Combining Compliance Control, CAD Based Localization, and a Multi-Modal Gripper for Rapid and Robust Programming of Assembly Tasks

Gal Gorjup, Geng Gao, Anany Dwivedi, and Minas Liarokapis

***Abstract*— Current trends in industrial automation favor agile systems that allow adaptation to rapidly changing task requirements and facilitate customized production in smaller batches. This work presents a flexible manufacturing system relying on compliance control, CAD based localization, and a multi-modal gripper to enable fast and efficient task programming for assembly operations. CAD file processing is employed to extract component pose data from 3D assembly models, while the system's active compliance compensates for errors in calibration or positioning. To minimize retooling delays, a novel gripper design incorporating both a parallel jaw element and a rotating module is proposed. The developed system placed first in the manufacturing track of the Robotic Grasping and Manipulation Competition of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2019, experimentally validating its efficiency.**

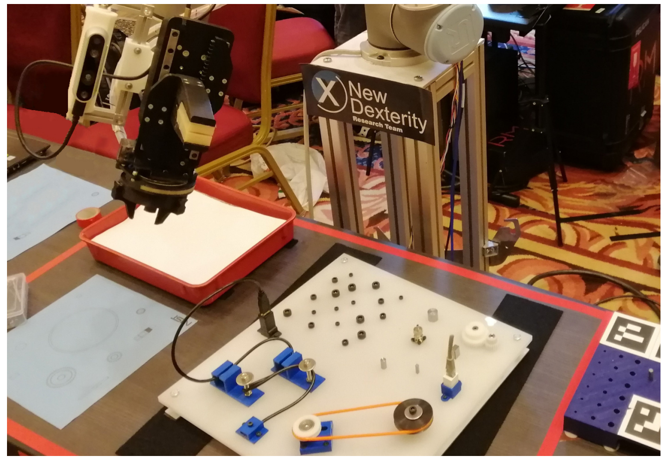

Fig. 1. The developed flexible manufacturing system that was used to participate and win the manufacturing track of the Robotic Grasping and Manipulation Competition of IEEE IROS 2019 (Macau, China).

I. Introduction

Industrial robots have become a core component of modern manufacturing processes. Particularly in the context of assembly tasks, such automation offers several advantages. Automated assembly lines have the capacity to operate at considerably high speed, lowering production costs and increasing process efficiency. Due to the high accuracy and repeatability of robot systems, an appropriately configured production line can also reduce the amount of faulty products. Another consideration is securing worker health and safety, as prolonged labor in production lines increases the risk of work-related musculoskeletal disorders [1], [2].

Despite their exceptional run-time performance, the deployment and reconfiguration of most existing robot systems still requires a significant amount of time and effort [3]. This is largely due to the inherent complexity of assembly operations involving contact-rich object manipulation in constrained spaces, such as bolt screwing, tight fit insertions, and cable routing. Furthermore, the success or failure of a particular task affects the subsequent steps. To increase process robustness, most existing approaches use customized jigs and fixtures that ensure repeatable positioning of individual parts. Frequently, such adaptations escalate to dedicated end-effectors for different components and sub-tasks, demanding elaborate gripper replacement procedures during execution. Although these methods increase process stability, they are specific to particular component types and assembly layouts. This introduces additional development delays with every change of the underlying task requirements, further reducing the overall system agility.

Gal Gorjup, Geng Gao, Anany Dwivedi, and Minas Liarokapis are with the New Dexterity research group, Department of Mechanical Engineering, The University of Auckland, New Zealand. E-mails: {ggor290, ggao102, adwi592}@aucklanduni.ac.nz, minas.liarokapis@auckland.ac.nz

Assembly system flexibility is becoming progressively more important as manufacturing trends move away from production in large series to accommodate for the fast pace of innovation and rapidly changing market demands [4]. For smaller enterprises, the time and effort associated with the setup and reconfiguration of robotic systems are not the only factors limiting their adoption. Often, the level of robotics expertise in such businesses is limited, raising a demand for systems that are not only agile in terms of adaptation capability, but also easy to configure. To challenge global research and encourage novel ideas, pioneers in the field organize challenges that test the flexibility and robustness of novel systems in various manufacturing tasks [5], [6].

This paper presents a flexible manufacturing system that combines compliance control, CAD based localization and a multi-modal gripper for fast and efficient programming of assembly tasks. By extracting information from provided assembly CAD data, the system is capable of rapid adaptation to arbitrary configurations of the manufacturing task without human involvement. The utilized active compliance control scheme compensates for minor positioning errors and enables passive contact handling with appropriate force profiles. Through a novel gripper design incorporating a parallel jaw element and a rotating module, the system is able to tackle different assembly task types without retooling. Placing first in the manufacturing track of the Robotic Grasping and Manipulation Competition of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) 2019, the system has been thoroughly validated.

The rest of this work is organized as follows: Section II introduces the related work, Section III details the assembly task specifications, Section IV describes the developed system, Section V presents results of the international competition, Section VI discusses the system performance, while Section VII concludes the paper.

II. Related Work

Rising product demands and labor costs have led researchers to explore robotic assembly automation for improving the task efficiency while maintaining product quality [7]. To evaluate the capabilities of developed systems, a number of benchmarking procedures and performance metrics that rely on standardized task boards have been proposed [8], [9]. In many aspects, such task boards can accurately represent a real-world assembly problem, as they are designed to contain several classes of different assembly sub-tasks. The board-based benchmarks consider important factors such as the size and symmetry of parts, tool usage, mechanical resistance, mechanical fastening, visual and physical obstruction, etc.

The default approach used in industry to program a robotic system is the teach and playback method. In the teaching phase, users may utilize teaching pendants, joysticks, or the gravity compensation mode for kinesthetic teaching [10] to guide the robots along the desired trajectories. During teaching, the robot joint values are recorded and later replayed through the controller to execute the desired task [11], [12]. While this method is fast and easy to apply for simpler tasks, it lacks flexibility and reusability. A small change in the manufactured product may require retraining of the whole assembly process, which is tedious and time consuming for tasks of higher complexity. To increase system flexibility, the recorded robot motions can be used by various learning algorithms [13], although their performance depends on user skill and the complexity of the task. Moreover, during teaching, the user may be exposed to the dangerous factory environment and the robot can not be used in production.

To increase system flexibility in the manufacturing tasks, vision based methods can be used to detect and localize objects of interest. Such systems can be expanded to recognize new objects, allowing the system to adapt to the changing manufacturing environment. They can either use an image database of the objects or a well defined geometric model to support detection and tracking [14], [15]. Vision based servoing can also be used for autonomous end-effector alignment in Cartesian space [16]. This methodology can remove the robot programmer from the factory floor during system configuration. The main weakness of vision based methods is their sensitivity to environmental lighting and occlusion. Some object detection models may also require a large image training database, leading to longer setup times.

Computer Aided Design (CAD) represents a core visualization and simulation component in most modern product development workflows. Nearly all products suited for automated assembly are therefore accompanied by a collection of CAD files precisely describing the component geometry and positioning. Despite their availability, these models are rarely used to enhance the flexibility of manufacturing systems. The CAD files can be employed to drastically increase the rate of system adaptation to novel products, with the extracted information utilized in applications ranging from basic component localization to automated planning of complete assembly processes [17]. Additionally, motion plans obtained through CAD-based approaches may be used to enhance the performance and training speed of various reinforcement learning approaches [18]. Component CAD models can also be used to generate stable pose candidates through simulation, boosting perception system's efficiency [19].

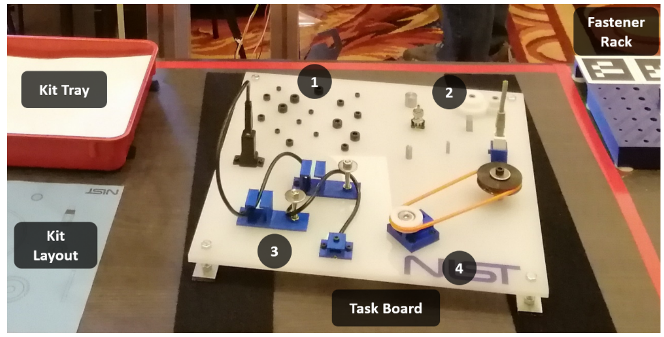

Fig. 2. The task board incorporates four task classes: 1. Fastener Threading, 2. Insertions, 3. Wire Routing, and 4. Belt Threading and Tensioning. During disassembly, removed components are placed into the kit tray. For assembly, the fasteners are initially arranged in the fastener rack, while the rest of the components lie on the kit layout.

A major concern in manufacturing are errors associated with part misalignment during grasping and assembly, which are caused by positioning or pose estimation uncertainty. Failing to compensate for such errors may result in large contact forces which can damage the robot or assembly components. To overcome these issues and make up for perception uncertainty, many existing approaches utilize active compliance and force control [10], [20]. The other approach for minimizing positioning uncertainty is through customized jigs, fixtures, and dedicated grippers [21], at the cost of longer reconfiguration time. Particularly for assembly operations involving diverse task classes, frequent retooling introduces significant delays. This can be bypassed by employing versatile systems. Such general-purpose designs were proposed in [14], where the authors utilized two robot arms; one equipped with a pinching gripper, and the other with a rotary gripper. A multi-modal end-effector integrating a suction module and a parallel-jaw element was also effectively employed in the Amazon Picking Challenge [22].

III. Manufacturing Track

The task specifications for the manufacturing track of the Robotic Grasping and Manipulation Competition of the IEEE IROS 2019 was defined by the National Institute on Standards and Technology (NIST) [23]. The track was composed of assembly and disassembly operations performed on a dedicated task board that incorporated four representative classes of industrial assembly tasks (Fig. 2). The *Fastener Threading* class consisted of 18 standard socket cap screws

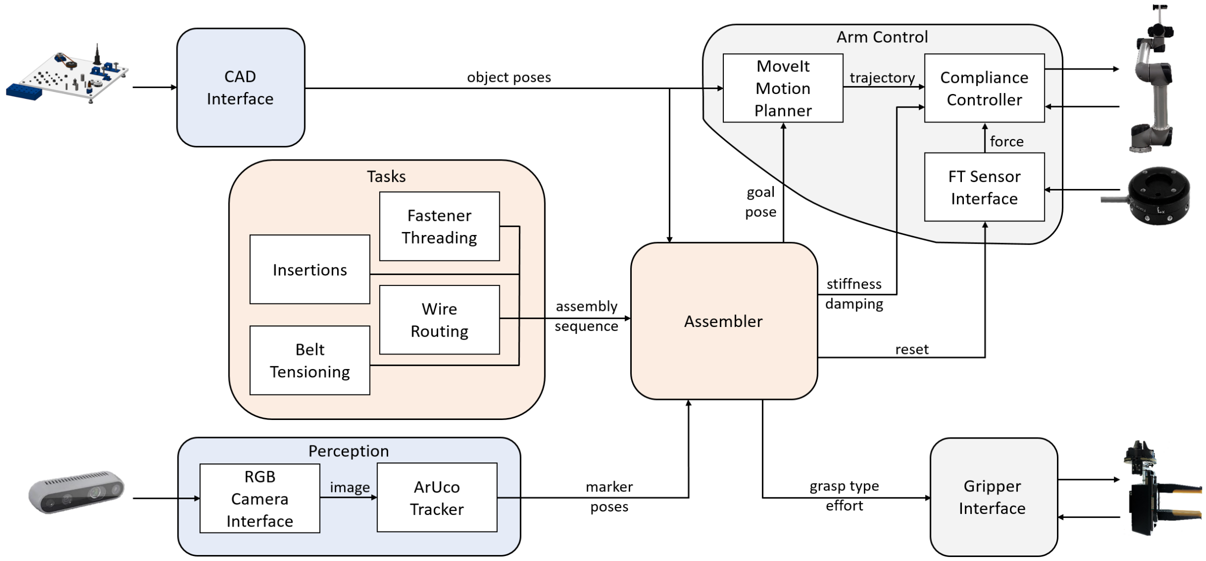

Fig. 3. Framework architecture of the developed flexible manufacturing system.

with size M4, M6, and M8, threaded into holes on the task board. The *Insertions* class consisted of four different-sized pegs (2x round, 2x square), two meshing gears, a BNC connector, an RJ45 connector, and a USB connector. The *Wire Routing* class consisted of a USB cable routed around two vertical pins, through two brackets, and plugged into its respective slot (as part of the *Insertions* class). The *Belt Threading and Tensioning* class consisted of an elastic belt tensioned on two pulleys. The class components were randomly positioned within their respective quadrants. The task board, kit tray, and fastener rack were fixed on a rigid table surface. Participants were able to obtain a practice board and associated CAD files ahead of time, but the final component locations on the task board and kit layout were undisclosed until the start of the official competition.

Scoring was point based, with the disassembly operation worth half as many points as assembly. In disassembly, each component that was removed from the fully assembled board and placed into the kit tray was worth the same amount of points. The exception was the cable, where marks were assigned based on each successfully completed bracket. In assembly, the belt and *Insertions* components were initially placed on the kit layout, the fasteners were arranged in the fastener rack, and the USB cable was unrouted. The four task classes were worth roughly the same amount of points, with additional marks obtained for picking and placing components on the board.

The total time available for the competition was 120 min (40 min for disassembly and 80 min for assembly). At time 0, the participants received a new, unseen configuration of the task board and kit layout, along with the associated CAD files. To encourage development of flexible systems, the allotted time included the time required for adapting the system to the new task board, as well as for executing the assembly and disassembly operations. After starting autonomous operation, no manual intervention or tool changes were allowed. The participants could choose to restart the assembly or disassembly operation at any point, losing all secured points for that task and resetting the board. Fully completing either the disassembly or the assembly task within the allocated time was worth additional marks.

IV. Designs and Methods

An overview of the developed framework structure is presented in Fig. 3. The framework is implemented within the Robot Operating System (ROS) [24], which provides the necessary communication, testing, and visualization utilities. The *CAD Interface* module interprets the provided CAD data of the assembly, extracting component positions, orientations, and collision models. The *Perception* module processes RGB video data obtained from the Intel RealSense Depth Camera (model D435), performing detection and pose estimation of the ArUco markers [25] detected in the image. The system was designed to accommodate a depth camera in order to support future extensions that might require 3D data, although a standard RGB camera suffices in this setting. The *Arm Control* group handles planning and control of a 6 Degree of Freedom (DoF) serial manipulator of Universal Robots (UR5, with CB2 series control box), equipped with a Robotiq FT 300 force torque sensor. The group relies on the MoveIt [26] motion planning environment, which produces arm trajectories based on the desired goal poses and the collision space extracted from CAD. The *Compliance Controller* executes and adjusts arm trajectories with respect to detected end-effector forces and compliance parameters. For the developed gripper, a custom *Gripper Interface* module offers command inputs for the desired grasp type, effort, and offset. The *Assembler* module represents the central component of the framework, handling process state control and subsystem synchronization. Depending on component type, the main module calls upon task execution subroutines that rely on part poses extracted from CAD.

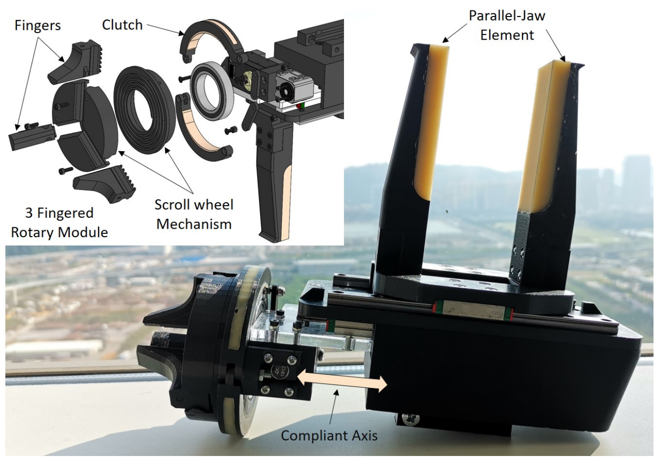

Fig. 4. The proposed gripper consists of a 3 fingered rotary module and a parallel-jaw element. The 3 fingered rotary module utilizes a scroll wheel mechanism and a clutch to perform grasping and rotational motions. The full mechanism is depicted in exploded view. The parallel-jaw element uses a rack and pinion mechanism to execute grasping motions with a set of modular fingers with highly compliant finger pads.

A. Gripper Design

Due to the diversity of manufacturing tasks, a combination of different skills (e.g., insertion, threading, or routing) is necessary in order to complete a full assembly / disassembly operation. To enable efficient execution of such tasks with minimal retooling, complementary hardware is needed to better assist control and planning techniques. Hence, a novel gripper design was proposed that combines a parallel-jaw element and an axially compliant, non-backdrivable, 3 fingered rotary module. The gripper is equipped with a total of three actuators (two Dynamixel XM-430-W350-R, and one Dynamixel XL-320). The parallel-jaw element of the gripper utilizes a rack and pinion mechanism to linearly drive a set of modular fingers with highly compliant finger pads that can conform to different object geometries. The rotation module uses a scroll wheel mechanism to achieve both grasping and rotation of a grasped object. In addition, a clutch facilitates the selection of the two states, enabling the use of a single high torque motor (Dynamixel XM-430-W350-R) for securing the object. All the gripper components can be seen in Fig. 4. To reduce the complexity of control, mechanical compliance along the translational axis of the rotary module was implemented to compensate for potential errors during the execution of threading tasks. The proposed gripper allowed the execution of three different grasping primitives. To maximize the versatility of the system, the primitives were selected to complement each other, equipping the robot with at least one primitive per task class. The grasping primitives can be seen in Fig. 5 and are as follows:

1) Pinch: This primitive accomplishes pinching grasps that are required for insertion tasks or wire routing.

2) Extension: The use of extending motions in the parallel jaw gripper allows contact forces to be exerted with the back of the fingers, enabling better handling of certain objects like the belt, as depicted in Fig. 5c.

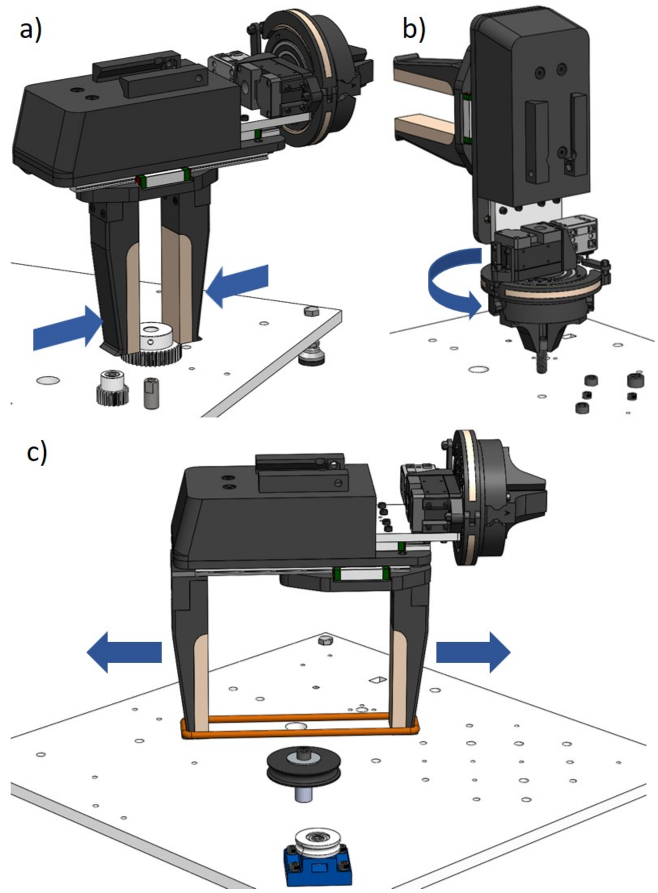

Fig. 5. Multiple grasping primitives of the developed gripper showing different manufacturing actions being performed on the manufacturing track task board of the Robotic Grasping and Manipulation Competition of the IEEE IROS 2019. Subfigure a) displays the pinching primitive executing an assembly motion mounting a gear onto a shaft. Subfigure b) presents a bolt being threaded into a screw hole with the spinning action of the rotary module. Lastly, subfigure c) shows the utilization of the extension motion and supporting with the fingernail to install a belt around a pulley system.

3) Rotation: Many tasks in manufacturing scenarios require rotary motions: drilling holes, milling workpieces, screwing and unscrewing fixtures, etc. The rotation primitive accomplishes this through the non-backdrivable, 3 fingered rotary module that complements the main parallel jaw element. The rotary module can spin continually in both directions while securely holding on to screws, drill bits, and other rotary tool bits. The module is mechanically compliant in its translational axis, which passively compensates for robot arm motion errors during threading.

B. CAD Localization

A core feature of an effective flexible assembly system is rapid adaptation to different component types and variations in their positioning. The first step in a conventional assembly procedure is thus obtaining this information and feeding it into the system, which can take a considerable amount of time, depending on the method. Since all modern product development workflows rely on CAD for visualization and simulation, the developed system utilizes available models

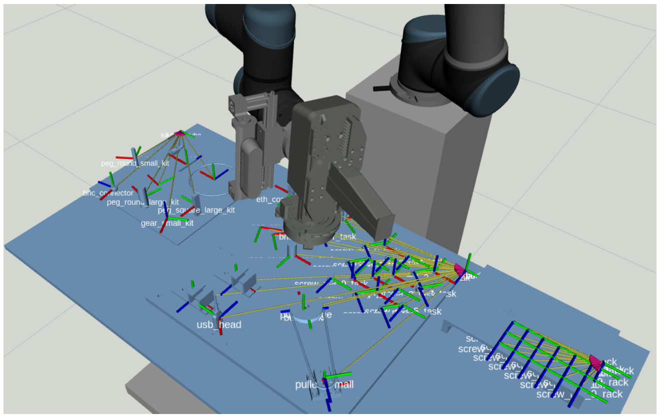

Fig. 6. Assembly component poses and geometries extracted from the practice CAD files and imported into the RViz visualization environment.

to instantaneously extract ground truth goal pose data for each part. In addition to the component poses, the CAD files offer geometric data that can be efficiently employed in the collision checking routines of the path planning module. The *CAD Interface* module of the framework was designed to accept assembly CAD models in the STEP file format defined by the ISO 10303 standard. The developed interface extracts origins of assembly components associated with a set of defined labels, encouraging a synergistic collaboration between product modeling and assembly design. An example assembly setup with component poses and geometries extracted from practice CAD files is presented in Fig. 6.

C. Pose Calibration

The component poses extracted from CAD data are all obtained in reference to the origin of the 3D model of the task board assembly. Before starting the manufacturing process, the assembly origin must be identified in the global frame, with respect to the robot platform. The developed framework supports two calibration methods for placing the task board and components into the global reference frame. The first approach utilizes the end-effector camera to estimate the poses of fiducial markers mounted on the main assembly components (e.g., fastener rack in Fig. 2). The marker pose estimates for each major component are appropriately offset to coincide with the model origin and they are averaged to increase accuracy of the result. The advantage of this method is its speed, as the robot only needs to have the components in view to perform the calibration. However, the resulting estimate quality depends on the accuracy of hand-eye calibration, marker placement, and depth estimation from the 2D images. The second, kinesthetic calibration approach requires the user to physically guide the robot in gravity compensation mode and mark key positions with the rotary module of the gripper. The captured key positions (e.g., the corners of the task board) are then used to construct the full component pose with respect to the global reference frame. This method is slower and requires more human involvement, but produces results with higher accuracy as it relies only on the forward kinematics of the robot.

D. Active Compliance

In general, the component poses are estimated with a certain amount of error, especially if the calibration result is suboptimal. To compensate for this, an active compliance control scheme for the robot arm was integrated into the platform. The scheme is based on a compliance controller [27], built within the ROS Control [28] framework. The controller adjusts the robot end-effector velocity based on force/torque data recorded with the FT 300 sensor mounted on the wrist, as discussed in the Generalized Contact Control Framework in [29]. The velocity adjustment is computed for each end-effector degree of freedom separately and supports selective compliance in different axes. Adjusted end-effector velocity values are converted to joint velocities using the arm Jacobian and they are passed to the low-level robot controllers. The stiffness and damping parameters can be adjusted online, which enables indirect control over force and torque profiles acting on, or exerted by the gripper. The stiffness parameter corresponds to the end-effector resistance against external forces, while the damping parameter influences the response rate. The velocity adjustments of the compliance controller can be performed while following a trajectory, which affects the final goal pose. This behavior can be effectively exploited in disassembly, especially when grasping fixed objects such as pegs or plugged-in connectors with position uncertainty. Even if the end-effector is off by several millimeters, the arm compliance will passively align the gripper while it is closing. The same mechanism can be employed for hole alignment in peg or screw assembly. Starting at the initial, uncertain hole pose estimate, a simple spiral search motion is executed until the part locks against the hole edges and prevents further end-effector motion.

E. Assembler

The central module of the framework, the *Assembler*, handles process state control and execution by interfacing with its peripheral modules. Upon system initialization, it checks for a valid global pose calibration of the CAD models (Section IV-C) and constructs the obstacle space. For each part to be assembled, the *CAD Interface* provides a pose with respect to the assembly origin, which is then transformed into the global reference frame. This is performed for the part's initial pose in the kit layout or bolt rack, as well as for its goal pose in the task board. Upon obtaining the relevant information, the central module loads the appropriate subroutine from the *Task* group, which depends on the part type. Each subroutine contains an execution strategy for its particular part type, generally involving grasping, alignment, assembly, and releasing. The strategies adapt to the extracted part poses, which means that the same subroutine can be used for assembling several components of similar type. The task subroutines can handle the peripheral interfaces, allowing them to directly control the hardware, change compliance parameters, and request additional information from the CAD models.

TABLE I

COMPETITION SCORE BASED ON THE NUMBER OF ASSEMBLED AND DISASSEMBLED COMPONENTS

Class	Assembly		Disassembly	
	Placement	Assembled	Removed	Placed in Tray
Threading Fasteners	16 / 18	13 / 18	Not Attempted	Not Attempted
Insertions	6 / 9	4 / 9	8 / 9	8 / 9
Wire Routing	Not Attempted	Not Attempted	4 / 4	1 / 1*
Belt Fastening	1 / 1*	0 / 1	1 / 1	1 / 1

V. RESULTS

This section presents the official results from the manufacturing track of the Robotic Grasping and Manipulation Competition of the IEEE IROS 2019. The teams were given 120 minutes to program and perform the complete assembly and disassembly sequences, using an unseen configuration of the task board and kit layout revealed at time 0. Due to technical difficulties, all teams were given a 20 minute extension in the assembly task, and a 40 minute extension to attempt disassembly again, with the condition of losing their previous disassembly score. Once properly configured, the system performed very well, placing first in the competition. The results are reported in Table I, where the number of successfully assembled or disassembled components is presented with respect to the total number of components in the task class. Highlights of the competition assembly and disassembly processes are presented in Fig. 7, as well as in the accompanying video, which is available in HD quality at the following URL:

www.newdexterity.org/iros2019rgmc

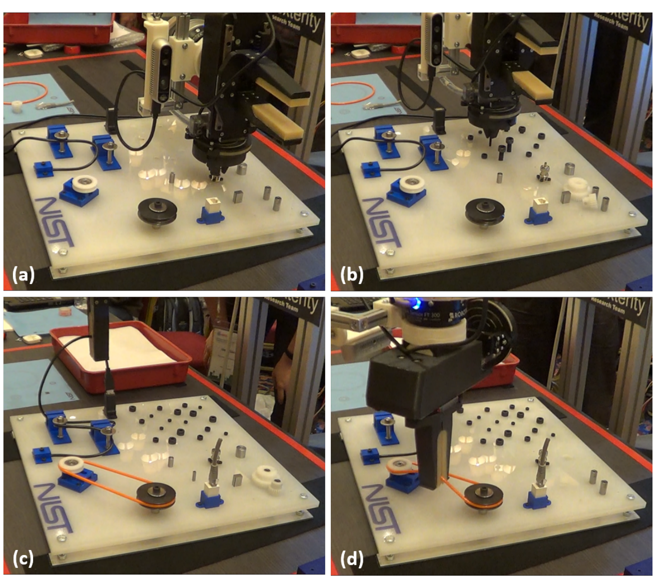

Fig. 7. The proposed system performing: (a) BNC connector assembly, (b) fastener threading, (c) cable disassembly, and (d) belt disassembly during the IEEE IROS 2019 Robotic Grasping and Manipulation Competition.

For the assembly task, the global poses of the task board, kit layout, and bolt rack were identified with the kinesthetic pose calibration approach. The task was started three times in total, as the first two attempts were canceled in order to improve calibration accuracy. The *Placement* column in Table I presents the number of components that were successfully picked up and placed on the task board, while the *Assembled* column presents the number of components that were successfully assembled. Belt fastening was attempted first. Although the component was successfully picked up and brought to the correct position, belt assembly was not successful. Since it was partially executed in one of the canceled trials, belt positioning was not counted in the final score[1]. The final assembly trial was started with the insertion class, where three of the larger pegs and the BNC connector were successfully assembled. The two gears were brought to the correct goal position, but were not properly seated. After insertions, nearly all fasteners were successfully positioned, with 13 of them threaded and 10 fully seated. Even though the rotary module was operating at maximum speed, the fastener threading task took over 30 minutes. Due to the time limit, wire routing was not attempted during the competition.

For the disassembly task, the global pose of the task board was obtained through kinesthetic calibration, while the pose of the kit tray was obtained through the marker-based calibration approach. In Table I, the *Removed* column presents the number of components that were successfully removed from the task board, while the *Placed in Tray* column presents the number of components that were successfully placed into the kit tray. Wire routing was attempted first, and the USB cable was successfully unplugged and unhooked from all four brackets. The USB connector was also placed into the kit tray, although that was not required and did not contribute to the competition score. After that, the belt was successfully removed and placed into the tray. From the insertion class, all components except the RJ45 connector were successfully disassembled and placed into the kit tray. Upon starting with fastener disassembly, the robot control hardware shut down completely and remained unresponsive for the rest of the competition, possibly due to a power surge or grid overload in the venue. Because of this outage, unfortunately, the straightforward fastener disassembly was not attempted during the competition.

[1]Results with asterisk are not counted in the final score in Table I

VI. Discussion and Future Directions

Even though the developed system performed well in the competition, there are several aspects of the approach that can be improved. Concerning hardware, the developed rotary module has proven to be invaluable in flexible assembly, as the three-point grasping and continuous rotation have allowed for fastener threading without tool changes. However, threading has shown to be rather slow, due to the limited maximum speed of the employed motor. Furthermore, the gripper provides no information on the rotary module aperture, which currently requires additional calibration stages before grasping. The rotary module can therefore be enhanced with aperture sensing capabilities and a faster motor. The parallel-jaw element can be improved by reducing finger thickness, as their width prevents the gripper to access some of the more tightly grouped components. Overall, the gripper weight and size can be reduced by optimizing its frame structure. A lower weight of the gripper will have many benefits, including a lower inertia that will allow for higher operating speeds, increased robot payload, and lower energy expenditure. System performance could also be improved by enhancing the gripper with in-hand manipulation capabilities, which would facilitate efficient component reorientation.

As one of the core modules, the CAD interface allowed for precise and instantaneous extraction of all component start and goal poses, based on the ground truth 3D assembly models. A weakness exposed in the competition was the issue of mismatched component names in the models, which caused significant delays in system configuration. To compensate for this, a keyword matching or graphical user interface (GUI) based configuration approach can be implemented. A GUI would also be helpful for visual inspection of the assembly process and identification of possible errors. In its current state, the system only uses the CAD interface for component pose extraction and relies on the user to configure the assembly procedure. This means that the framework can be rapidly adapted to accommodate similar tasks of the same class, such as threading new types of fasteners, by updating the fastener names, targets, and offsets in the rack. Updating the framework for a completely new class of tasks (e.g., sliding insertions), would take more time because new task subroutines would have to be prepared. In the current state of the framework, preparing new task subroutines still requires an expert, but a functional GUI could potentially allow any user to define the paths and forces required. For even higher framework flexibility, the available 3D model data could be used for autonomous synthesis of the assembly process.

The overall framework functionality can also be enhanced in several aspects. The implemented calibration procedures, for instance, have proven to be reliable, but they were not able to produce results with exceptional accuracy due to sensor or human calibration errors. A possible solution could be a continuous calibration, where the system starts with an initial estimate that is gradually refined during task execution. This approach would be appropriate for the marker-based calibration, where the estimate could be refined whenever the markers are in view. The solution may also be applied in disassembly, where a calibration sample could be taken whenever the gripper passively aligns to a fixed grasped component (peg or connector) due to the system compliance. To facilitate adaptation to novel assembly tasks and surprise parts, an intuitive kinesthetic programming approach could be incorporated into the framework. The system could also be expanded to support multiple arms, which would facilitate part regrasping and speed up the assembly process.

VII. Conclusion

This work presented a flexible manufacturing system that allows for fast and robust programming of assembly tasks. Relying on CAD file processing to extract component poses and geometries, the developed system can adapt to arbitrary task configurations without human involvement. Minor errors in positioning and calibration are compensated through compliance control, which enables the system to self-align during task execution. The proposed gripper design supports three different grasping primitives by integrating a parallel-jaw element and a rotary module, which maximize its versatility in executing different manufacturing tasks. The developed system was successfully validated by winning an international grasping and manipulation competition. Based on the system performance, possible improvements and future directions were discussed.

Acknowledgement

The authors would like to thank Che-Ming Chang and Ruobing Yu for their support during the competition.

References

[1] W. Shin and M. Park, "Ergonomic interventions for prevention of work-related musculoskeletal disorders in a small manufacturing assembly line," *International Journal of Occupational Safety and Ergonomics*, vol. 25, no. 1, pp. 110–122, 2019.

[2] H. R. Cheshmehgaz, H. Haron, F. Kazemipour, and M. I. Desa, "Accumulated risk of body postures in assembly line balancing problem and modeling through a multi-criteria fuzzy-genetic algorithm," *Computers & Industrial Engineering*, vol. 63, no. 2, pp. 503–512, 2012.

[3] L. Dürkop, L. Wisniewski, S. Heymann, B. Lücke, and J. Jasperneite, "Analyzing the engineering effort for the commissioning of industrial automation systems," in *2015 IEEE 20th Conference on Emerging Technologies Factory Automation (ETFA)*, Sep. 2015, pp. 1–4.

[4] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, "Industry 4.0," *Business & information systems engineering*, vol. 6, no. 4, pp. 239–242, 2014.

[5] K. Van Wyk, J. Falco, and E. Messina, "Robotic grasping and manipulation competition: Future tasks to support the development of assembly robotics," in *Robotic Grasping and Manipulation*, Y. Sun and J. Falco, Eds. Cham: Springer International Publishing, 2018, pp. 190–200.

[6] Y. Yokokohji, Y. Kawai, M. Shibata, Y. Aiyama, S. Kotosaka, W. Uemura, A. Noda, H. Dobashi, T. Sakaguchi, and K. Yokoi, "Assembly Challenge: a robot competition of the Industrial Robotics Category, World Robot Summit – summary of the pre-competition in 2018," *Advanced Robotics*, vol. 33, no. 17, pp. 876–899, 2019.

[7] J. Frohm, V. Lindström, J. Stahre, and M. Winroth, "Levels of automation in manufacturing," *Ergonomia-an International journal of ergonomics and human factors*, vol. 30, no. 3, 2008.

[8] "Assembly Performance Metrics and Test Methods," National Institute of Standards and Technology (NIST), Accessed: 7.2.2020. [Online]. Available: https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-assembly/assembly

[9] “Assembly Challenge,” World Robot Summit (WRC), Accessed: 7.2.2020. [Online]. Available: https://worldrobotsummit.org/en/wrc2018/industrial/assembly.html

[10] C. Sloth, A. Kramberger, and I. Iturrate, “Towards easy setup of robotic assembly tasks,” *Advanced Robotics*, pp. 1–15, 2019.

[11] M. M. Kaluarachchi and F. Y. Annaz, “Gui teaching pendant development for a 6 axis articulated robot,” in *International Conference on Intelligent Robotics, Automation, and Manufacturing*. Springer, 2012, pp. 111–118.

[12] S. Choi, W. Eakins, G. Rossano, and T. Fuhlbrigge, “Lead-through robot teaching,” in *2013 IEEE Conference on Technologies for Practical Robot Applications (TePRA)*. IEEE, 2013, pp. 1–4.

[13] Z. Zhu and H. Hu, “Robot Learning from Demonstration in Robotic Assembly: A Survey,” *Robotics*, vol. 7, no. 2, 2018.

[14] J. Hughes, K. Gilday, L. Scimeca, S. Garg, and F. Iida, “Flexible, adaptive industrial assembly: driving innovation through competition,” *Intelligent Service Robotics*, pp. 1–10, 2019.

[15] D. Kragic, H. I. Christensen *et al.*, “Survey on visual servoing for manipulation,” *Computational Vision and Active Perception Laboratory, Fiskartorpsv*, vol. 15, p. 2002, 2002.

[16] T. Nammoto, K. Hashimoto, S. Kagami, and K. Kosuge, “High Speed/Accuracy Visual Servoing Based on Virtual Visual Servoing With Stereo Cameras,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2013, pp. 44–49.

[17] J. Michniewicz, G. Reinhart, and S. Boschert, “Cad-based automated assembly planning for variable products in modular production systems,” *Procedia CIRP*, vol. 44, pp. 44 – 49, 2016, 6th CIRP Conference on Assembly Technologies and Systems (CATS).

[18] G. Thomas, M. Chien, A. Tamar, J. A. Ojea, and P. Abbeel, “Learning Robotic Assembly from CAD,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, 2018, pp. 3524–3531.

[19] C. Schlette, A. G. Buch, F. Hagelskjær, I. Iturrate, D. Kraft, A. Kramberger, A. P. Lindvig, S. Mathiesen, H. G. Petersen, M. H. Rasmussen, T. R. Savarimuthu, C. Sloth, L. C. Sørensen, and T. N. Thulesen, “Towards robot cell matrices for agile production – SDU Robotics’ assembly cell at the WRC 2018,” *Advanced Robotics*, pp. 1–17, 2019.

[28] S. Chitta, E. Marder-Eppstein, W. Meeussen, V. Pradeep, A. Rodríguez Tsouroukdissian, J. Bohren, D. Coleman, B. Magyar, G. Raiola, M. Lüdtke, and E. Fernández Perdomo, “ros_control: A generic and simple control framework for ROS,” *The Journal of Open Source Software*, 2017.

[20] R. Li and H. Qiao, “A Survey of Methods and Strategies for High-Precision Robotic Grasping and Assembly Tasks—Some New Trends,” *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 6, pp. 2718–2732, 2019.

[21] F. von Drigalski, C. Schlette, M. Rudorfer, N. Correll, J. C. Triyonoputro, W. Wan, T. Tsuji, and T. Watanabe, “Robots assembling machines: learning from the World Robot Summit 2018 Assembly Challenge,” *Advanced Robotics*, pp. 1–14, 2019.

[22] S. Wade-McCue, N. Kelly-Boxall, M. McTaggart, D. Morrison, A. W. Tow, J. Erskine, R. Grinover, A. Gurman, T. Hunn, D. Lee, A. Milan, T. Pham, G. Rallos, A. Razjigaev, T. Rowntree, R. Smith, K. Vijay, Z. Zhuang, C. F. Lehnert, I. D. Reid, P. I. Corke, and J. Leitner, “Design of a Multi-Modal End-Effector and Grasping System: How Integrated Design helped win the Amazon Robotics Challenge,” *CoRR*, vol. abs/1710.01439, 2017.

[23] J. A. Falco, “IROS 2019 Robotic Grasping and Manipulation Competition: Manufacturing Track,” National Institute of Standards and Technology (NIST), Accessed: 7.2.2020. [Online]. Available: https://www.nist.gov/el/intelligent-systems-division-73500/iros-2019-robotic-grasping-and-manipulation-competition

[24] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, “ROS: an open-source Robot Operating System,” in *ICRA Workshop on Open Source Software*, 2009.

[25] S. Garrido-Jurado, R. Muñoz-Salinas, F. Madrid-Cuevas, and M. Marín-Jiménez, “Automatic generation and detection of highly reliable fiducial markers under occlusion,” *Pattern Recognition*, vol. 47, no. 6, pp. 2280 – 2292, 2014.

[26] I. A. Sucan and S. Chitta. MoveIt. Accessed: 7.2.2020. [Online]. Available: http://moveit.ros.org

[27] A. Zelenak and A. Pettinger, “Compliance Controller,” UT Nuclear and Applied Robotics Group, Accessed: 7.2.2020. [Online]. Available: https://github.com/UTNuclearRobotics/ros_controllers/tree/melodic-devel/compliance_controller

[29] A. Pettinger and M. Pryor, “Completing Complex Contact Tasks Using Integrated Active and Passive Compliant Control Methodologies,” ser. Dynamic Systems and Control Conference, vol. 3, 2019, v003T20A006.