IOP Conference Series: Materials Science and Engineering

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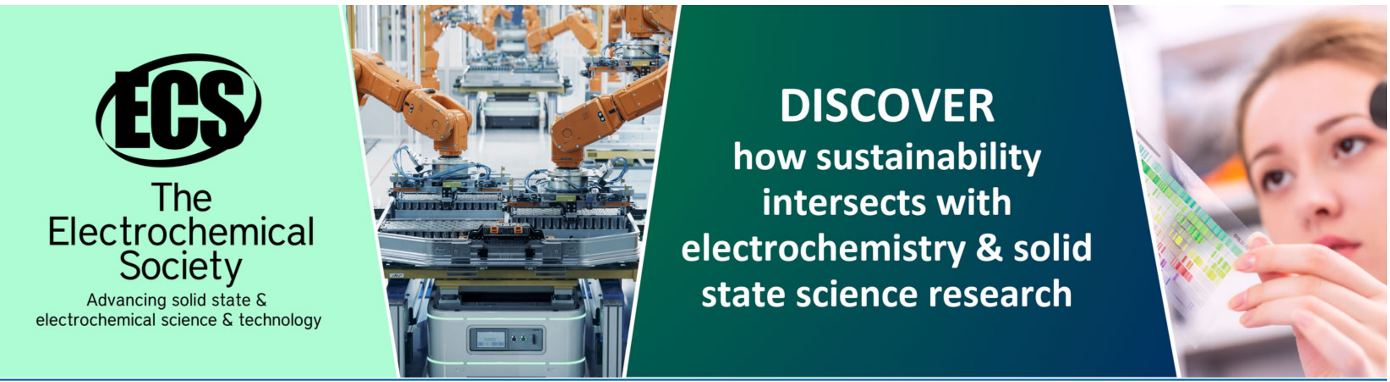
To cite this article: Shaohua Meng *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **493** 012128





IOP Conf. Series: Materials Science and Engineering **493** (2019) 012128 doi:10.1088/1757-899X/493/1/012128

# Digital Twin-Driven Control Method for Robotic Automatic Assembly System

**Shaohua Meng[1, a], Shaolin Tang[2, b], Yahong Zhu[1, c] and Changyu Chen[1, *]**

[1]Beijing Institute of Spacecraft Environment Engineering, Beijing, China
[2]Beijing Shenzhou Aerospace Software Technology Co. Ltd., Beijing, China

*Corresponding author e-mail: chenchangyu_cast@163.com, [a]msh1206@126.com, [b]tangshaolin@bjsasc.com, [c]zhyhzymail@163.com

**Abstract.** In order to improve the intelligent level of the robotic assembly system, a digital twin model is established to control the robot for automatic assembly of large-scale spacecraft components. Through a three-dimension virtual simulation model of the industrial robot, the physical properties of the assembly elements are described. Then the behavior model is built based on the robot kinematics so that the state of the virtual simulation model can be consistent with the real robot. The interface protocol is set to construct an information model, which can be used for the virtual-real interaction between the simulation model and the physical system. Based on the digital twin model, probabilistic roadmap method (PRM) is performed to generate a collision-free path and control the robot to accomplish the assembly mission. Experiment results show that this method can control the robot to automatically, safely and efficiently complete large-scale components installation.

## 1. Introduction

Assembly is the last and most important stage in the spacecraft manufacturing process, which has a marked impact on the quality, performance and reliability of the spacecraft [1]. Currently, spacecrafts are still assembled manually by using lifting equipment, which is difficult to meet the requirements on precision, quality and efficiency in the assembly process. With the technical indicators continuously improving, spacecraft components become more large and heavy, such as optical camera, antenna. Moreover, the number of payloads in a cabin is increasing and the operation space is extremely confined. It is necessary to develop new assembly technologies and equipment.

In recent years, robotic assembly system combined of the automated positioning and the precision measurement system has been developed to improve precision and save time. It has been widely used in various fields [2-4], such as automobile assembly, aviation manufacturing, electronic product production and so on. But for the large-scale components, there are still some problems to overcome, such as single pieces production, unfixed assembly position, complex and changeable working condition.

As for the above problem, digital twin technology is considered as a feasible and effective approach. Digital twin technology refers to the mehtod of describing and modeling a physical entity's characteristics, behavior, and performance by means of digital technology. It is considered as a key technology to realize the interaction and convergence between the cyber and physical worlds.

Numerous research have been made to explore the application of digital twin technology in manufacturing [5-6]. But research on robotic assembly system are still rarely reported at present. In this paper, digital twin technology is used to carry out state monitoring and task control of robot assembly system. This can not only reduce personnel labor costs, reduce personnel errors, but also improve operation efficiency. Therefore, the application of digital twin technology in satellite assembly has certain theoretical and practical significance.

The remainder of the paper is organized as follows: Sect. 2 outline the system architecture. In Sect. 3, the digital twin model is established. Based on digital twin, Sect. 4 presents a path planning framework for robotic assembly system. Sect. 5 details a experimental test. The last part concludes the main contributions of the paper and discusses research issues in the future.

## 2. System architecture

The configuration of the proposed automatic large components assembly system for spacecraft is illustrated in Fig. 1. The system is composed of the following components:

1) A 6-DOF robot manipulator for holding and moving the component;

2) A central computer for processing the input images and controlling the robot;

3) Three charge-coupled device cameras, one for long-distance visual guidance and other two for close-range visual alignment;

4) Three 1-D laser sensors for measuring the angles between the assembly component and the installation framework.

The data of the vision and laser sensors are collected to the computer, and then they are processed by the detection and localization algorithm. The industrial robot moves according to the command made by the computer. The processes are carried out iteratively until the whole task is completed.

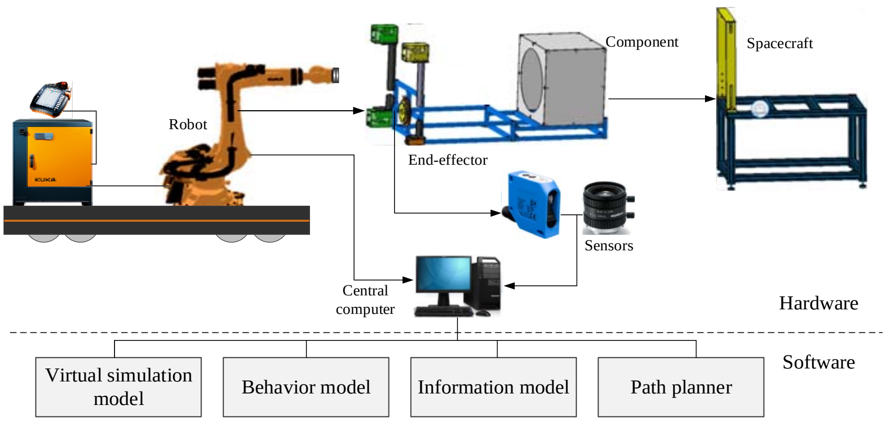



**Figure 1.** Hardware architecture of robotic assembly system.

## 3. Preliminaries

In this section, a digital twin model is established to control the robotic assembly system. Firstly, a three-dimension virtual simulation environment including the robot, components and spacecraft is used to desribe the physical properties of the assembly elements. Then the behavior model is built based on the robot kinematics so that the state of the virtual simulation model can be consistent with the real robot. Finally, the interface protocol is set to construct a information model, which can be used for the virtual-real interaction between the simulation model and the physical system.

### *3.1. Virtual simulation model*

The virtual model is the foundation of digital twins, which should be able to accurately describe the static physical properties and dynamic behavior shapes of assembly elements. The industrial robot is the actuator of the assembly system and is also the most difficult part of virtual modeling due to its complex geometric shape and 6-DOF movement.

The virtual simulation environment is constructed based on CAD models of elements in the physical scene. In the virtual environment, the complex objects are composed of many triangular patches which are surrounded by simple geometries, such as spheres and rectangles. After that, a tree structure data base is con-structed to represent the real object, and it can be used to efficiently execute the overlapping test of the ideal geometry.

### *3.2. Behavior model*
In order to simulate the behavior of the robot in assembly process, kinematics is used for modelling. Its task is to describe the changes of joints and end effector during the movement of robots. It involves two aspects: forward kinematics and inverse kinematics. The robot forward kinemat-ics is the connecting rod parameters and the joint variables of the robot to solve the position and attitude of the end-effector, and the inverse kinematics of the robot is exactly the opposite. The position and attitude of the end-effector are known, and the joint variables of the robot are solved. The inverse kinematics of the robot is much more complicated than the forward kinematics problem, and with the increase of the freedom of the robot, the solution of the inverse kinemat-ics will become more and more complex. In this paper, the Denavit-Harenberg method is implemented for solving the positive solution problem [7].

### *3.3. Information model*
The program is implemented on a computer, which communicates with indus-trial camera and robot controller through Ethernet TCP/IP protocol. In order to ensure the real-time and reliability of data transmission, the data exchange be-tween industrial computer and robot is realized by using the RSI (Robot Sensor Interface) communication software of KUKA Company. The industrial computer receives the state information of speed, position and attitude returned by the ro-bot, transmits the path planning information to the RSI, and transmits the RSI to the robot, thus realizing the monitoring and control of the robot.

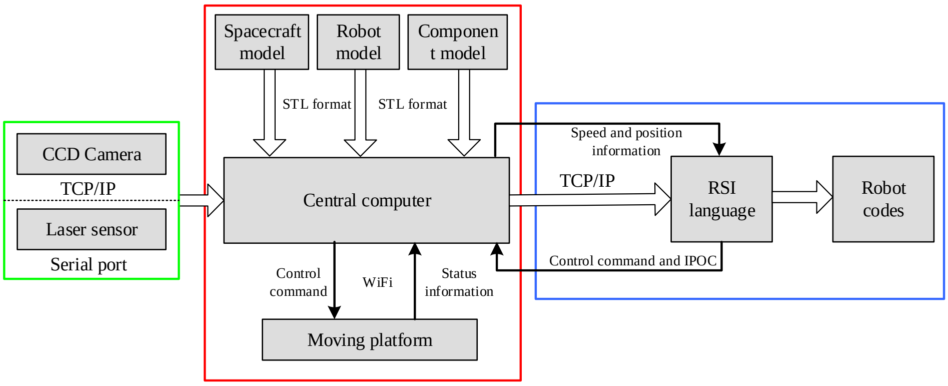



**Figure 2.** Communication scheme of the robotic assembly system.

## 4. Path planning for the robot
The difficulty of industrial robot path planning is that it has high motion di-mensions and complex three-dimensional geometric shape. In the process of large-scale components installation, it is not only to avoid the collision between the components and the cabin, but also to ensure that there is no interference between the robot body and environmental objects. This paper implements the PRM based on sampling to carry out the robot assembly path planning.

### *4.1. Collision detection*
Fast and accurate collision detection is a prerequisite for path planning based on sampling method. The virtual simulation environment is constructed based on CAD models of elements in the physical scene. In the virtual environment, the complex objects are composed of many triangular patches which

are surrounded by simple geometries, such as spheres and rectangles. After that, a tree structure data base is constructed to represent the real object, and it can be used to efficiently execute the overlapping test of the ideal geometry.

This paper employs axis-aligned bounding boxes (AABB) technology [8] for collision detection. The AABB is the smallest hexahedron which surrounds complex objects and the sides are parallel to the coordinate axes.

### *4.2. Path planning*

The PRM is a sampling-based planner that can achieve some form of completeness. The PRM algorithm presented below is easy to implement and works well even with rather high-dimensional problems (5-12 degrees of freedom) [9]. It is a good choice for industrial robot to plan a collision-free path of assembly operations in a complex environment.

For a given robot workspace, the PRM algorithm first constructs a roadmap in a probabilistic way, which can be represented by an undirected graph G= (V, E). The nodes in V are a set of robot configurations chosen randomly from a uniform distribution in the free space $Q_{free}$. The edges in E are connecting lines between configuration nodes, which correspond to collision-free paths. These edges are referred to as local paths computed by a local planner. The PRM algorithm uses the searching algorithm to find a feasible path for the robot to connect the starting node $q_{int}$ and the target node $q_{goal}$. The algorithm needs to be completed in two stages: the learning phase and the query phase. The details can be found in [10].

## 5. Assembly experiment

In order to verify the effectiveness of the presented approach, a satellite component was selected to carry out the assembly experiment. The size of the component is more than 1m, and its weight is 80kg. It is a typical scene of the assembly of spacecraft products. It is of practical significance to verify the application of the proposed approach.

The computer communicates with the robot through TCP / IP protocol. The communication period is 12 ms. Fig. 3 shows the change curve of the robot joints obtained by path planning. Fig. 4 gives the simulation and real test results of the robot assembly process.

The simulation result shows that the industrial robot can skillfully change the position and pose of the component, avoid collision with the side wall of the satellite and send it into the confined space, until the target location is reached. During the whole assembly process, the joint angle of the robot is changed more smoothly. The planned path was translated into motion sequences by robot off-line programmer. The real test result proves the correctness of the simulation results.

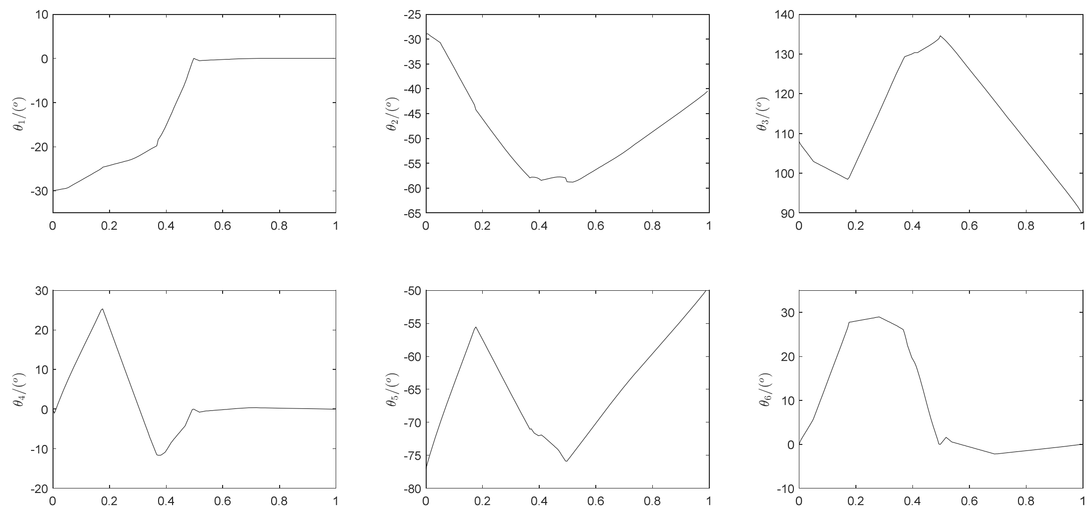



**Figure 3.** Variation curves of the robot joints.

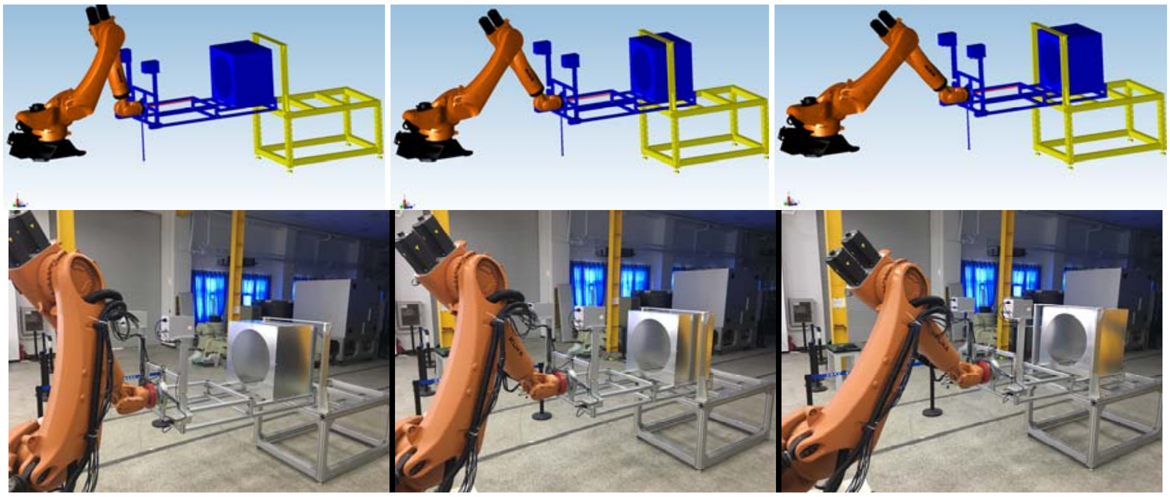


**Figure 4.** Simulation and real test results for robot assisted assembly.

## 6. Conclusion

This paper presented a digital twin model for the robotic assembly system, which includes virtual simulation model, behavior model and information model. Based on the digital twin model, the PRM planner was performed to generate a collision-free path for the industrial robot to move the component from the initial position to the target location. The planned path was translated into motion sequences by the robot off-line programmer. The experiment results show that the proposed method can quickly plan a collision-free assembly path, and then control the industrial robot to automatically, safely and efficiently complete large-scale components installation.

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