P. Koomsap et al. (Eds.)

doi:10.3233/ATDE230643

Development of Collaborative Multi-Robotics Assembly System with Digital Twin Approach

Kyaw HTET OO and Pisut KOOMSAP[1]
Industrial Systems Engineering, School of Engineering and Technology, Asian Institute of Technology, Pathumthani 12120, Thailand

Abstract. Assembly may be an undesirable but unavoidable step for most manufacturers. Industrial robots are commonly used for repetitive tasks in large-scale mass production, but customized medium-sized products with wide variations in small batch production for robot-to-robot collaborative manipulation assembly tasks demand increased dexterity, which comes at a higher cost due to limited sensing capabilities. The utilization of collaborative robots or cobots in robot-to-robot collaborative in hand manipulation assembly tasks will not only enhance flexibility and dexterity but also provide cost-effectiveness. This paper presents the development of a collaborative multi robots assembly system with a digital twin approach to support robot-to-robot collaborative assembly process for various products with small batch sizes. A digital twin is adopted to enable human workers to supervise and train the collaborative multi-robotics assembly system virtually to determine the assembly sequences whenever new orders arrive without interrupting the operation of the physical system to minimize downtime for setting up the assembly line and commissioning process. Besides, image processing is applied to recognize parts that come to an assembly station in random orientations to provide flexibility during the physical assembly further.

Keywords. Digital twin, Cobots, pattern recognition, assembly process

Introduction

In many industries, assembly processes are viewed as necessary but not ideal. The traditional approach of using industrial robots and integrated machines to perform specific repetitive tasks is effective for mass production due to their ability to handle large volumes [1]. However, this approach is inadequate for meeting the increasing customer demand for customized medium sized products with wide variations in products' shape and geometry information [2]. A rigid system that solely relies on pre-programmed machines is not only unable to respond promptly to changes in product variety but is also costly. Hence, there is a need for more flexible and effective transdisciplinary approaches that can meet the requirements of customization while maintaining production efficiency [3]. One effective transdisciplinary approach to enhance the flexibility of the production process is the reconfiguration of robots to function robot-to-robot part manipulation collaboratively.

[1] Corresponding Author, Mail: pisut@ait.asia.

The utilization of collaborative robots or cobots with advanced sensing, is a potential avenue for enhancing flexibility in small batch production by addressing products' shape and geometry information variations [4]. Employing cobots in robot-to-robot collaborative in hand manipulation assembly tasks for customized medium-sized products enables manufacturers to maintain production efficiency while increasing flexibility. However, implementing physical multi robotic systems for robot-to-robot collaborative assembly processes poses a challenge due to the potential for significant downtime required to reconfigure the system for new assembly processes.

To address this issue, the use of digital twin (DT) methods for multi-robotic assembly systems have been explored in previous studies, including for finding optimal robot configurations [5] and for optimal task allocation in collaborative assembly operations [6]. Additionally, an autonomous robotic assembly system has been developed for soma cube assembly [7]. A virtual world planner has also been created for optimal assembly sequence for a dual-arm robot to assemble the soma blocks [8]. The proposed approaches have identified the shortcomings of current multi-robotic assembly systems, which have thus far been evaluated using simple-shaped parts in fixed positions and have yet to be adapted for more complex and customizable parts that may be presented in random configuration.

This study presents a collaborative multi-robotics assembly system that utilizes a DT approach to handle complex shaped parts with small batch sizes for real industrial assembly applications. The DT approach provides a virtual representation of the physical assembly process, enabling human workers to train and supervise the collaborative multi-robotic system without interrupting physical production. Furthermore, the system incorporates image processing techniques to enhance flexibility and adaptability, enabling it to adjust to variations in part orientation and new customer orders. This solution offers improved flexibility and adaptability while reducing downtime associated with reconfiguration, making it a promising solution for assembly processes involving small batch sizes with complex shape parts.

1. Digital Twin Approaches for Multi-Robotics Assembly Planning

Assembly planning for multi-robotics assembly systems is an essential process for ensuring efficient production of a wide range of products. In recent years, there has been a significant focus on optimizing assembly planning approaches for multi-robotics systems to accommodate variations in product designs. This has led to a growing body of experimental and theoretical studies aimed at investigating various aspects of assembly sequence planning, including the development of algorithms for generating optimal assembly sequences, the impact of part variation on assembly performance, and the use of DT and simulation tools to analyze and optimize assembly processes.

The recent studies have explored the use of DT for multi-robotics assembly tasks. Doger developed a digital twin method to find robot configurations for collaborative assembly operations with constraints between robots, assembly components, and mating components [5]. Yu created a digital twin approach for a multi-robotic assembly simulation environment with two robots that need to pick up two parts sequentially, mate them, and return for the next pickup movement [6]. The system was tested with 220 chairs from the PartNet dataset, and two settings were used: the object-centric setting, where no robots are loaded, and the full setting, where two seven DoF Franka-Arm robots mounted on three DoF mobile platforms perform the assembly process while fixed-base holders hold the parts.

Furthermore, two different DT approaches for multi-robotic assembly systems planning have been investigated for soma cube assembly. The first DT system is an autonomous robotic assembly system that plans and executes the assembly motion sequence by calculating all possible block configurations for the target shape by using virtual world simulation [7]. The second DT system is a virtual world planner that can automatically find an optimal assembly sequence for a dual-arm robot to assemble the soma blocks by permuting the workpieces involved in the assembly and considering stability and the need for a second arm [8].

In conclusion, these studies have identified the limitations inherent in existing DT, which have predominantly been assessed using simple shape and straightforward geometries of parts positioned in static orientations. However, these systems have not yet been adequately tailored to accommodate the complexities and customization requirements of parts that may present complex shape parts in random configurations. Further research is necessary to overcome these limitations, exploring novel avenues to enhance assembly planning by employing in-hand manipulation techniques among multiple robots to reorient parts and achieve the desired final assembly configuration.

2. Collaborative Multi-Robotics Assembly System: Digital Twin Approach

2.1. The research concept

The main concept of the digital twin approach is to allow human workers to virtually supervise and train the collaborative multi-robot assembly system, allowing for determination of assembly sequences when new orders are received without interrupting the operation of the physical system. The digital twin system is utilized primarily for conducting pre-assembly planning processes virtually, such as verifying the initial and final grasp locations of each part and performing multiple simulations to generate different robotics programs for multiple robotics arms.

The physical robots acquire the digital twin robotics program from the virtual world, and the camera captures snapshots and analyzes coordinate data to transfer to the physical robots. This research aims to develop the digital twin system for the 3D assembly process of the collaborative multi-robotics assembly system to better support the handling of complex 3D parts in random configurations at the initial state. The main concept of the digital twin system for both the physical and virtual worlds is depicted in Figure 1.

2.2. Co-MRAS: digital twin approach

A collaborative multi-robotics assembly system (Co-MRAS) involves multiple robotics arms working together in a shared workspace to acquire sub-assembly components or final assembly products. However, the handling of complex 3D parts in random initial configurations for Co-MRAS presents four significant challenges. These challenges are related to extracting the exact initial grasp location to convert to the final assembly configuration, allocating the common task to multiple robots in a shared workspace, recognizing the different random initial configurations of parts in 3D space, and generating collision-free motion for multiple robotics arms in a shared workspace. To address these transdisciplinary challenges, four primary phases must be undertaken while taking the difficulties into consideration.

As illustrated in Figure 2, the first step involves identifying the collision-free grasps location on each part in every initial random configuration, while also considering the geometric constraints of the complex-shaped objects in 3D space and their stable placement on the work table. The second step is focused on motion planning for multiple robotics arms during the assembly process, which takes into account the collision-free initial and final grasps location and considers the coordination of multiple robots and potential collisions among them. In the third step, the position and rotation information of each workpiece is detected through the collection of parts' coordinates from the real world. Finally, the fourth step involves the generation of the final program to be applied to the physical robots.

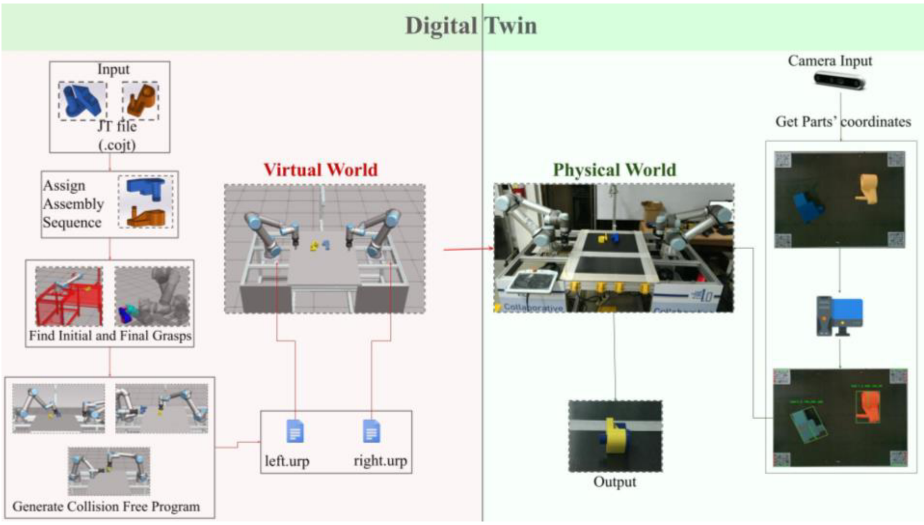

Figure 1. The Digital Twin Concept.

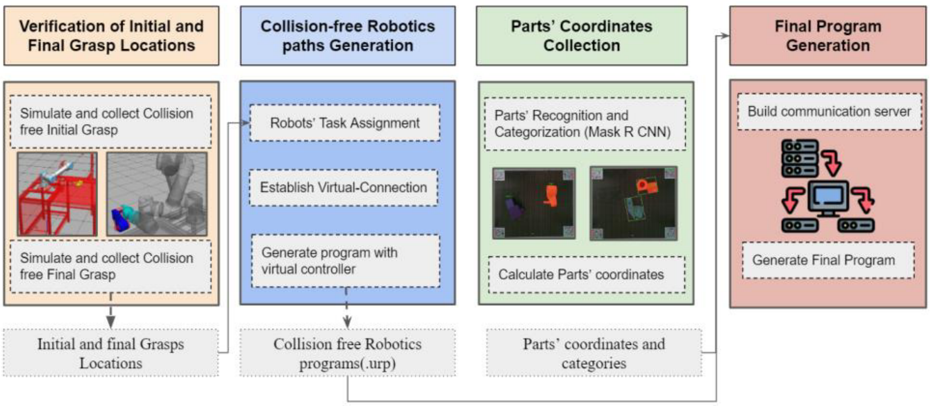

Figure 2. The Digital Twin Approach for Co-MRAS.

2.3. Verification of initial and final grasps location

In order to generate collision-free initial and final grasps locations for each workpiece on the work table, based on their stable placement numbers, the operator conducts simulations in a virtual world environment by applying the geometric constraints of center of gravity, parallel and cylindrical faces, and final assembly pose for each assembly component as demonstrated in Figure 3(a)-(d). Additionally, in order to determine the collision-free final grasp location of each assembly component, a collision checking simulation is conducted between the gripper and partially assembled components, using 3D (.cojt) files for each assembly component and their final assembly poses as input. The output is the collision-free final grasps location for each robotic arm, which is obtained by removing all collision grasps identified in the simulation, as presented in Figure 3 (e) and (f).

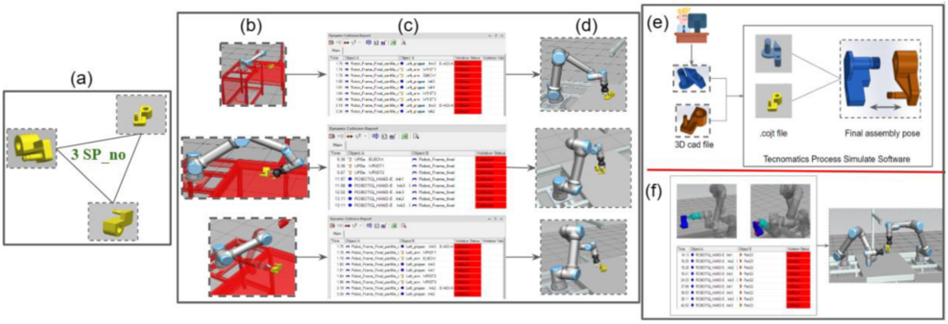

Figure 3. Verification of initial and final grasps location.

2.4. Collision free robotics path generation

This section describes a method for generating collision-free robotics paths based on different initial part placements on the worktable. The system simulates stable placements of assembly parts in the virtual world to generate non-repetitive tasks for each robot. The total number of initial stable placements is calculated using equation 1, which takes into account the number of stable placements for each part. The resulting different non-repetitive tasks for each robot are shown in Figure 4.

$$\text{Total SP} = \text{SP1} \times \text{SP2} \times \ldots \times \text{SPn} \tag{1}$$

Figure 4(a) shows that the yellow part has three stable placements, and the blue part has five stable placements on the work table, resulting in 15 task assignments generated for multiple robots. In Figure 4(b), the yellow cycle body has three stable placements, the green cycle body has two, and the two wheels have one stable placement each on the work table, resulting in six different robotics tasks for multiple robotics arms.

The proposed system generates collision-free paths for multi-robotic systems by obtaining initial and final grasp locations for each stable placement, enabling the system to efficiently handle complex 3D parts and increase the flexibility of the assembly process. Figure 5(a), (b) and (c) demonstrate the changes in generated paths based on different initial placements. The system establishes a live connection and generates predefined paths for non-repetitive tasks in Tecnomatix, with the virtual Polyscope controller recording generated way points. This approach is crucial for minimizing

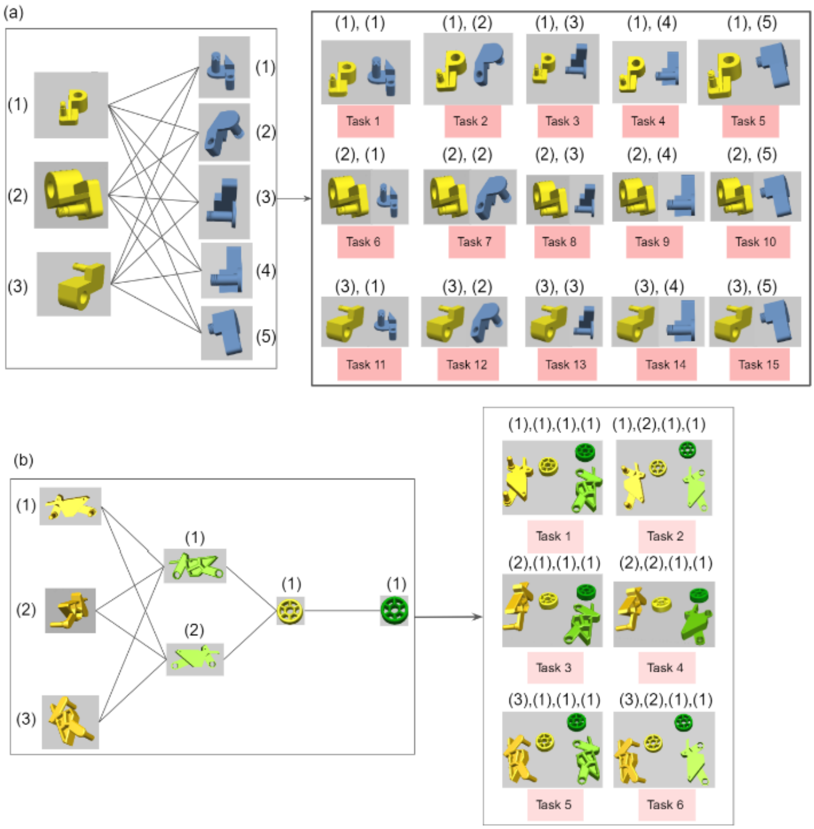

Figure 4. Different non repetitive tasks according to initial stable placements.

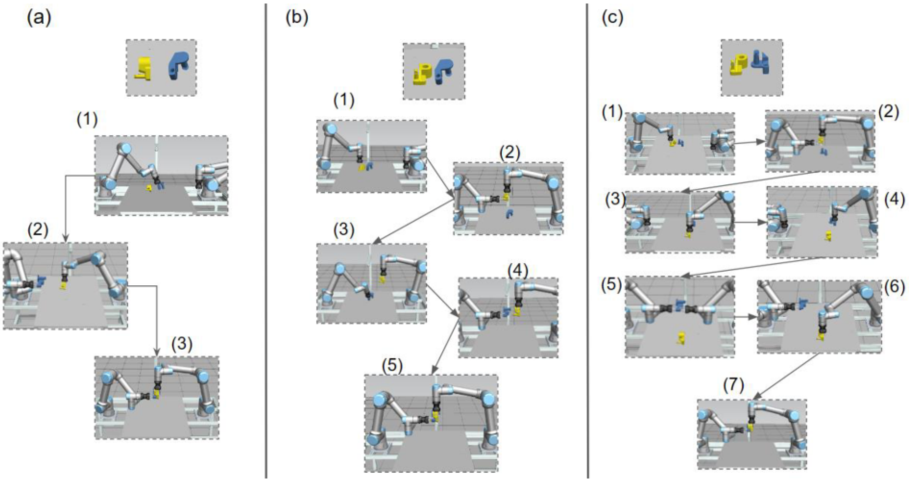

Figure 5. Generate Different Tasks for random placements in Virtual World.

accidents and ensuring safety in multi-robotic systems and is an important step towards achieving a successful and efficient collaborative multi-robot assembly system.

2.5. Extraction of parts' coordinates and generation of final program

The Parts' Coordinate Collection method consists of two main sections: Parts' recognition and categorization, and Calculate Parts' coordinates. The Mask-R CNN algorithm is used for Parts' recognition and categorization, which categorizes the images according to the part and its stable placement number. To calculate part's coordinates, the fixed camera frame method is set up using 4 QR codes as reference points, and the target is calculated using translation and rotation matrix from the reference point using equation 2. The output of the training is the parts' recognition with masking, and 500 training images are used for each part.

$$\text{Target} = \text{pose\_trans}(\text{reference point, offset}) \quad (2)$$

This section discusses the communication method for transferring real-time part coordinates data to physical robotics arms. The proposed method involves developing a connection between a PC and robots using an XML_RPC server. The output of the parts' coordinate is collected as a CSV file, which is uploaded to the server and sent to the robot. The robotics controller needs to run the XML_RPC server program call before starting the sequence. The final .urp files for both robotics arms are transferred from the virtual controller to the physical robots as shown in Figure 6.

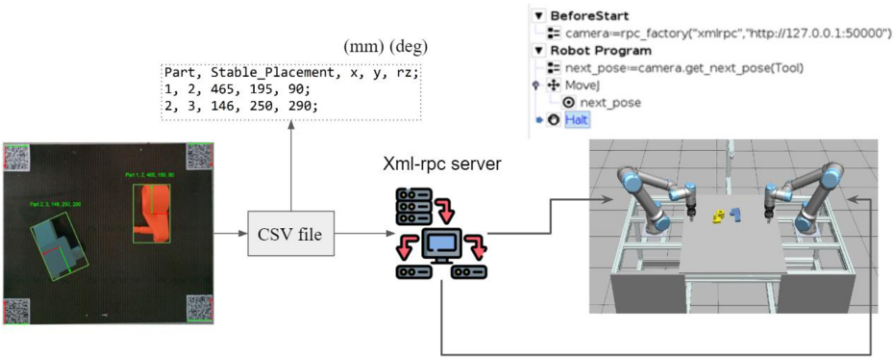

Figure 6. Parts' coordinates transfer via XML_RPC communication server.

3. Implementation and Results

This section describes the implementation of the developed concept as an algorithm using two robotics arms. It includes the development process of the Co-MRAS, which focuses on virtual simulation for collision avoidance and image processing for part recognition and coordinate collection. The algorithm is developed to complete the assembly process from the CAD file, and a flow diagram of the algorithm is shown in Figure 7. Additionally, digital twin program development, object coordinates extraction program and the result of digital twin approach are illustrated in detail.

The digital twin program is used to generate collision free robotics paths for each robotic arm in the proposed algorithm. Tecnomatix Process Simulate software is used to extract the collision free initial and final grasps location and develop different non-repetitive tasks for each robot. Tecnomatix Process Simulate includes the 3D viewer, operation tree, object tree, and robotics path editor where the program can be developed. The Jupyter Notebook is used to analyze the parts' coordinates and extract it to transfer the coordinates to the physical robots.

The accuracy of image coordinated feedback for assembly components is dependent on their placement on the work table due to camera resolution and distortion. Although camera calibration can reduce distortion error, shifting in the x and y coordinates of components occurs on the worktable. To obtain accurate component coordinates, a red rectangle box with dimensions of 400*300 mm was created as shown in Figure 8. If the

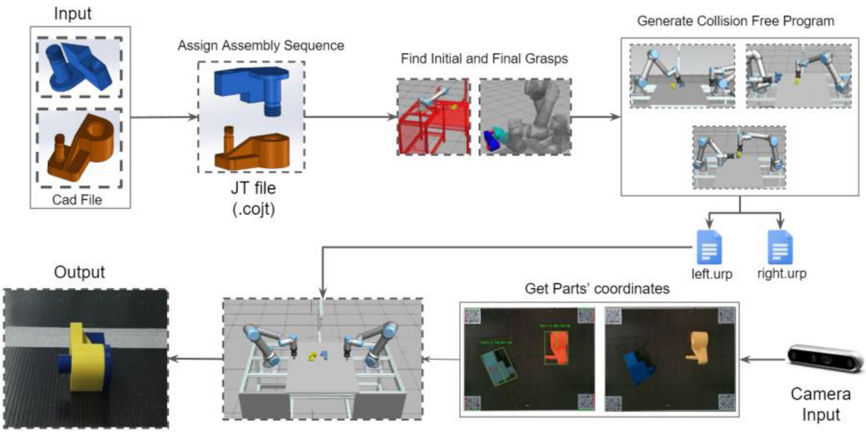

Figure 7. Developed algorithm for autonomous Co-MRAS.

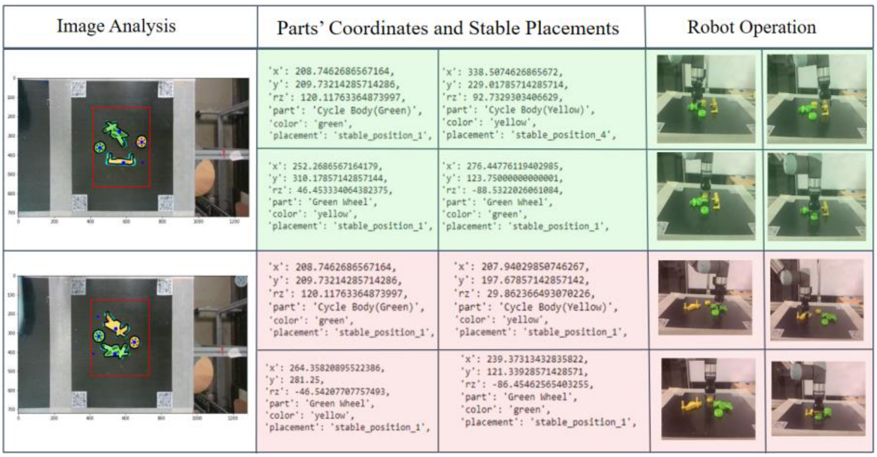

Figure 8. Image Analysis, Parts' coordinates and results for Cycle Assembly case.

tested sample coordinates are outside the box, the accuracy is reduced by 4 percent error due to camera resolution and distortion, which can affect the final outcome of the assembly process. Recognition precision between inside and outside of the box is illustrated in Figure 9.

To evaluate the effectiveness of the proposed method, experiments were conducted on various assembly scenarios that involved complex parts with different initial stable placements on the work table. A complete digital twin operation was performed, as shown in Figure 10 (a), to generate step-by-step assembly processes for two customized 3D mechanical brackets using two robotics arms in both physical and virtual worlds. Another case involving four customized 3D mechanical parts for cycle assembly was also considered, as depicted in Figure 10 (b), and the generated robotics programs were based on the initial stable placement of each component on the work table.

The collaborative assembly processes employed a double peg-in-hole assembly to achieve accurate mating. Overall, the experimental results demonstrated the effectiveness of the proposed method in handling complex assembly scenarios with various initial stable placements of components.

4. Conclusion

In conclusion, this study proposes a step-by-step approach for generating collision-free robotics programs for multi-robotics assembly systems using a digital twin. The approach aims to handle complex and non-repetitive tasks for customized mechanical parts in 3D space by verifying the initial and final grasps locations. Although the approach is established by being separated into different programs, it can be further improved by developing integrated software that uses all the approaches in one program platform.

The proposed approach was validated through experiments involving different assembly cases with varying initial stable placements on the work table, demonstrating its ability to address the challenges of complex assembly tasks. This digital twin approach has the potential to enhance efficiency and eliminate the downtime required for reconfiguration in assembly processes for new customer orders, thereby facilitating the successful implementation of collaborative multi-robotics assembly systems.

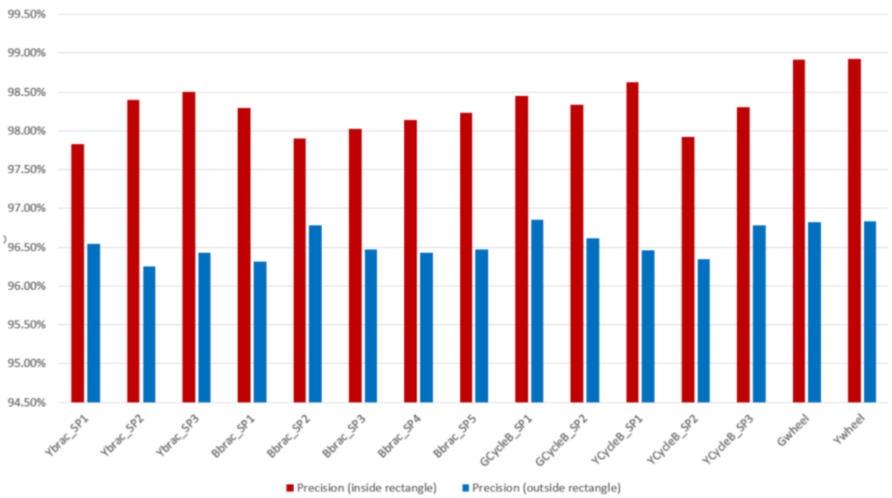

Figure 9. Recognition precision between inside and outside of the box.

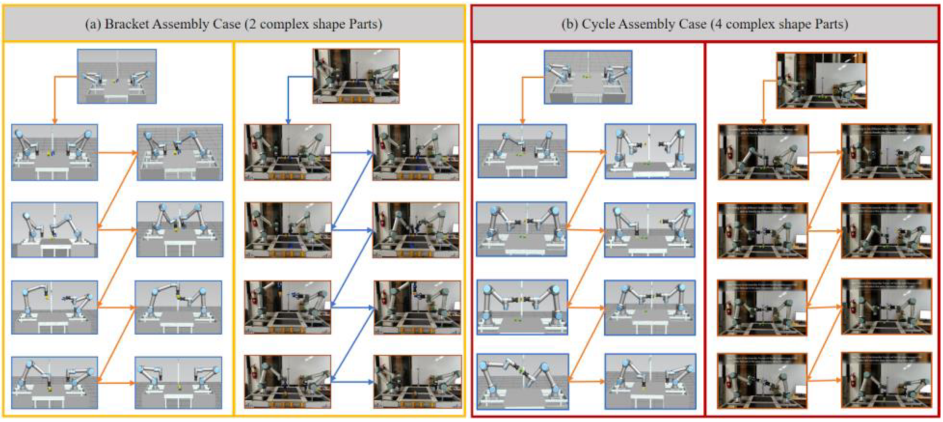

Figure 10 Complete Digital Twin Assembly Operations for Bracket Assembly and Cycle Assembly Case.

References

[1] G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssolouris, Automotive Assembly Technologies Review: Challenges and outlook for a flexible and adaptive approach, *CIRP Journal of Manufacturing Science and Technology*, 2010), (2), 81-91

[2] N. Kousi, S. Koukas, G. Michalos and S.Markris, Scheduling of smart intra–factory material supply operations using mobile robots, *International Journal of Production Research*, 2019, 57(3), 801-814.

[3] Y. C. Chiang, H. Bier, and S. Mostafavi, Design to Robotic Assembly: An Exploration in Stacking. *Frontiers in Digital Humanities*, 2018, *5*, 23.

[4] M. Dogar, A. Spielberg, S. Baker, & D. Rus, Multi-robot grasp planning for sequential assembly operations, *Autonomous Robots*, 2019, 43(3), 649-664.

[5] F. Sherwani, M. M. Asad and B. S. K. K. Ibrahim, Collaborative Robots and Industrial Revolution 4.0 (IR 4.0), *2020 International Conference on Emerging Trends in Smart Technologies (ICETST)*, Karachi, Pakistan, 2020, pp. 1-5, doi: 10.1109/ICETST49965.2020.9080724.

[6] M. Yu, L. Shao, Z. Chen, T. Wu, Q. Fan, K. Mo, and H. Dong, RoboAssembly: Learning Generalizable Furniture Assembly Policy in *a Novel Multi-robot Contact-rich Simulation Environment*. arXiv preprint arXiv:2112.10143. 2021.

[7] T. Kang, J.B. Yi, D. Song, and S.J. Yi, High-Speed Autonomous Robotic Assembly Using In-Hand Manipulation and Re-Grasping, *Applied Sciences,* 2021, *11*, no. 1: 37. https://doi.org/10.3390/app11010037.

[8] H. Chen, W. Wan, and K. Harada, Planning to build soma blocks using a dual-arm robot. *In 2021 IEEE International Conference on Development and Learning (ICDL),* 2021, pp. 1-7.