image processing toolboxes for image stitching and 3D point cloud generation can be employed. These toolboxes include MATLAB Image Processing Toolbox and open source databases such as Open CV (Open source computer vision library at the University of Washington) and PCL (Point Cloud Library). In this study, Autodesk 123D Catch (www.123dapp.com/catch) is employed. The 3D reconstruction of construction assemblies using images is composed of a set of steps:

- Finding common features in the images taken,
- Matching the common features detected,
- Transforming the images into a global coordinate space based on the common features.

Based on the required processing steps mentioned above, more images taken improves the applicability and performance of the algorithm. Furthermore, a sufficient level of overlapping between images must exist in order to find a reliable set of matching features. Once a 3D model of the construction environment is roughly generated, unwanted objects and the existing noise are filtered. Noise removal is performed manually by removing the objects outside the region of interest. This can be automated in the future.

3.2 Processing

Once appropriate 3D model is generated using the proposed image-based framework, a set of processes is required to quantify the incurred discrepancies based on the framework developed by Nahangi et al. (2015b). Such processes include:

- Registration: the filtered 3D model can now be used for registration with CAD drawings converted to an appropriate format (i.e. point cloud format such as STL), in order to enhance a comparison. A modified iterative closes point (ICP) is used for registration in this study.
- Kinematics chain development: the geometric relationship is established using an analogy of robotics. The kinematics chain development results in a set of transformations required to identify the geometry of assemblies.
- Local registration: a sliding cube moves along the assembly and quantifies the discrepancies where it is occurred. A local registration is performed on the contained points in the cube at each location that the discrepancy is being investigated. The resulted discrepancy is then transformed to the local coordinate system defined by the previously developed kinematics chain.

The quantified discrepancy can be fed into a realignment planning framework for potential realignment strategies (Nahangi et al. 2015a).

4 EXPERIMENTAL VERIFICATION

A set of experiments is designed to verify and validate the performance of the explained image-based algorithm for discrepancy quantification.

4.1 Design of Experiments

The experiments are validated on a small-scale set of pipe spools existing in Civil Infrastructure Sensing Laboratory at University of Waterloo. The pipe spool is designed so that the connections and joints allow reconfigurability. In other words, the pipe spool can be reconfigured by introducing any alteration; so that the algorithm for discrepancy quantification can be tested. The reconfigurable pipe spool used for the experimental tests is shown in Figure 3.

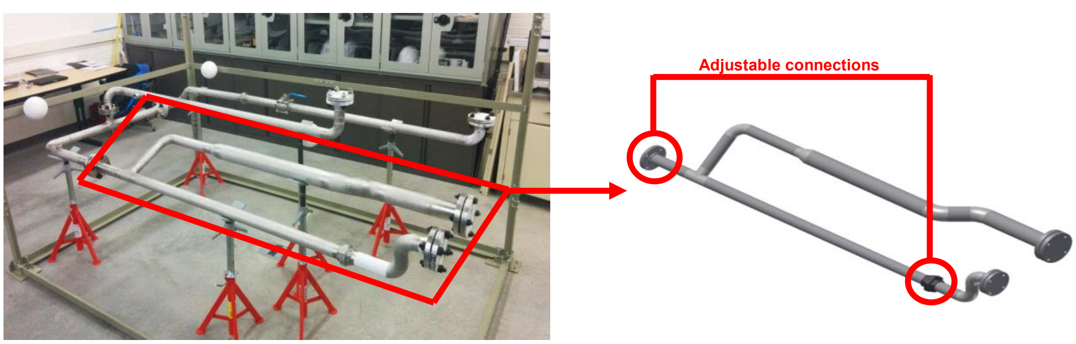

Figure 3: The experimental specimen (reconfigurable set of pipe spool) and the investigated branch.

An off-the-shelf digital camera is used for this experimental study. An SX40-HS Canon camera was used at 12.2 megapixel resolution. Technical details of the camera can be found in Table 1.

Table 1: Technical details for Canon SX 40-HS used in the experiments

Camera type	Digital camera
Image resolution (size)	4000×3000 [L] *, 2816×2112 [M1] * 1600×1200 [M2] *, 640×480 [S] *
Shutter speed	1/3200 sec (min)- 15 sec (max)
Focal length	24-840 mm

* [L]: Large, [M]: Medium, [S]: Small.

In order to compare the accuracy of the proposed image-based framework with laser-based point clouds, a similar set of alterations to the previous experimental study by (Nahangi et al. 2015b) is applied. The alteration is applied in the form of rotational, translational, and combined discrepancies on the investigated branch shown in Figure 3.

4.2 Results

After uploading the taken images they are uploaded to the server for generating the 3D point cloud of the tested assemblies and spool branches. Typical photogrammetry data and results of the generated point cloud for the original state of the investigated branch are shown in Table 2 and Figure 4.

Table 2: Typical photogrammetry data and results for the pipe spool original state

Size of images taken	[L]: 4000×3000
Number of images processed	59
Total number of points retrieved	134,742
Number of points retrieved from the pipe spool	15,152
Total processing time	26 *min*

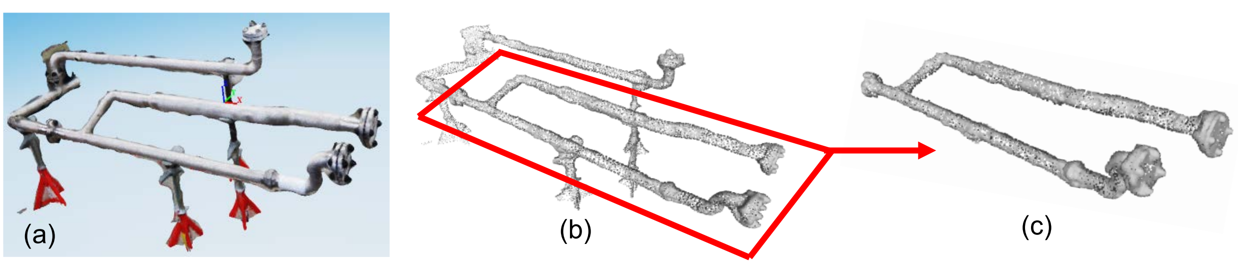

Figure 4: Photogrammetry results. *123D Catch* software output (a); the mesh is converted to point cloud (b); the noise is manually removed and the branch is properly retrieved (c)

Experimental results (Figure 5) show that the quantified discrepancies provided by photogrammetry are less accurate comparing to the similar tests performed on laser-based technologies. Maximum error for the image-based framework developed in this work is 0.369º and 0.184 *cm* for rotational and translational discrepancies, respectively; while, maximum error for the laser-based technique used in the previous study by Nahangi et al. (2015b) is reported as 0.237º and 0.02 *cm*. However, the image-based 3D point cloud is still reliable for discrepancy quantification based on the required level of accuracy in some applications. Moreover, using a finer mesh for 3D reconstruction will provide a more accurate point cloud although it is computationally more intensive.

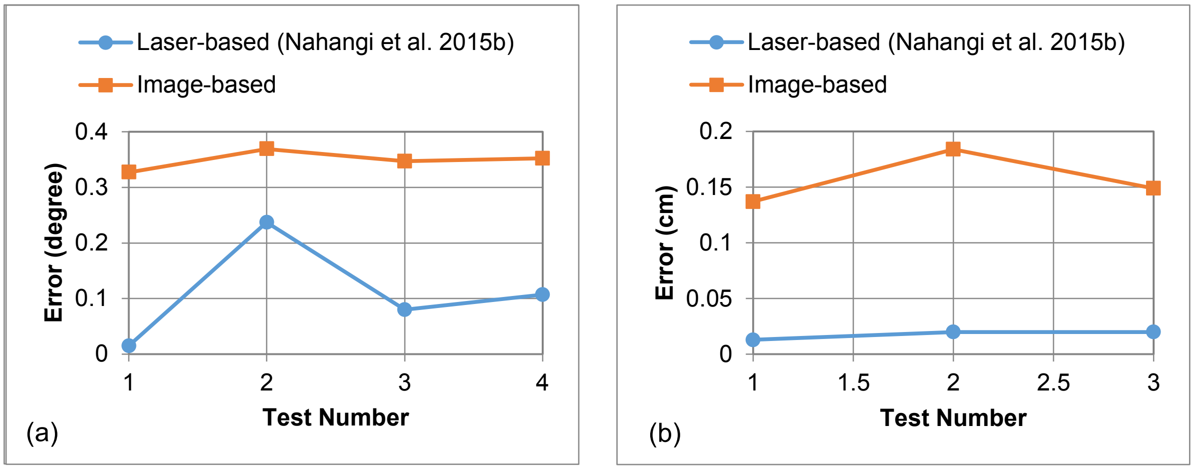

Figure 5: Experimental results for rotational discrepancy (a); and translational discrepancy (b).

5 CONCLUSIONS AND RECOMMENDATIONS

An image-based framework was presented for automated discrepancy detection and realignment planning. The scope of this study was industrial assemblies, in general, and pipe spool assemblies, in particular. Typical users who are QA/QC managers or inspectors use cellphones, tablets or digital cameras to take unordered photos and upload to a cloud server for processing. The processing step results in a 3D point cloud representing the built status that will be compared with the original CAD drawings. For the comparison purpose, 3D image registration is employed. Once the two representing states are appropriately registered, an analogy of robotics results in the development of geometries of the assemblies. Such an approach provides localized discrepancy feedback to be used for realignment strategies. Some remarks on the experimental verification follow:

- The enhanced image-based framework is significantly cheaper than laser-based techniques. This makes it more applicable, particularly for the cases where a lower level of accuracy is required.
- The data acquisition step for the proposed image-based framework requires minimal prior knowledge and training.
- Image-based discrepancies are reasonably reliable and accurate; however, laser-based point clouds are more precise, which concurs with the previous evaluation studies (Bhatla et al. 2012; Dai et al. 2013; Golparvar-Fard et al. 2011)

A limitation of the proposed methodology is that it requires more processing time for the images to be retrieved and generate the 3D point cloud.

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