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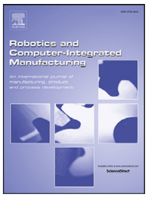

Full length Article

Seam tracking of large pipe structures for an agile robotic welding system mounted on scaffold structures

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ABSTRACT

This paper proposes a seam tracking technique for an agile robotic system for automated welding of large pipe structures at elevated heights. The welding system is designed to adapt to the scaffold structure which is generally erected around large workpieces. Large intersecting pipe structures are selected as the welding target because of their complex curved seams and wide applications in jackup oil rig manufacturing. A pipe localization method using only two profile scans is proposed to effectively localize the pipe and compute the initial location of the weld seam. The initial weld seam is then refined by a correction procedure to minimize the kinematic errors caused by base compliance, sensor measurement and system calibration. Subsequently, the seam is tracked to maintain a constant weld speed. Experimental results in a laboratory simulated environment show the feasibility of both the proposed seam tracking method and the concept of the agile robotic welding system for such applications. The precision of the mean tracking error for this system was found to be within 0.14 mm and 0.06 mm of the tool x and z axis respectively.

1. Introduction

Robots are widely used in manufacturing industries to improve productivity and quality. Typically, robots are deployed in a highly structured factory environment, where workpieces are transported to a fixed workcell and secured with respect to the robot. However, this approach is deemed unsuitable for large workpieces or structures due to their weight and size. It is recommended for the robot to move to the workpiece instead. For instance, in jackup oil rig (Fig. 1(a)) manufacturing, enormous welding works are required to assemble pieces of large pipes together using TKY joints. This results in truss structures that span over a length of 20 m for each leg (Fig. 1(b)). Welding such a joint requires at least a full day of manual welding due to the amount of filler pass involved (Fig. 1(c)). This makes robotic welding to perform this mundane task highly attractive.

This motivation drives the design of mobile robotic welding system for the purpose of deployment around these large immobile workpieces for welding. There are numerous ways in which a robot can be deployed with respect to such workpieces. Dharmawan et al. [1] broadly classified them into three types: (i) manual handling; (ii) gantry or rail guidance; and (iii) autonomous mobile base. For instance, Lee et al. [2] developed a portable 2-dof welding robot that could be manually handled to perform planar positioning and weaving operations. Moon et al. [3] designed a modular rail guidance system to support a welding robot for welding large H-beam columns at elevated heights. For mobile base, numerous concepts have been proposed and magnetic attachment seems to be popular for connecting the robot to the metal workpieces involved [4–7]. An interesting concept was employed specifically for pipe structures [8–11], where mechanical grippers are used to secure robots onto the cylindrical workpieces. Although robots that cannot be lifted by humans can be transported using gantry or rail guidance, lightweight robots typically weighing less than 30 kg offer the advantage of not requiring specialized transportation system to deploy them to the workpiece. In addition, most of these mobile robotic systems were mainly designed for workpieces with specific material properties and geometries, which in turn limit its adaptability to a variety of applications.

2. Related works

One of the key challenges associated with mobile robotic welding system is seam tracking. Traditionally, teaching and playing back is used to track weld seams, but it requires human operator intervention. This method may work well in static workcells where the relative position between workpiece and welding robot is fixed, and hence only one teaching procedure may be required for the same type of workpiece. Nonetheless, even in static welding cells, there are problems of workpiece tolerances, positioning system precision, torch precision

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Fig. 1. The large and heavy workpiece in consideration: (a) The jackup oil rig consists of numerous legs; (b) The leg structure during fabrication; (c) The welded TKY joint. (Photograph courtesy of SembCorp Marine Limited, Singapore).

and distortion during welding, which hinder the use of just one teaching procedure for the whole production. In such cases, real-time seam tracking finds intense application. Furthermore, in dynamic working environments where robots may move relative to the workpieces, automated seam tracking is also preferred. To achieve automated seam tracking, several procedures need to be performed before the robot can perform the welding accurately. These include workpiece localization, seam identification, and seam tracking.

2.1. Workpiece localization

Workpiece localization can be performed either manually or automatically. In manual workpiece localization [12], the robot needs to be accurately positioned at the start of the welding seam as an initialization. This method is quick and easy for welding path that has a distinct starting point. However, this would be challenging for TKY joints where a definite starting point is hard to define and manually locate. For automated workpiece localization [13], it requires the robot to locate the position of the workpiece relative to itself. Numerous approaches have been developed to localize through sensing of the workpiece surfaces [14–17]. However, they are limited to planar surfaces. This is carried out using some form of contact or non-contact type of sensing. The readers can refer to Kah et al. [18] for a detail analysis of the advantages and drawbacks for each of these types of sensing technique. Among these, optical sensing approaches are recommended for large complex workpieces localization.

2.2. Seam identification

Seam identification is typically achieved through optical sensing such as stereo cameras [19], depth cameras [20] or laser scanners [21]. They can be performed with or without prior knowledge of the trajectory of the weld seam. When using stereo vision, one important procedure is to abstract the unnecessary background in the image, which is usually carried out by comparing pixel intensities. As such, it requires a high constant contrast between the workpiece and the background intensity. This might be hard to achieve in field application where the background may not be easy to control and may not have high background contrast or even include unnecessary background details (refer to Fig. 1(b) and (c)). Depth sensing cameras may require multiple RGB-D sensors to be positioned accurately apart surrounding the workpiece. This is not feasible for field applications where the setup needs to be moved all the time. Even if the camera is mounted on the robot, motion planning of the robot to scan the 3D structure will add another complexity to the process due to the presence of obstacles. Hence, all these limitations render these approaches unsafe for field operations if prior knowledge of the seam is not available.

2.3. Seam tracking

Seam tracking can be performed either offline or real-time. The former means that seam tracking is performed prior to the welding process to correct for any slight disparity between the identified seam geometry model and nominal seam using a refined path [22]. The latter means that seam tracking is performed simultaneously as the robot welds the structure [23–27]. This is usually carried out by putting sensors, such as laser scanners or camera systems, to look ahead of the weld torch and correct for any seam deviation. One main difficulty in real-time seam tracking is getting a clear vision of the weld seam under intense illumination from the welding process. This is usually anticipated by developing a dedicated vision system and an elaborated image processing algorithm that might actually be computationally expensive for real-time implementation.

3. System description

All these observations inspire the authors to design an agile robotic welding system characterized by its light weight, small footprint, easy deployment, and task independence. Despite the advances mentioned earlier, there have not been a mobile welding system that shows both hardware and software adaptability capability to various conditions on site. The main contribution of this paper thus lie in the development of an agile robotic system that can automatically in-situ identify and determine the 3D coordinates of the welding seams of intersecting pipe structures accurately for use on industrial robotic welding system.

3.1. The agile mobile robotic system

Fig. 2(a) shows the proposed design of the mobile robotic system meant for deployment in a scaffold environment. The mobile robotic system consists of two subsystems, a mobile platform and a lightweight 6R serial welding robot. The mobile platform as shown in Fig. 2(b), is designed based on the principle of exact kinematic constraint and it enables the robot to be deployed as a simple addition to the scaffolding construction process. It consists of wheels for sliding along the scaffold and quick release locking mechanism for clamping the system in place. The robot can be any lightweight industrial robot. The Universal Robot UR10 was chosen due to its weight (28.9 kg) and reach (1.3 m). This makes it easy for deployment within the scaffold environment to perform human tasks. For a detail performance evaluation of this system, see Sedore et al. [28] and Dharmawan et al. [29].

3.2. Overview of seam tracking algorithm

Fig. 3 shows the workflow of the proposed seam tracking approach. The main algorithm consist of four key steps: pipe localization, initial seam computation, seam tracking, and motion planning. The pipe localization process uses the geometry of pipes to determine its cylindrical axis. This is followed by computing the seam poses by solving for the intersecting curves of two intersecting cylinders. An iterative offline seam tracking via detection and correction is subsequently performed to formulate a motion planning strategy for the robot. Lastly, the weld seam is tracked using the robot controller through joint velocity specification to perform the welding task at a constant velocity. The details are explained in the following sections.

4. Pipe localization

To localize the pipe, the geometrical characteristic of cylindrical objects is exploited to develop an effective method to localize pipes using a 2D laser scanner. This built upon the results of Perez and White [30] who investigated into the problem of locating cylinders using a depth scanner. Fig. 4 shows the proposed concept of pipe localization, where two laser depth scans are used to identify the pipe axis and locate its center with respect to the robot base.