

# User-oriented Development Method in FSM-supported Multiprocessor Embedded Programmable Logic Controllers

**Abstract**—Programmable logic controllers (*PLCs*) are a foundation of automation, but applications become complex in logic and motion control mixed scenarios, while a PC-based *PLC* incurs a high monetary cost and comprises a complex system that cannot meet the customized requirements of large equipment. In addition, the development of *PLCs* has encountered bottlenecks. Hence, in this paper, we present a user-oriented development method in which we propose a customized multiprocessor embedded *PLC* (*ePLC*), to enhance the performance, a multi-language supported uniform development platform to improve the adaptability of developers, and an optimized system structure (reasonable memory allocation, user-oriented thread structure, proposed *LPM* data interaction, modular software design, and finite state machines) to reduce the development complexity. Ultimately, we adopt the proposed method to implement a distributed control system on a 200-T injection-molding machine. Through comparison with *TECHMATION* and *KEBA* systems, the startup time of the implemented system was increased by more than 5 times, while the key performance is almost identical. In addition, the implemented system adopts the customized multiprocessor embedded *PLC* and detached human machine interface (*HMI*).

**Index Terms**—Multiprocessor, motion control, injection-molding machine, embedded *PLC*, user-oriented

## I. INTRODUCTION

Some concepts, such as smart factory and intelligent manufacturing [1], [2], and some technologies, such as the Internet of Things, 5G, and augmented reality [3], [4], are paving the road of the fourth industrial revolution. Normally, a typical plant is full of large equipment; for instance, cranes, computerized numerical control (CNC) machining centers, injection-molding machines (*IMMs*), air pumps, chillers, automatic-guided vehicles, and various types of robots, and most of them are controlled by programmable logic controllers (*PLCs*), which have become a primary control system. Numerous researchers are focusing on *PLC* technologies that significantly extend the application fields of *PLCs*. [5]–[7] guaranteed *PLC* reliability by verifying their programming, [8]–[10] improved the performance of *PLCs* using advanced algorithms, [11] alleviated the development complexity of *PLCs* using special software structure, and [12], [13] proposed methods of updating *PLCs* programs dynamically. However, with the rapidly growing demand for, and the trends of, applications to be user-oriented and mix complex logic and motion control [14], [15], *PLCs* still encounter bottlenecks, especially on large equipment (CNC machining centers, *IMMs*, etc.).

### A. Motivations

Currently, the hardware architecture of *PLCs* can take two directions: embedded *PLCs* (*ePLCs*) and PC-based *PLCs*.

PC-based *PLCs* are increasingly used in applications of complex logic and motion control mixed scenarios on account of its high performance and numerous user-oriented tools [15]. Considering the *IMM* industry, Table I lists the composition of *IMMs*, including parts (described as modules for programming), digital input/output (DI/Os), and analog input/output (AI/Os). Normally, the simplest *IMM* system consists of 10 modules, 20 DIIs, 30 DOs, three AIS, and seven AOs. Complex relations among them and the high-performance requirements of algorithms tremendously increase the difficulty of programming. Hence, as listed in Table II, a comparison of *KEBA*, *BECKHOFF*, *GAFRAN*, and *TECKMATION* systems, which are the main brands of *IMM* controllers, illustrates that almost all of them use PC-based *PLCs*. According to the complexity of an *IMM* system and the software architecture of PC-based *PLCs*, the *HMI* is integrated with the *PLC*, which leads to little independence among *IMM* manufacturers.

*ePLCs* have a wide area of application in automation due to their easy programming and high reliability; however, some disadvantages still limit its further development [15], especially when coping with complex logic and motion control mixed applications. In addition, advances in fields such as wireless communication and the Internet of Things, have an accelerated requirement for low-power consumption [16], which is an advantage of *ePLCs*. How to integrate low power consumption, easy programming, and the high reliability of *ePLCs* with high performance and user-oriented development is therefore the focus of this research.

### B. Related Works

Various researchers have presented methods of integrating motion control algorithms (e.g., linear interpolation, position control, arc interpolation, etc.) into *PLCs* [17]–[19], and thus logic control and motion control become inseparable. There are two ways to realize this integration: 1) an individual motion control module integrated with the *PLC* [20], and 2) *PLCs* featuring motion control functions [17], [21]. Regarding an individual motion control module, different kinds of modules and *PLCs* coded in different languages and developed on their own platforms tremendously increase the complexity of implementing applications. [20], [22] and [23] both describe these modules. The second way simplifies the development method; nevertheless, it is difficult to guarantee high-reliability logic control and high-accuracy motion control simultaneously, since they run in the same thread.

We propose the concept of a multiprocessor *ePLC* (multiprocessor chips and multiple cores in one chip are

all called multiprocessors in this paper). In this *ePLC*, extra processors (e.g., DSP, FPGA, etc.) are introduced to enhance performance. Various technologies contribute to the improvement of multiple processors. [24], [25] proposed data-interaction methods among multiple processors, [26] presented a method to balance the computing ability of the processors, [27] proposed a thread-scheduling method in multiprocessors. All of these works are not implemented in the *ePLC*, but have inspired us to build the architecture of a multiprocessor *ePLC*. Moreover, some research [28], [29] introduced additional high-performance processors into *ePLCs*, although no improvement in the development method was proposed for complex logic and motion control mixed applications.

In terms of the development methods of the individual module, which is very convoluted, users should take considerable time in selecting the platform and additional time in learning the particular software and its supported language. For instance, PMAC uses C++ [20], [22], MC421/221 of the OMRON CS1 series is supported by G-Code [30], the FP series *PLC* of Panasonic adopts special instructions embedded in a ladder diagram (LD). Therefore, the uniform development methodology in *PLC* platforms has attracted our interest. Since the 1990s, IEC-61131 has been focused on the standardization of *PLCs* [31]. In 2005, the PLCopen organization released a related standard [32] that standardizes the motion control in *PLCs* and then publications, such as [33], suggested interactions using it, and companies, such as 3S [34], provided some tools. However, regarding such complex applications, programmers occasionally prefer to use more popular or object-oriented languages (e.g., C, C++, etc.) [35]–[37] have accepted the languages specified in IEC-61131-3. Recently, some methods, such as model- and component-based software [38], [39] have also been researched to reduce the complexity of *PLC* programs. However, facing the complex control and motion control scenario, a more comprehensively improved development method still should be proposed. Hence, considering the popular user-oriented concept [40], [41], in this paper we present a user-oriented development method.

### C. Our Contributions

To the best of our knowledge, a user-oriented development method should improve every aspect of the *PLC* system (development method, program, processor, *RAM*, and threading) and contain a comprehensive optimization approach. Hence, we pose a flexible solution to enhance performance by adding sufficient processors, a multi-language-supported graphical component to improve the adaptability of developers, an optimized system structure (reasonable memory allocation, user-oriented thread structure, *LPM* data interaction, modular software design, and finite state machines) to reduce the development complexity. Ultimately, we adopt the proposed method to implement a distributed *IMM* system that is considered a kind of complex logic and motion control mixed application.

This rest of this paper is organized as follows. In Section II, we introduce the system architecture, multi-language supported graphical component, memory allocation, user-oriented

TABLE I  
MODULES, DI/DO, AI/AO OF *IMM*

No.	Module	DI	DO	AI	AO
1	Mold	Safety valve	Mold close	Mold position	System pressure
2	Injection	Heating detection	Mold open	Injection position	System flow
3	Core	Servo alarm	Inject	Nozzle position	Back pressure
4	Nozzle	Motor overload	Charging	Temperature 1	
5	Heating	Emergency button	Green light	Temperature 2	
6	Ejector	Injection shield	Red light	Temperature 3	
7	AirValve	Detection switch	Yellow light	Temperature 4	
...	....	...	...	...	...
50		Screw speed			

TABLE II  
SYSTEM COMPARISON OF PC-BASED *PLC* IN *IMM*

Brand	CPU	ROM	Language	Distributed	HMI
TECHMATION	DSP	Built-in	Assembly language	No	Irreplaceable
KEBA	Intel	1G	IEC61131-3	Yes	Irreplaceable
BECKHOFF	Intel	1G	IEC61131-3	Yes	Irreplaceable
GEFRAN	Intel	1G	IEC61131-3	Yes	Irreplaceable

multi-threading, and modular design. In Section III, we present the compilation of graphical components, the *LPM* data interaction mechanism, the execution of multi-threading, and finite state machines. Finally, in section IV, we implement the *IMM* distributed system with the proposed method and compare it with the TECHMATION and KEBA systems from aspects of system condition, system structure, and key performance.

## II. SYSTEM ARCHITECTURE

### A. Hardware Structure of *ePLC*

Figure 1 shows one type of hardware structure of a multiprocessor *ePLC* that contains a master processor and two slave processors. The master processor is responsible for logic control, communication, etc. The slave processor is designed for complex algorithms that can be customized on demand (the number of processors, DI/Os, AI/Os, and controlled servo motors).

### B. Multi-language supported graphical component

In order to develop the logic program and algorithm program on a uniform platform, we package the algorithm into graphical component that is multi-language-supporting. The component is defined as follows:

$$LDC < Name, ID, PI, RI, PT, SF >, \quad (1)$$

where **Name** is the name of component used to describe the function; **ID** is the unique identifier of the component in the graphical program; **PI** is a collection of service interfaces, including output data interfaces, right serial connection, downwards parallel connection, and some auxiliary interfaces; **RI** is

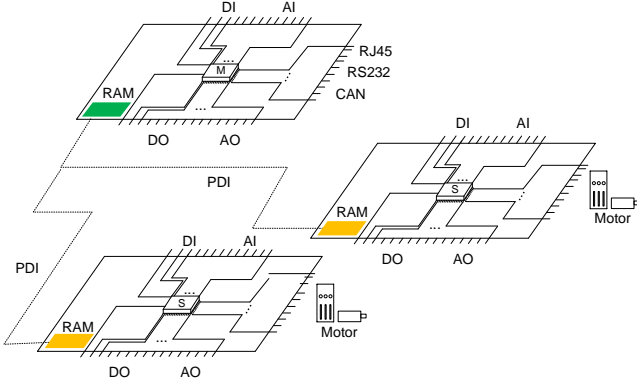


Fig. 1. One type of hardware structure of multiprocessor *ePLC* containing a master processor and two slave processors.

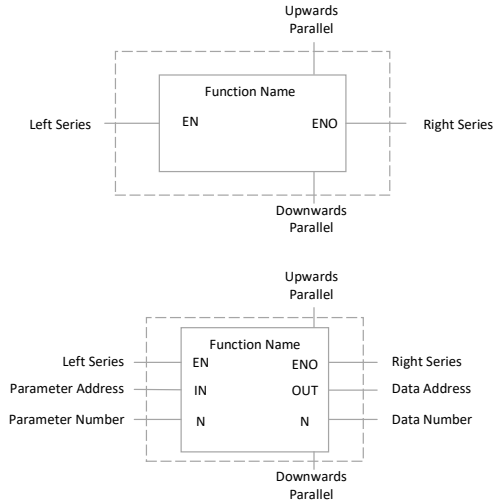


Fig. 2. Two typical designs: single component and component with input and output.

a collection of requirement interfaces, including input data interfaces, left serial connection, downwards parallel connection, and some auxiliary interfaces; **PT** is an attribute collection of the component, including position, size, comment, etc.; and **SF** is the function description explained by specific text, formula, or frame template. The basic graphical components are divided into contact components, functional block components, coil components, cross-line vertical components, change lines, comments, etc. The multi-language component, in particular, includes the development language, the supported compiler, and the executing processor.

Figure 2 illustrates two component designs: a single component and a component with input and output. The single component has function name, left series, right series, upwards parallel, and downwards parallel. The component with input and output contains function name, left series, right series, upwards parallel, downwards parallel, parameter address, parameter number, data address, and data number.

As shown in Fig. 3, from the user's point of view, after inducing the multi-language component, the algorithm and

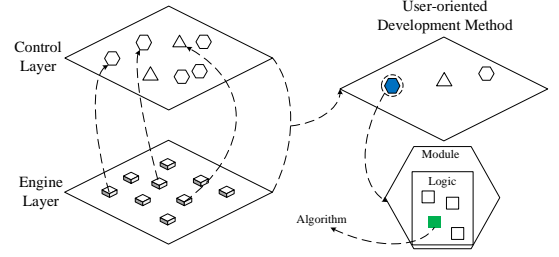


Fig. 3. From the user's point of view, after inducing the multi-language component, the algorithm and logic program can be developed on a uniform *PLC* platform.

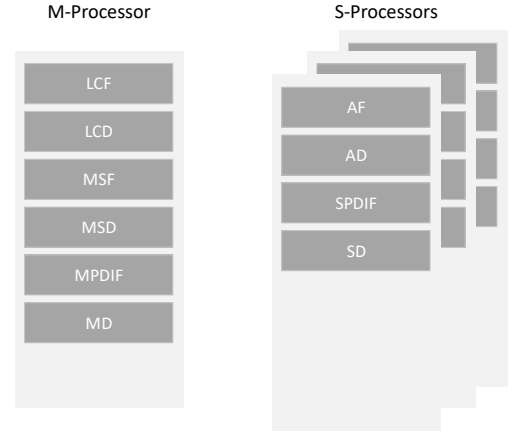


Fig. 4. Memory allocation in master and slave processors.

logic program could be developed in a uniform *PLC* platform. Multi-language components are supported by multiple languages, such as IL instructions, ST language, C language, C++ language, etc. Algorithms contained in components are mainly motion control algorithms.

### C. Memory Allocation

The dedicated storage area of a *PLC* in memory is made up of a bit data area (*M* area) and byte data area (*D* area). Meanwhile, we regard *M* area and *D* area as set *M* of bit and set *D* of byte. Furthermore, in the rest of this paper, if  $\exists$  set *T*, we describe its subscript lower-case letter  $t_i$  as an element of *T*, and the subscript *i* is used to distinguish the elements. Henceforth, two definitions are illustrated below.

**Definition 1** If  $T \subseteq M$ , the value saved in  $t_i \in \{0, 1\}$  and each element  $t_i$  has four operators:  $\mathcal{S}_0(t_i)$  denotes that  $t_i$  is set to 0,  $\mathcal{S}_1(t_i)$  denotes that  $t_i$  is set to 1,  $\mathcal{J}_0(t_i)$  represents that the value of  $t_i$  is judged as 0, and  $\mathcal{J}_1(t_i)$  represents that the value of  $t_i$  is judged as 1. We then define the set *T* as having **B** attribute.

**Definition 2** If  $T \subseteq D$  and  $\forall t_i \in T$  has 4 bytes. We define the set *T* as having **D** attribute.

Figure 4 shows the memory allocation of master and slave processors. All slave processors have the same storage structure.

**LCF** (Logic Control Flag Area): the flags are used to start the modules. It has  $\mathcal{B}$  attribute.

**LCD** (Logic Control Data Area): these data will be used to deliver to the algorithm. It has  $\mathcal{D}$  attribute.

**AF** (Algorithm Flag Area): includes the algorithm flag of execution (*AFE*) and algorithm flag of state (*AFS*). Both have  $\mathcal{B}$  attribute.

**AD** (Algorithm Data Area): these data help the specified algorithm execute. It has  $\mathcal{D}$  attribute.

**MF** (Message Flag Area): includes defined message flag (*DMF*) and user-customized message flag (*UMF*). *DMF* is the necessary message for system execution, e.g., start module flag, alarm flag, etc. *UMF* can be defined by users. Both have  $\mathcal{B}$  attribute.

**MD** (Message Data Area): used to transfer message information, which includes system message data area (*DMD*) and user message data area (*UMD*). It is defined in *D* area.

**MPDIF** (Master Processor Data Interaction Flag Area): contains begin data transfer flag from master to slave (*MSB*), transfer state of master from master to slave (*MSF*), acknowledge flag of master from master to slave (*MSA*), and transfer state of master from slave to master (*MSS*). All have  $\mathcal{B}$  attribute.

**MSD** (Master Processor Data Interaction Data Area): an area that stores the data delivered from slave processors. It has  $\mathcal{D}$  attribute.

**SPDIF** (Slave Processor Data Interaction Flag Area): includes the begin data transfer flag from slave to master (*SMB*), transfer state of slave from slave to master (*SMF*), acknowledge flag of slave from slave to master (*SMA*), and transfer state of slave from master to slave (*SMS*). All have  $\mathcal{B}$  attribute.

**SMD** (Slave Processor Data Interaction Data Area): stores the data delivered from master processor. It has  $\mathcal{D}$  attribute.

#### D. User-oriented Thread Design

From the user's point of view, in most cases, the logic control program (*LCP*) and algorithm program (*AP*) can be developed independently [11]; hence, we have a logic thread and algorithm thread. However, in order to satisfying the ever-growing performance requirements of users, we proposed the customized multiprocessor *ePLC*. Correspondingly, an individual motion thread is designed into every slave processor. The user-oriented thread structure can be seen in Fig 5. Every processor is a four-level pre-emptive scheduling thread structure: **Emergent Thread**, **Communication Thread**, **Diagnose Thread**, and **APC Thread** as seen in [11]. Two special threads are explained below.

**Control Thread**: runs in the master processor and has functions including dealing with DI/O, executing logic program, exchanging data with slave processors, etc.

**Algorithm Thread**: runs in the slave processor and contains functions including interacting data with master, executing algorithm program, controlling actuators, etc.

#### E. Modular Design

In applications, modular design will reduce the complexity of programs [39]. Therefore, we provide a system-level frame

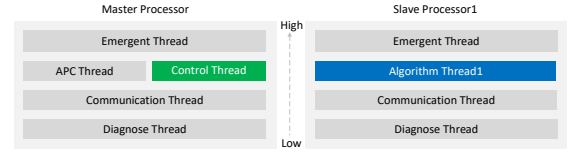


Fig. 5. User-oriented thread design in master and slave processors.

for modular design. The modular design is depicted in Fig. 3. The program is composed of many modules, and a module consists of a logic program and several related algorithms. Modules work under mechanisms: reasonable memory allocation, *LPM* interaction, with a data mechanism, and running multi-threading. Hence, we can define an *ePLC* program as follows:

$$\begin{cases} PS = \{MS, MA, LPM, TD\}, \\ ms_i \in MS = \{lcp_i, \bigcup_{j=g}^h ap_j\}, \\ lcp_i \in LCP = \{ip_i, lcf_i, lcd_i, lpb_i\}, \\ ap_j \in AP = \{afe_j, afs_j, adj, ab_j\}. \end{cases} \quad (2)$$

The programming structure (*PS*) consists of modules (*MS*), memory allocation (*MA*), *LPM* data interaction, and threads (*TD*). Each  $ms_i$  has two parts: a logic control program  $lcp_i$  and several algorithm programs ( $ap_g, ap_{g+1}, \dots, ap_j, \dots, ap_h$ ). Each  $lcp_i$  includes an initial program ( $ip_i$ ), logic control flag ( $lcf_i$ ), logic control data ( $lcd_i$ ), and logic program body ( $lpb_i$ ). Each  $ap_j$  contains  $afe_j$ ,  $afs_j$ ,  $adj$ , and algorithm body ( $ab_j$ ).

### III. SYSTEM IMPLEMENTATION

#### A. Compilation of graphic program

The compilation of the graphic program contains two parts: 1) compiling the graphic language into instruction list, and 2) compiling the multi-language components.

In the first part, since we see the multi-language components as a common component, the compilation of graphic language embedded multi-language components is almost the same as the process of [42], in which readers can find a detailed explanation. For the example shown in Fig. 6, we adopt three steps to implement the first of the two above-mentioned compilations:

**Step 1:** Convert topology structure to directed graph according to LD syntax library and analyze the errors of the topology.

**Step 2:** Generate a binary decomposition tree according to series and parallel rules.

**Step 3:** Generate IL instructions according to the IL grammar library. For multi-language components, it is described as a program entry.

In the second part, the multi-language components are compiled. For the convenience of users, they can still use the same grammar to program the *ePLC* dedicated storage area inside the multi-language component, such as  $M2000 = 1$ , which represents giving 1 to the bit area *M2000*, whereas it is illegal in other languages. Hence, we should compile the component to the identifiable code which contains the following two steps:

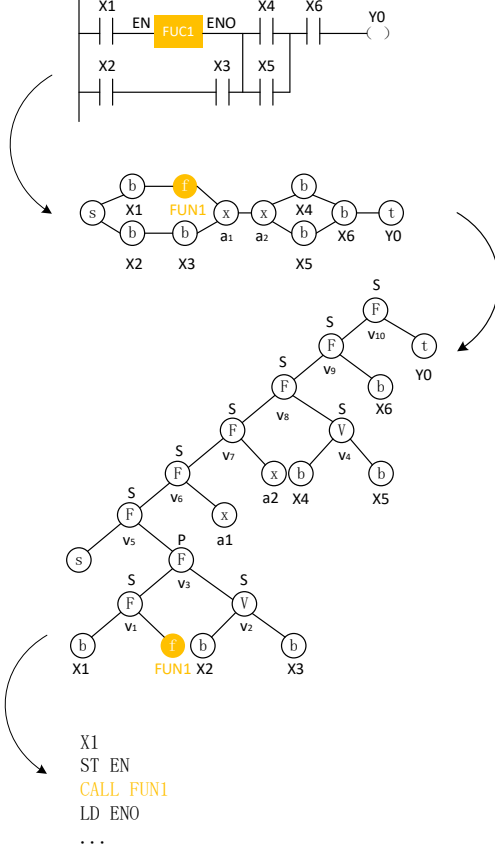


Fig. 6. Three steps in compilation of graphic program, which contains multi-language component: 1) convert topology structure to directed graph, 2) generate a binary decomposition tree, and 3) generate IL instructions.

**Step 1:** Address mapping. Every type of processor has its own address mapping rules (*AMR*), e.g.,

$$APR = \{CID, MAS, DAS, \mathcal{A}_m, \mathcal{A}_d\}, \quad (3)$$

where *CID* is the compiler identity and *MAS* and *DAS* are the start address of *M* and *D* areas, respectively.  $\mathcal{A}_m$  and  $\mathcal{A}_d$  are the rules for mapping *M* and *D* to the address of the processor, respectively, see Algorithms 1 and 2. Algorithm 1 translates the four operators of each element  $m_i$ , which are  $S_0(m_i)$ ,  $S_1(m_i)$ ,  $J_0(m_i)$ , and  $J_1(m_i)$ , to recognizable the form of the *CID* compiler. In addition, in the *PLC* platform, we adopt the octal system, so it is necessary to translate the octal number to a decimal number. Algorithms 1 and 2 both contain this process.

**Step 2:** Call the corresponding compiler to compile the component.

### B. LPM data interaction

As shown in Fig. 7, we define the *LPM* data interaction as having three parts:  $\mathcal{L}$  (layer data interaction),  $\mathcal{P}$  (processor data interaction), and  $\mathcal{M}$  (module data interaction).  $\mathcal{L}$  seen in [11] is the process of exchanging the data between the application-customized layer and control layer.

#### Algorithm 1: $\mathcal{A}_m$

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**Input:** string *oStr* of  $m_i$  contained its operator  
**Output:** converted string *cStr*  
 Get the number *i* from *oStr*;  
 Get operator *opt* from *oStr*;  
 remainder  $r = i \% 10$ ;  
 Octal  $oI = i / 10$ ;  
 Convert *oI* to decimal *dI*;  
**for** *opt* **do**  
   **if**  $opt == S_0$  **then**  
     *cStr* = "CassMen[MAS+dI]  $\gg r == 0$ ";  
   **end**  
   **if**  $opt == S_1$  **then**  
     *cStr* = "CassMen[MAS+dI]  $\gg r == 1$ ";  
   **end**  
   **if**  $opt == J_0$  **then**  
     *cStr* = "CassMen[MAS+dI]  $|\sim(1 \ll r)$ ";  
   **end**  
   **if**  $opt == J_1$  **then**  
     *cStr* = "CassMen[MAS+dI]  $\& (1 \ll r)$ ";  
   **end**  
**end**

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#### Algorithm 2: $\mathcal{A}_d$

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**Input:** string *oStr* of  $d_i$   
**Output:** converted string *cStr*  
 Get the number *i* from *oStr*;  
 Convert *i* to decimal *dI*;  
*cStr* = "CassMen[DAS+dI]";

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$\mathcal{P}$  is used to establish the data interaction between master processor and slave processors; hence, it contains the process of transferring data from master to slave ( $\mathcal{P}_{mts}$ ) and the process of transferring data from slave to master ( $\mathcal{P}_{stm}$ ), both of which are defined as follows:

$$\begin{cases} \mathcal{P}_{mts} = \mathcal{U}(msb_i, msf_i, sma_i, sms_i, smd_i), \\ \mathcal{P}_{stm} = \mathcal{U}(smb_i, smf_i, msa_i, mss_i, msd_i), \end{cases} \quad (4)$$

where  $\mathcal{U}$  is the function that implements the process of data interaction between master and slave processors.  $\mathcal{P}_{mts}$  and  $\mathcal{P}_{stm}$  use the same function  $\mathcal{U}$ .

The process flow of  $\mathcal{P}_{mts}$  is expressed as follows:  
 $S_1(msb_i) \rightarrow S_1(msf_i) \rightarrow send(smd_i) \rightarrow S_0(msb_i) \rightarrow S_1(sms_i) \rightarrow check(smd_i) \rightarrow S_1(sma_i) \rightarrow S_0(sms_i) \rightarrow S_0(sma_i) \rightarrow S_0(msf_i)$ .

Here, *send*(*smd<sub>i</sub>*) denotes sending data to *smd<sub>i</sub>* in the slave processor. *check*(*smd<sub>i</sub>*) denotes checking the data of *smd<sub>i</sub>*.  $\rightarrow$  denotes the transition to the next step, e.g.,  $S_1(msb_i) \rightarrow S_1(msf_i)$  denotes that *msb<sub>i</sub>* and is set one, and then *msf<sub>i</sub>* is set one.

$\mathcal{M}$  is used to establish the data interaction among modules. It includes two types of messages: system-defined message interaction  $\mathcal{M}_d$  and user message interaction  $\mathcal{M}_u$ . The process is defined as follows:

$$\begin{cases} \mathcal{M}_d = \mathcal{V}(dmf_i, dmd_i, \mathcal{E}), \\ \mathcal{M}_u = \mathcal{V}(umf_i, umd_i, \mathcal{E}), \end{cases} \quad (5)$$

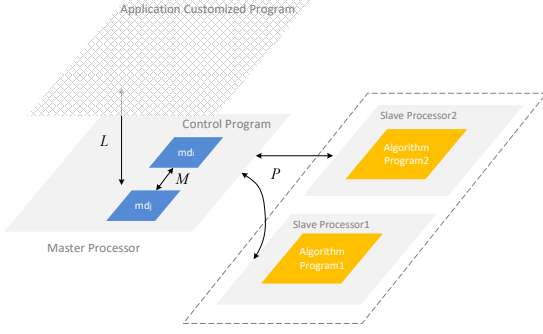


Fig. 7. LPM data interaction defined as having three parts:  $\mathcal{L}$  (layer data interaction),  $\mathcal{P}$  (processor data interaction), and  $\mathcal{M}$  (module data interaction).

where  $\mathcal{V}$  is the function used to broadcast messages and transfer data,  $\mathcal{E}$  is the collection of all execution functions after receiving a related message, and  $\mathcal{M}_s$  and  $\mathcal{M}_u$  have the same function  $\mathcal{V}$ .

One module receives a system-defined message as follows:  $\mathcal{J}_1(sm f_i) \rightarrow GetMessage_j(dm f_i) \rightarrow GetData(dmd_i) \rightarrow \mathcal{E}_j$ .

Here,  $GetMessage_j(dm f_i)$  represents the  $i$ th module receiving a message  $dm f_i$  and  $GetData(dmd_i)$  represents the  $i$ th module receiving the message information.

### C. Execution of threads

Commonly, threads in master processor and in slave processors execute separately according to their priority, and the interaction between control thread and algorithm threads occurs when using  $\mathcal{P}_{mts}$  and  $\mathcal{P}_{stm}$ . Basic execution units of control thread are as follows:

- $C_1$ : start a module.
- $C_2$ : transfer data to slave processor by  $\mathcal{P}_{mts}$ .
- $C_3$ : deal with the feedback data.
- $C_4$ : broadcast a message.
- $C_5$ : handle the message.

A motion thread contains the following basic execution units:

- $M_1$ : start the algorithm.
- $M_2$ : execute the algorithm.
- $M_3$ : feedback the data to master processor by  $\mathcal{P}_{stm}$ .
- $M_4$ : end algorithm.

Two cases shown in Fig. 8 are explained below:

**Case 1:** Execution of a control thread and two algorithm threads among three processors. The control thread (CT) traverses  $LCF$ , finds  $ms_i$  to be executed, runs  $lcp_i$ , finds  $ap_j$ , executes  $C_1$  unit, executes  $C_2$  unit, and then transfers data from  $LCD$  to  $SMD$  of processor 1. Algorithm thread (AT) 1 executes  $M_1$  unit, executes  $M_2$  after transferring data from  $SMD$  to  $AD$ , runs  $M_3$  unit, and feedbacks data to CT. When  $ap_j$  finishes, AT 1 executes  $M_4$  and informs CT of the end of  $ap_j$ . CT executes  $C_3$  to end the process and then finds  $ap_{j+1}$ , executes  $C_1$  and  $C_2$ , transfers the data from  $LCD$  to  $SMD$  of processor 2, AT 2 executes  $M_1$  unit, and executes  $M_2$  after transferring data from  $SMD$  to  $AD$ . When  $ap_{j+1}$

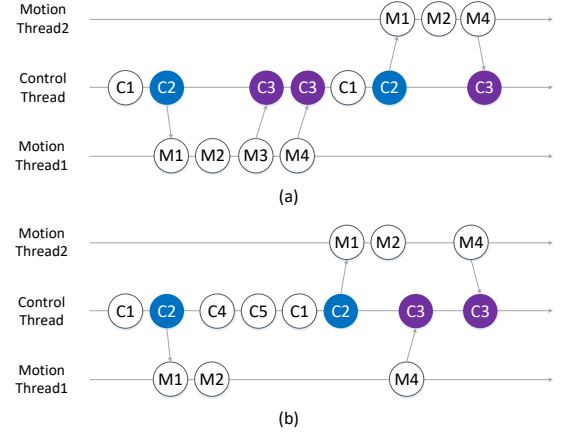


Fig. 8. Execution of control thread and two algorithm threads among three processors with and without messages.

finishes, AT 2 executes  $M_4$  unit and informs CT of the end of  $ap_{j+1}$ . CT executes  $C_3$  to finish the process.

**Case 2:** Execution of control thread and two algorithm threads among three processors together with message mechanism. The CT traverses  $LCF$ , finds  $ms_i$  to be executed, runs  $lcp_i$ , finds  $ap_j$ , executes  $C_1$  unit, executes  $C_2$  unit, and then transfers data from  $LCD$  to  $SMD$  of processor 1. AT 1 executes  $M_1$  unit and executes  $M_2$  after transferring data from  $SMD$  to  $AD$ . During the execution of  $ms_i$ , CT executes  $C_4$  to broadcast the message  $dm f_x$  to inform  $ms_k$  to run. After execution of  $C_5$ ,  $ms_k$  obtains data and starts, and then CT finds  $ap_{j+1}$  in  $ms_k$ , executes  $C_1$  and  $C_2$ , transfers the data from  $LCD$  to  $SMD$  of processor 2, AT 2 executes  $M_1$  unit, and executes  $M_2$  after transferring data from  $SMD$  to  $AD$ . During the execution of  $ap_{j+1}$ , AT 1 executes  $M_4$  and informs CT to execute  $C_3$ . After that,  $ap_{j+1}$  finishes, and then CT executes  $C_3$  to finish the process.

### D. Finite state machines

The finite state machines adopt the 5-tuple, which is similar to [43]:

$$\mathcal{F} = (Q, X, Y, \delta, \lambda), \quad (6)$$

where  $Q = \{q_0, q_1, \dots, q_i\}$  is the collection of states,  $q_0 \in Q$  is the initial state,  $X$  is the finite set of inputs,  $Y$  is the finite set of outputs, and  $\delta$  is the state transition function  $\delta : Q \times X \rightarrow Q$ .  $\lambda$  is the output function  $\lambda : Q \times X \rightarrow Y$ . If  $F$  is in state  $q$  and  $x$  occurs, then  $F$  transitions to state  $q' = \delta(q, x)$  and outputs  $y = \lambda(q, x)$ . This transition is denoted  $\tau = (s, x/o, s')$ .

Hence, we have the following finite state machines of the master processor:

$$\begin{cases} \mathcal{F}_m = \{Q_m, X_m, Y_m, \delta_m, \lambda_m\}, \\ Q_m = \{mstop, mrun, mbm, pdi\}, \\ X_m = \{x_{m1}, x_{m2}, x_{m3}, x_{m4}, x_{m5}, x_{m6}, x_{m7}\}, \\ Y_m = \{y_{m1}, y_{m2}, y_{m3}\}, \end{cases} \quad (7)$$

where  $mstop$  is the stop state and the initial state of master processor,  $mrun$  is the run state,  $mbm$  is the broadcast state,



and  $pdi$  is the data interaction state. The inputs are defined as follows:

$$\begin{aligned}
x_{m1} &\Leftrightarrow \exists lc f_i : \mathcal{J}_1(lc f_i), \\
x_{m2} &\Leftrightarrow \forall lc f_i : \mathcal{J}_0(lc f_i), \\
x_{m3} &\Leftrightarrow \exists m f_i : \mathcal{J}_1(m f_i), \\
x_{m4} &\Leftrightarrow \forall m f_i : \mathcal{J}_0(m f_i), \\
x_{m5} &\Leftrightarrow \exists m s f_i, m s s_j : \mathcal{J}_1(m s f_i) \vee \mathcal{J}_1(m s s_j), \\
x_{m6} &\Leftrightarrow \forall m s f_i, m s s_j, m f_k : \mathcal{J}_0(m s f_i) \wedge \mathcal{J}_0(m s s_j) \wedge \mathcal{J}_0(m f_k), \\
x_{m7} &\Leftrightarrow \forall m s f_i, m s s_j, \exists m f_k : \mathcal{J}_0(m s f_i) \wedge \mathcal{J}_0(m s s_j) \wedge \mathcal{J}_1(m f_k), \\
y_{m1} &\Leftrightarrow C_1, \\
y_{m2} &\Leftrightarrow C_4, \\
y_{m3} &\Leftrightarrow C_2 \text{ or } C_3.
\end{aligned}$$

Here, e.g.,  $x_{m1} \Leftrightarrow \exists lc f_i : \mathcal{J}_1(lc f_i)$  denotes that  $x_{m1}$  is an input of  $X_m$  and this input is equivalent to the existence of a logic control flag  $lc f_i$  whose value is 1.

We then can obtain the state transitions of the master processor:

$$\left\{ \begin{array}{l} \tau_{m1} = (mstop, x_{m1}/y_{m1}, mrun), \\ \tau_{m2} = (mrunch, x_{m2}, mstop), \\ \tau_{m3} = (mrunch, x_{m3}/y_{m2}, mbm), \\ \tau_{m4} = (mbm, x_{m4}, mrun), \\ \tau_{m5} = (mrunch, x_{m5}/y_{m3}, pdi), \\ \tau_{m6} = (pdi, x_{m6}, mrun), \\ \tau_{m7} = (mbm, x_{m5}/y_{m3}, pdi), \\ \tau_{m8} = (pdi, x_{m7}, mbm). \end{array} \right. \quad (8)$$

The finite state machines of every slave processor are as follows:

$$\left\{ \begin{array}{l} \mathcal{F}_s = \{Q_s, X_s, Y_s, \delta_s, \lambda_s\}, \\ Q_s = \{sstop, sready, srun, pdi\}, \\ X_s = \{x_{s1}, x_{s2}, x_{s3}, x_{s4}, x_{s5}\}, \\ Y_s = \{y_{s1}, y_{s2}, y_{s3}\}, \end{array} \right. \quad (9)$$

where  $sstop$  is the stop state and the initial state,  $srun$  is the run state,  $sready$  is the ready state, and  $pdi$  is the data interaction state. The events are defined as follows:

$$\begin{aligned}
x_{s1} &\Leftrightarrow \exists sms_i : \mathcal{J}_1(sms_i), \\
x_{s2} &\Leftrightarrow \exists afe_i : \mathcal{J}_1(afe_i), \\
x_{s3} &\Leftrightarrow \exists afs_i : \mathcal{J}_1(afs_i), \\
x_{s4} &\Leftrightarrow \forall afs_i : \mathcal{J}_0(afs_i), \\
x_{s5} &\Leftrightarrow \exists smb_i, sms_j : \mathcal{J}_1(smb_i) \vee \mathcal{J}_1(sms_j), \\
y_{s1} &\Leftrightarrow M_1, \\
y_{s2} &\Leftrightarrow M_2, \\
y_{s3} &\Leftrightarrow M_3.
\end{aligned}$$

We then can obtain the state transitions of the slave processor:

$$\left\{ \begin{array}{l} \tau_{s1} = (sstop, x_{s1}/y_{s1}, pdi), \\ \tau_{s2} = (pdi, x_{s2}, sready), \\ \tau_{s3} = (sready, x_{s3}/y_{s2}, srun), \\ \tau_{s4} = (srun, x_{s4}, sstop), \\ \tau_{s5} = (srun, x_{s5}/y_{s3}, pdi). \end{array} \right. \quad (10)$$

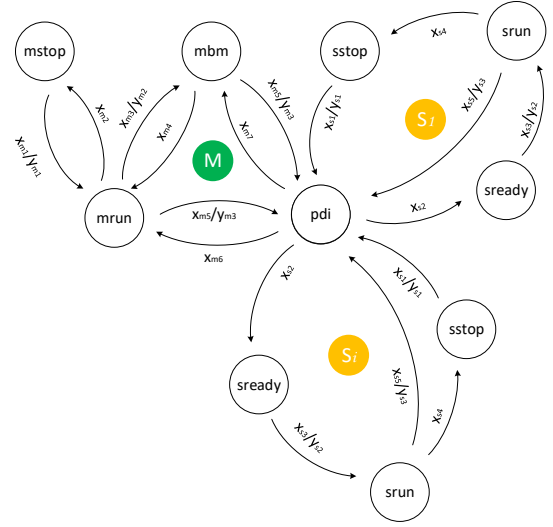


Fig. 9. Finite state machines of  $ePLC$ , which contains master processor  $M$ , slave processor  $S_1$ , and slave processor  $S_i$ .



Fig. 10. 200-T IMM and its control distributed system.

Figure 9 illustrates all of the finite state machines of  $ePLC$ , which contains master processor  $M$ , slave processor  $S_1$ , and slave processor  $S_i$ . This is the graphical form of Eqs. 7 and 9.

## IV. EXPERIMENT

### A. Distributed control system

As shown in Fig. 10, we verified the proposed development method on a 200-T IMM. The TI F28M35 chip was chosen as the main chip of the  $ePLC$ . It has two cores: a TI C28x and an ARM Cortex M3. Considering the DSP is more suitable for motion control, the Cortex M3 is chosen as the master

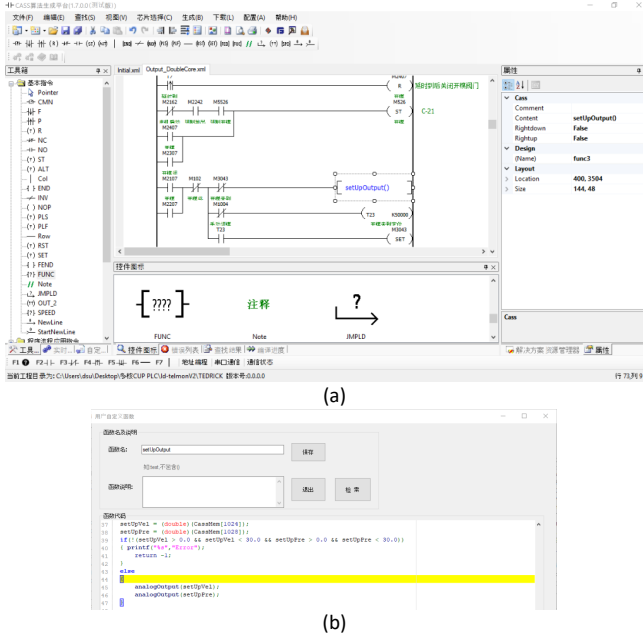


Fig. 11. (a) uniform development platform with C-language component in dotted-line box and (b) its partial code. This component represents to output a small velocity and pressure in setup mode.

processor and C28x as the slave processor. The *ePLC* has an RJ45, an RS232 and a CAN. The RJ45 is used to download programs, the RS232 for connecting with HMI, and the CAN is designed to extend the DI\O and AI\O. The *HMI* can be customized by users.

### B. Software structure

Figure 11 shows the uniform development platform that we devised. The dotted-line box of Fig. 11 (a) represents the C-language component and Fig. 11 (b) its partial code. This component represents to output a small velocity and pressure in setup mode.

After the design of every used component, we designed the modules according to Table I. Additionally, a special module was designed to control the execution flow of all modules with the *DMF* and *DMD*.

Three typical requirements for using the proposed user-oriented development method are as follows:

- 1) Using multiprocessors: Add S-curve acceleration and deceleration algorithms. For this case, we ran the S-curve in the DSP (slave processor).
- 2) Design in the uniform development platform: Add an ejector module containing a T-curve. We designed the *LCP* with *LD* and the T-curve packaged as a component in the same platform.
- 3) Modular design: Inject before high pressure of the mold closes. We customized a message flag in *MSF* and broadcast the message at the beginning of high pressure, after which the injection module received the message and the *CT* started it.

TABLE III  
SYSTEM PERFORMANCE COMPARISON

Brand	ST	DP	mean EoCP	mean EoCM	mean EoCEP	mean EoMOEP
TECHMATION	27 s	0.27%	0.094	0.2	0.13	0.17
KEBA	72 s	0.24%	0.064	0.1	0.1	0.12
Implemented	5 s	0.25%	0.05	0.1	0.11	0.11

### C. Analysis

We compared the system information, development method, and key performance indicators among the TECHMATION system, the KEBA system, and the proposed system. The compared controller types of KEBA and TECHMATION system are i1000 and TE-CH2, respectively.

- 1) System information. The TECHMATION and KEBA systems account for the majority of market share. Owing to its reduced complexity, our system can have a customized *PLC* and separate *HMI*. To some extent, this lowers the cost significantly. The proposed system adopts the widely used distributed structure, which decreases wire usage and increases resistance to interference.
- 2) Development method. Our system adopted a user-oriented development method, including a customized multiprocessor *ePLC*, component-based uniform development platform, and comprehensive optimization of the system. It is difficult to achieve these in other systems and they cannot support a C-language component. In particular, the TECHMATION system is developed by assembly instruction and does not support IEC61131-3.
- 3) Key performance indicators. With our best knowledge, we adopted defective percentage (*DP*), error of change-over position (*EoCP*), error of cushion minimum (*EoCM*), error of charging end position (*EoCEP*), and error of mold open end position (*EoMOEP*) as the key performance indicators. All the systems were adjusted to use a T-curve and the key parameters were set to the same value. The cycle time, mold close time, mold open time, injection time, charging and cooling time, and ejector forward time and ejector backward time were controlled at approximately 8, 2, 2, 1, 1, 1, 0.5, and 0.5 s, respectively. Figure 12 shows the 100-times error line graph of the key performance indicators. The proposed system has nearly identical performance as the KEBA system, which is better than that of the TECHMATION system. Table I shows the comparison of startup time (*ST*), *DP*, and the mean of the key performance indicators. The proposed system's startup time was increased by more than 5 times in the case of almost identical key performance.

### V. CONCLUSIONS

In this paper, we presented a user-oriented development method in which a customized multiprocessor *ePLC* was proposed to enhance performance, a multi-language-supporting



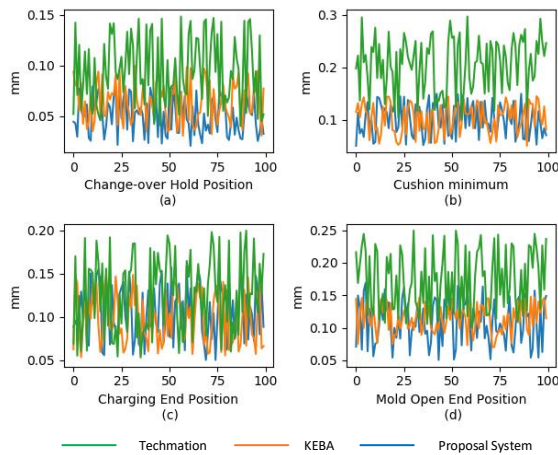


Fig. 12. (a) is EoCP, (b) is EoCP, (c) is EoCM, (d) is EoMOEP.

graphical component was proposed to improve the adaptability of developers, and an optimized system structure (reasonable memory allocation, user-oriented thread structure, *LPM* data interaction, modular software design, and finite state machines) was proposed to reduce the developmental complexity. Ultimately, we adopted the proposed method to implement a distributed *IMM* system. Through comparison with the *TECHMATION* and *KEBA* systems, our system startup time increased by more than 5 times in the case of almost identical key performance. Furthermore, our system supports a customized multiprocessor *ePLC* and detached *HMI*.

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