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CNC-controller for flexible fixture in aircraft component manufacturing and assembly

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Abstract: This paper studies the CNC-controller which is suited to control varied type of flexible fixture in aircraft component manufacturing and assembly. It presents and analyses the mechanisms and control requirements of flexible fixture. The hardware and software architecture and implementation of CNC control system are proposed. The flexible fixture mechanism is described using configuration parameters. According to this parameter, the CNC-controller automatically generates the control feature and HMI (human machine interface) operation function. A CNC control system is developed based on the proposed architecture and the system configuration parameters. This system is implemented in a flexible fixture for skin-stringer assembly.

Keywords: CNC, motion control, aircraft assembly, flexible fixture

CateGory Index: TG659

1 INTRODUCTION

Fixtures are important tool in aircraft component manufacturing and assembly. Traditional fixtures have fixed structure. One fixture is dedicated to one assembly task. Flexible fixture, also termed NC fixture (numerical controlled fixture), consists of a basic platform and a number of numerical controlled moveable fixture units with clamps. The fixture can be adjusted to fit different components by controlling movable clamps to the pre-programmed position for fixing. Therefore, fewer fixtures will be needed by using flexible fixture in aircraft manufacturing and assembly. The costs and floor space will also be saved, while high quality is obtained. It costs less time of reconfiguration among the same component family or reconstruction between different productions. [1, 2, 3]

Flexible fixtures are controlled by CNC system. Two shortcomings are found:

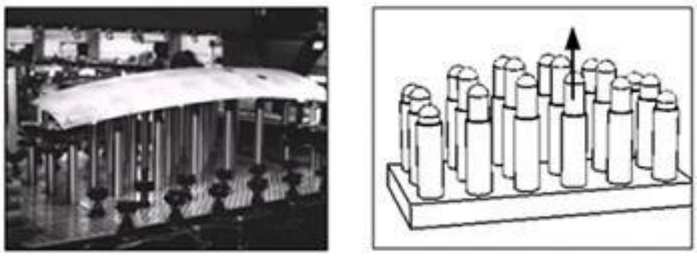
(1) Common commercial CNC system could not satisfy the control requirements of NC fixture, because it could maximally control about 32 drive axes at most, for example, Siemens 840D [4] and Fanuc 30i [5]. However, the number of moveable clamps of one flexible fixture is up to over one hundred. Furthermore, common CNC systems also require high cost because of the complicated control functions that are not used by

flexible fixture.

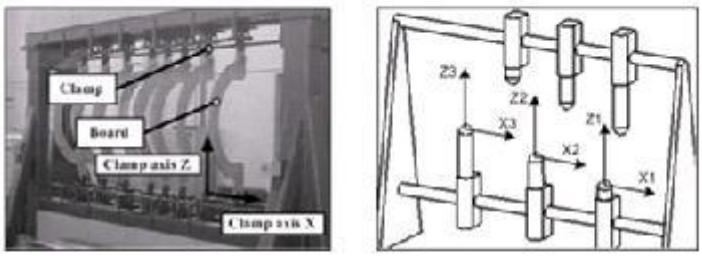
(2) The CNC system, developed by flexible fixture producer, could be hardly applied to fixture mechanism of different types or the fixtures produced by different companies [6, 7].

This paper aims to introduce a CNC-controller which serves as a general platform to satisfy the control requirements of almost all types of NC fixture. The software and hardware architecture of control system provides the features to satisfy the requirements of the most types of flexible fixture. It analyzed the mechanisms and control requirements of commonly used flexible fixtures in aircraft production, proposed CNC-controller architecture based on field bus topology, and developed a CNC-controller for flexible fixture control system. The presented CNC-controller can control up to 250 axes of coordinate. Considering different mechanisms of flexible fixture, a method of system configuration is proposed. The mechanism of flexible fixture will be described using system configuration parameters which are input to CNC-controller. According to this parameter, the CNC-controller automatically generates the control feature and especially the HMI (human machine interface) operation function for the defined mechanism.

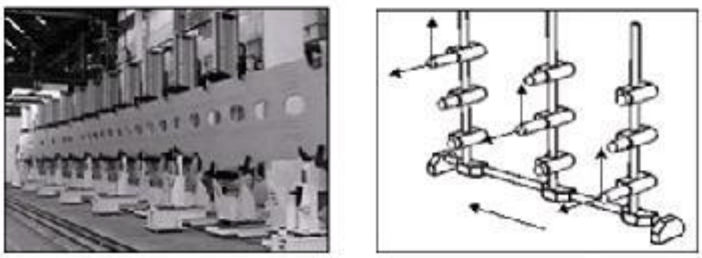
2 MECHANISMS OF FLEXIBLE FIXTURE



(a) Single degree-of-freedom



(b) Two degree-of-freedom



(c) Three degree-of-freedom

Fig.1 Mechanisms of flexible fixture

A lot of research on flexible fixture was achieved since mid 1980's and early 1990's. The research was accomplished by many enterprises and research institutes such as McDonnell Douglas and M.I.T. [1]. Nowadays, flexible fixtures are efficiently used by aircraft producers: EADS CASA [8], Boeing [9, 10], and Airbus [3, 11, 12]. Three main types of flexible fixture mechanism are commonly found in aircraft production, as shown in Figure 1. The mechanisms are classified into three types according to motion freedom and combination of clamps.

- Single degree-of-freedom mechanism (Figure 1a). Each clamp of this mechanism has only one degree-of-freedom controlled by servo motor, e.g. milling fixture. It is used for sheet-forming [13] or aircraft skin milling [14].
- Two degree-of-freedom mechanism (Figure 1b). Each clamp of this mechanism has two degree-of-freedom controlled by servo motors separately, e.g. assembly fixture [15, 16].
- Three degree-of-freedom mechanism (Figure 1c). Each clamp of this mechanism has three degree-of-freedom. Two freedom degrees are controlled independently by servo motors, and the third one is controlled together with some other clamps by one servo motor, e.g. riveting fixture. It is used to fix panel or spars for drilling, milling, and riveting [12].

3 REQUIREMENTS ON CNC-CONTROLLER

To satisfy the requirements of flexible fixture, the CNC-controller of flexible fixture should possess three main features:

Motion control

CNC control system controls the movements of all clamps by servo motors as shown in Figure 1. CNC-controller executes NC program so that clamp can reach final position with programmed velocity. Unlike common CNC-controller of machine tool, multi-axis interpolation is not required. Only the final position of each axis should be specified, while the clamp path accuracy is less significant.

System configuration

The CNC control system of flexible fixture should be available to control over 200 control axes [17, 18, 19]. It must be suitable for three types of mechanism according to the analysis result of section 2. The CNC-controller provides the following functions to satisfy the requirements:

(1) Clamp axis grouping for HMI according to mechanism of flexible fixture.
(2) Automatic HMI generation, including operation, display, diagnosis, and function of data file edit.
(3) Mapping between drive axes and programming control axes.

Drive communication

CNC-controller connects servo drives using field bus which is suited to long distance and multi-device control. Servo drive products are provided by servo drive manufacturer using different communication protocol and topology. It is necessary that CNC-controller can match the servo drive products with varied category of communication and topology.

4 ARCHITECTURE OF CNC CONTROL SYSTEM

The architecture of CNC control system is illustrated in Figure 2. It consists of 4 essential modules, including HMI, NC function kernel, field bus communication, and servo drive. HMI and NC function kernel are realized by software integrated in industrial PC.

Based on PC, HMI provides the operation interface and functions. NC function kernel is a software module and contains series of numerical control function. Field bus communication connects CNC-controller and servo drive. Usually, two types of network topology are provided by servo manufacturer in Figure 3:

(1) Bus type: Servo drives have open interface and protocol to users and can communicate with CNC-controller directly as shown in Figure 3a.

(2) Tree type: Servo drives use only company internal field bus interface, which is controlled by PLC. PLC provides open field bus interface or serial communication interface (e.g. RS422) to users. In this case, PLC is available to communicate with CNC-controller, as shown in Figure 3b.

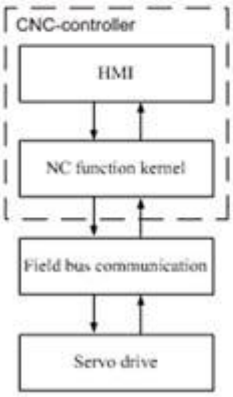
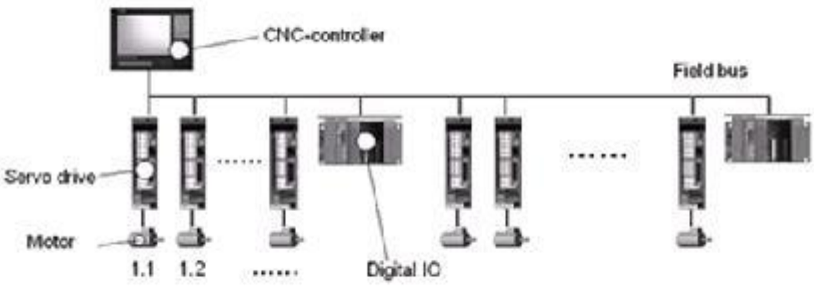
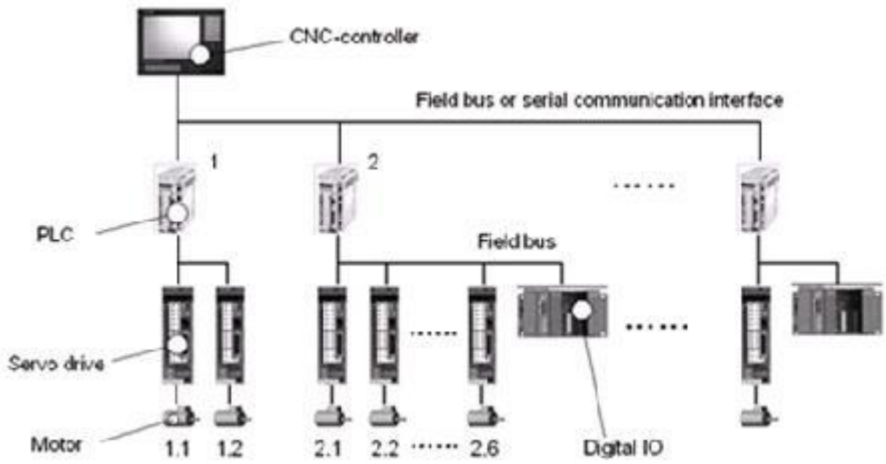


Fig. 2 CNC control system architecture



(a) bus network



(b) tree network

Fig. 3 Network topology of field bus communication

5 SYSTEM CONFIGURATION

In order to use CNC-controller in various NC fixture mechanisms and network topology without software modification, the system configuration of CNC-controller is an essential function. The CNC-controller can generate HMI display function and NC control function automatically by using system configuration parameters to satisfy a certain fixture and network topology. Three steps followed are necessary:

Clamp axis name definition

In order to control a clamp, each clamp axis is defined by a given name, such as X1 and Z1, in Figure 1b. The given name is used for display, HMI operation, and NC program control.

Axis grouping

The clamp axes are organized by logic group as shown in Figure 4. For example, logic group 1 consists of clamp axes of X1, Z1, X2, Z2, X3, and Z3. Clamp axes collected in one logic group will be displayed in a same screen page of HMI. The logic grouping is designed by the user or operator of CNC-controller.

Logic identification (L) is the index or address number of a clamp axis in logic group. Each clamp axis has unique logic identification. For example, L1.2 represents the second axis in the first logic group and its clamp axis name is Z1.

Servo drives are organized by physical group that is coincident with communication network topology.

Physical identification (P) is the index or address number of a servo drive in physical group. The physical identification equals to physical address of servo drive in field bus communication. For example, P2.6 represents servo drive No.6 connecting with PLC No.2 and its physical address in field bus communication is 2.6. Thus, field bus topology can be specified by physical identification.

Axis mapping

To determine the relation between clamp axis and servo drive, the axis mapping process is necessary.

Axis mapping defines the relation between fixture mechanism and CNC-controller software so that the CNC-controller can be adapted to various types of mechanisms and network topology. As shown in Figure 4, the logic identification L1.2 (Z1) corresponds with physical identification P2.5.

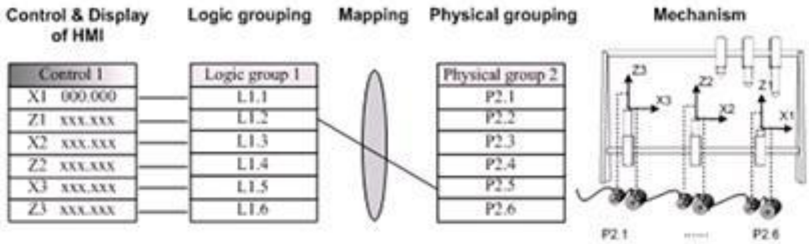


Fig. 4 Example of axis grouping and mapping

6 REALIZATION OF CNC-CONTROLLER

Control functions are realized by computer software. The architecture and data stream of CNC-controller are illustrated in Figure 5.

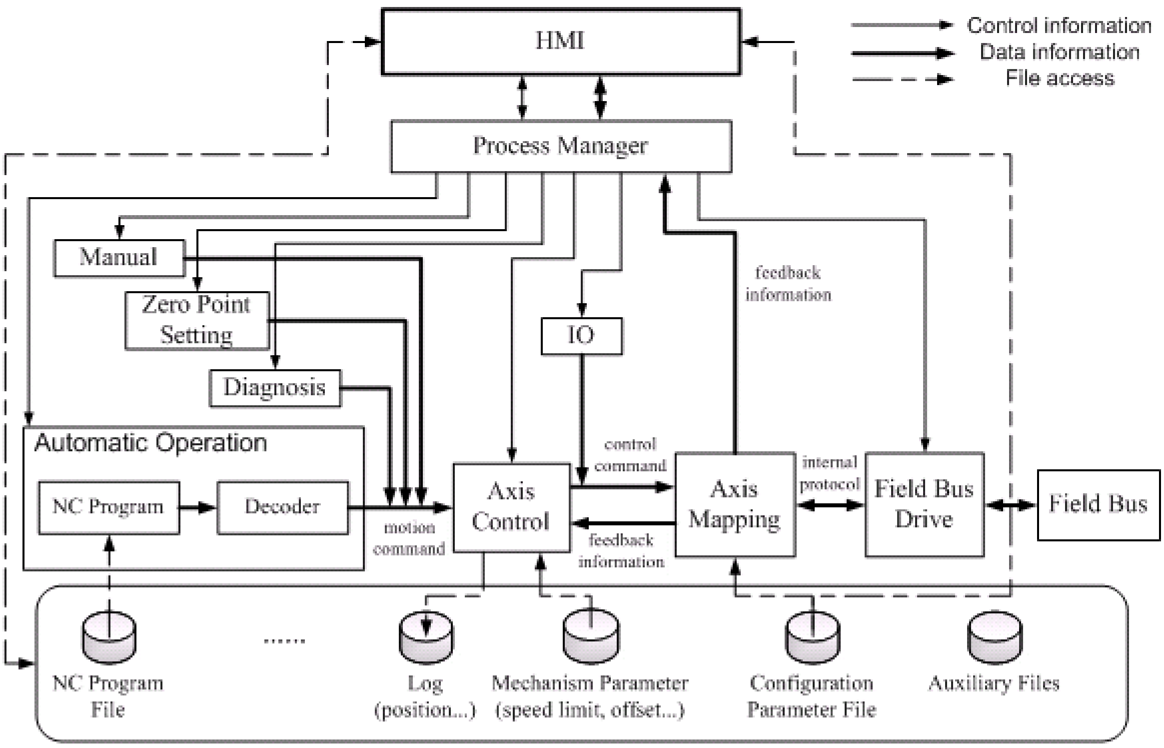


Fig. 5 CNC-controller software architecture and data stream

HMI and process manager

HMI exchanges control and display information with process manager.

Process manager determines control process and the execution of software blocks to realize the operation modes, including automatic operation, manual operation, zero point setting, MDI (manual data input), diagnosis, NC program edit, system configuration parameter edit, data file management, and system management.

Axis control

The software block of automatic operation, manual operation, zero point setting, and diagnosis generates motion command. The command is sent to axis control block. The main functions of axis control include position interpolation, acceleration/deceleration control, feed rate override, and feed hold. Axis control block can also be used to control servo drive with integrated positioning function. In this case, the position interpolation function should be switched off.

Automatic operation and NC program format

In automatic operation mode, CNC-controller moves the clamps automatically to the programmed position and fixes them according to NC program so that manufacturing and assembly process can continue. Table 1 shows the data format of NC program. Comparing with ISO dialect NC programming, this NC program format is simpler to record and represent a positioning program.

The items of number, name, position, velocity, and compensation define respectively the motion sequence, clamp axis name, clamp position, feed rate, and position error compensation value. Position error compensation is necessary to reduce the mechanical error of clamp axis. CNC-controller stores and transfers NC program information in XML format. Thus, it can exchange program file with CAD/CAM and other application software.

Table 1 NC program format

Number	Name	Position/mm	Velocity/mm·min^{-1}	Compensation/mm
1	X1	800.000	500	0.21
2	X2	500.000	500	0.35
3	X3	100.000	500	0.47

Axis mapping and system configuration

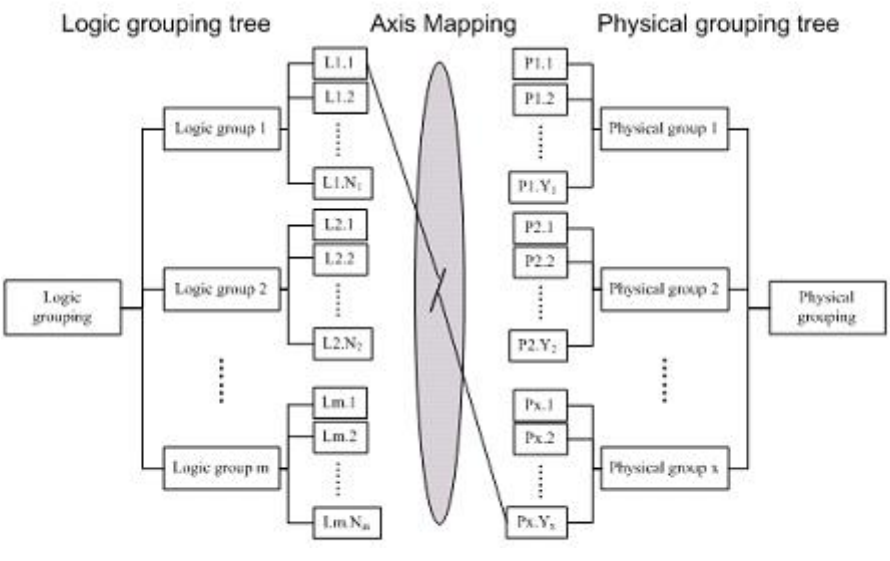


Fig. 6 Data structure for axis mapping

Axis mapping block transfers control command from logic group to physical group. The mapping relation between axes of logic group and axes of physical group is defined in the file of system configuration parameters. Axis mapping block uses two types of data structure (Figure 6), which are created by CNC-controller according to the system configuration parameters:

(1) The data structure of physical grouping tree is as same as the field bus communication network topology. The nodes of physical group correspond with PLC components in tree network (Figure 3b). There is only one physical group in the tree, if the system consists of bus network (Figure 3a).

(2) The data structure of logic grouping tree describes the screen page of HMI. CNC-controller generates screen page automatically using this data structure. The information used by control functions in software is stored based on this data structure.

Field bus drive and protocol

SERCOS, Profibus, and Industrial Ethernet are field bus and protocol mostly used in servo drive. The field bus drive of CNC-controller must satisfy the two topology types and multiple kinds of protocol.

Control command will be sent to servo drive by field bus communication. In order to connect servo drive using different field bus protocol, an internal protocol is defined as shown in Table 2. It includes the data format of command frame and feedback frame. A protocol adaptor in software can convert the data between internal protocol and the drive protocol.

Table 2 Internal protocol

Physical Id.	Type	Mode	Data

Physical Id.	Physical identification
Type	Device type A: PLC B: Servo drive C: Digital IO
Mode	Data mode A: Drive command B: Drive status C: Parameter read/write
Data	Command data or feedback data

7 APPLICATION

CNC-controller serves as a general platform and is implemented in a skin-stringer assembly fixture as shown in Figure 1b. This fixture is used to fix board for fuselage or wing component assembly. It consists of 16 clamps to fix board. Each clamp has two degree-of-freedom. Skin-stringer assembly fixture and its control system are shown in Figure 7. The control system consists of industrial PC, 2 PLCs, and 32 servo drives. CNC-controller is realized by software based on PC. The motion of one clamp is controlled by 2 servo drives. Servo motor and PLC are products of AMK, Germany. Motors with integrated servo drive are linked to PLC by CANopen field bus. CNC-controller controls PLC by RS422 serial interface. It coincides with tree network (Fig. 3b).

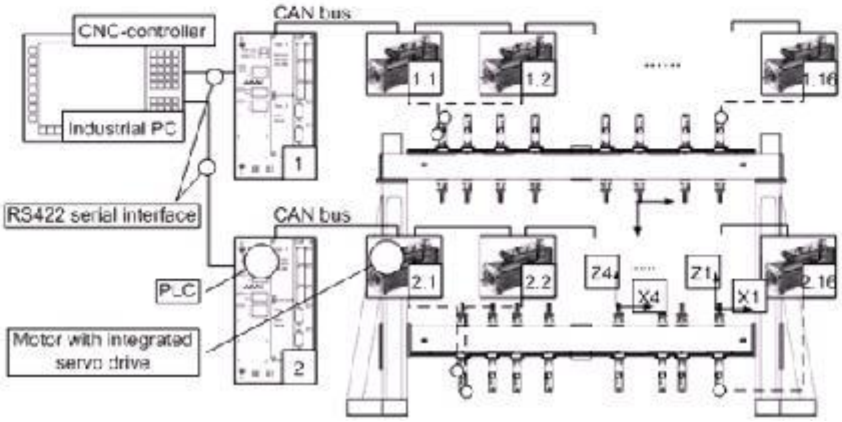


Fig. 7 Skin-stringer assembly fixture and control system

It is only necessary to modify the file of system configuration parameters, while the CNC-controller is implemented in a flexible fixture. Table 3 outlines a part of the file of system configuration parameters, which is used by the skin-stringer assembly fixture. After giving the system configuration parameters, the CNC-controller automatically generates the HMI operation function (Fig. 8) and servo drive mapping. Control command with logic identification is transferred to physical identification according to mapping relation. The feedback information for display, diagnosis, and process monitoring are sent back to CNC-controller from physical axis by inverse mapping. For example, the servo motor (2.16) drives clamp axis X1. And the control information of X1 is displayed as the first axis in the first screen page (L1.1).

The measurement result shows that the positioning accuracy of the fixture in the vertical and horizontal direction is within ±0.05mm. The adjustment time between different components is within 3 minutes. Figure 1b shows that the boards are fixed for component assembly.

Table 3 Example of configuration parameters

No.	Logic Id.	Clamp axis name	Physical Id.
1	L1.1	X1	P2.16
2	L1.2	Z1	P2.15
3	L1.3	X2	P2.14
4	L1.4	Z2	P2.13
5	L1.5	X3	P2.12
6	L1.6	Z3	P2.11
…	…	…	…

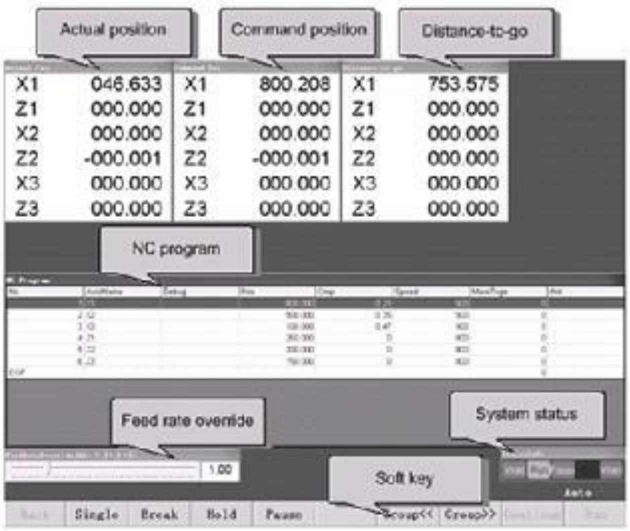


Fig. 8 Automatic operation screen page

8 CONCLUSION

This paper proposed CNC control architecture and described a control system for flexible fixture control. Hardware and software architecture of CNC control were considering the commonly used flexible fixture and NC technology. The developed control system can satisfy the requirements of flexible fixture and various mechanisms in aircraft production without software modification. The CNC control system was used in a skin-stringer assembly fixture in practice, which demonstrated the feasibility and advantages.

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