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A modular factory testbed for the rapid reconfiguration of manufacturing systems

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Abstract

The recent manufacturing trend toward mass customization and further personalization of products requires factories to be smarter than ever before in order to: (1) quickly respond to customer requirements, (2) resiliently retool machinery and adjust operational parameters for unforeseen system failures and product quality problems, and (3) retrofit old systems with upcoming new technologies. Furthermore, product lifecycles are becoming shorter due to unbounded and unpredictable customer requirements, thereby requiring reconfigurable and versatile manufacturing systems that underpin the basic building blocks of smart factories. This study introduces a modular factory testbed, emphasizing transformability and modularity under a distributed shop-floor control architecture. The main technologies and methods, being developed and verified through the testbed, are presented from the four aspects of rapid factory transformation: self-layout recognition, rapid workstation and robot reprogramming, inter-layer information sharing, and configurable software for shop-floor monitoring.

Keywords Reconfigurable · Testbed · Smart factory · Distributed control

Introduction

The manufacturing paradigm has shifted from mass production to batch production (or mass customization), and recently to "batch size one production," in accordance with changes in market conditions over time, such as supply-demand reversal, diverse customer requirements, and shortening product lifecycles (Mehrabi et al. 2002; Koren and Shpitalni 2010; Duffie et al. 2017; Huang et al. 2018). From the perspective of manufacturing cost, however, it is common that continuous production of large amounts of standardized products in a dedicated manufacturing facility is advantageous over small batch production for which a group of multi-purpose workstations and flexible material handlers keep changing their operational parameters to produce differing batches of various products (see Fig. 1). Therefore, it can be said that new manufacturing systems are functionally

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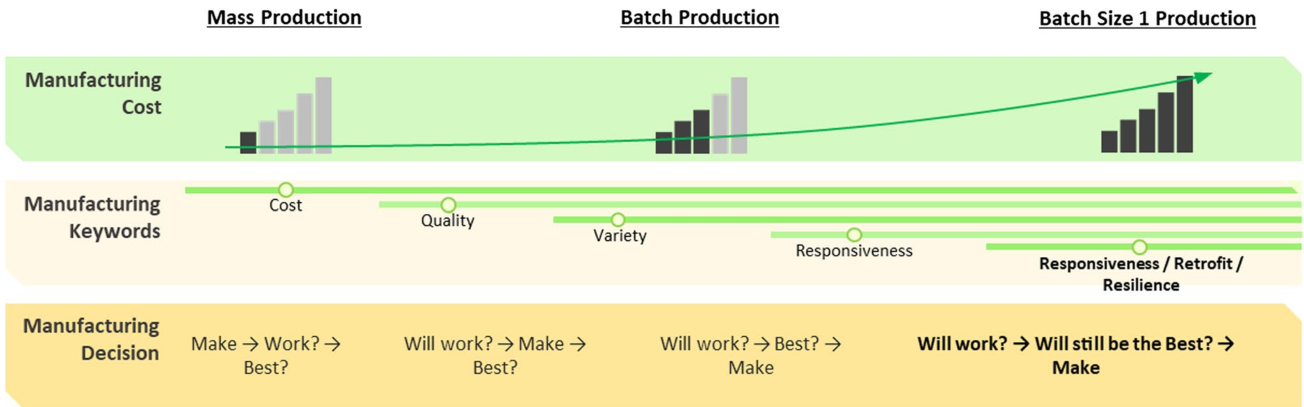


Fig. 1 Manufacturing paradigm shift

aiming to produce highly personalized products at mass production cost exactly when they are needed.

In general, prototyping and testing are conducted for mass or batch production in order to verify the functionality and manufacturability of products in advance, whereas it is necessary to reconsider the role of prototyping in batch size one production, namely, one-of-a-kind production (OKP) because prototyping might be too expensive for very small quantity production, and further a prototype itself can be a final product in OKP (Xie and Tu 2006; Tu and Dean 2011).

New manufacturing considerations and corresponding keywords have emerged along with the changes in the manufacturing environment, such as cost, quality, variety, and responsiveness, to name a few. A manufacturing system needs to be reconfigurable in order to (1) quickly respond to customer requirements, (2) resiliently retool machinery and adjust operational parameters for unforeseen system failures and product quality problems, and (3) retrofit old systems with upcoming new technologies. For these reasons, the authors consider the following “three Rs” of manufacturing: responsiveness, retrofit, and resilience, as the keywords for new manufacturing systems. These three words explain the main reasons for factory reconfiguration: businesses would seek to strategically accommodate factory changes associated with responsiveness and retrofitting in order to remain in business, while minimizing and preventing factory changes caused by system failures.

Conventional Flexible Manufacturing Systems (FMSs) offer the ability to produce different products in various batch sizes by means of reprogrammable machines and dynamic process flow controls as shown in the top panel of Fig. 2. However, the benefits of FMS can be maximized when the range of customer preferences and potential demand volume are bounded and predictable. In other words, the product lifecycle should be sufficiently long to ensure a return on such high FMS investment. At present, product lifecycles are becoming ever shorter due to unbounded and unpredictable customer requirements, thereby requiring Reconfigurable Manufacturing Systems (RMSs) that highlight modularity, integrability, convertibility, and interoperability of manufacturing systems to operate in rapidly changing markets (Koren and Shpitalni 2010; Farid 2017; Bruccoleri et al. 2006).

The concept of RMSs underpins the basic building blocks of smart factories. The smart factory aims to reduce factory planning and setting time by using smart devices that has intelligence (Zuehlke 2010). All virtual and physical manufacturing resources should be interconnected to facilitate big data analysis in a self-organizing factory (Wang et al. 2016). In order to support shop-floor communication across interconnected but heterogeneous manufacturing resources, standardized communication protocols, services, and platforms must be developed for the smart factory (Theorin et al. 2017).

There are many challenges and research issues to realize the smart factory as shown in Fig. 3. This study focuses on the main technologies for rapid factory transformation that have been developed and verified through the presented modular testbed (gray-shaded and highlighted in bold in Fig. 3).

Related works

In light of the growing importance of smart factories in the current competitive manufacturing environment, manufacturing system testbeds have been developed for research, industrial demonstration, and educational purposes as summarized in Table 1. A distributed reconfigurable factory testbed was developed by the Engineering Research Center for Reconfigurable Manufacturing Systems at the University of Michigan (Luntz et al. 2005). The testbed consists of both real and virtual machines, and demonstrates a software architecture to control the machines over a communication

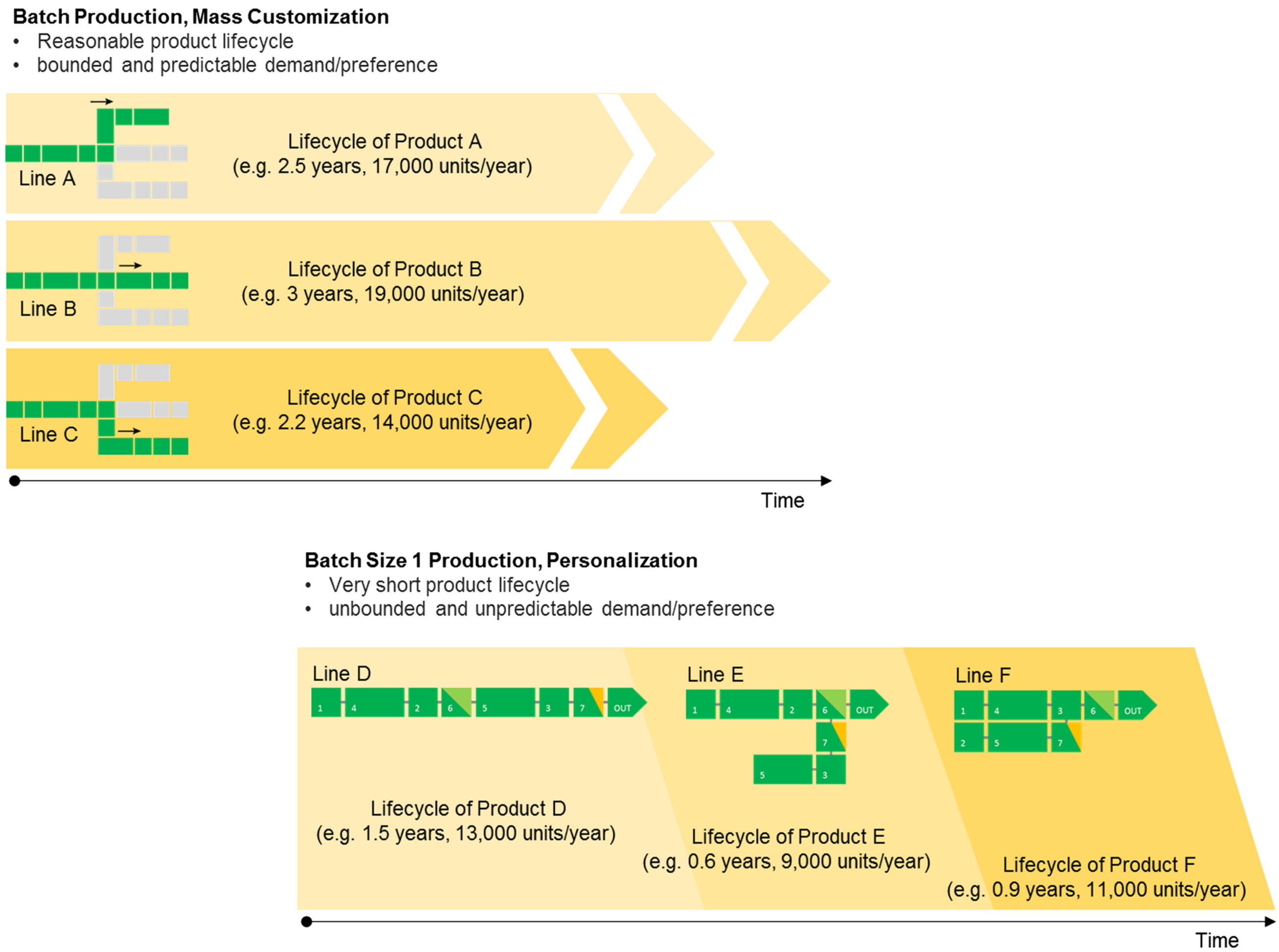


Fig. 2 Shorter product lifecycles in the era of "batch size one" production

network. Luntz et al. (2006) updated this communication network and utilized the testbed to train students, including simulation of virtual factories, development of programming control logic, and configuration of field networks. Moreover, a reconfiguration control was tested across a wireless communication network (Wijayah et al. 2006). The German Research Center for Artificial Intelligence has developed a smart factory testbed jointly with many renowned industrial partners, such as Siemens and Harting, to demonstrate the ability to produce highly customized products (e.g., business card holders) using various industrial standard solutions and ICT (Information and Communication Technology) platforms (Zuehlke 2010). The Institute for Advanced Manufacturing at the University of Nottingham proposed a software architecture for Evolvable Assembly Systems (EAS), emphasizing decentralization, context-awareness, and intelligent resources (Chaplin et al. 2015). EAS comprises five main components: reconfiguration, monitoring, agent environment, translation, and definition. The components are controlled via a unified user interface, and every device is networked with intelligent resources (e.g., programmable logic controller). The developed software provides a training environment for manufacturing automation and a basic tool box for implementing evolutionary learning algorithms for the reconfiguration of manufacturing systems.

As the main drivers of factory reconfiguration technologies, agent-based manufacturing systems and the concept of "plug-and-produce" have been widely studied (Monostori et al. 2006; Antzoulatos et al. 2014; Rocha et al. 2014; Zhang et al. 2017). Rocha et al. (2014) introduced a data model to facilitate information sharing between agent systems for more flexible monitoring and reconfiguration of a manufacturing system while minimizing production downtime. Järvenpää et al. (2018) emphasized that an ontology model for production state information must be carefully defined for information sharing across shop-floor equipment. Monostori et al. (2006) summarized the essential characteristics of agents, such as mobility for accessing remote resources or other agents, identification of objects, transparency, and credibility. Shea et al. (2010) proposed

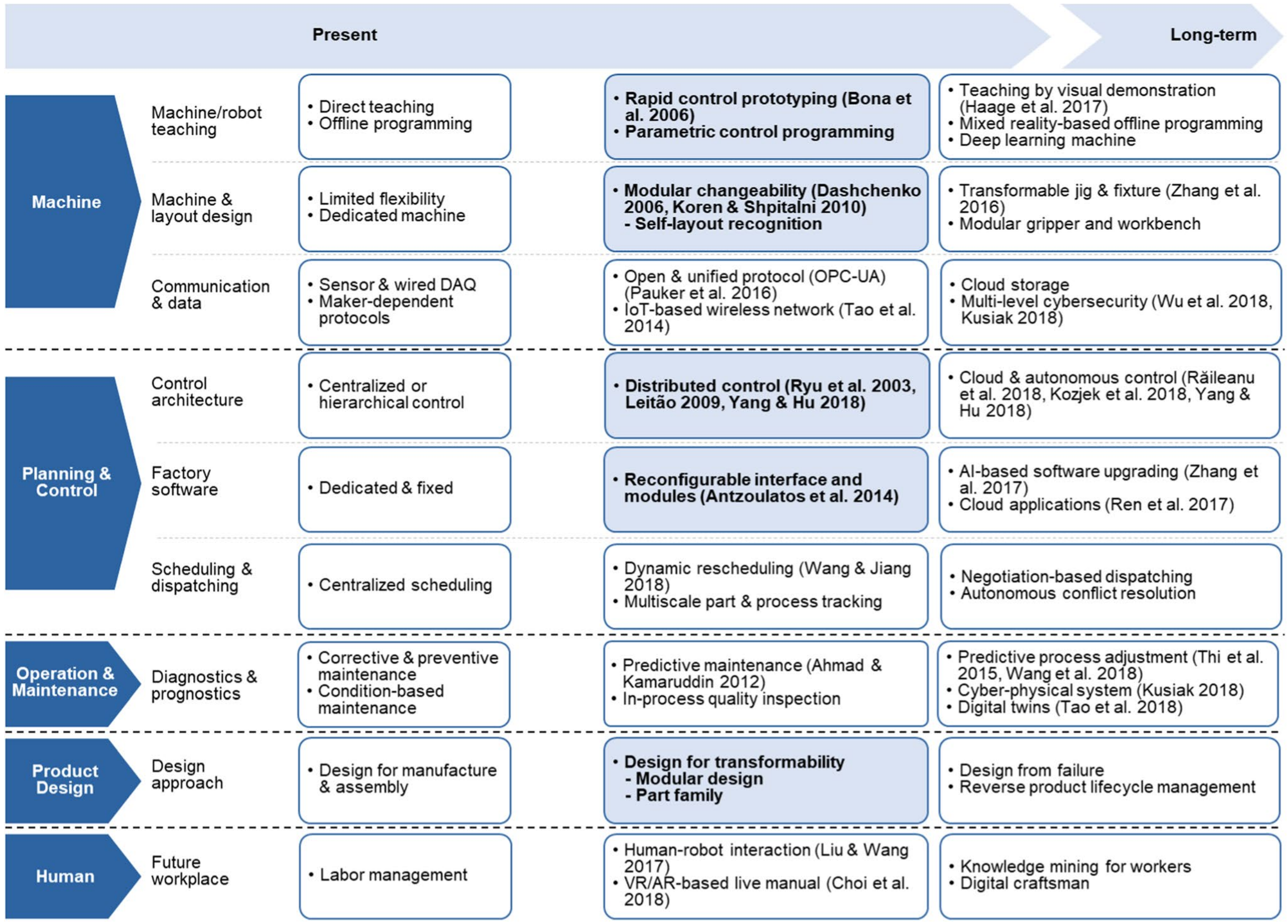


Fig. 3 A research roadmap for smart factories (main focuses of this study for rapid factory transformation are gray-shaded and highlighted in bold)

an autonomous design-to-fabrication system using cognitive agents for a reconfigurable machine shop. They proposed a process reconfiguration ontology for computerized numerical control machinery, and presented a geometry-based fixture design for a reconfigurable machine. Park and Tran (2012) proposed a swarm of cognitive agents for autonomous manufacturing systems. Each cognitive agent controls and monitors workpieces, machines, robots, and transporters, respectively.

Yang and Hu (2018) proposed a Petri Net-based flexible process routing method to overcome resource failure and machine breakdowns in the distributed manufacturing system. To generate a reliable process route in real-time, they provided a deadlock resolution mechanism considering process uncertainty. Qamsane et al. (2017) defined the functions and properties of distributed controllers in order to support the PLC programming process for manufacturing system reconfiguration. They adopted the IEC 60848 standard of graphical modeling language for functional descriptions of controllers' behavior.

In summary, many multi-purpose smart factory testbeds have been developed and the most of them addressed the importance of reconfigurable systems and industrial standards by emphasizing the scalability and interoperability (Cardin et al. 2017; Liu et al. 2017; Jardim-Goncalves et al. 2016). However, from the practical implementation point of view, little attention has been made to the detailed methods and systematic processes (1) to automatically recognize physical layout changes, (2) to support shop-floor communication for reconfiguration, and (3) to facilitate the update procedure of the factory management and control software. Therefore, this study particularly aims to (1) describe what specific technologies and procedures are necessary for rapid reconfiguration and (2) demonstrate how the reconfiguration process works via the developed testbed. In this regard, the developed testbed can be considered as a reconfigurable manufacturing testbed according to the classification made by Kovalenko et al. (2017).

Table 1 Smart factory testbeds for research, demonstration, and educational purposes

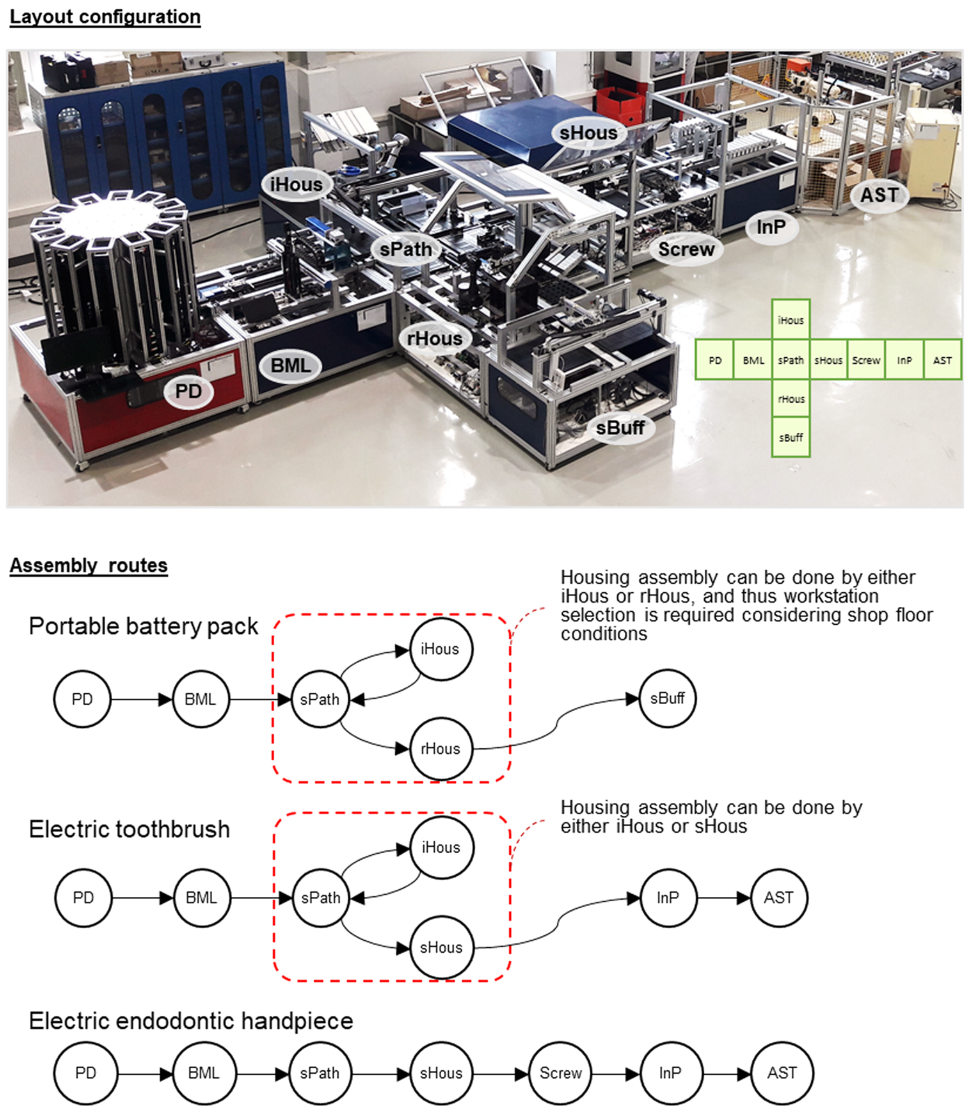
Testbed (location)	Main focus and feature	References
SMART Testbed (University of Michigan, Ann Arbor, United States)	Reconfigurable manufacturing systems Distributed and open control Digital twin Cloud manufacturing Learning factory	Luntz et al. (2006), Kovalenko et al. (2017)
Smart manufacturing systems Testbed (NIST, Maryland, United States)	Integration of design and manufacturing (computer-aided engineering and machining) Web-based production data management Production information standard Applications of MTConnect	Feeney et al. (2017)
SmartFactory^{KL} (DFKI, Kaiserslautern, Germany)	Smart automation and HMI Plug and produce Standardization of modular workstations Artificial intelligence in manufacturing Learning factory	Zuehlke (2010), Stephan et al. (2009)
Smart factory web (Industrial Internet Consortium)	Web-based cross-site engineering framework OPC-UA and AutomationML standards Plug and work Secure data aggregation 5G communication network	https://www.smartfactoryweb.de
Industrial IoT Testbed (Smart production systems research group, HTW Dresden, Germany)	Collaborative robot modules Autonomous transport vehicles RFID-based real-time product tracking	https://www.htw-dresden.de
iFactory (IMS Center, University of Windsor, Canada)	Reconfigurable manufacturing systems Rapid prototyping Product variety management Learning factory	ElMaraghy and ElMaraghy (2015)
Deloitte digital factory (Deloitte, Düsseldorf, Germany)	Learning factory Digital manufacturing execution Analytics and predictive maintenance Intelligent supply chain	Deloitte (2018)
Stena industry innovation lab Testbed (SII Lab, Chalmers University of Technology, Sweden)	Learning factory Collaborative robots VR & AR for training In-house logistics	Chalmers University of Technology (2018)
CIP Testbed (Center for industrial productivity, TU Darmstadt, Germany)	Learning factory for lean production Flexible machining and in-house logistics Quality management	Abele et al. (2017)
SZTAKI smart factory Testbed (MTA SZTAKI, Budapest, Hungary)	Learning factory for 'maker space' and 'mechatronics education' Cyber-physical systems RFID/NFC applications	Kemény et al. (2016)

The developed testbed configuration

Modular workstations

The major products of the testbed are laboratory-scale electric endodontic handpieces, electric toothbrushes, and portable battery chargers that are assembled by 10 main workstations as shown in Fig. 4: part dispenser (PD), battery mounting and labelling (BML), smart path switch (sPath), smart housing assembly (sHous), intelligent housing assembly (iHous), screwing (Screw), inspection and packaging (InP), automated storage (AST), rapid housing assembly

Fig. 4 Layout configuration versions according to product assembly



(rHous), and smart buffer (sBuff). All workstations except AST are of the same size (1500 × 1500 mm) in order to facilitate modular reconfiguration, similarly to LEGO blocks.

PD is an automated pallet-racking system designed to store and dispense product base-parts or control Printed Circuit Boards (PCBs) on flexible pallets. It provides 12 cassette drawer columns of 14 stacks of pallets. NFC tags are attached to each individual cassette and pallet. The part type information from the NFC tag on a cassette allows the PD workstation agent to dispense the correct base part exactly when it is required. NFC tags on pallets contain the following information for in-process part-tracking and assembly operation control: part type, start time, current workstation ID, and fault status.

sPath has four pallet-in and -out ports and 40 pallet parking lots for flexible process control. A workstation can be attached to any side of sPath in order to transfer and receive a part or a subassembly for the next assembly operation. Therefore, sPath eventually functions as a traffic controller and short-term parking lot in determining the best assembly process flow according to dispatching rules such as remaining processing time, assembly priority, and shortest processing time.

iHous, rHous and sHous are parallel machines for housing assembly as illustrated in Fig. 4. For example, housing assembly for a portable battery charger can be done by either iHous or rHous. Hence, the traffic controller, sPath will determine which one of them is the best route according to the shop-floor conditions. Only sHous can perform a dedicated process for the housing assembly of electric endodontic handpieces.

The main components of the assembly workstations include an assembly manipulator, jig and fixture, pneumatic Inter-workstation Pallet transfer system (InterP), Direct Pallet positioning system (DirectP), subpart feeder, NFC reader/writer, infrared communication module, and main industrial controller as shown in Fig. 5. Infrared communication modules are installed on the four sides of each workstation to enable spontaneous inter-workstation communication during factory reconfiguration.

The InterP was developed to quickly transfer a pallet from one workstation to the next by means of a pneumatic cylinder. This new conveying unit works by moving a pusher back and forth following a guided path whose start and end are curved downward. Consequently, the pusher moves downward to ensure a soft pallet-transfer between workstations. Unlike conventional conveyors, the InterP operates only when a proximity sensor is activated. An InterP can function as either the input or output port of a workstation depending on the assembly sequence. A DirectP, controlled by a linear actuator, takes a pallet from an input port of a workstation and places it on the main assembly stage according to a preset arrangement, and then feeds it to an output port for conveying to the next workstation.

Communication and control architecture

The testbed adopted a multi-agent architecture for distributed shop-floor control (Maturana and Norrie 1996; Shen et al. 2000; Leitão 2009). The testbed employs a three-layered agent architecture for all shop-floor decisions and communication, comprising: coordinator, workstation agent, and workstation executor (see Table 2).

The coordinator (software interacting with users, developed using Microsoft C#) manages factory configuration and operation including daily production planning. A workstation agent for a particular workstation (a software application acting autonomously, developed using ANSI C) is responsible for controlling and monitoring the assembly operations in the workstation. It also transmits and receives important operational messages amongst all other agents. To support efficient message exchange and process monitoring, two different wireless communication networks were employed for typical assembly operation control and sensor data transmission. This is because a high sampling rate for sensor data acquisition creates a high volume of network traffic and hence tends to cause network latency and data loss. For message communication between agents, we employed a high-performance medium-range wireless equipment (802.11ac protocol, 2.4 GHz frequency, 72 Mbps) for each workstation to ensure reliable message transmission. For stable data acquisition from the multiple sensors of each workstation, we used different wireless equipment (802.11ac protocol, 5 GHz frequency, 867 Mbps), such that each workstation has two independent wireless connections.

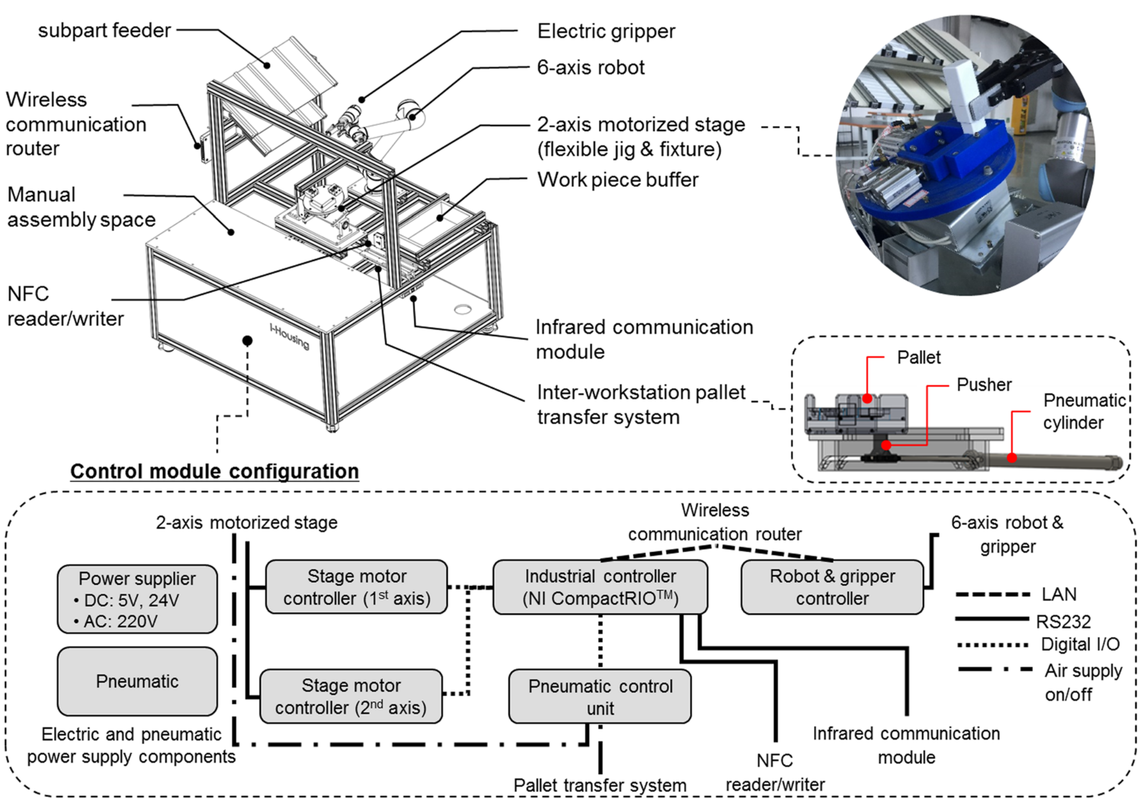


Fig. 5 Main components and modules of i-Housing workstation

Table 2 Main functions of coordinator, workstation agent, and workstation executor

Agent	Function module	Description
Coordinator (ISA 95[a] Levels 2 and 3)	Factory configuration	Layout management (self-layout recognition)
		Network configuration
		Product and process definition
		Control-program management
	Production plan	Production planning
	Factory operation management	Production speed control
		Integrated monitoring
		Deadlock resolution
		Off-line analysis for system diagnostics
	Communication	Message handling (send/receive, encoding/decoding)
		Message distribution (forward and share)
Workstation agent (ISA 95 levels 2 and 3)	Scheduling (part dispatching)	Choice of the next part to be manufactured in the workstation
		Choice of the next workstation destination for the part being manufactured in the present workstation
	Workstation operation management	Workstation initialization/termination
		Takt time adjustment for process balancing
		In-process workstation status monitoring and prognostics
	Communication	Message handling (send/receive, encoding/decoding)
Workstation executor (ISA 95 level 1)	Real-time control	Real-time device control
		Sensor data acquisition
		Detection of new workstation-to-workstation connections
	Communication	Message handling (send/receive, encoding/decoding)
		Infrared communication
		Fieldbus communication
		NFC-based part-information handling

[a]For more information on ISA95, refer to https://www.isa.org/isa95/

A workstation executor (embedded control software developed using LabVIEW) controls the motion of all devices and manages internal communications in a workstation. In summary, the coordinator and workstation agents are responsible for the shop-floor management functions of ISA95 level 2 and 3, and workstation executors perform the functions of ISA95 level 1, sensing and manipulating of the production process (Unver 2013).

To enable users to test various ICT applications and PC-based software in the testbed, this study employed real-time embedded industrial controllers (NI CompactRIO) and laptop computers with I/O interfaces instead of a conventional Programmable Logic Controller (PLC) for workstation executors as illustrated in Fig. 6. These PC-based control systems ensure rapid reconfigurability of the testbed, since it is comparatively easy to change and update control programs via PC-based interfaces in comparison to PLCs that requires new I/O node information for developing a new ladder diagram for task sequences.

In addition, it is very important to ensure data security in the communication and control layer. For this reason, a commercial built-in encryption module, D'Amo (Penta Security Systems, Seoul, South Korea) was installed in some workstations to prevent ID spoofing, data sniffing, network sniffing, and data tampering. Data encryption and decryption performance was tested for the communication between the coordinator (server) and the workstation agents (clients).

Rapid factory transformation

Reconfiguration scale

The reconfiguration scale represents the amount of changes in manufacturing resources required for reconfiguration, as classified in Fig. 7. Manufacturing resources include primary equipment for processing, assembly, and material handling and storage; and auxiliary devices such as tools, fixtures, pallets, and grippers (Cho et al. 1997). Level 1 represents a scenario in which the entire system is changed throughout a factory. Hence, most manufacturing resources will be replaced or reconfigured to adapt to new manufacturing processes. Level 2 implies the deployment of some new workstations in the current factory. Level 3 represents

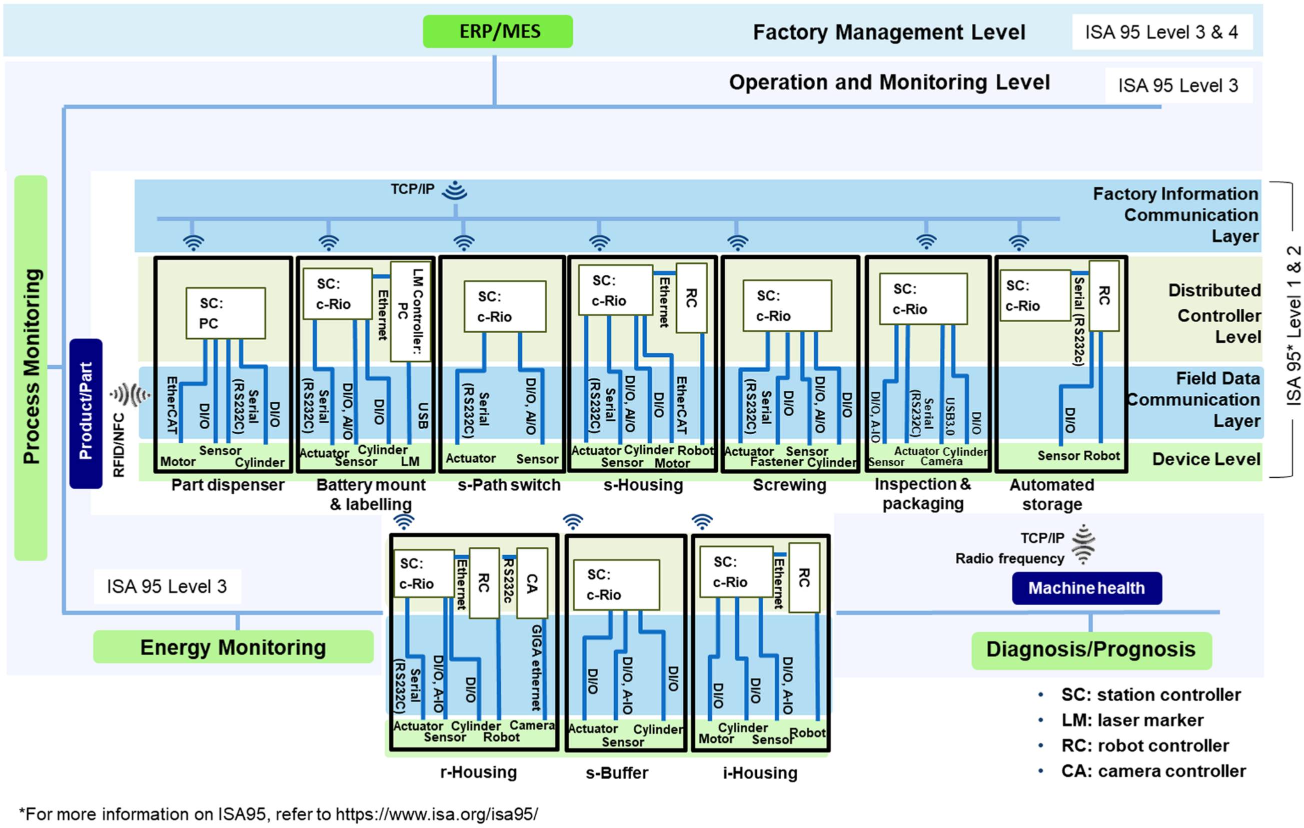


Fig. 6 Communication and control structure of the testbed

a minor update that usually entails trivial modifications to control software, grippers, jig and fixtures, and other auxiliary devices.

Figure 8 illustrates two examples of factory reconfiguration. The left panel of Fig. 8 shows an example of level 2 reconfiguration: Screw and sHous are substituted with BML and rHous respectively, which will change the original manufacturing system for electric endodontic handpiece production to a new one for electric toothbrushes. The right panel of Fig. 8 illustrates a minor, level 3 reconfiguration of a manufacturing system: the original layout is rearranged in order to reduce the factory footprint, for which some control programs of existing workstations require updates in order to correctly control the newly revised flow of parts.

Product design for ready-to-transformation

The impact of decisions at the design phase on manufacturing performance cannot be overestimated (Kim and Xirouchakis 2010). Therefore, it is important to contemplate both design changeability and manufacturability from the early design phase. Modular design approaches offer great benefits for design changeability by sharing common components and a platform across a product family (Agrawal et al. 2013).

The testbed, as listed in Table 3, can produce a total of 14 different products having different shapes and capacities in a product family: two model variants of an electric endodontic handpiece, seven variants of electric toothbrush, and five variants of portable battery charger. Each product consists of some combination of the following components: handpiece head, toothbrush head, motor assembly, control PCBs, rechargeable battery pack, housing, and cover. Control PCBs are loaded on flexible pallets equipped with NFC tags, and these pallets are automatically conveyed to the next assembly workstations.

Design for X techniques, such as design for assembly and manufacture, have been widely utilized to drive reductions in manufacturing costs (Boothroyd et al. 2001). For example, this study reduced the number of parts for the housing and cover of an electric toothbrush from four parts to two. For easy and faultless insertion operations by a manipulator, the corner geometry of a component was revised to include fillet and chamfer features, and further redesigned the cover part for rotational symmetry in order to minimize reorientation of parts during assembly.

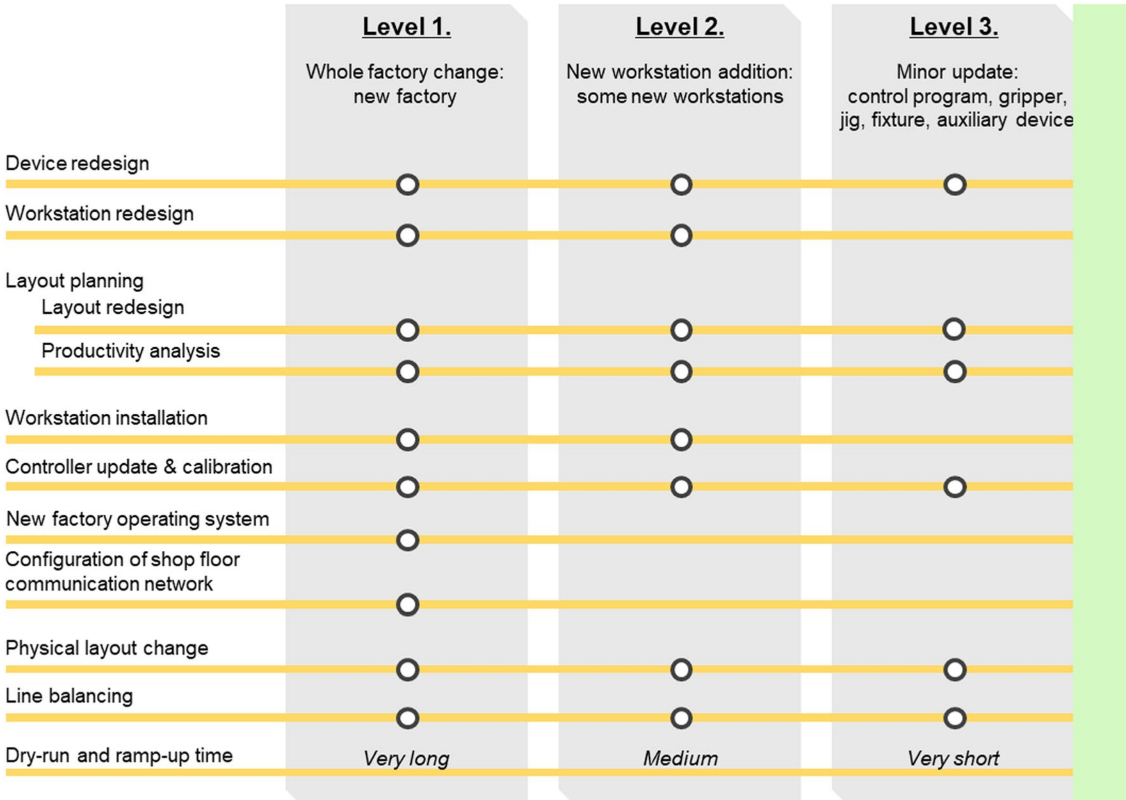


Fig. 7 Factory reconfiguration scale and required tasks

Self-layout recognition

In order to facilitate the reconfiguration process, this study developed an infrared communication module to automatically acquire physical status information for workstation-to-workstation connections. This communication module enables each workstation to recognize new connections and update relevant information such as new process and layout information, process plans, and corresponding part flows.

The procedure for self-layout recognition consists of four main steps (refer to Fig. 9). Firstly, the coordinator sends a message for reconfiguration initialization to all workstation agents; then all workstations initialize themselves for reconfiguration, such as disabling sensors and shutting down devices. Secondly, physical layout changes are performed by workers; then all workstations are set to listening mode to receive new connection messages. Thirdly, if two workstations, for example W1 and W2, are newly connected, an infrared communication module installed on the four sides of W1 transmits NEC format messages containing workstation ID, connected port ID, and workstation state to W2; then the executor of W2 decodes the infrared signals received from W1, and reports the connection information to the coordinator. The coordinator is listening for new connection information from all workstations, and eventually updates the new layout information by analyzing messages using the following pre-specified message protocol in the fourth step: (i) Command: enforcement of receiver's action; (ii) Request: call for required information or action of a receiver; (iii) Response: answer the received message; and (iv) Reference: notice of sender's information.

Rapid workstation reprogramming

Rapid factory control prototyping

Off-Line Programming (OLP) has been widely used for teaching shop-floor robots, including determining the optimal sequence of robot movements and collision-free paths by simulation with a robot model in a virtual environment (Mitsi et al. 2005). The main advantage of OLP over manual on-line programming is rapid program development in planning the robot paths necessary for completing the tasks involved in new manufacturing processes, and consequently the avoidance of extended down-time when reconfiguring the production operations. However, OLP is, by its nature, only conceivable when a virtual robot exists in a pre-defined model library. Commercial OLP software usually includes virtual models only for popular robots used in many industry applications. Therefore, if new manufacturing tasks require

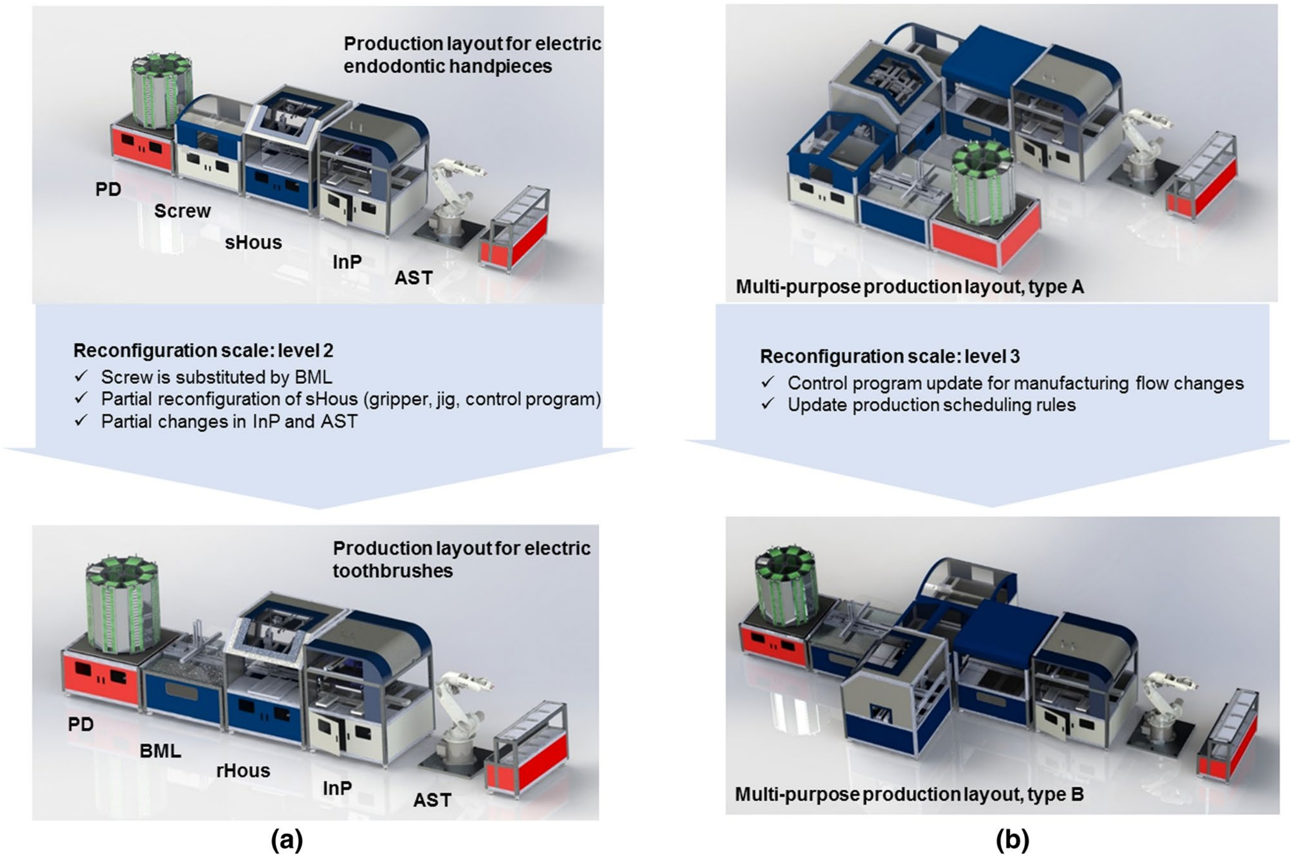


Fig. 8 Factory reconfiguration examples: **a** level 2 reconfiguration, adding new BML workstation, **b** level 3 reconfiguration, revised layout to reduce factory footprint

the use of a newly designed workstation, then it is necessary to develop the entire underlying virtual model of that particular robot's movement mechanism.

This study synchronized workstation design, its virtual model definition, and control algorithm development for rapid installation of a new workstation. This synchronization procedure will be called Rapid Factory Control Prototyping (RFCP), highlighting the time-consuming process of reprogramming. The RFCP process involves an iterative loop of the following four main steps: (i) Workstation design and virtual factory modelling, including the selection of major components such as main controller, actuators, sensors, assignment of input/output ports, and kinematics of motions; (ii) Control programming in a virtual environment; (iii) Program verification in the virtual factory; and (iv) Program upload and calibration in the real factory.

This study examined the RFCP procedure by designing, configuring, programming, and verifying a new workstation, termed rHous. The SoftMotion module (National Instruments, Austin, TX) was employed for control programming in the 3D virtual environment of SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France). The developers, a group of graduate students, spent approximately 6 weeks to interactively design, build, and install rHous using the RFCP procedure, whereas it took slightly less than double that time for the other similar workstation, sHous without RFCP. In short, by integrating motion simulation with workstation design, we could expect rapid workstation deployment for new manufacturing processes in an actual factory by minimizing expensive iterations.

Message-based parametric reprogramming

In general, primary manufacturing equipment such as robots and CNC machines are programmed to execute predefined sequences of motions. If the old motion profiles must be revised to accommodate newly introduced parts or new manufacturing processes, it was necessary for engineers to modify robot or part programs, or to select other suitable pre-defined program module through a control panel interface. As in the case of a direct numerical control environment, i.e., networked CNC, program modification is performed remotely and then the new program is uploaded to the machine.

In order to reduce the reprogramming time required for workstation reconfiguration, this study defined a control

Table 3 List of products (14 product variants)

Product family	Model (code)	Common components		Design for assembly
Electric endodontic handpiece 	SF Endodontic (ERMDO)	BC-battery		Chamfered edge
	SF Endodontic (ERMDN)	BC-battery		Chamfered edge Assembly guide rib Joint reduction
Electric toothbrush 	SF Electric toothbrush-SL Plus (ETLLO)	AL2A-battery CV-motor EL01-PCB		Chamfered edge
	SF Electric toothbrush-SL Plus (ETLLN)	AL2A-battery CV-motor EL01-PCB		Chamfered edge Assembly guide rib
	SF Electric toothbrush-SH (ETSHO)	1450LI-battery ROH-motor EH02-PCB	ES-housing End cap	Chamfered edge
	SF Electric toothbrush-SL (ETSLO)	1450LI-battery ROM-motor EH02-PCB	ES-housing End cap	Chamfered edge
	SF Electric toothbrush-OH (ETOHO)	1450LI-battery ROH-motor EH02-PCB	EO-housing End cap	Chamfered edge
	SF Electric toothbrush-OL (ETOLO)	1450LI-battery ROM-motor EH02-PCB	EO-housing End cap	Chamfered edge
	SF Electric toothbrush-Neo (ETDHN)	1450LI-battery ROH-motor EH02-PCB		Chamfered edge Assembly guide rib
Portable battery pack 	SF portable battery pack-O186 (BTOHO)	BH-PCB 1865LI-battery BO-housing		Chamfered edge Assembly guide rib
	SF portable battery pack-O145 (BTOLL)	BL-PCB 1450LI-battery BO-housing		Chamfered edge Assembly guide rib
	SF portable battery pack-S186 (BTSHO)	BH-PCB 1865LI-battery BS-housing		Chamfered edge Assembly guide rib Part reorientation reduction
	SF portable battery pack-S145 (BTSLO)	BL-PCB 1450LI-battery BS-housing		Chamfered edge Assembly guide rib Part reorientation reduction
	SF portable battery pack-Neo (BTDHN)			Chamfered edge Assembly guide rib Part reorientation reduction

command format that encompasses the combination of control parameters for representing a single operation by a device in the workstation. A control command consists of three main parts: command type, device ID, and instruction/state as shown in Fig. 10. There are two types of control commands: command (C) for enforcing a device operation and requirement (Q) for waiting the completion of a single operation, as indicated by the first byte in a control code in

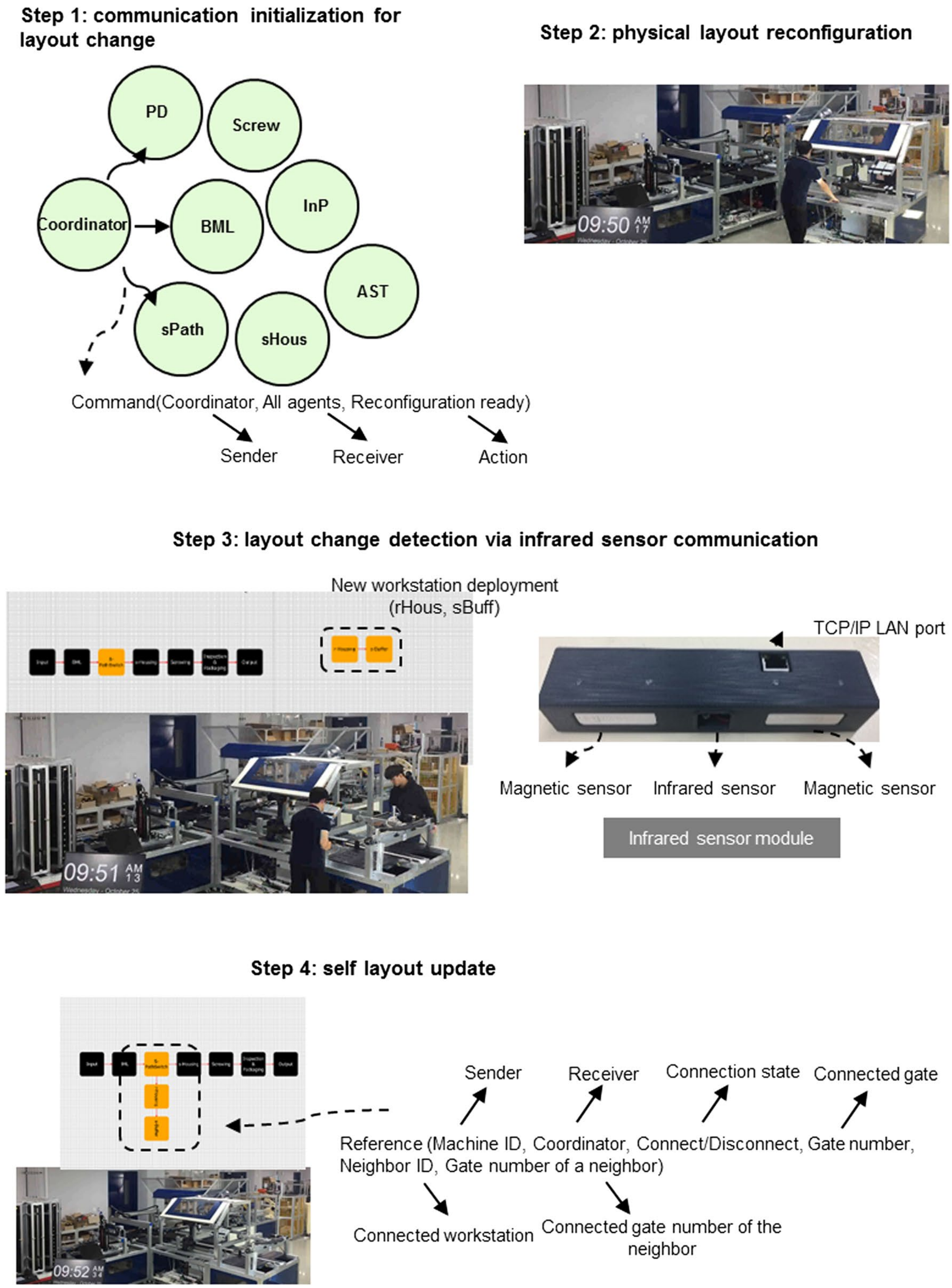


Fig. 9 Procedure for self-layout recognition

Fig. 10. Four bytes Device ID identifies a specific device for a single operation, and the last three bytes are allocated for either detailed operation instruction or state of operation completion. The operation sequences performed by a workstation can then be updated simply by transmitting a control command message to the corresponding workstation.

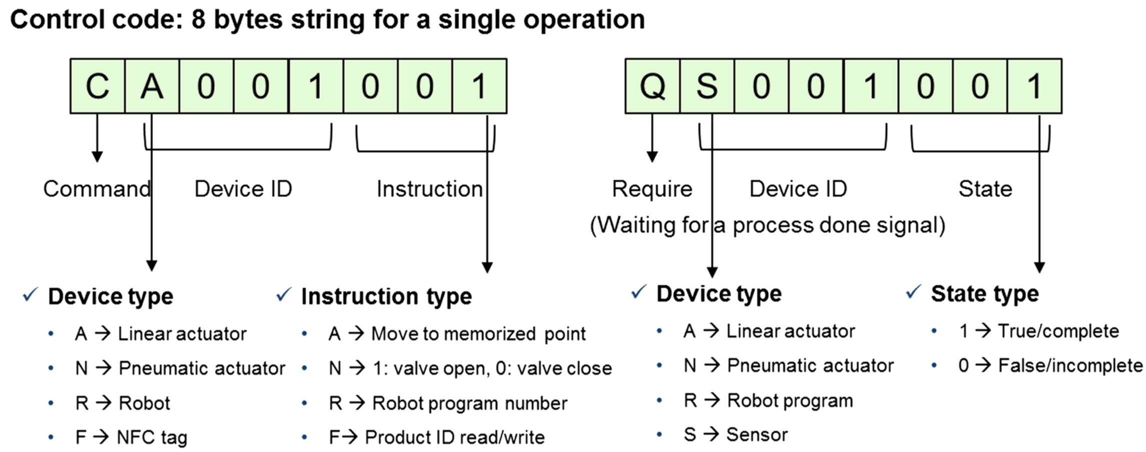
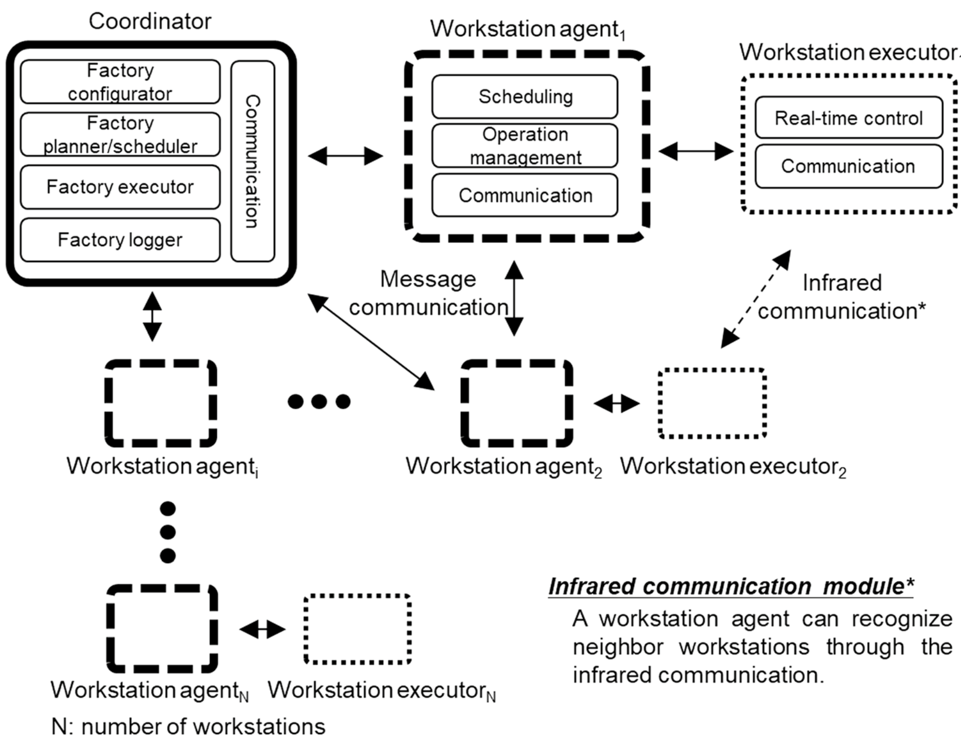


Fig. 10 Control command format for updating workstation operations

Fig. 11 Three layered-agent communication framework for rapid factory reconfiguration



Inter-layer information sharing

Since the era of flexible manufacturing, distributed control approaches have received increasing attention by underlining their characteristics of modularity, information accessibility, scalability, and adaptability (Duffie and Prabhu 1994; Spicer and Carlo 2007; Vallee et al. 2011; Carlo et al. 2012). In conventional hierarchical manufacturing systems, a supervisory and master shop-floor controller usually makes daily production decisions such as planning, scheduling, and control, based on a large amount of centralized information. On the other hand, distributed control approaches intend to share all important manufacturing information and to make them accessible to every workstation controller (e.g., corresponding workstation agent) (Lin and Solberg 1992). As a result, each autonomous workstation agent can make decisions independently to optimize its operation and resolve unforeseen troubles. All necessary information is here requested and transferred asynchronously among all agents without any predefined direction of message flows.

The authors extended the agent communication for rapid factory reconfiguration as shown in Fig. 11. The coordinator mainly supports a factory configuration process and mediates workstation agents. The coordinator consists of five main function modules: factory configurator, factory planner/scheduler, factory executor, factory logger, and communication module. The factory configurator usually manages the factory layout and supports RFCP preparation for workstation updates as shown in Fig. 12. The factory planner/scheduler generates production plans by considering shop-floor conditions. The factory executor performs integrated monitoring of the shop-floor and manages factory operations such as production speed control, deadlock resolution, and off-line analysis for system diagnostics. The factory logger collects and saves the shop-floor data. The communication module handles and distributes production-related messages.

The workstation agent has three function modules concerned with scheduling, operation management, and communication. The scheduling module independently chooses the optimum part flow. The workstation operation management module performs in-process monitoring of workstation status and prognostics, and the communication module handles the exchange of messages.

The workstation executor is responsible for real-time control of devices. Besides that, the executor undertakes infrared communication directly with a neighboring workstation executor in order to exchange their information such as workstation ID and In/Out port ID. Workstation agents and the coordinator can recognize changes in the physical layout based on these infrared communications among workstation executors.

Configurable software for shop-floor monitoring

In general, factory reconfiguration is necessary for new manufacturing processes owing to new products or new production volumes. Therefore, user-interactive process planning and new control program selections should be done first via the factory configurator module of the coordinator software as shown in Fig. 12. When physical factory reconfiguration begins, the factory configurator will wait for new connection message from all workstations. The real-time layout change is visualized via the graphical user interface of the coordinator software, such that the user can easily monitor the reconfiguration status. Once the user confirms the completion of physical factory changes, wireless communication

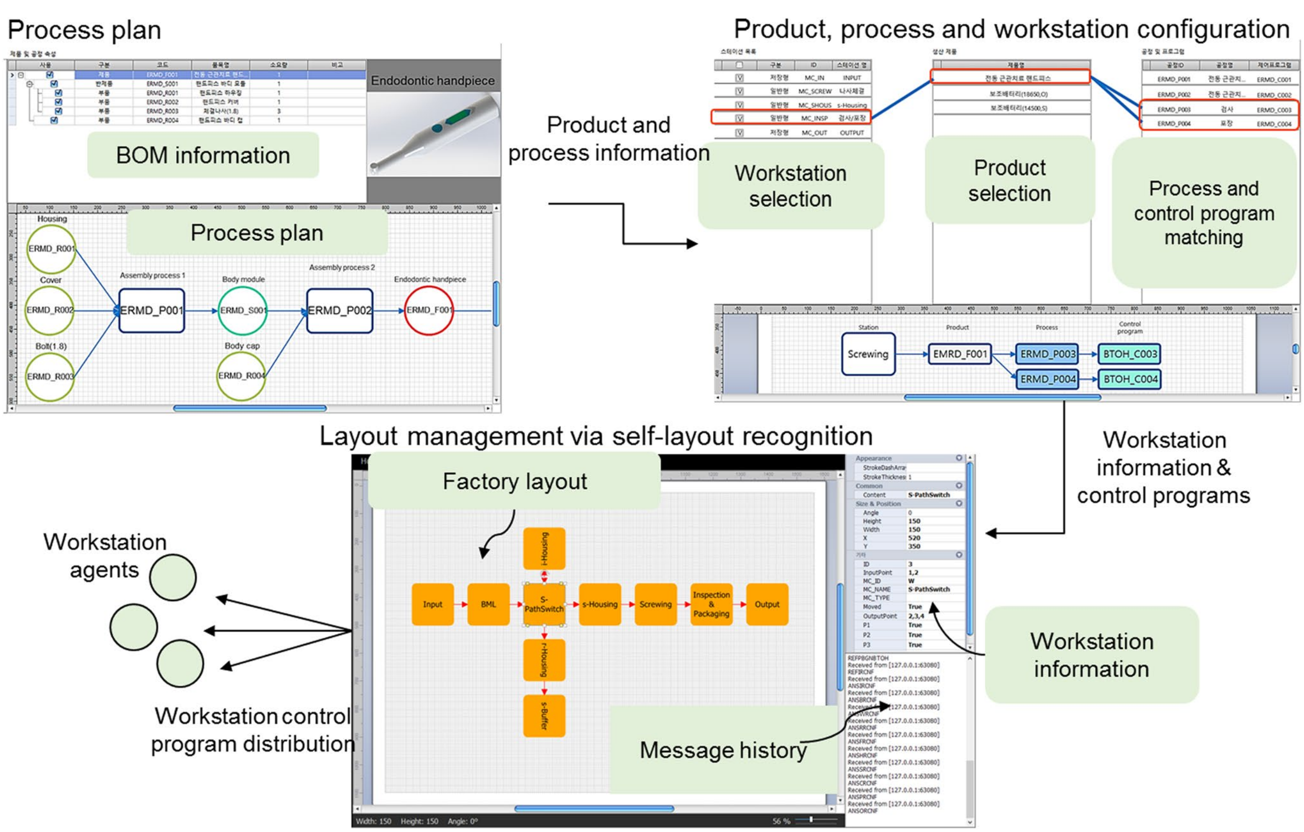


Fig. 12 Screenshots of the factory configurator module of the coordinator software

channels between the coordinator and all workstation agents are initialized.

Shop-floor process monitoring is conventionally performed by identifying defect patterns, through correlating in-process monitoring signals with manufacturing quality, and subsequently providing adaptive strategies for process adjustments via real-time matching between defect patterns and control parameters. The developed software consists of diagnostics and monitoring modules. The diagnostics module is an offline analysis program that interprets and extracts fault patterns using monitored multi-sensor signals in the form of time series.

Electrical usage, temperature and vibration sensor signals of each workstation are collected via a commercial wireless data acquisition system and stored in a database. The module can specify fault decision thresholds or classify fault regions in the space of historical sensor values in the database by statistical training methods. In cases where the fault regions are too widely scattered or else arbitrarily overlap normal regions in the space, the module can extract sensor signal patterns in the fault states by event codification and code pattern mining. Specifically, the discretized state vectors of sensor signals, called event codes, are decoded to investigate the correlation between specific code patterns and manufacturing faults. These extracted patterns are stored in a fault pattern library that will be used as the main reference source to diagnose present manufacturing process and predict potential fault occurrences. The monitoring module is an online program for condition monitoring that analyzes the similarity between the current operational states of manufacturing processes and the stored fault patterns in real-time.

The two software modules are reconfigurable in response to manufacturing system changes that involve new sensors, new workstations, and multiple strategies for analytics. In other words, each module allows users to flexibly select the target sensors and workstations, without additional software programming, and offers several detection and prediction strategies with editable parameter settings.

Discussion and future work

Summary of testbed reconfiguration experiments

The infrared communication system enables each workstation to recognize a physical layout change in the shop-floor. The two workstation addition process and the entire rearrangement of the testbed (level 2 and 3 reconfigurations in Fig. 7) lasted approximately 15 and 35 min respectively. Most of that period was spent in the physical rearrangement of workstations by the users, while the required logical changes, including software updates, proceeded automatically owing to the proposed reconfiguration methods. For example, the communication initialization, physical layout change, layout change detection and update, message-based control program update, and test runs including monitoring software update took 4, 13, 5, 3, and 10 min respectively in the case of level 3 reconfiguration as shown in Table 4.

In general, it is time-consuming to develop a new workstation that involves system design and configuration, software programming, and test & calibration. Similar assembly workstations, rHous and sHous were developed by a group of graduate students. rHous consists mainly of a 2.5-axis gantry robot and a linear actuator as a main manipulator, InterP, DirectP and a subpart feeder that performs 45 assembly subtasks including transfer, 'push, rotate, pick and place operations whereas sHous employs a 6 axis robotic arm, for which programming library and user-friendly interface were provided by the manufacturer (Universal Robotics, Odense, Denmark). As summarized in Fig. 13, the students spent approximately 6 weeks by using the RFCP procedure to develop rHous, whereas it took slightly less than double that time for sHous without RFCP.

Table 4 Experimental results for level 2 and 3 reconfigurations

Reconfiguration phase	Reconfiguration level 2			Reconfiguration level 3		
	Time (min)	NoM		Time (min)	NoM	
		Send	Receive		Send	Receive
LR						
Step 1	2	14	14	4	18	18
Step 2	(2)		2	13		
Step 3, 4	4		36	5		36
PR	1	18	24	3	18	36
MU	8	18	18	10	18	18
Total	15	50	92	35	54	108

LR: self-layout recognition, PR: parametric reprogramming, MU: shop-floor monitoring software update and test-run, NoM: number of messages from/to the coordinator

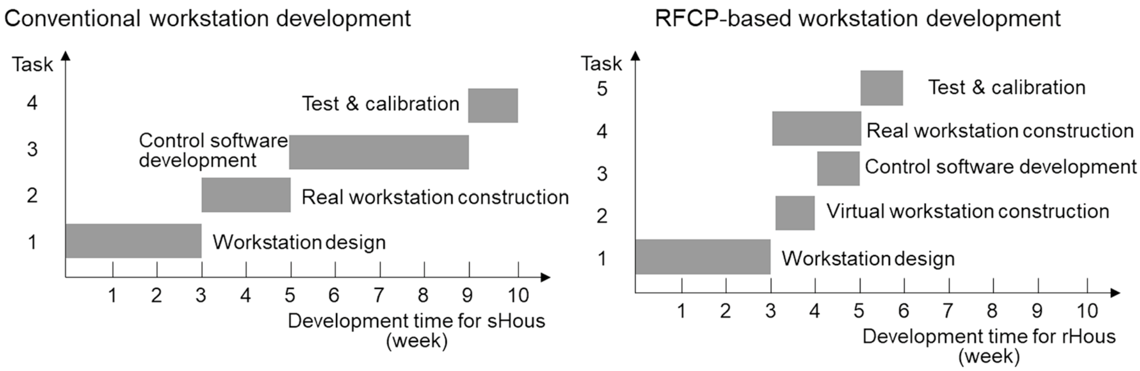


Fig. 13 The comparison of workstation development periods: conventional approach (left) and RFCP-based development (right)

The proposed parametric reprogramming approach can change workstation control programs just by transmitting formatted control program messages to a workstation. As summarized in Table 4, small but quick changes were made in workstation operations by the parametric reprogramming approach.

The coordinator, workstation agents, and workstation executors interactively communicate with each other by using the pre-defined message protocol. The numbers of send/receive messages from/to the coordinator are 50/92 for the reconfiguration level 2, and 54/108 for the reconfiguration level 3 respectively. Every workstation agent sends reference messages including physical connection states to the coordinator whereas the coordinator sends a reconfiguration command and request messages especially at the self-layout recognition. Moreover, in the parametric reprogramming phase, the coordinator additionally receives the messages of control codes. For these reasons, the number of receiving messages is greater than the sending messages.

As shown in Table 4, the shop-floor monitoring software was reconfigured by the user after the control program update process. It is necessary to set and test a data analysis strategy for the newly selected sensors, and thus it took a relatively longer time to update the monitoring software.

Future research challenges

The testbed was developed for research and educational purposes, and therefore there are still many future challenges and various issues for the industry, ranging from the early design phase to product warranty claims.

Robot teaching by visual demonstration

In recent decades, direct teaching by demonstration and related sensor technologies, e.g., multi-axis force/torque sensors, have seen substantial developments for robot programming, which demonstrates the possibility of human–robot collaboration on the shop-floor. In particular, recent machine vision technologies such as hand position tracking (Vakanski et al. 2017), sparse feature tracking by motion segmentation and component pose estimation (Pillai et al. 2015), and grasp force adaptation (Pham et al. 2015), have been incorporated into robot teaching in order to help a robot itself understand the complex hand movements and gestures of a human worker who is demonstrating, for example, how to perform an assembly task using two hands. Interpretation of the elaborate human finger movements involved in assembly operations remains a task for future research.

Transformable jig and fixture

Robot paths for new tasks can be updated by robot programming methods, whereas it is usually necessary to develop new jigs and features in order to securely hold new products or workpieces. Therefore, it is necessary to develop a shape-transformable jig and fixture system, e.g., a pin-jig system or a modular fixturing system to enable efficient production of multiple products on the same workstation. In order to ensure assembly quality using such a non-dedicated jig and fixture system, the positioning of product components must be optimized through stress and deformation analysis based on the geometric features of assembly parts.

Tracking and tracing across the product lifecycle

In the past, decisions to commence manufacturing were made after developing a physical prototype and testing its functionality and performance. However, the advent of advanced simulation and optimization technologies has provided the capability for pre-evaluation and refinement, so that design and ramp-up periods have been dramatically reduced across the entire product lifecycle. Nevertheless, many unforeseen system failures and product quality problems persist during the high-usage phase of products. These critical issues cannot always be predicted at final product inspection during manufacturing, such as in cases where all important quality control metrics satisfy the specified tolerances. The root causes of such failures may lie not in manufacturing but may instead originate from the early design phase. Therefore, ideally, a tracking and tracing system would be developed to span the product lifecycle, thereby providing feedback on design problems for manufacturing, in order to avoid repeating the same mistakes, and to provide advice on improving the current design, since all product lifecycle costs are committed at the early design phase.

In-process quality inspection

High-resolution measurement for manufacturing quality inspection usually requires a long calibration and setup time. This has often led to random sample inspection in order to maintain a required takt time. For example, for dimensional quality inspection by either conventional contact or non-contact techniques (e.g., coordinate measuring machines and 3D vision systems), it is very important to accurately locate and fixture a target object in a specified home position. In order to accelerate the measurement procedure in a highly reconfigurable manufacturing system, the automatic coordinate registration of randomly positioned objects represents a challenging research topic. This can be achieved by aligning the 3D CAD model of a target object and the measured point cloud data, by finding an optimal transformation matrix followed by iterative calibration processes.

As another example, irritating noises coming from inaccurately assembled parts could incur potential warranty claims. Therefore, it is necessary to identify those defective parts during the assembly process. Sampling inspection can employ a subjective 'find and fix' method in an anechoic chamber, but this is extremely resource-intensive in terms of inspection time and cost. Therefore, the challenge is to detect noises from defective assemblies in the high ambient noise environment of a typical shop-floor.

Conclusion

This study developed a modular factory testbed for research and pedagogical purposes, emphasizing rapid factory reconfiguration. For rapid factory transformation, this study proposed and tested the following methods: self-layout recognition, rapid workstation and robot reprogramming, inter-layer information sharing, and configurable software for shop-floor monitoring. The developed infrared communication system helps each workstation recognize a physical layout change immediately in the shop-floor. Layout change information will then be automatically reported by using the pre-defined message protocol to all other workstation agents and the coordinator, and hence the required logical update can be accomplished rapidly. RFCP supports a concurrent process of workstation design and control programming in such a way that rapid workstation deployment for new manufacturing processes can be expected. The case studies of different reconfiguration levels demonstrated considerable time-savings in the reconfiguration of production facilities to match the demands of newly introduced products.

The proposed methods and procedures for rapid factory transformation can be practically applied to various discrete assembly and machine shops for consumer products such as home appliances and cars. However, the concept of modularization and fast physical layout reconfiguration, by its nature, does not directly suit for continuous production, e.g., steel & iron manufacturing. Furthermore, a careful economic analysis must precede all other factors to ensure a return on such high investment for realizing reconfigurable workstations.

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