# CNC SYSTEM OF FLEXIBLE FIXTURE IN AIRCRAFT COMPONENT MANUFACTURING AND ASSEMBLY

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**Abstract**: The computer numerical control (CNC) system is suited to control varied types of flexible fixtures in aircraft component manufacturing and assembly. The mechanisms and control requirements of flexible fixtures are presented and analyzed. The hardware and software architecture and implementation of CNC system are proposed. The flexible fixture mechanism is described using configuration parameters. According to the parameters, the CNC system automatically generates the control feature and the human machine interface (HMI) operation function. The CNC system is implemented in a flexible fixture for skin-stringer assembly, and results show the effectiveness of the system.

**Key words**: computer numerical control (CNC); motion control; aircraft assembly; flexible fixture

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## INTRODUCTION

Fixtures are important tools in aircraft component manufacturing and assembly. Traditional fixtures have fixed structure. One fixture is dedicated to one assembly task. Flexible fixture, also termed numerical controll (NC) fixture, consists of a basic platform and a number of NC 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 are needed by using flexible fixture in aircraft manufacturing and assembly. The costs and floor space are also saved, while high quality is obtained. It costs less time of reconfiguration among the same component families or reconstruction between different productions[1-3].

Flexible fixtures are controlled by computer numerical control (CNC) system. Two shortcomings are found:

(1) Common commercial CNC system cannot satisfy the control requirements of NC fixture, because it can 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 in flexible fixture.

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

This paper aims to introduce a CNC system which serves as a general platform to satisfy the control requirements of almost all types of NC fixtures. The software and hardware architecture of control system provides the features to satisfy the requirements of the most types of flexible fixtures. This paper also analyzes the mechanisms and control requirements of commonly used flexible fixtures in aircraft production, and proposes a CNC system based on field bus topology for flexible fixture control system. The CNC system can control up to 250 axes of coordinate. Considering different mechanisms of flexible fixture, a method for system configuration is proposed. The mecha-

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nism of flexible fixture is described using system configuration parameters which are input to CNC system. According to the parameters, the CNC system automatically generates the control feature and especially the human machine interface (HMI) operation function for the defined mechanism.

# 1 MECHANISMS OF FLEXIBLE FIXTURE

A lot of research on flexible fixture was achieved from mid 1980′s to early 1990′s. The research was accomplished by many enterprises and research institutes such as McDonnell Douglas and MIT[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 mechanisms are commonly found in aircraft production, as shown in Fig. 1. The mechanisms are classified into three types according to motion freedom and combination of clamps.

(1) Single degree-of-freedom (DOF) mechanism (Fig. 1(a)). Each clamp of this mechanism has only one DOF controlled by servo motor, e. g. milling fixture. It is used for sheet-forming[13] or aircraft skin milling[14].

(2) Two DOFs mechanism (Fig. 1(b)). Each clamp of this mechanism has two DOFs controlled by servo motors separately, e. g. assembly fixture[15-16].

(3) Three DOFs mechanism (Fig. 1(c)). Each clamp of this mechanism has three DOFs. Two DOFs 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].

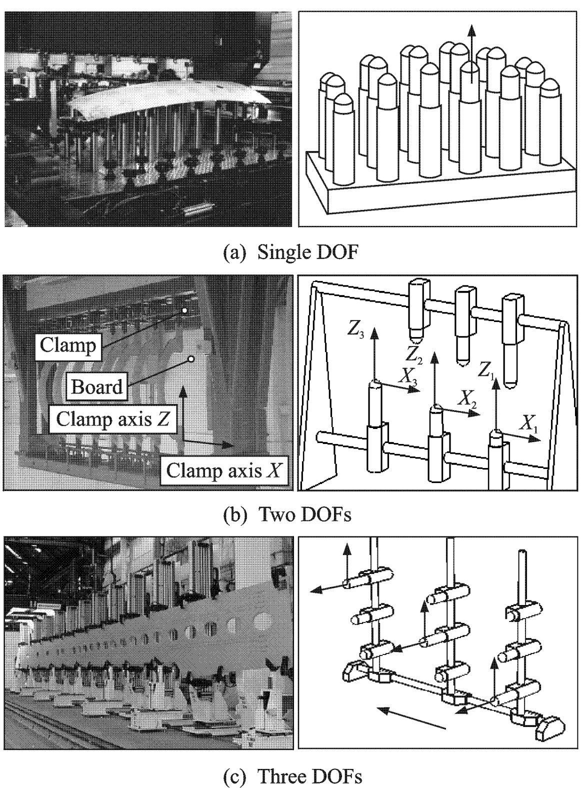


Fig. 1 Mechanisms of flexible fixture

# 2 REQUIREMENTS OF CNC SYSTEM

To satisfy the requirements of flexible fixture, the CNC system should possess three main features.

## 2.1 Motion control

The CNC system controls the movements of all clamps by servo motors as shown in Fig. 1, and executes NC program so that clamp can reach final position with programmed velocity. Unlike common CNC system 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.

## 2.2 System configuration

The CNC system should be available to control over 200 control axes[17-19]. It must be suitable for three types of mechanisms according to the analysis result of section 1. The CNC system 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.

### 2.3 Drive communication

The CNC system 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 the CNC system can match the servo drive products with varied categories of communication and topology.

## 3 ARCHITECTURE OF CNC SYSTEM

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

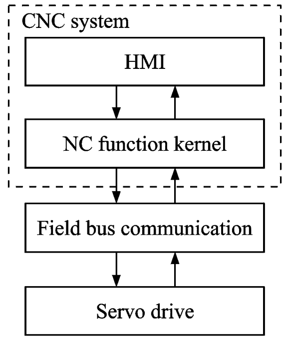


Fig. 2 CNC system architecture

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 system and servo drive. Usually, two types of network topologies are provided by servo manufacturer in Fig. 3.

(1) Bus type: Servo drives have open inter-

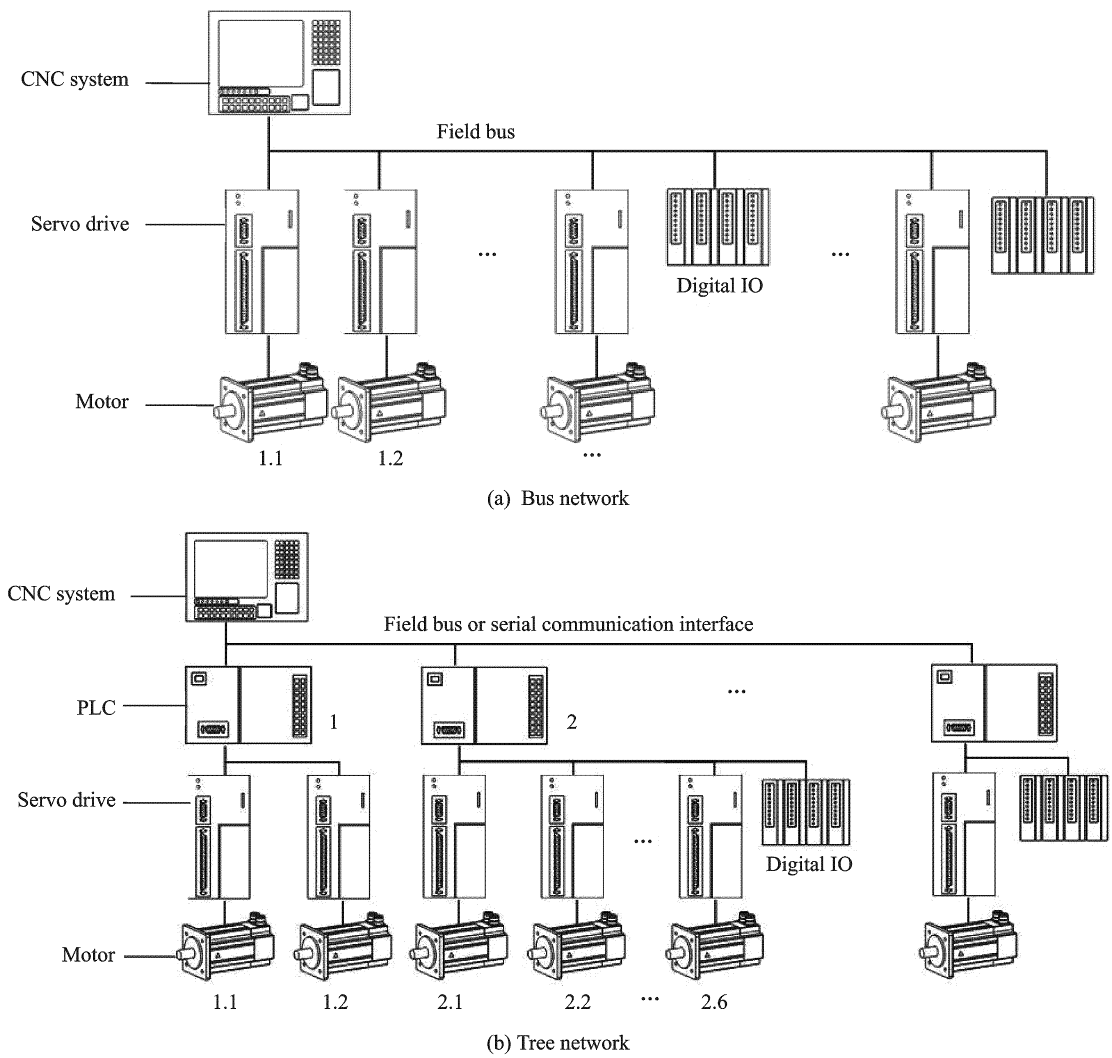


Fig. 3 Network topologies of field bus communication

face and protocol to users and can directly communicate with CNC system, as shown in Fig. 3(a).

(2) Tree type: Servo drives only use 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 system, as shown in Fig. 3(b).

# 4 SYSTEM CONFIGURATION

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

## 4.1 Name definition of clamp axis

In order to control a clamp, each clamp axis is defined by a given name, such as $X_1$ and $Z_1$, as shown in Fig. 1(b). The given name is used for display, HMI operation, and NC program control.

## 4.2 Axis grouping

The clamp axes are organized by logic group as shown in Fig. 4. For example, logic group 1 consists of clamp axes of $X_1$, $Z_1$, $X_2$, $Z_2$, $X_3$, and $Z_3$. Clamp axes collected in one logic group are displayed in a same screen page of HMI. The logic grouping is designed by the user or operator of CNC system.

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 $Z_1$.

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.

## 4.3 Axis mapping

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

Axis mapping defines the relation between fixture mechanism and CNC system software so that the CNC system can be adapted to various types of mechanisms and network topologies. As shown in Fig. 4, the logic identification L1.2 ($Z_1$) corresponds with physical identification P2.5.

# 5 REALIZATION OF CNC SYSTEM

Control functions are realized by computer software. The architecture and data stream of CNC system are illustrated in Fig. 5.

## 5.1 HMI and process manager

HMI exchanges control and display informa-

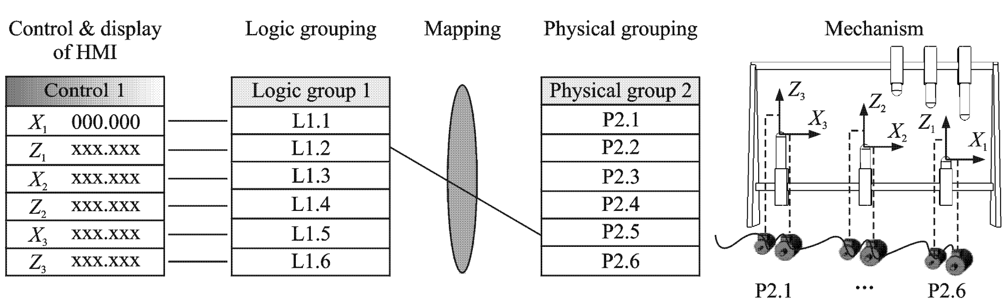


Fig. 4 Example of axis grouping and mapping

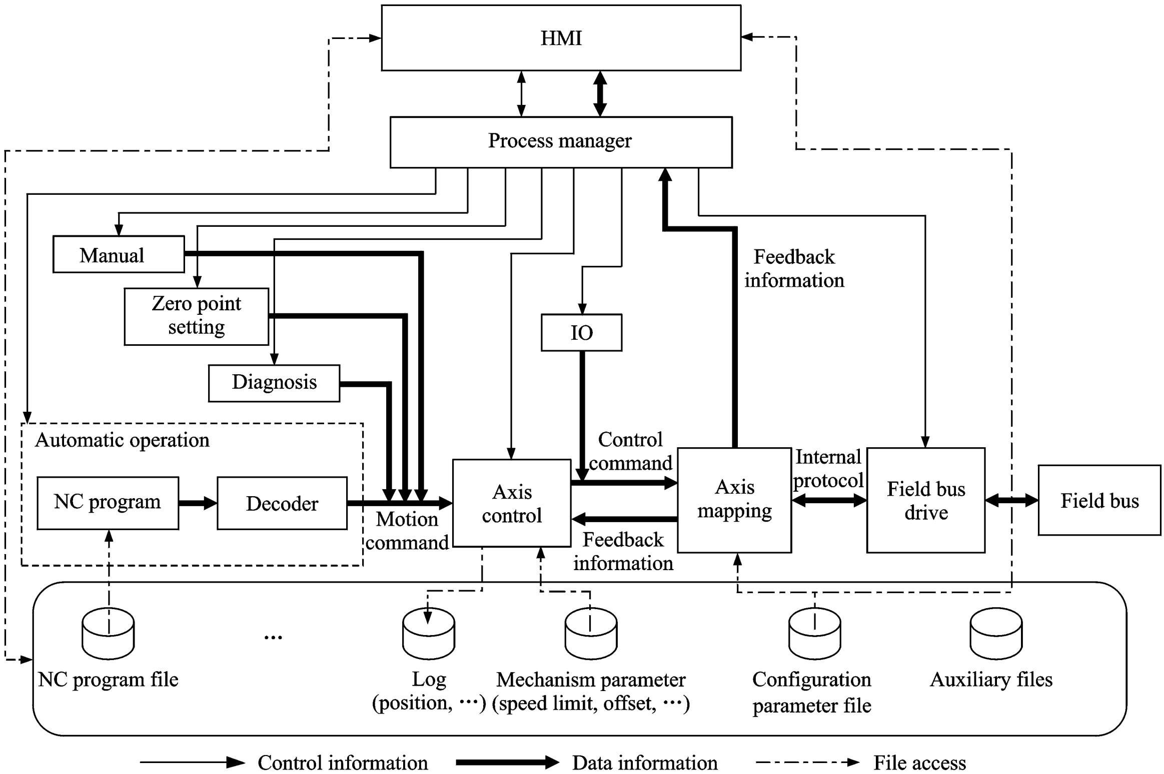


Fig. 5 Software architecture and data stream of CNC system

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

## 5.2 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.

## 5.3 Automatic operation and NC program format

In automatic operation mode, the CNC system automatically moves the clamps 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. Compared with ISO dialect NC programming, the NC program format is simpler to record and represent a positioning program.

The items of number, name, position, velocity, and compensation respectively define 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. The CNC system 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 | $X_1$ | 800.000 | 500 | 0.21 |
| 2 | $X_2$ | 500.000 | 500 | 0.35 |
| 3 | $X_3$ | 100.000 | 500 | 0.47 |

### 5.4 Axis mapping and system configuration

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

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

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

### 5.5 Field bus drive and protocol

Serial real time communication specification (SERCOS), Profibus, and Industrial Ethernet are field bus and protocol mostly used in servo drive. The field bus drive of CNC system must satisfy the two topology types and multiple kinds of protocols.

Control command is sent to servo drive by field bus communication. In order to connect servo drive using different field bus protocols, 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 the internal and the drive protocols.

**Table 2 Internal protocol**

| Item | Content |
|---|---|
| Physical ID | Physical identification |
| Device type | A: PLC<br>B: Servo drive<br>C: Digital IO |
| Data mode | A: Drive command<br>B: Drive status<br>C: Parameter read/write |
| Data | Command data or feedback data |

## 6 APPLICATION

The CNC system serves as a general platform and is implemented in a skin-stringer assembly fixture as shown in Fig. 1(b). The fixture is used to fix board for fuselage or wing component as-

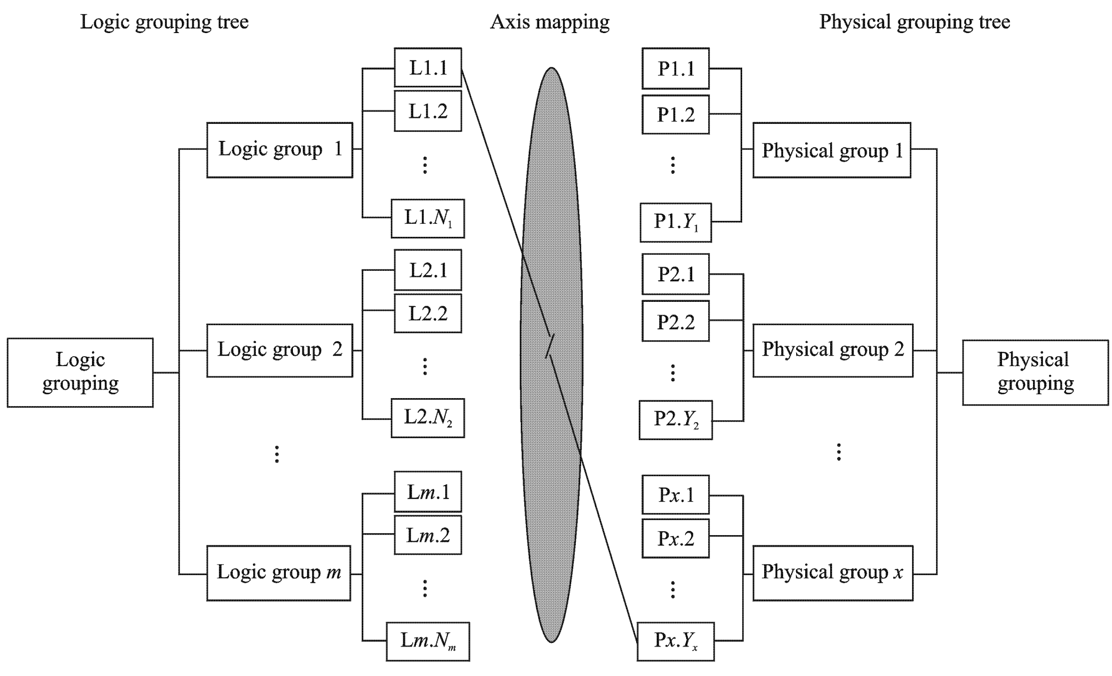


Fig. 6 Data structure for axis mapping

sembly. It consists of 16 clamps. Each clamp has two DOFs. Skin-stringer assembly fixture and its control system are shown in Fig. 7. The control system consists of industrial PC, two PLCs, and 32 servo drives. The CNC system is realized by software based on PC. The motion of one clamp is controlled by two servo drives. Servo motor and PLC are products of AMK, Germany. Motors with integrated servo drive are linked to PLC by CANopen field bus. The CNC system controls PLC by RS422 serial interface. It coincides with tree network (Fig. 3(b)).

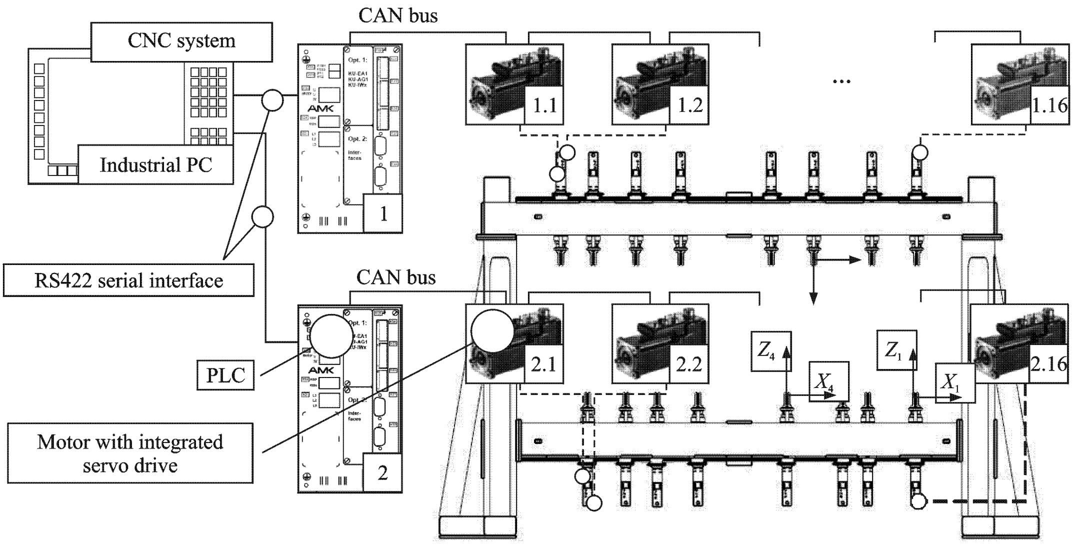


Fig. 7 Skin-stringer assembly fixture and control system

It is only necessary to modify the file of system configuration parameters, while the CNC system is implemented in a flexible fixture. Table 3 outlines a part of the file of system configuration parameters, which is used in the skin-stringer assembly fixture. After giving the system configuration parameters, the CNC system automatically generates the HMI operation function (Fig. 8) and servo drive mapping. The 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 system from physical axis by inverse mapping. For example, the servo motor (2.16) drives clamp axis $X_1$. And the control information of $X_1$ 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 directions is within $\pm 0.05$ mm. The adjustment time between different components is within 3 min. Fig. 1(b) shows that the boards are fixed for component assembly.

**Table 3 Example of configuration parameters**

| No. | Logic ID | Clamp axis | Physical ID |
|---|---|---|---|
| 1 | L1.1 | $X_1$ | P2.16 |
| 2 | L1.2 | $Z_1$ | P2.15 |
| 3 | L1.3 | $X_2$ | P2.14 |
| 4 | L1.4 | $Z_2$ | P2.13 |
| 5 | L1.5 | $X_3$ | P2.12 |
| 6 | L1.6 | $Z_3$ | P2.11 |
| ⋮ | ⋮ | ⋮ | ⋮ |

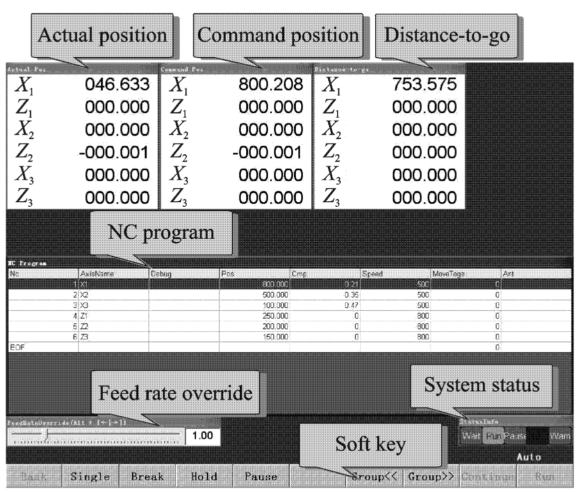


Fig. 8 HMI operation function display

## 7 CONCLUSION

This paper proposes a CNC system for flexible fixture control. Hardware and software architecture of the CNC system considers the commonly used flexible fixture and NC technology. Therefore, the CNC system can satisfy the requirements of flexible fixture and various mechanisms in aircraft production without software modification. And it is used in a skin-stringer assembly fixture in practice, which demonstrates the feasibility and advantages.

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# 用于飞机零部件制造装配的柔性工装数控系统


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**摘要**:研究了柔性工装计算机数字控制(Computer numerical control,CNC)系统,该系统适于控制多种用于飞机零部件制造和装配的柔性工装设备。给出了柔性工装的机械结构分类,分析了柔性工装设备的控制需求。同时提出了一种 CNC 系统的硬件和软件架构,并予以实现。该系统利用配置参数描述柔性工装的机械结构。根据配置参数,CNC 系统可以自动生成其控制功能和人机界面(Human machine interface,HMI)操作功能。将该 CNC 系统应用于某蒙皮-桁条装配柔性工装设备,结果证明了系统的有效性。



**关键词**:计算机数字控制;运动控制;飞机装配;柔性工装

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