A flexible control system for reconfigurable assembly lines

Leicai Xiao1,a, Xinghui Jing2,b, Long Zeng3,c*, Xueping Liu4,d
1234Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, Guangdong, 518055, China
eaemail: xlc19@mails.tsinghua.edu.cn, bemail: xhjing99@163.com, demail: liuxp@sz.tsinghua.edu.cn
c*email: zenglong@sz.tsinghua.edu.cn

Abstract: With the rising demand for customized and frequently updated products, the current assembly systems require a higher level of reconfigurability and flexibility. Thus we proposed a scheme of reconfigurable assembly line and hierarchical control system. To increase the flexibility of control systems, a communication method and control strategy is presented in this paper. This approach will endow the reconfigurable assembly system with flexibility by encapsulating the ladder diagram program and providing an external interface for the control software to call. This approach is validated with one assembly unit assembling shuttle valve, which takes 40s during the process. The control system can not only monitor the assembling process, but also control the action of the actuator via control panel or control commands.

1. Introduction
Currently the majority of the industrial assembly lines are specialized for certain tasks, but unable to be quickly reconfigured. Based on the wide application of industrial robots, the assembly lines are capable of assembling space vehicles [1] (2017), crankshaft [2] (2018), PCB boards [3] (2018) and electronic switches [4] (2020). Meanwhile, the concepts of reconfigurable assembly and flexible control system are developed by many leading researchers. Hsieh [5] (2003) designed a dual robot assembly system based on the reconfigurable concept. Minca [6] (2014) used mobile robots developing a flexible assembly line that could assemble and disassemble. Muller [7] (2019) proposed a modular virtual control system model for the complex flexible assembly system. The flexible web control program by Schafer [8] (2019) was applied in a seat assembly workshop.

This study proposes a scheme of assembly unit cluster for the reconfigurable assembly line, and a hierarchical architecture of the control system. The complex assembly task is divided into many small parts. Each part is processed by one unit and consequently leads to the final product. The computer builds up communication with the programmable logic controller (PLC) based on the Snap7 library. The control software exchanges data in bit or integer with the PLC, and calls the encapsulated PLC subprograms by using a section of VB area as an external interface. The experiment is carried out on a single assembly unit to assemble the shuttle valve.

The contribution is structured as follows: firstly, the reconfigurability of the assembly lines and flexibility of control system is explained. Secondly, our study explores a reliable method to build communication between the Qt software and the Siemens PLC. Thirdly, a modular and flexible control methods is introduced. Finally, we argue that the assembly unit helps improving the level of assembly automation of the shuttle valve.
2. Scheme of reconfigurable assembly line

The reconfigurable assembly line is made of the assembly units, tool library, clutch library, and the transferring robots. The peripheral material conveying system transports assembled parts to the corresponding trays. The assembly tool library supplies various assembly tools, and fixture library stores all kinds of assembly fixtures. These tools and fixtures are changed by quick couplings, which are located at the end of the robot and tray base respectively. The transferring robot transfers semi-finished products between different units. The scheme is shown in Figure 1.

Each assembly unit is roughly divided into four parts: the assembly tools and tool racks, the fixtures and tray bases, the industrial robot, and the parts trays. Assembly fixtures and tools are supplied by the corresponding libraries. The robot acquires assembly tool from the tool rack, then carries the main component to the fixture on the table. Next, the robot takes different parts from the part trays and moves them to the fixture continuously, where the components are assembled.

Figure 1. Scheme of the reconfigurable flexible assembly line

Many assemble units jointly form cluster assembly lines, which can be reconfigured according to the production task. In complex assembling processes, multiple assembly units are clustered to reach the overall objective by arranging a certain number of assembly units from the corresponding trays, tools and fixtures.

3. Hierarchical architecture of control system

The architecture of the control system includes four levels. The top layer is the controlling software that monitors and controls assembly processes. There are numerous monitoring and control windows in the control software that are independent from one another. Each assembly unit is controlled by an independent PLC. If the machine is halted in one unit, another unit can replace the location so the accident will not impede the running of the remaining units. Each PLC that is connected to the industrial switch through ethernet cable has a unique address and port in the switch, resulting in a cluster control system. The structure is shown in Figure 2.
The executive layer contains various outputs such as the industrial robot and the magnetic valve. The magnetic valve controls the actions of the air cylinders, the air grippers and the quick-couplings. Meanwhile, the input terminal of the PLC collects various signals from the sensors. The communication between the industrial robot and the PLC is allowed through the IO interface. Since there are \(-12V/+12V\) voltage signals at the IO ports of the robot, relays are used to isolate the PLC from voltage. The robot movement program is coded in a teach pendant. The robot program stores important points on the moving path of the assembly and plans the motion path automatically.

The bottom layer includes the tool library and fixture library. According to the specific task of each assembly unit, it is configured with related tools and fixtures.

4. Principle of flexible control
The common usage of the PLC programming aims at specific production tasks. The design process is as follow: determine the input and output devices, allocate IO address, and then design PLC program according to the flow chart. In the previous approaches, the whole program needed to be modified every time the task changed. It lacked flexibility and make the reconfiguration of the assembly task impossible. In this study, the PLC programs are encapsulated in several subroutines. When the control task is changed, it is not necessary to change the whole ladder diagram program. Instead, the program only needs to add a new subroutine in the program's, while the original one remains unchanged. Each subprogram reacts to one assembly process and provides a unique external interface for the computer to call. When the assembly task changes, the program only needs to select and combine the related subprograms. These can be achieved by using different control commands in the software.

It is worth mentioning that only part of the data blocks in PLC are available to work as an interface. The input and output blocks used in PLC programming cannot be written on once the program runs. As shown in Figure 3, the modification of the previously used address I2.0 or I3.0 failed while the value of unused address Q0.2 changes. In particular, the VB data block is always readable and writable, which is the ideal area to receive control signal from computer.
changed when a modification occurs in the variables VW1, VD1 or VB1 as they cover VB1.1. If it occurs other components are self-designed.

Solenoid valves and SMC pneumatic components, while the end-effector’s, trays, platform body and other components purchased include the above-mentioned quick couplings, an IPE six-axis robot, the SMC Schunk Co., Ltd are used to lock the assembly fixtures and the assembly tools. For this experiment, the rubber ring is stretched and put on the valve body, as shown in Figure 5. The quick couplings from the valve body is placed on the fixture and clamped, second the steel ball is put into the valve body, and third, the assembly process is as follows: first

5. Experiment in one assembly unit

In this study, the experiment of the reconfigurable assembly, communication, monitoring and control, and flexible commands control are performed on a single assembly unit.

5.1. Hardware

The object of the experiment is the shuttle valve produced by IPE GROUP Co., Ltd in Guangzhou. The valve is composed of the valve body, steel ball and rubber ring. The assembly process is as follows: first the valve body is placed on the fixture and clamped, second the steel ball is put into the valve body, and the rubber ring is stretched and put on the valve body, as shown in Figure 5. The quick couplings from Schunk Co., Ltd are used to lock the assembly fixtures and the assembly tools. For this experiment, the components purchased include the above-mentioned quick couplings, an IPE six-axis robot, the SMC solenoid valves and SMC pneumatic components, while the end-effectors, trays, platform body and other components are self-designed.

The quick-coupling (2 in Figure 5) that is fixed at the end of the industrial robot can connect the trays handing tool (3), ring tool (4) or ball tool (5) immediately. The industrial robot carries the assembly clutch workbench (6) to position of clutch quick-coupling (8) when it is connected with the tray handing tool. After the clutch quick-coupling (8) locks the workbench that just arrived, the industrial robot returns to the tool rack and places the tray handing tool back. After acquiring a new tool, the robot
moves to the position of the valve shell (10), ball (9) or ring tray (7), then grabs the parts and carries them to the assembly workbench. S7-200SMART PLC works as the control center of the unit, which runs various modular ladder diagram programs. The VB block of PLC provides the external interfaces for these subprograms to be called by the upper computer.

5.2. Software UML architecture
In the industrial controlling field, the upper computer software is mainly built by C#, an object-oriented programming language. Given that the C# program can only be developed and run in the Window system, in order to improve the common utilization of the software, this study adopts Qt 5 to develop the software interface. Qt is a cross-platform interface development tool based on C++, which is also able to run in Linux, Unix, and MacOS system. The communication between the PLC and computer is allowed by snap7, which is an open source ethernet communication library for Siemens S7 series PLC, supporting a variety of programming languages like C#, C++ and Python.

As shown in Figure 6, the control software mainly consists of three parts. The class PLC200Smart tests communication and ensures data exchange between the computer and PLC, the MonitorPLC monitors and controls the assembly unit, and the PLCController serves as the main interface to execute the control commands. The class TS7Client using snap7 library are initialized by the three interfaces, so the data of PLC memory can be accessed by them. The subprograms of the PLC can be called by functions of the monitoring and controlling interface and the main control commands interface. Precisely, there are ten subfunctions in the class MonitorPLC, like on_btnToolSwitchON_clicked(), which locks the tool quick coupling.

5.3. Verification of the control system

5.3.1. Monitoring
The PLC’s data is continuously read using a multi-thread technique. The child thread scans the PLC’s memory every half a second and updates the display of monitoring interface. The monitoring result is shown in Figure 7 and Figure 8. The monitoring interface accurately displays the sensor signal when the device is running. On the pictures, the tray handling and double gripper tool are placed on the tool rack, so the indicator lights of the two tools’ positions are on. The Tool Ring Pos indicator corresponding to the used tool is turned off. The tool quick coupling successfully locks the ring tool, so the indicator for Tool FastSwitch remains lighted.

5.3.2 Modular and flexible control
As it is shown in Figure 8, the control panel in the middle of the software is used for testing each subprogram in the PLC. The indicator lights beside reflect the operating state of the pneumatic components. Moreover, the function of the subroutine is further encapsulated as one control command,
which controls one or several assembly procedures.

Figure 9. Command control interface

There are two methods calling the subprograms of the PLC: by clicking on the controlling button (Figure 8), or by executing control commands (Figure 9). The information bar shows the current operating status when the controlling signal is sent to the PLC. When the Lock command locks the quick coupling, the indicator light Q0.3 of the PLC output terminal is on. When the Unlock command is executed, the tool is separated from the robot through the quick coupling. The Grasp command closes the right gripper while Loosen command opens it. Command Mov and Mos are executed in the robotic arm. After executing the PLC controlled subroutines, the internal programs of the robotic arm start.

The operations of the six types of assembly behaviors are as shown in Figure 10. The fixing cylinder 3 locks the valve body, the tool quick coupling 1 and the clutch quick coupling 2 change the tool and fixture immediately, the double air grippers 4 and 5 grasp the valve body and steel ball firmly, and the ring tool 6 stretches the rubber ring and puts it on the valve body.

Experiments have confirmed that the approach of reconfigurable assembly is feasible based on the realization of shuttle valve assembly in a single unit. The whole assembly process takes about 40 seconds. The signal from the control software reaches PLC and calls the subprogram correctly, which proves that the snap7 communication and flexible control methods work as expected. The response delay of the transistor-type PLC is less than 1ms, and the total control response time is much shorter than the assembly time of each part, which meets the assembly control requirements.

6. Conclusions
The paper describes a scheme for reconfigurable robotic assembly line and its control system that can be applied to a variety of products. The shuttle valve assembly experiment was conducted on a single assembly unit. It is shown that the necessary information of the assembly is collected by the control systems, and the control commands flexibly call the subroutines of PLC to control the actuator. Changing the assembly tasks does not require adjusting the whole ladder program, which is in accord with the concept of modularization and flexible control.

Based on the realization of one assembly unit, the reconfigurable assembly line could follow the same approach and multiple assembly units work jointly to fulfill tasks that are more complex. Our next goals include improving the control software by displaying the operational status graphically, as well as adding more control commands. Combined with digital twin technology, the assembly can be controlled remotely, which will improve production efficiency and assembly intelligence.

Acknowledgments
Thanks IPE GROUP (Guangzhou) Co., Ltd’s supports for this work. This paper is also stably supported by the Key Projects funded by Shenzhen Science and Technology Commission (WDZC20200821140447001).

References
[1] Yu, Y., Wang, J.L., Liu, W. (2017) Design of the Control System of Automatic Picking and Conveying Line Based on PLC. 2nd International Conference on Robotics and Automation
[2] Li, H.D. (2018) Automatic Assembly of Engine Crankshaft Based on MOTOMAN Industrial Robot, Manufacturing Technology & Machine Tool, 670(04): 172-177.

[3] Tang, S. (2018) Research on Automatic Assembly Line Based on Industrial Robot, Shenzhen University, The Shenzhen.

[4] Duan, H.F, Han, W., Jiang, L.Z. (2020) Design of Flexible Assembly Automation System for Switch Based on Industrial Robot, Manufacturing Technology & Machine Tool. 3: 13-19.

[5] Hsieh, S.J. (2003) Re-configurable dual-robot assembly system design, development and future directions. Industrial Robot-an International Journal, 30(3): 250-257.

[6] Minea, E., Filipescu', A., Voda, A. (2014) Modelling and control of an assembly/disassembly mechatronics line served by mobile robot with manipulator. Control Engineering Practice, 31: 50-62.

[7] Muller, R., Scholer, M., Karkowski, M. (2019) Generic automation task description for flexible assembly systems. 52nd Cirp Conference on Manufacturing Systems. In: Amsterdam. pp730-735.

[8] Schafer, M., Moll, P., Brocke, L. (2019) Model for Web-Application based Configuration of Modular Production Plants with automated PLC Line Control Code Generation. 11th Cirp Conference on Industrial Product-Service Systems, In: Amsterdam. pp292-299.