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Paper:

Development of a Flexible Assembly System for the World Robot Summit 2020 Assembly Challenge

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The assembly challenge of the World Robot Challenge (WRC) 2020, which was a part of the World Robot Summit (WRS) 2020, aimed to complete rapidly changing tasks in high mix/low volume production through building agile and lean production systems that can respond to one-off products. The authors of this paper participated in the challenge with the team PneuBot from the Industrial Robotics Facility of the Italian Institute of Technology by developing a flexible assembly system. The purpose of this work was to develop an assembly system able to handle variations of parts and tasks with a minimal changeover in hardware and software. In particular, assembly tasks were carried out, such as the assembly of a DC motor, pulleys, and a flexible belt on a plate, starting from pieces of unknown positions and orientations on a tray. The proposed work cell is light-weighted and can be fast deployed and replicated. It is composed of two Universal Robots; an RGB-D camera mounted on the wrist of the robot, able to detect both the position and orientation of the different objects to manage; a custom gripping system composed of 3D printed fingers for manipulation purposes and miniature force sensors for the grasping detection.

Keywords: World Robot Challenge, industrial robot, assembly, gripper design, system integration

1. Introduction

Industrial robots are widely used in large-scale manufacturing scenarios, such as the automotive industry, in which products with little variations are manufactured. However, in recent years, as manufacturing shifts towards high mix/low volume production, the demand for fast adaptiveness in the production system is rising. This trend in production systems expects these ones to be capable of handling diverse product variations, small life cycles, and small batch sizes, in the extreme case, batch size one [1].

In order to meet the demand for high mix/low volume production, the assembly challenge of WRC 2020 was held in Japan during the WRS 2020. The ultimate goal of the assembly challenge was to develop agile and lean manufacturing systems that can achieve efficient manufacturing even for one-off products by quickly reconfiguring the system without human demonstration for trajectories or jigs [a]. In this paper, our solution and methodology proposed to solve the assembly challenge are described.

In detail, we present the implementation of the developed system, the design of an exchangeable finger gripping system, the strategy used in the challenge, the laboratory experiments, and the problems encountered during the challenge. A special focus will be pointed on the designed work cell and on the experiments performed with the aim of demonstrating the effectiveness of our system. Lessons learned from the challenge and future directions of improvement were discussed to enhance the performance of the developed assembly system.

This paper is structured as follows: related work is discussed in Section 2; Section 3 briefly introduces the tasks, rules, and system overview; Section 4 describes the design of the gripper, tools, and jigs we used in the challenge; the software architecture and workflows are explained in Section 5; experiments results are given in Section 6; lessons learned and future improvements are discussed in Section 7.

2. Related Work

In large-scale manufacturing, industrial robots work in a structured or semi-structured environment. The robots are often programmed through conventional methods, with trajectories of robots demonstrated by humans and stored in the robot controllers so that they can be executed in a repetitive manner. However, these conventional methods lack flexibility and agility when it comes to frequently changing production scenarios due to robot reprogramming and redesign of system components [2], like the grippers.

Several innovative concepts of assembly systems have been proposed for increasing flexibility and agility. The Fully Flexible Assembly System (F-FAS) [3], which is composed of a fully-flexible feeder, assembly stations, and a manipulator, was introduced and a prototype work cell was developed to validate the concept of F-FAS. The F-FAS had better performances in terms of flexibility, compactness, throughput and unit direct production costs than the traditional flexible assembly system and the manual assembly system. The Hybrid Flexible Assembly System (H-FAS) [4] was derived from F-FAS for maximizing performance and minimizing costs. Although the cost of H-FAS work cell was higher than F-FAS one, in some cases due to the introduction of vibratory bowl feeders, the complexity of the assembly process was reduced. Jackson et al. presented the architecture of a framework that uses digital manufacturing tools, cloud computing, and the internet of things for flexible assembly in aerospace production systems [5].

An axiomatic design based approach dealing with system complexity was proposed to design a flexible and rapidly changeable manufacturing and assembly system by Rauch et al. [6]. The limits of this approach lie in different quality of the initial state of the assembly system and in specific characteristics of different industrial sectors. Tirmizi et al. proposed a framework to increase the flexibility of assembly by a faster and more intuitive programming way [7]. This framework utilized speech recognition to speed up programming and computer vision to handle reflective pieces. The aforementioned works were centered around the general design, framework, methodology, and approach in a flexible and agile assembly system. Traditionally, the development of robotic work cells based on these concepts and frameworks requires a lot of time, especially for the designing of customized modules such as end effectors, feeders and jigs. However, our system was designed in a way that could save design and implementation time. This feature makes it favorable for the production of small and medium-sized enterprises (SMEs).

Recently, applications of flexible assembly systems have a drastic increase in different fields, such as the assembly of air conditioners [8] and dashboards [9] in automotive, aluminum profile constructions [10], plastic bricks [11], microscope [12], heat exchanger coils [13], cables with connectors [14]. Experiments for variations of products showed the effectiveness of these flexible assembly systems. Automatic robot generation, task sequence planning, error-tolerant mechanism, and special-designed end-effectors were implemented in these assembly systems to enhance flexibility and increase efficiency. Previous research focused on a specific type of product to enhance the efficiency of the assembly system, but our system aimed to solve the problem of handling products of different shapes, dimension, both rigid and compliant.

In traditional assembly without vision sensors, successful manipulation of parts can be achieved in the case their arrangement is known a priori but at the risk of grasping and alignment failure because of pose uncertainties. However, in non-arranged scenarios, vision sensors are indispensable for deciding the grasping points of parts. The visual information extracted from the camera significantly assists robots to perform a variety of tasks such as pick and place, with an accuracy that satisfactorily meets the industrial demands [15]. There are numerous works that utilize vision sensors in flexible assembly systems for object detection and pose estimation. Nerakae et al. proposed the primary prototype of a flexible automatic assembly system combined with machine vision that can detect and identify the shape, and orientation of the assembly space correctly [16], in which the SCARA robot can pick the right assembly parts and place them into the assembly space perfectly. However, this system had difficulties in detecting reflective and luminous parts. In addition, the assembly sequence can be optimized according to the visual information. A flexible assembly system with machine vision guidance and a dexterous multi-finger gripper was developed by Mishra et al. for parts assembly [17]. This system was implemented with a genetic algorithm approach for the generation of optimal assembly sequences and a knowledge-based system for generating the robot task-level plan. The Computer-Aided Design (CAD) model can be used to increase the accuracy of parts recognition and pose estimation. A 3D vision-guided flexible automated assembly system for randomly placed and overlapping mechanical components were developed by Ogun et al. [18]. The recognition and estimation of the poses of the components were achieved by matching their CAD models with the acquired point cloud data of the scene. 3-D sensing system for automatic alignment of connector-fitted cables in robot assembly is constructed by Domae et al. [19]. The above research works adopt a fix mounted camera or a bulky vision module on the end effector; on the other hand, we approached the part recognition and localization problem with a compact RGB-D camera-on-hand method, which allows the robots to move faster and have a larger workspace compared with the previous research.

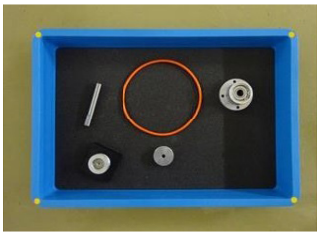
In addition to vision sensors, force/torque sensing contributed to decreasing the uncertainty in flexible assembly. These sensors can be combined with vision ones to further enhance the flexibility and adaptiveness of the assembly system.

A framework comprising a robot equipped with a force/torque sensor at the wrist, an optical motion capture system, and a parallel gripper based on manipulation primitives was presented by Suárez-Ruiz and Pham [20]. In 2020 Watson et al. proposed a taxonomy of the manipulation primitives focusing on parallel-jaw grippers and multi-object interactions for designing the system [21]. A system consisting of a smart gripper with integrated 3D perception and force/torque sensing ability as well as a suite of algorithms to perform standard assemblies was developed. The authors showed that the perceptual modes available to the system were sufficient to accomplish common assembly tasks. The robots we used in the competition with build-in force/torque sensors facilitate the integration work among robots, sensors, and grippers.

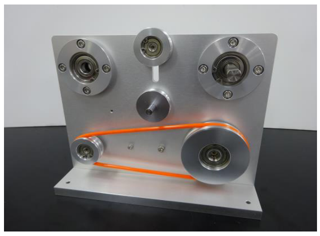
Peg-in-hole is a common task in assembly, and several methods based on force/torque sensors were proposed for this task [22, 23]. These approaches achieved active compliant control used for searching the hole and inserting the parts by the feedback from force/torque sensors. Conversely, instead of using direct information from force/torque sensors, several researchers proposed indirect methods to estimate the contact force by knowing motor torques [24] or joint control errors [25]. The new trend for solving this problem is impedance/admittance control. A position/velocity compliance controller was implemented for the insertion tasks of cylinder shape parts in the competition.

Another important module in flexible assembly is the gripper design. In order to handle parts with different geometric features, two types of designs for grippers are used. One option is adaptive grippers. The design examples of these grippers include gripper using a combined structure of two kinds of shape adaptive mechanisms where one is the granular jamming and the other is a multi-finger mechanism driven by a single wire [26] and 3-finger 5-DOF adaptive gripper which has active transition capability between the precise parallel pinch and compliant grasp [27]. This type of design uses specific mechanisms such as sliders and springs, which usually enlarges the dimension of the gripper. The other design method is a reconfigurable finger mechanism. The examples include a soft robotic gripper with an active palm and reconfigurable fingers [28] and a multi-modal, adaptive gripper with reconfigurable finger bases [29]. In our developed system, we took a similar way to the aforementioned papers by combining force/torque sensing, 3D perception, and exchangeable finger grippers.

The manipulation and assembly of compliant/flexible parts is also an important related research topic, with applications in many areas such as in the footwear industry [30], in the food industry [31], in the electrical industry (e.g., the assembly of cables with connectors) [14], etc. Sensors and compliant control strategies are necessary to perform the required tasks, but also the passive compliance of the robot (and/or end-effector) could be used [32]. Recently, an approach to perform the sensorless compliant control of a collaborative robot has also been proposed [33]. A compliant control system for the assembly of flexible objects has been integrated within the flexible assembly system presented in this paper, which can therefore handle both rigid and compliant objects.

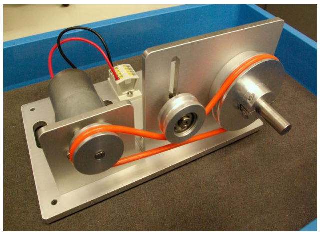


(a) Task-board task layout.



(b) Task-board task product.

(c) Assembly task layout.



(d) Assembly task product.

Fig. 1. Parts layout and final product for both tasks.

The innovation of the developed flexible assembly system is related to its high flexibility and versatility; both rigid and compliant objects, with variations in shape, dimensions, position/orientation in the working table, and tasks can be handled, thanks to the integration of a custom finger magazine design, sensors (force/torque and vision), a dedicated compliant control, and a custom tasks allocation software.

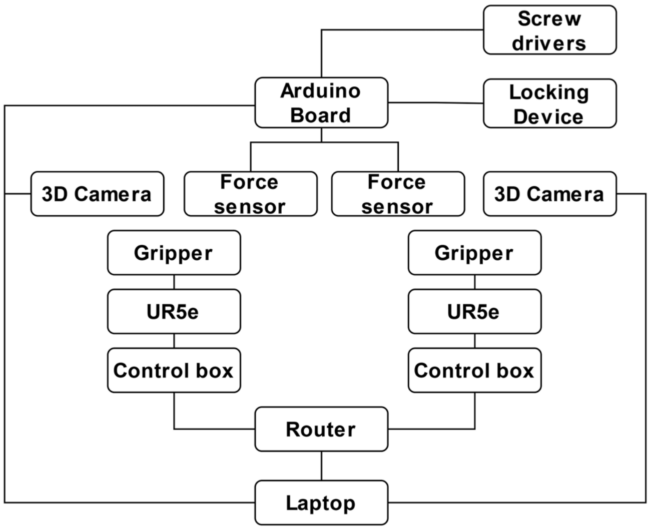
3. Tasks and Rules

The committee of WRS divided the levels of production systems into 5 categories from Level 1 to Level 5. Different levels have different agility, leanness, and operation requirements, and high-level systems have better agility and leanness. The target level for the assembly challenge of WRS is Level 4: the system has to be capable of shifting to a new product only by recombining existing equipment in two days [34].

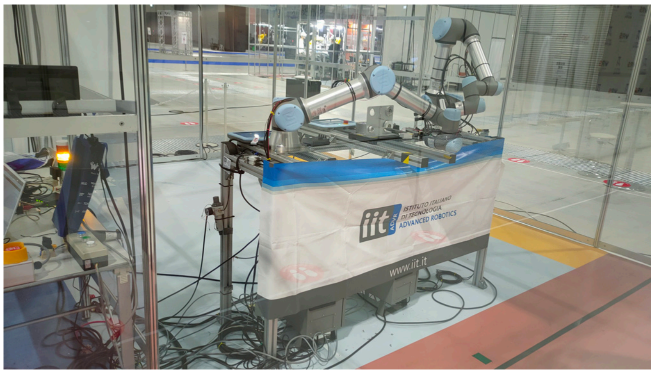
The assembly challenge in WRS 2020 consisted of two tasks, named task-board task and assembly task, respectively. The final product of both tasks is a belt drive system. **Fig. 1** shows a sample of the parts layout in the tray and the final products for both tasks. The procedures for trials of task-board task and assembly task are the same, which consist of multiple steps: the supplied parts are randomly placed on a tray by a referee before each trial starts; the tray is carried by an AGV to the initial position; the team starts the assembly system and the scores are awarded according to the completion level of each task by the referee. For common small parts such as screws and nuts, the team can use a self-designed supply device to hold them. The time period of each trial comprises three phases: preparation, operation, and reset. In the preparation phase, the team can check the quality of parts and test the assembly system. In the operation phase, the team

Table 1. Sequence of subtasks for task-board task and assembly task (T for tray, S for supply device, TS for both and N for none).

Subtask sequence	Part handling	Location
1	Bearing with housing	T
2	4 × M4 bolts for bearing and M4 bolt on plate	TS
3	Idler pulley	T
4	M6 nut	S
5	30 mm diameter pulley	T
6	Pulley shaft	T
7	Round belt	T
8	M3 set screw and M3 bolt	S
1	Base plate	T
2	Motor plate and 2 × M4 screw	TS
3	Output shaft plate and 2 × M4 screw	TS
4	Motor and 6 × M3 screw	TS
5	Motor pulley and 1 × M3 set screw	TS
6	Bearing with housing	T
7	4 × M4 bolts for bearing	S
8	Pulley shaft	T
9	Shaft cap and 1 × M4 screw	S
10	Spacer	T
11	Output shaft pulley and 2 × M4 screw	TS
12	Round belt	T
13	Tension pulley, tension pulley spacer, washer and shaft	TS
14	M6 nut and washer	S
15	Motor wires	N
16	Product deliver	N



(a) System diagram for our setup.



(b) Experimental setup at the competition event.

Fig. 2. System diagram and experimental setup.

can only monitor the assembly process and anything controlling the system is not allowed. If errors happen in the operation phase, the team can call a reset, and in the reset phase, the team should recover the system from errors and restore the parts to their initial position.

Picking part from the tray or custom-designed supply device is the first step in most subtasks. The parts are placed in an organized way without overlapping in the tray but the position and orientation may change in each trial. In the task-board task, the team can place the task board anywhere on the worktable in the preparation phase. **Table 1** presents the parts to be assembled in each task and their picking location (e.g., tray or supply device). Furthermore, the layout of the different parts can influence the sequence of manipulation steps. For example, to insert the bearing with pulley with a wide end and a narrow end into the hole when its narrow end faces up on the parts tray, one more handling maneuver between robots is necessary for this situation.

Both the tasks of the challenge can be divided into different subtasks, such as peg-in-hole, hole-on-peg, pick and place, screwing, belt looping, fastening nut and bolt. Basically, the assembly task is more complicated than the task-board task because of frequently performing coordinated tasks between the two robots, the subtask of insertion of motor power cables into the terminal and the flexibility to adapt the system to a surprise product and surprise-plus product challenge that gave a bonus score. The surprise product and surprise-plus product were variations of the normal product and their specifications were announced several hours before the start of the trials.

4. Hardware Setup

The proposed assembly work cell was composed of two 6-axis robots, namely two UR5e from Universal Robots, a worktable made of lightweight frames, a customized gripper with exchangeable fingers, vision sensors, force sensors, tools, and jigs. The system diagram is shown in **Fig. 2(a)** and the experimental setup at the competition site is shown in **Fig. 2(b)**.

According to the parts specifications and subtask sequences, the assembly system should be capable of the following: manipulation of cylindrical parts (from 2 mm diameter to 54 mm), plates and final product (about 2 kg weight), flexible parts (belts and power cables) and screwing bolts and nuts (M3, M4, M6).

4.1. Robots and Worktable

The two UR5e robots can work together to complete coordinated tasks like handover parts and components assembly, as per the tension pulley. These collaborative robots are characterized by an 850 mm reach, 5 kg payload, and repeatability of ±0.03 mm. They have a control box, and are normally equipped with a built-in force sensor. In addition, for the challenge we equipped them with a customized pneumatic gripper and a RGB-D camera. Each robot was mounted on a steel square plate, which was rigidly connected to the worktable, at the same height with a 1.1 m distance between the centers of the robots.

The worktable was made of an aluminum frame and can be simply extended by installing extra frames for fixing different devices, such as light sources, cameras, jigs, and tool holders. However, in the case of the robots moving at a high speed, the accuracy of manipulation decreases define in consequence possible vibration.

4.2. Pneumatic Gripper with Exchangeable Fingers

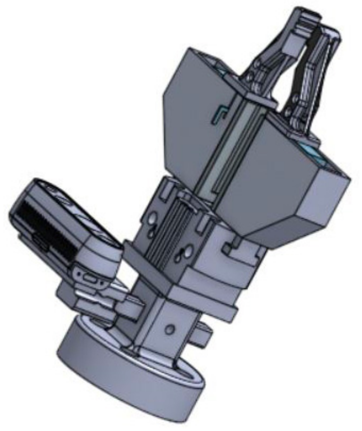
The ideal gripper for the assembly challenge should be capable of handling parts with different dimensions, self-centering over each of them, generating high gripping force, and compensation for pose estimation uncertainty. However, it is difficult to design a universal gripper able to manipulate all parts, due to the high shape variability. Consequently, a custom exchangeable finger gripper was first designed and then manufactured.

The proposed solution is composed of a pneumatic actuator, two finger holders, a set of exchangeable fingers, and two latching solenoids. The pneumatic actuator is the CGPT 25 manufactured by CAMOZZI, it is self-centering parallel with T-guide, with 6-bar nominal working pressure; the finger holders are screwed to it.

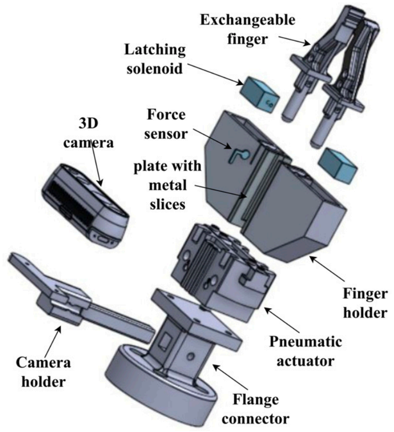
This gripper offers a high gripping force, yet lacks accurate position control because of the nonlinearity in the pneumatic actuator. In addition, electronic proportional regulators were used to guarantee adequate pressure, fast response time, and low energy consumption. The CAD model and exploded view of the gripper are depicted in **Fig. 3**.

The finger holders were manufactured out of steel and have empty space inside for accommodating latching solenoid and the fitting shaft of the exchangeable finger. A 3D printing plate with metal slices connecting the power of the screwdriver was attached to the closing surface of finger holders. The latching solenoid has a bobbin with a 9 mm stroke. It locks and unlocks in the procedure of finger changing, and it locks when the power is off (bobbin inserted in the hole of fingers), hence ensuring the fingers remain attached for safety reasons.

The short opening stroke had to be increased in order to account for the different dimensions of the parts to



(a) CAD model of the designed gripper.



(b) Exploded view of the designed gripper.

Fig. 3. CAD model and exploded view of the designed gripper.

grasp through a finger exchangeable mechanism. We divided the required maximum opening of the gripper into intervals according to the stroke of the pneumatic actuator and the dimension of the parts. Thirteen sets of exchangeable fingers were designed and 3D printed. These fingers are lightweight, cost-effective, and quickly adaptable in the case of new parts introduced in the assembly process. The disadvantages of 3D printed exchangeable fingers mainly consist of the deflection the fingertips that suffers in the case a large force is applied. Additionally, the abrasion between the fingers and finger holders during finger changing requires the fingers to be replaced very often.

Moreover, parts with different geometric features have different optimal grasping ways. For example, for grasping cylinder objects fingers with a circular surface are effective because it aligns the center of the objects to the center between the fingertips. However, fingers with a flat surface fail to do the center alignment because of less contact area. Hence, the gripping surface was designed in different shapes to effectively conform to the geometric features of the parts in corresponding intervals.

The upper segment of the finger is the fitting shaft that inserts into the finger holder, and the lower segment of

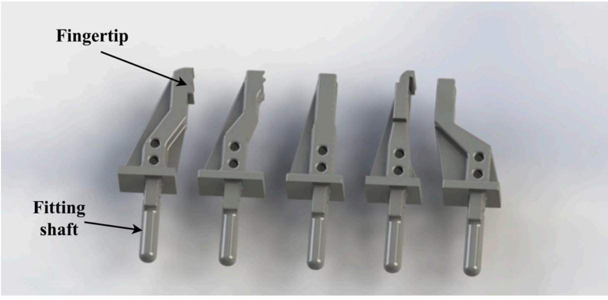


Fig. 4. Examples of CAD models for designed exchangeable fingers.

the finger is the fingertip for grasping parts. The CAD models of several fingers are presented in **Fig. 4**. The initial design was tested for corresponding parts in the working interval for the pick and place task. Optimization for the shapes of the fingertips was made according to the performance of the task. Each finger has a uniform size hole in its shaft for the insertion by the bobbin of latching solenoid.

4.3. Vision Sensor and Force Sensor

A vision system was integrated with the assembly system for recognizing the position and orientation of the different parts. Given the different lighting conditions at the competition site, 3D cameras were preferred to detect the parts tray. Thus we used two compact and lightweight cameras, namely the Intel RealSense D435 mounted on the wrist of the two robots by adjustable camera holders. These cameras can output RGB images with matching depth information.

Miniature force sensors were attached to fitting surfaces of finger holders for detecting the gripping status, as shown in **Fig. 3**. When the gripper is holding or grasping parts, the reacting force from the parts causes the fitting shaft of the finger to press the surface of the force sensor stronger. Therefore, a raise in sensor reading indicates holding or grasping parts. Similarly, a reduction in sensor reading indicates releasing parts. The sensor output was connected to an Arduino board, which is used for controlling electronics, through a microcontroller unit.

4.4. Jigs, Supply Device and Finger Magazine

The jigs were used to firmly hold the parts and adjust their orientations. In an assembly system, the fewer the jigs the better the flexibility. Nevertheless, several jigs were introduced into our system for the purpose of assembly efficiency. We designed jigs for the base plate, shaft, motor, and screwdrivers. The base plate jig has two locking devices which are driven by step motors when the base plate is put in the jig.

Unfortunately, it is difficult to recognize the orientation shaft and motor by the vision system because of the lack of recognizable features on both ends. After picking up the shaft or motor and having inserted them into the jigs, a combined motion of rotation and pushing is required to obtain the desired orientation. The screwdriver jig holds the screwdrivers with different heads (M3, M4, M6). The gripper can hold the screwdriver by the closing surfaces of finger holders.

The supply device was used for accommodating different sizes of screws, bolts, nuts, and washers. All the supplied parts have redundancy in the case of unexpected drops or losses during assembly. Due to the weak magnetic property of the supplied parts, an adhesive groove was made on the supply device. Before picking up the screws and bolts, the screwdriver was stuck in the adhesive groove to avoid parts dropping during robot motion.

The finger magazine was used to change the fingers as presented in Section 6. It was a cubic hollow box with several lead screws across the surfaces. Three surfaces were used to hang the fingers, and each surface hangs two pairs of fingers. The depth of the finger hanging on lead screws was adjusted by adding nuts and washers proportionally to the preferred depth.

The finger changing begins with detaching the fingers, and it works as follows: gripper moves to the approaching position of empty slots of the finger magazine; aligns the holes on fingertips with the lead screw; moves down, and hangs the current fingers on empty slots; releases the latching solenoids and gripper retreats the fingers holder. After detaching the fingers, the finger to be attached is inserted in the finger holders; gripper moves to the approaching position of the fingers, inserts the fitting shaft of fingers until a large enough force is detected, moves the fingers and push them on the frame of the worktable to ensure a full insertion, and finally lock latching solenoids. The 3D printed jigs, finger magazine and supply device are shown in **Fig. 5**.

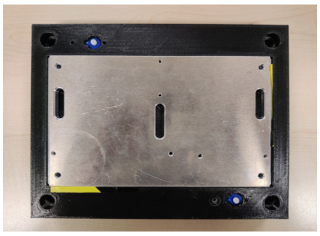
5. Software System

5.1. Overview

The developed system was based on Robot Operating System (ROS) [b] framework. ROS is an open-source distributed framework consisting of nodes that enable executables to be individually designed and loosely coupled at runtime. Thousands of packages are available, free to use, open-sourced, and easy to customize, and the main ones used in our system include:

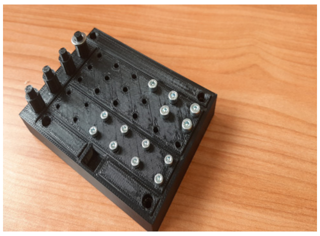
- MoveIt: Trajectory planning and collision detection of two UR5e robots (independent or coordinated).
- Universal Robots ROS Driver: Control the robots using ROS from laptops such as start and stop robot/program, send scripts, read/write I/O and read robot sensor information.
- ROSSerial: Communication with Arduino, which is used to control other tools such as the locking devices and screwdriver.

The codes in the ROS framework were implemented in C++/Python. Two state machines were designed to control the workflow of the assembly process. The first state

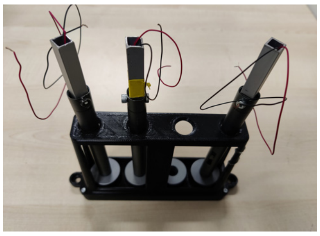


(a) Base plate jig

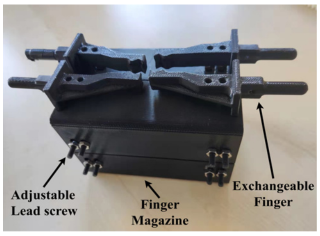
(b) Motor and shaft jig



(c) Supply device.



(d) Screwdriver jig.



(e) Finger magazine.

Fig. 5. Jigs, supply device and finger magazine.

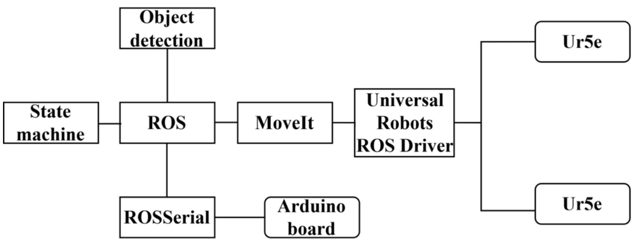
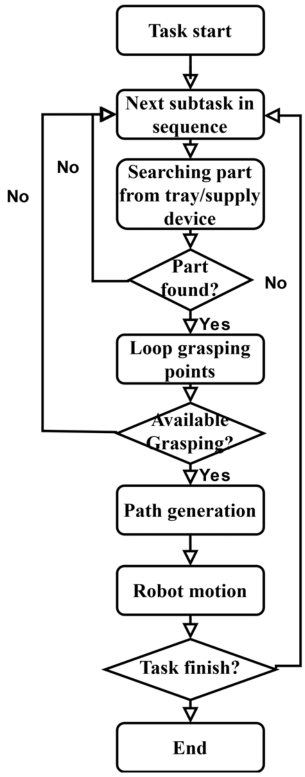
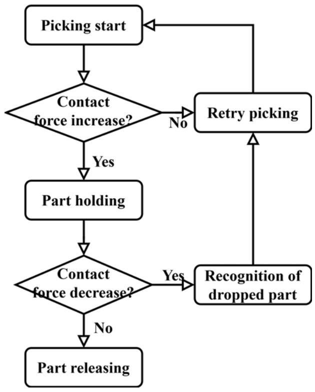


Fig. 6. Software architecture for developed system.

machine models the competition phases and hence consists of auto-running, manual, and stop modes. This state machine starts to run at the beginning of competition trials. The second state machine consisting of preparation, running, delivery, completion, and reset controls the assembly process in the operation phase. **Fig. 6** shows the software architecture. Both task-board and assembly tasks were divided into subtasks, with few of them resulting to be in common. The sequence of subtasks was optimized in order to decrease the total number of gripper fingers and tools changing. Only one subtask is executed at one time. The sequence of subtasks is listed in **Table 1**. For each subtask, the execution file was implemented in Python. The task execution files read parameters from the YAML file which defines geometric features of parts, transformation of frames, grasping points of parts and subtasks state information. The path of robots was



(a) Workflow of task execution.



(b) Workflow of grasping failure handling mechanism.

Fig. 7. Workflow of implemented software (a) and grasping failure handling mechanism (b).

generated by MoveIt according to task information. The workflow of implemented software in assembly is shown in **Fig. 7(a)**. The system was deployed and tested on a laptop (an i7-10750H processor, Nvidia GTX 1650 as GPU) running Ubuntu 20.04 and ROS Noetic version.

5.2. System Safety

Since the work cell is operating without fences and moving fast while carrying parts, the robots may hurt the people around it. It is necessary to make sure the robots stop in certain conditions. Thus, a safety mechanism was designed to prevent unexpected dangerous situations. Three modes (automatic mode, emergency stop mode, and manual mode) were implemented as suggested by the competition manual. The transitions between the modes were trigged by signals from safety switches, door switches, mode select switches, and emergency stop switches. The safety mechanism was implemented on the digital inputs and digital outputs in robot controllers and the laptop without any other peripherals like a programmable logic controller. **Fig. 8** shows the mode transitions mechanism.

5.3. Object Detection

At the beginning of both task-board task and assembly task, the position of the parts tray is identified, and the

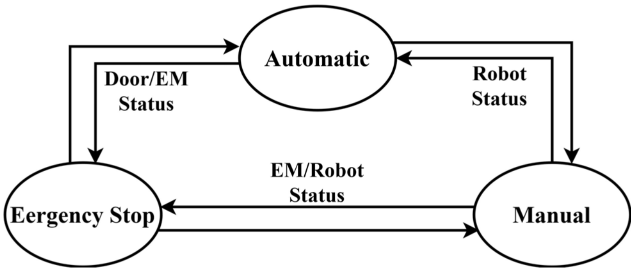


Fig. 8. States transition of system safety mechanism.

center of the tray is recorded. The camera is then calibrated by identifying the markers placed at the corners of the tray, the shape and size of which are known by the rulebook. Only at this stage, the system is ready to identify the different parts in the tray. Such object detection task is performed by using YOLOv5, implemented with Darknet neural network framework [35]. YOLOv5 is a deep learning approach widely used to perform object detection, that produces in output the bounding boxes surrounding the identified objects, and hence identifies their location. The accuracy of object classification was about 88%. The training data set contained 200 labeled images for each object class. Moreover, the identified objects are processed one at a time in order to compute the orientation with respect to the tray, and consequently determine the best grasping points. In detail, we designed an algorithm based on OpenCV, that processes the images and identifies the holes of the screws, the contour and the center of mass of every object. Then, the positions of the screw holes were used to compute the orientation.

5.4. Robot Motion Planning

Both a position controller and a compliance controller were implemented in our system. The Cartesian position control was used in general motion. When the robot is performing a contact task with a tight clearance such as insertion of shaft or pulley, a compliance controller is used. For example, in the subtask of bearing with housing insertion, a position controller was used until the end effector reaches the approaching position for insertion. At this point, a compliance controller was used until the vertical direction component of the end-effector contact force indicates a stable contact.

For each part, there were one or more grasping points written in the YAML file. The actual grasping point was selected according to availability and priority after the identification of the position and orientation of a part in the tray. The availability was evaluated by checking the collision between the gripper and the other parts / parts tray and the collision between robots and the environment. Different grasping points may require different manipulation steps. For instance, the bearing with housing has two grasping points with one small-diameter surface and one large-diameter surface, which has higher priority over the other one because it reduces the time of handling between the two robots.

5.5. Grasping Failure Handling

Because we have real-time feedback information from force sensors, a failure handling mechanism is implemented in the execution of tasks. When the gripper is grasping a part, the force sensor detects an increasing signal because of the squeezing between the finger holder and finger. Similarly, when the gripper is releasing a part, the force sensor detects a decreasing signal. If a step in a subtask has a grasping action, and the sensor reading during this step has no step change, this means that there is a failure in the grasping. After a successful grasping, the gripper holds the part and the reading should maintain a stable value until the releasing action. A reading drop during the holding also means a failure. The flow chart of how the failure handling works is shown in **Fig. 7(b)**.

6. Simulation and Experimental Result

In this section, we showed the simulation result for the task-board task in ROS. In the second part, the results coming from the experimental test will be described.

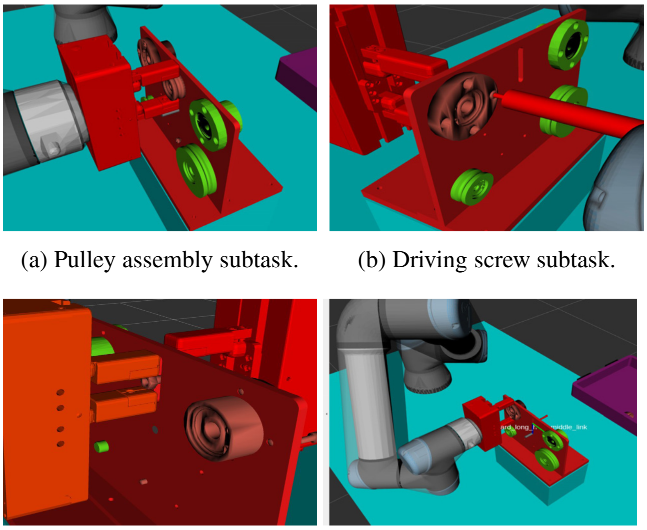
6.1. Simulation

A simulation platform of the developed assembly system was built in ROS, and Rviz was used to visualize the results. The main purpose of our simulation is to validate the effectiveness of paths before moving robots in real scenarios. Furthermore, the simulation is faster than the experiment test for the comparison of different strategies, such as trajectories with different key points and changing the sequence of subtasks. The robot model of UR5e was built by MoveIt configuration tools. The trajectories of robots were generated by MoveIt in order to avoid collisions. The custom gripper, worktable, jigs, and tools were implemented in the URDF file and the contact model was simplified by the combination of basic geometric shapes. The parts in the tray were arranged in an organized way with accurate position and orientation information. The simulation case was designed to complete the task-board task. **Fig. 9** shows several snapshots of this task.

6.2. Experimental Result

6.2.1. Parts Recognition

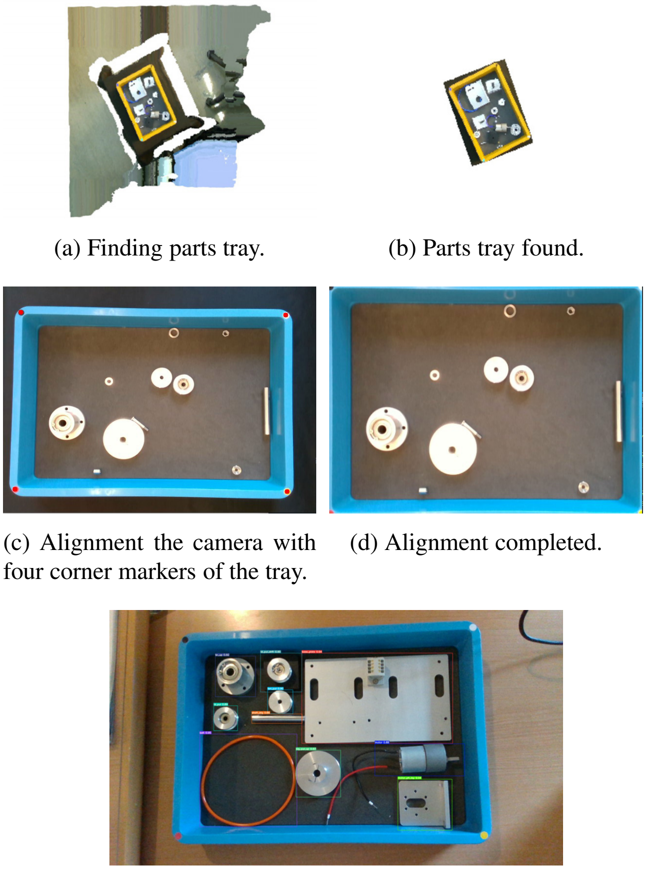
Parts recognition is meant to recognize and localize the parts in the tray. Because the position of the parts tray on the AGV and the stop position of the AGV are not fixed, the first step consists in recognizing the tray on the AGV. After we have the location of the center of the tray, the alignment between the camera and the parts tray is performed by matching four markers with the one on the corner of the parts tray. After alignment, confidence predictions of each part are calculated by YOLOv5. The procedure of parts recognition and an example of prediction results are shown in **Fig. 10**.



(a) Pulley assembly subtask. (b) Driving screw subtask.

(c) Nut insertion subtask. (d) Bearing insertion subtask.

Fig. 9. Snapshots of simulation for the task-board task.



(a) Finding parts tray. (b) Parts tray found.

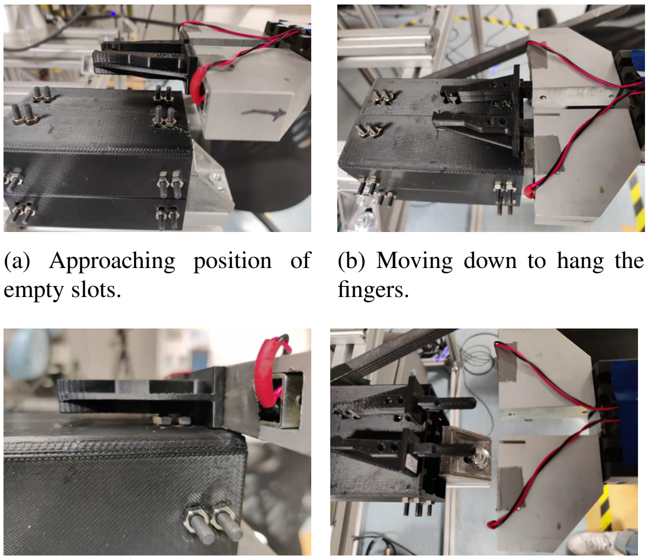
(c) Alignment the camera with four corner markers of the tray. (d) Alignment completed.

(e) Example of prediction results of the parts in parts tray.

Fig. 10. Parts recognition procedure and example of prediction results.

6.2.2. Finger Changing

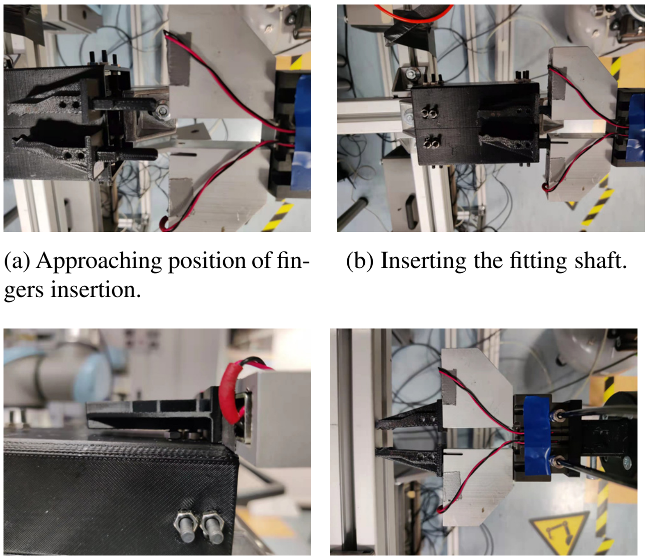
The finger-changing time is crucial for decreasing the total assembly time. The designed finger change mechanism can complete finger changes in twenty seconds. The procedure of finger detaching and attaching are illustrated in **Figs. 11** and **12**.



(a) Approaching position of empty slots. (b) Moving down to hang the fingers.

(c) Unlocking solenoids. (d) Retreating finger holders.

Fig. 11. Procedure of finger detaching.



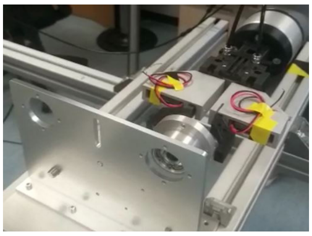
(a) Approaching position of fingers insertion. (b) Inserting the fitting shaft.

(c) Insertion complete and lifting up. (d) Pushing fingers on the frame and Locking solenoids.

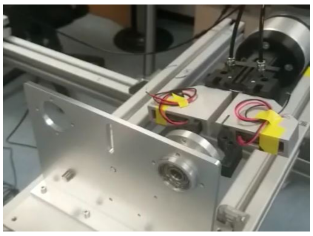
Fig. 12. Procedure of attaching.

6.2.3. Bearing Assembly and Belt Looping

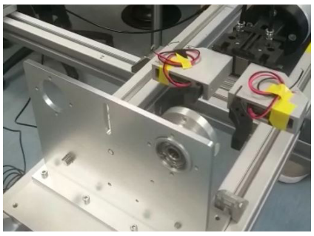
This section explains our approach to assembling the bearing with housing and looping the belt. For the bearing with housing subtask, it can be considered as a peg-in-hole assembly with the requirement of orientation alignment. Our procedure for this subtask can be summarized as follows: the gripper picks the bearing with housing from the parts tray and aligns it with the holes on the task plate by camera inspection from the other side of the plate, moves to the approaching position while maintaining the



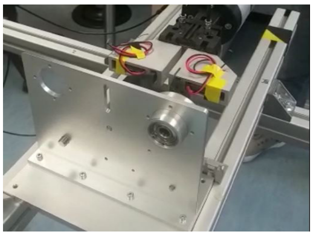
(a) Aligning of the bearing and task plate.



(b) Partially inserting the bearing in.

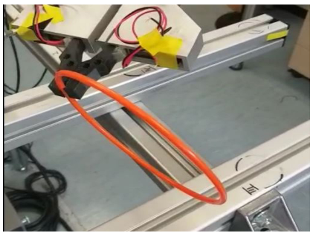


(c) Retreating after partial insertion.

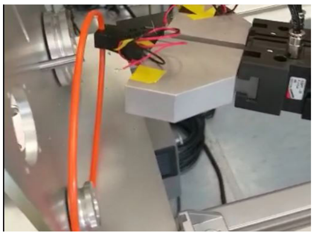


(d) Pushing the bearing to ensure contact.

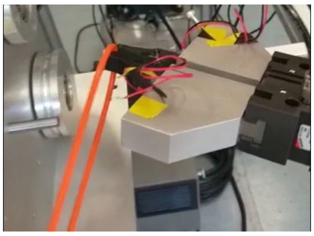
Fig. 13. Procedure of insertion of bearing with housing.



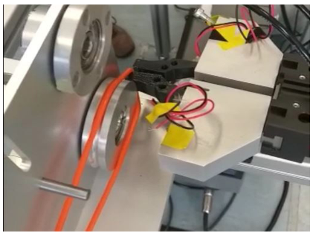
(a) Picking the belt.



(b) Looping from the small pulley.



(c) Moving to large pulley side.



(d) Looping the belt on the large pulley.

Fig. 14. Procedure of belt looping.

orientation of the bearing, insert the bearing for a certain distance or until detecting a predefined force level, release the bearing and retreat, pushing the center of bearing with only one finger until detecting a large enough force, and check the alignment of holes of bearing and the task plate, if not correct them.

For the belt looping subtask, the key points of trajectory are stored in a file. We performed this subtask as follows: pick the round belt from the parts tray, start looping from the small pulley, move to the large pulley side, fit the belt in the upper part of the large pulley first, then, move down to fit the lower side of the large pulley. **Figs. 13** and **14** show the process of bearing insertion and belt looping.

Table 2. Experiments performance.

Experiment	Complete time (average of 20 times)	Success rate
Parts recognition	8.8±1.7 s	93/100
Finger changing	18.1±0.8 s	19/20
Bearing assembly	17.2±1.5 s	17/20
Belt looping	38.0±2.0 s	16/20

6.3. Experiments Performance and Analysis

The above experiments are tested repetitively in our lab. **Table 2** shows the performance and success rate of several groups of testing. The success rate and task completion time were used as indicators for the performance evaluation. **Table 2** shows the performance matrix. The part recognition takes around 8 seconds due to the limitation of the graphics card on our laptop (GTX 1650). The finger changing worked well in the first 50 to 100 times after it was printed but as more time we used it, the failure chance increased both for assembly tasks, because the TCP lose its expected position and orientation, and finger changing task because of the misalignment between the hanging hole on the finger and the lead screw increased. The performance of the assembly of the pulley and belt partially depends on the speed of the robot and the setting value during force/contact motion. Aggressive settings can achieve faster speed but increase the chance of failure. A balanced setting was adopted in our experiment.

7. Lessons from WRC and Discussion

PneuBot tackled the WRS assembly challenge by developing an assembly system comprising of two collaborative robots, custom exchangeable finger grippers, vision/force sensors, and a few jigs and tools. Such a system is characterized by modularity and flexibility, in order to satisfy the requirements imposed by the high variety of components and tasks. In fact, a custom exchangeable finger gripper was designed for handling different parts. This quickly adaptable design greatly increased flexibility by manipulating parts with different dimensions and geometric features. Moreover, a vision system with a RGB-D camera mounted on the wrist of each robot was implemented, in order to recognize and localize the parts tray, the different parts and their screw holes. Furthermore, the system is comprised of a grasping failure mechanism, implemented via miniature force sensors. In addition, the simple worktable, 3D printed jigs, fingers, and other tools lower the overall cost of the assembly system, and it is easy to implement this hardware.

During grasping and assembly execution, position uncertainty is partially compensated by finger design and robot compliance control. The effectiveness of the de-

Table 3. Encountered problem and improvements

Type	Details	Improvement
Calibration	Uncertainty increases as we disassemble and reassemble the system.	Design a quick and reliable re-calibration for the system.
Communication	Arduino board communication with ROS lost.	Implementation of reconnection and redundant hardware.
Accuracy	Not enough accuracy for assembly status.	Sensor information fusion among force/toque, vision and tactile.

signed assembly work cell was validated by laboratory experiments and in the competition at WRS. Unfortunately, the developed system proved to produce better results in laboratory experiments than at the competition event. The problems our team encountered are list in **Table 3**. Also, possible improvements are proposed and will be implemented in the future.

Despite the results obtained in the competition phase, the developed system proved to be highly efficient in manipulating objects of different shapes and sizes in a very short time. Most notably, such tasks were achieved by using 3D printed components, which enables the technology transfer to a wide plethora of applications at a very low price, yet guaranteeing great results.

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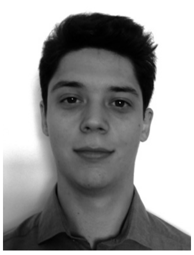

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