Measurement 117 (2018) 326–338

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Accurate radius measurement of multi-bend tubes based on stereo vision

Xiao Wang, Jianhua Liu, Shaoli Liu*, Peng Jin, Tianyi Wu, Zhi Wang

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, PR China

ARTICLE INFO

Keywords:
Bend radius
Measurement
Photo-consistency
Stereo vision

ABSTRACT

To realize accurate and fast radius measurement for the multi-bend tubes in the 3D environment, a stereo vision based method was approached in this paper. Firstly, the mapping from tube's center line to edge point in the image was modeled and discussed. Then, the photo-consistency was used to reconstruct 3D center line of the bend tube. Furthermore, a segmented parametric model of tubes with curved parts and straight parts was developed, and the problem was converted to a constrained optimization problem. The experiments show the measurement accuracy of this approach can reach to ± 0.5 mm with 3σ reliability. The results of measurements showed good performance in terms of precision and reliability, even when lacking corresponding points or with incomplete edges. Besides, the approach can measure the bend radius automatically without artificial operations.

1. Introduction

1.1. Measurement of a tube's bend radius

Complex spatially bend tubes with different shapes and types have been used widely in cars, aircraft, and other systems for fuel transportation and heat exchange. To achieve a precise and stress-free assembly, the three-dimensional (3D) shape of the tube, including its endpoint positions, directions [1], and the angles and radii of the bent tube's curved parts must be guaranteed. However, during processing, uneven tension and compressive stresses can cause multiple defects, such as springback, which influence the tube's precise assembly [2–4]. Thus, in the production of a tube, it is essential to accurately measure the geometric error between the intended design model and the part actually manufactured, and to then use the measured results to 'fix' the bent tube or refine the production parameters [2,3,5].

Usually, a tube manufactured with a bending machine is formed by pushing, rotating, and bending. Thus, the shape of the tube can be described by a combination of straight parts (cylinders) and curved parts (arc segments) [1]. Also, because the radius, r_i, of each part of the tube is the same, the 3D shape of the tube can be described by its center line, which can be generated by control points and endpoints [1]. An example with 4 straight segments and 3 arc segments was shown in Fig. 1. Where, L_i (i = 1,2,3,4) represents the length of the straight lines. The angle between two neighboring straight line vectors are noted as v_i,v_{i+1}(i = 1,2,3), the angle between the non-neighboring straight line vectors are noted as v_i,v_{i+2} (i = 1,2), and the bend radii are noted as r_i(i = 1,2,3).

Most reported studies have focused on measuring 3D parameters, such as straight lines lengths and the angle between straight lines. The bend radius, r_i, is usually set according to the parameters of the bending machine. However, the need for an accurate bend radius measurement has increased in recent years. For some kinds of tubes, the bend radius must be guaranteed to avoid obstacles or to fulfill assembly requirements. For example, the bend radius of heat exchange tubes that are spread over the surface of a spacecraft must be sufficiently accurate to avoid obstacles, or it cannot be assembled successfully [6]. Moreover, the bend radius of the exhaust pipe in cars should be accurate enough to ensure that there is no interference during the assembly process; otherwise, assembly stress may be introduced, which could decrease the reliability of the product. A precise tube bend radius measurement is one of the most effective methods to guarantee the accuracy of the tube made. It is also an important step to measure the bend radius of tubes that have many different radius values. Such tubes were first used in the field of furniture and now are being used increasingly in the fields of cars and aircraft. Obtaining an accurate value of a tube's bend radius is also helpful in analyzing the influence of tube defects caused by uneven tension and compressive stresses.

Thus, bend radius measurement is an important aspect of tube measurement. A rapid and accurate measurement method for this is desirable. Here, we describe an accurate and rapid radius measurement method for multi-bend tubes based on stereo vision. Firstly, the mapping from tube's center line to the edge point in image was modeled and discussed. Then, a segmented parametric model of tubes with curved

* Corresponding author.
E-mail address: liushaoli@bit.edu.cn (S. Liu).

https://doi.org/10.1016/j.measurement.2017.12.009
Received 19 June 2017; Received in revised form 1 September 2017; Accepted 7 December 2017
Available online 16 December 2017

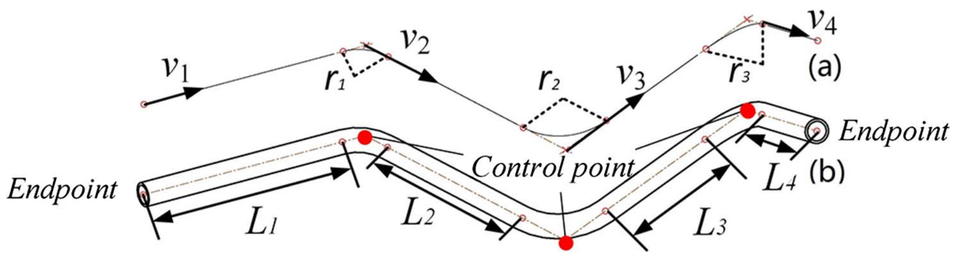

Fig. 1. Bend tube measurements: (a) center line and (b) 2D projection of the tube.

parts and straight parts was developed to calculate the radius. At last, to improve the accuracy and robustness of the method, an objective function was proposed based on the photo-consistency, and the radius measurement of multi-bend tube is converted into a non-linear optimization problem. Experimental results showed that the measurement accuracy of proposed method reaches to ± 0.5 mm with 3σ reliability. Besides, the effectiveness of the proposed method is high. It just requires the tube to be placed into the measurement area and the measurement results can be obtained within two minutes. Thus, the proposed method can simplify the measurement operations and reduce workload.

1.2. Related works

Based on the studies of Liu et al. [1], tube measurements can be classified into two broad categories: contact and non-contact methods.

1.2.1. Contact measurement

Contact measurement methods include the use of mechanical gauges [7–10] and three-coordinate measuring machines (CMMs) [11–14]. The angles and radii of a tube's curved parts can be measured with custom mechanical gauges [8]. For example, a Vernier device is a common and useful way to measure the angle and radius of tube's curved parts (Fig. 2(a)). A digital protractor can also be used to measure a U-shaped tube's curved radii quickly and accurately (Fig. 2(b)). However, these gauges or devices can only be used for measuring tubes with specific shapes such as 90° or a U-shape.

CMMs are good for measuring whole tube profiles. Points are collected with the probe of a CMM in a contact manner. By processing, such as fitting, segmentation, and reconstruction, the tube's parameters are acquired from cloud points of the tube surface [15–18]. However, the method is time-consuming. Other disadvantages include the low degree of automation and that the processing depends on the operator's experience.

1.2.2. Non-contact measurements

Non-contact measurement methods include scanning [19–22] and stereo vision-based methods [23–25]. An accurate 3D model of the tube can be reconstructed during the processes. Then, parameters can be obtained from the 3D reconstructed model.

1. Scanning method. This method uses a scanning device to scan the tube's surface to obtain point clouds [15–18,26,27]. Thus, this step is quicker and more convenient than using a CMM. There are several commercial instruments, such as those by Opton [20], Advanced tubular [21] and Tezet [22], available for tube measurements. However, the point clouds of a tube surface typically include a massive number (millions) of points. Furthermore, measurement problems may arise when the tube is occluded and in conditions where reflections occur. This can result in gaps or holes in the point cloud. Scanning repeatedly can overcome this and lead to robust results. However, the processing time is high and the precision is lower than with CMMs. Thus, this method has the disadvantages of being labor intensive, time consuming, and not readily automated.

Researches [25,28] have shown that the development of stereo vision-based methods offers a more rapid and less anthropogenic-influenced measurement with comparable accuracy.

2. Stereo vision-based method. In recent years, this method has been developed to measure the 3D shapes of tubes. Instruments, also referred to as photogrammetry devices [29,30], such as TubeInspect from AICON [23], Tuboscan from Tracto-Technik [23], and Vision-based tube measurement from BIT [28], offer non-contact measurements based on the principle of stereo vision with high performance in terms of robustness, efficiency, automation, and accuracy, in measuring a tube's 3D shape.

Generally, there are three classes of reconstruction methods. One is traditional close-range photogrammetry, which needs two corresponding points to be measured as a stereo pair to decide a point position in 3D space [31]. Marker points, which are usually pasted onto the object's surface, can be used to find the corresponding point accurately. However, this method is unsuitable for tube measurements

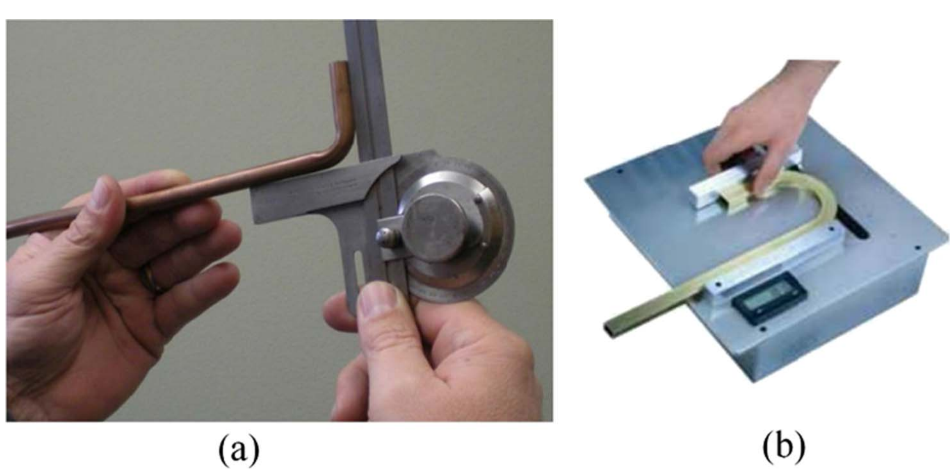

Fig. 2. (a) Vernier device and (b) digital protractor.