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Research Article

Control and Implementation of Positioning System with Symmetrical Topology for Precision Manufacturing

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In recent years, the needs of modularized controller for the multiaxes servo system increase significantly since traditional controller still exists many drawbacks such as limited control axes, low speed data acquisition, or heavy weight. In this paper, we present the design and implementation of both hardware and software for real-time express-based motion controller. This controller can meet the demand for high-speed motion control and high performance which conventional fieldbus controllers cannot realize. With modular design, the controller brings many benefits such as low-cost, expandable ability, multiaxes control, or small physical size. Experimental results for an industrial motion system indicate that the proposed modular controller can perform well in time critical data transmission and is feasible and applicable in various fields.

1. Introduction

Motion control system, which plays as an important role in the modern industry such as Computed Numerically Controlled (CNC) machine tools [1–4] and industrial robots, determines the whole system performance. For the demand for high reliability and high real-time manufacturing, modern motion control systems are growing in the direction of high speed, high precision, multifunctional, and opening that needs embedded and networked technique to implement. Networked motion control systems are special networked control systems [5–8] composed of controllers and multiaxes motor drivers, which can ensure the real-time synchronization of motion control order and motion state transmission.

A lot of buses based on Ethernet have been introduced into the motion control field, such as PROFIBUS, CAN bus, Interbus-S, and SERCOS [9–12]. C. C. Hsieh and P. L. Hsu [13, 14] proposed a CAN-based motion control system by introducing the event-time structure. Thus, the CAN-based motion control system achieves desired control performance even under lower transmission rate or heavier message loading on the bus. B. Chen et al. [15, 16] introduced three configurations of the networked synchronized motion control systems. In a networked synchronized motion control system, short communication cycle is needed in order to upgrade the synchronization accuracy. In other approaches, the authors are successful in developing the motion control system with the modern industry Ethernet buses. Y. Hu et al. [17, 18] reconfigured the open architecture CNC system based on the Mechatrolink-II Fieldbus [19, 20] that offers interoperability and portability. This component-based CNC architecture is flexible and reconfigurable and has more precise performance.

In time critical environment or where complex multitasking operations are employed, the execution time of such software can prove a significant overhead on the system. The development of a real-time executive consisting of both hardware and software codesign methodologies was introduced firstly [21, 22]. The researchers utilized this real-time executive as a prototyping tool for investigating different task scheduling schemes based on high performance evolutionary heuristics. Some of the results were obtained by implementing a Hopfield neural network to solve the task scheduling problem in embedded and real-time systems. However, this approach may be not expandable in the large-scale system, and it depends on each application. Related to motion control, the embedded framework and network communication are the cores of multiaxes motion controller. In [23–26], one kind of modular control component was presented. The network protocol from servo A6N could provide a huge chance to achieve high performance and advanced motion function. Nevertheless, it lacks graphical user interface to assist operator, limited function, and big size.

2. Related Works and Problem Statement

2.1. Related Works. The most common implementation of a control system in any process industry is through a central controller. A single controller is directly attached with its input and output devices by cables in a point-to-point mode. When hundreds of field devices are employed, enormous lengths of special cables are used. It led to the occurrence of a novel concept as fieldbus which is a digital, bi-directional, serial-bus communications network supposed to link various instruments, transducers, controllers, final control elements, process stream analyzers, and computer control systems. Nowadays, the considerable developments in fieldbus protocols in Table 1 have launched many modern industrial networks such as CC-Link and SSCNET from Mitsubishi, Profibus from Siemens, or DeviceNet from Allen-Bradley. In recent years, several advanced network protocols are introduced, for instance, RTEX from Panasonic or EtherCAT from Beckhoff.

Communication network protocol is one of the industrial networks based on RS485 utilizing the protocol standard of CC-Link [27]. Generally, the working mode on CC-Link consists of cyclic transmission and instantaneous transmission in which broadcast polling mode is mainly integrated. At initial stage, the master station firstly sends the acquired data to all slave stations. The data of synchronization mode on broadcast polling are performed by frame synchronization, and the instantaneous transmission must be completed by sending traffic. The automation of industrial production can be improved that CC-Link protocol well-established the communication between Programmable Logic Controller (PLC) and slave stations. However, in several applications which require the interactions with human, CC-Link does not match since the intelligent machine becomes the inevitable trend in our era. Therefore, a PC-based application in multiaxes synchronous motion such SSCNET-based system [28] could satisfy the modern requirements. In reality, computer-aided manufacturing has been no stranger anymore. The parametric curve interpolators attracted many researchers on investigating the analytical shapes, values of control points, weights, and knots. As the complexity of mathematical expression, the transmitting time could be costed so much. Hopefully, based on the powerful computer, the real-time performance of this system could be maintained.

In the context of competitive responses, it is crucial to evaluate the technical specifications of the motion networks. For instance, a study on comparison of Profinet and Profibus DP [29, 30] has been presented in order to provide a systematic view of communication protocol. The data collection is the input resource to estimate some key indicators. The experimental tests consist of a frequency converter, an electric AC motor, and an incremental encoder. Under these circumstances, the dynamics in the motion control network are to send the reference position by the controller via communication protocol to frequency converter. Then, the network data flow in various cycle times is gathered by a measurement system during a certain period while application performs position control. For the specialized controller network, CANopen is a real-time protocol for the distributed control system [31, 32]. To enhance interoperability and interchangeability among different products from dissimilar manufacturers, practical applications usually make use of communication services defined at the application layer, which are significantly more flexible than those provided originally by the data-link layer.

In these days, the advanced fieldbus technologies are presented by RTEX or EtherCAT. Both of them which derived from the Ethernet protocol contain the fundamental layers of general data frame. They also have high performance and flexible topology and deliver more options to user. In some reports [33, 34], EtherCAT is an overall highly performance real-time protocol, for example, high velocity of transmission, multislave nodes, various suppliers and manufacturers, and both academic and industry community. Contrary to its advantages, the existing drawbacks which comprise limited usages in software and hardware, or complex data structure, need more solutions to overcome. Many investigators in Panasonic Corporation [35] have innovated the real-time protocol for a high-speed synchronous motion network, named as RTEX. This system achieves fully synchronization, low-cost device, simple structure, and noise rejection. Industries like semiconductors, liquid crystal manufacturing equipment, and electronic parts mounter are strongly recommended to adopt this technique.

2.2. Problem Statement. Recently, there exists an innovative trend in multiaxes control that enables the fast response, supports the large number of slave devices, configures less wiring of mechanism, and ensures the high reliability. It is hard for previous network systems to be quite adaptive, but these constraints explicitly fit in well with real-time express protocol. This standard communication is primarily introduced by Panasonic group, and up-to-now it is one of the well-known network motion system in the global market. Hereafter, the contributions of this paper are that (i) a novel design of network motion module has been developed successfully. Adopting the framework of the embedded

Table 1: Summary of comparative reviews.

Authors	Methodology	Advantage(s)	Limitation(s)
[27] Yeon and Kim	A new CC-Link module utilizing R-IN32M3 to improve the expandability is proposed.	The probabilities of data loss could be managed and interference with equipment control could be decreased.	It requires a lot of pins because of parallel communication.
[28] Cheng and Tseng	Since the cutter contact (CC) velocity along the surface tends to vary, a PC-based real-time motion control network was investigated to achieve the goal of multiaxes synchronous motion.	Both the NURBS interpolator algorithm and SSCNET protocol are successfully realized with the RTX real-time kernel.	The burden computational cost on Windows-OS might cause a problem in traffic communication. Only limited axes are validated.
[29] Dias et al. and [30] Khaliq et al.	This work analyses the performance of industrial communication network by comparing Profinet and Profibus DP in cycle time and jitter.	It is found that Profibus DPV0 is faster and Profinet version IRT has higher determinism.	It does not allow to set fixed cycle time when working. These technologies are not newly developed and not much user utilized them.
[31] Cena and Valenzano, and [32] Liu et al.	A new automatic node discovery protocol for unregistered nodes when connected to the network is investigated.	This research helps to identify the nonconfigured nodes directly and provides a very good degree of compatibility with the existing devices.	Each device is assigned a unique node address and does not permit to alter online.
[33] Chen et al. and [34] Langlois et al.	The system structure evolves one master and slaves connected into a loop. Master device employs 100BASE-TX Ethernet adapter while slave controller utilizes an ASIC or a FPGA with EtherCAT IP core to handle the data frame.	Rapid transmission, numerous slave nodes, diverse manufacturers, and large academic community are benefits of EtherCAT.	It involves the licensed software, genuine equipment to gain the highly precise performance, and complicated data model to understand.

system, it was integrated into new network communication with highly real-time performance and stable protocol. In this current trend, the control issue of multiaxes becomes more critical, especially in the large-scale system. (ii) The problems that were addressed in synchronous control, network topology, time consuming, or maintenance service have been solved this by the real-time express method. (iii) The experiments with the practical servo system are established in order to prove the validity of our approach and the ability of powerful network control. The rest of this paper is organized as follows. Section 3 introduces some definitions, technical specifications, and analysis of the real-time system. In Section 4, the detailed development of hardware platform and several notifiable remarks are carried out. Also, this section briefly describes the control software which is programmed in C++ and interacted during a cycle servo. The results of experimental module have been completed to validate our proposed approach in Section 5. Several discussions consisting of experiences, practical performance, or tested method are revealed together with the conclusions with future work in Section 6.

3. Proposed Approach of Network Control

3.1. Introduction. Real-time express is a high-speed synchronous motion network developed by Panasonic Corporation. While being 100 Mbps very high speed (ten times higher than our previous model), the system cost can be kept low by using the commercially available LAN cable. It supports fully synchronization, full-duplex communication, and noise immunity with unique error correction. This protocol is connected via ring topology as shown in Figure 1 with advantages of simple data flow effects, high efficiency, and reliability. Comparing with line topology transferring data through many nodes which causes low efficiency, there is no cross-talk in ring structure that occasionally is sources of troubles in high-speed data. With only one master and many slaves, a large-scale system could be monitored and managed easily.

3.2. Description of New Concept. MNM1221 is a serial interface controller ASIC that enables to establish the real-time communication systems based upon the master-slaves communication. The MNM1221 requires to be used with a PHY (physical layer chip), a pulse transformer, and shielded twisted pair cables for 100BASE-TX (IEEE 802.3u) system. In other words, MNM1221 is a special MAC (Media Access Controller) in order to suit 100BASE-TX to the real-time communication system for the multiaxes servo control.

The MNM1221 serial interface system consists of one master and several slaves and exchanges the command data from the master and the response data from the slave cyclically. For that, MNM1221 has double banks (buffer) memory for each transmitting and receiving, and this function allows the CPU to operate efficiently.

Table 2 illustrates the information of period, axes, and modes. The number of controlled axes depends on different sources such as transferring data mode, communication period, and update period. The timing communication is a period of frame transmission while update cycle is to inform data inside the frame. The external device should be limited

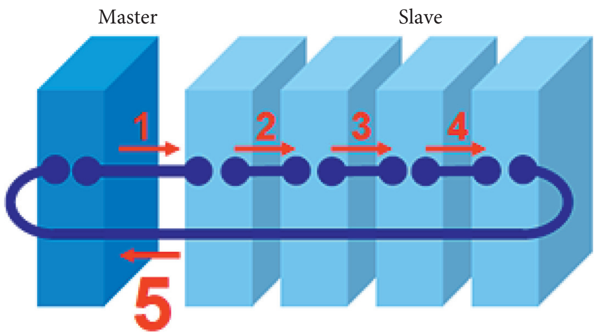

Figure 1: Structure specification of ring topology.

Table 2: Combination of period, axes, and modes.

Update period (ms)	Com. period (ms)	Max of axes
4	2	32
2	2	32
2	1	32
1	1	32
1	0.5	32
0.5	0.5	32
0.5	0.25	16
0.25	0.25	16
0.25	0.125	8
0.125	0.125	8
0.125	0.0625	4

to join in network since it impacts on number of controlled axes.

4. Design of Real-Time Express Module

4.1. Data Exchange. Traditional Ethernet is not proper to satisfy real-time performance of the motion system because of time delay, synchronous transmission, or data frame format. To overcome these drawbacks, a module of real-time express communication which is already well-defined to Industrial Ethernet solutions is proposed. Figure 2 represents the whole linkage in master unit. Once, the operator manipulates on host personal computer in central control room. The popular USB connection assists easy plug-in and fast data transportation between host and network module. There are two selections in circuit schematic, debug for development and release for commerce. The host controller links with servo pack by two LAN wires (receive and transmit) which could extend up to 100 meters. The A6N servo pack-based system is our target of motion controller. To visualize the feed-back signals, a built-in software installed in host computer interconnects with servo via USB type-B.

For the internal bus, the inside hardware schematic is designed in Figure 3. To expand more controlled axes, 16-byte mode is chosen by connecting BUSMODE pin to ground. The address bus access is from 0×000 h to 0×200 h for transmit memory, from 0×200 h to 0×400 h for receive memory, from 0×400 h to 0×480 h for control registers, and the rest for status registers. The timing schedule could be guaranteed owing to CS, RD, WR, and WAIT pins. The real-time express protocol IC has two timer sources that are an

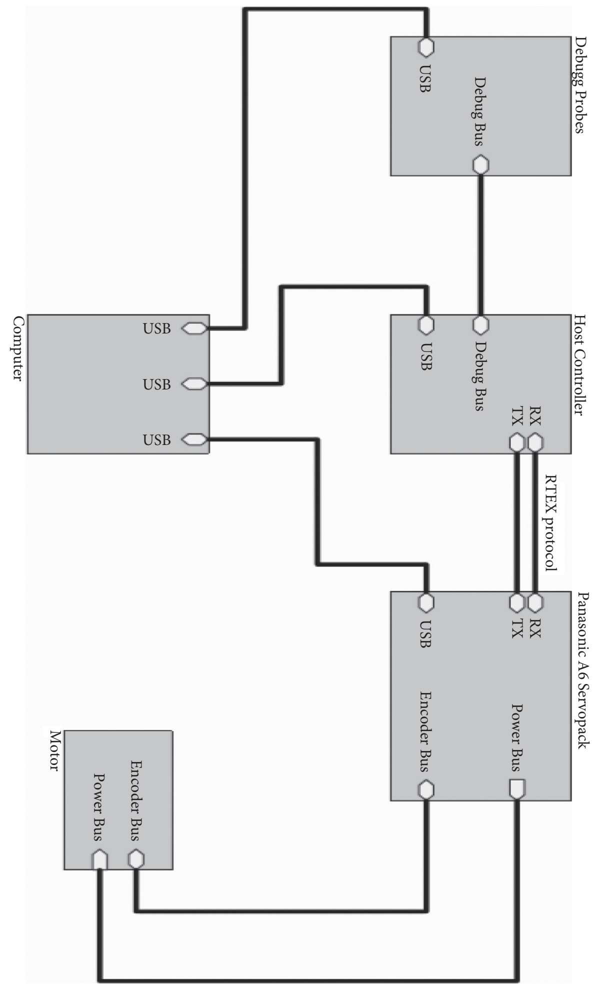

Figure 2: Block diagram of the whole master module.

external timer and an internal timer as shown in Figure 4. For external timer design, it requires that microprocessor provides a tick-clock signal to coordinate the operation of transmit and receive. In the case that using internal timer, MNM1221 utilizes its timer independently. The physical layer chip needs to configure the suitable operating mode from network protocol IC.

Communication period, that is, the same as transmitting period, cannot be set up freely because it must be synchronized with servo control. According to servo specifications, the period must be set to suitable value as accurately as possible. In servo A6N, the communication period must be selected from 2 ms, 1 ms, 0.5 ms, 0.25 ms, 0.125 ms, and 0.0625 ms. The command update period is the same or twice as the communication period and must be selected from 4 ms, 2 ms, 1 ms, 0.5 ms, 0.25 ms, and 0.125 ms. The default setting of the servo is that the communication period is 0.5 ms and the command update period is 1 ms.

4.2. Design of Control Exchange. In the firmware level, most of operations have been handled by CPU as shown in Figure 5. Initially, all variables in program should be given default

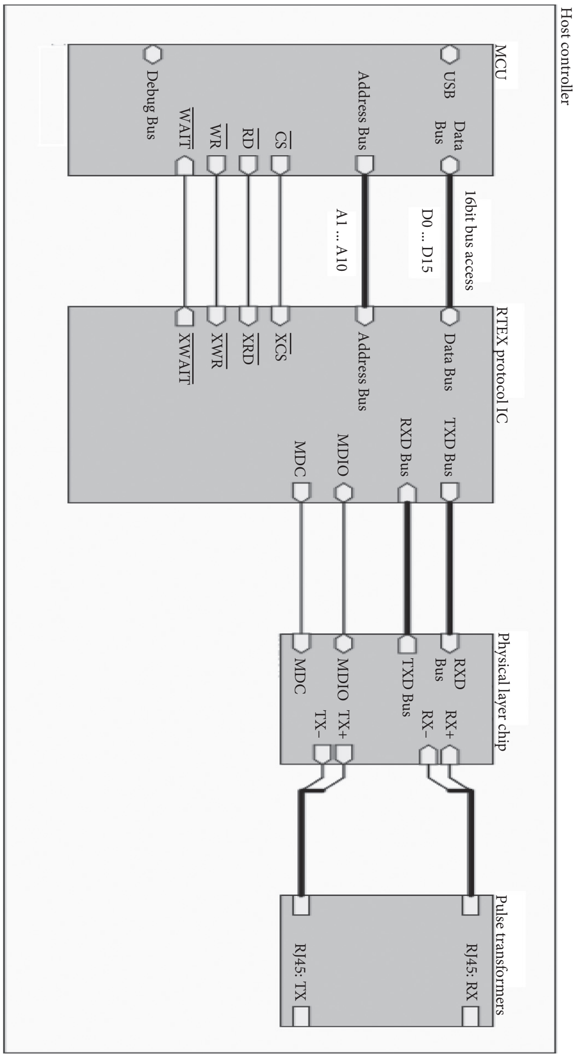

Figure 3: Hardware connection among microprocessor unit, real-time express ASIC chip, and peripheral devices.

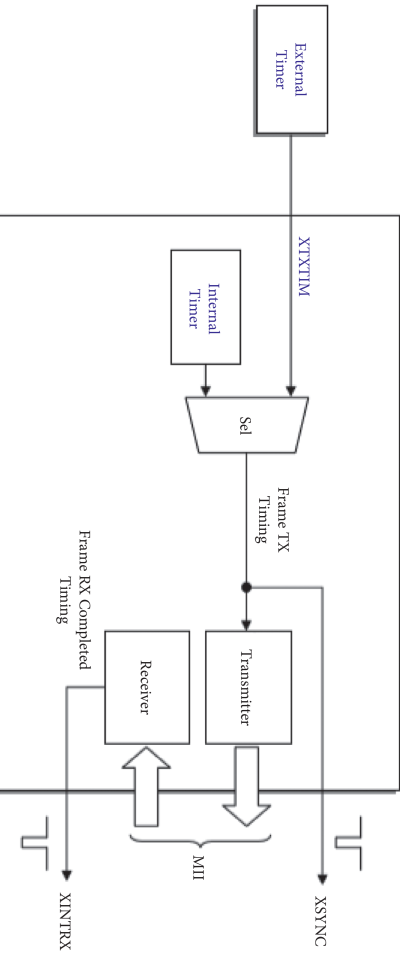

Figure 4: Timer sources of timing frame data.

values. Then, several registers of real-time express IC need to set up operating mode such as control registers (M_INIT_-DONE, M_INITF_TX, M_TXTIM_SEL) and status registers (M_STATE, M_NODE_SUM). The communication in network could be enabled by checking registers (M_TXMEM_SW, M_CYCL_START). There is an infinite loop which often reads data from status registers. As a result, the data from numerous slaves are updated frequently.

Since the synchronous interface plays an important role, a routine to incorporate among them is displayed in Figure 6. When slave sends a request to master, if this message is firstly notified, the readout pointer would record it. To verify the notification message, the process of redundancy check is cyclically executed. If there exists any error in transmission, the counter would label to monitor internal status. Later, this error count is stored in master station. In the case that there is no error, the receive buffer updates from network motion IC to internal side. Maybe, user's application takes this information, performs the execution, and releases currently internal state to network.

5. Results and Discussion

5.1. Laboratory Experiment. To verify the feasible, capable, and applicable design in our approach, an experimental test is carried out as shown in Figure 7. The host PC is Dell Latitude 5500 with powerful Intel core processor. Most of control software would execute in Windows 10 operating system as shown in Figure7(a). The software-based work is mainly programmed by Visual Studio with various C++ classes supported from Windows. The firmware which is written by C language handles the important role in data processing and exchanging. The information is traded between host and motion module through USB cable. Two LAN wires (from RX port of module to TX port of A6N servo pack and vice versa). One remarkable point is that this module offers on-the-fly adjustment parameters. Hence, as soon as plugging into port, the data flow has been established continuously. Furthermore, the integrated emulator should be utilized to track each missing command or system error as shown in Figure 7(b). Its benefit is to shorten the debugging period which is usually longer.

The laboratory validation on one axis is shown in Figure 8. In S-curve motion profile which is default mode, the command code (0×10) is transmitted from master to servo pack. Together with its, target position and target speed are

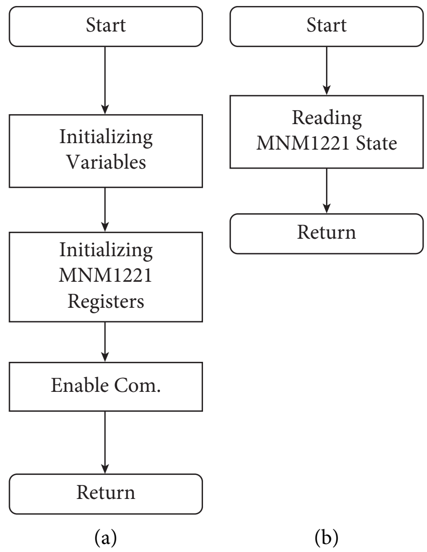

Figure 5: Flowchart of control firmware: (a) initializing and (b) main loop.

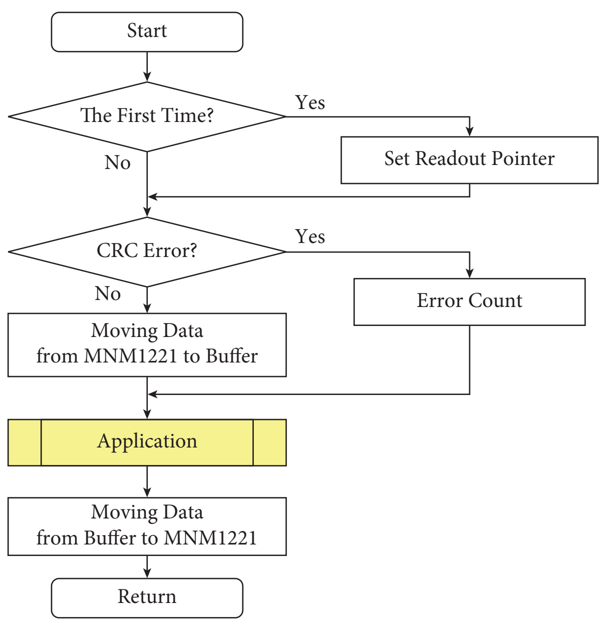

Figure 6: Flowchart of synchronizing routine.

written in data frame. Optionally, stop mode in byte 3 and absolute/incremental mode in byte 8 are set at start. Then, data frame is shifted to each node in the ring topology. The experimental results of symmetrical profile for position, velocity, acceleration, and jerk are illustrated in Figures 8(a)–8(d), respectively. During one cycle, a master module collects responses from all slaves. In the feed-back frame, except practical data, the servo status consisting of servo ready, alarm, warning message, or in position signal aids master to monitor online.

For asymmetric S-curve profile from Figures 8(e) to 8(h), it involves more setting parameters before executing. The values of acceleration and deceleration are registered in parameter 8.01 and 8.04. Several secondary parameters, for instance, digital filter, could bring more clear and enhanced performance. Figures 8(e)–8(h) present actual position, velocity, acceleration, and jerk in A6N servo pack. The technical specifications of both profiles are listed in Table 3. Generally, the symmetric motion profile must ensure the same period for acceleration and deceleration while the asymmetric one generates more time sequences to decelerate the servo motor. Hence, the duration of S-curve is shorter than AS-curve although the similar inputs are supplied. Actual position of AS-curve profile is slightly better because it slowly tends to target location. Some advantages of the asymmetrical profile are to suppress the oscillation-induced motion and flexibly generate the user-defined profile. The accuracy control in max velocity and max acceleration of

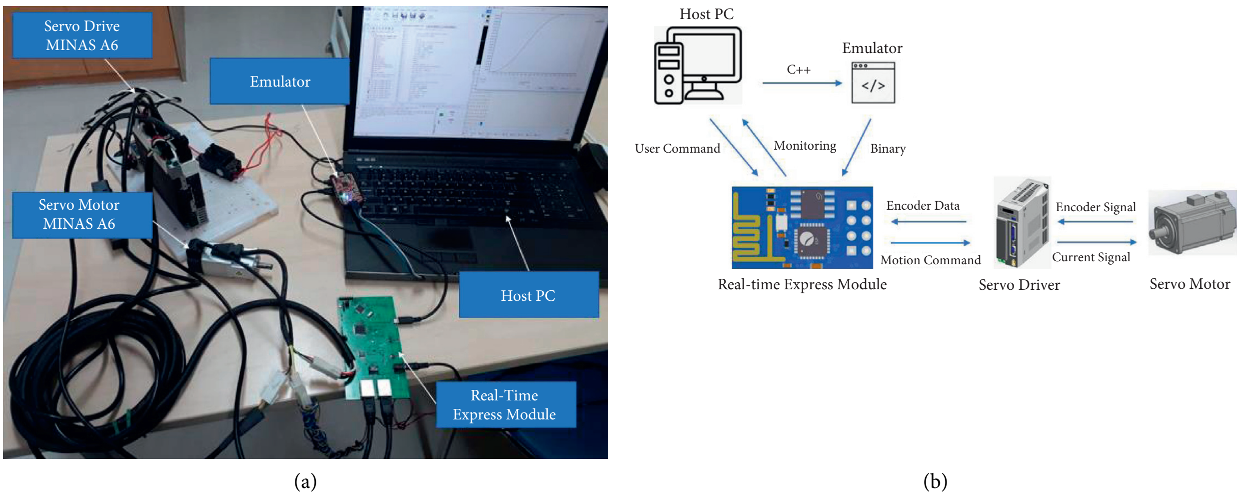

Figure 7: Experimental setup with proposed network module (a) and graphical presentation of the whole system (b).

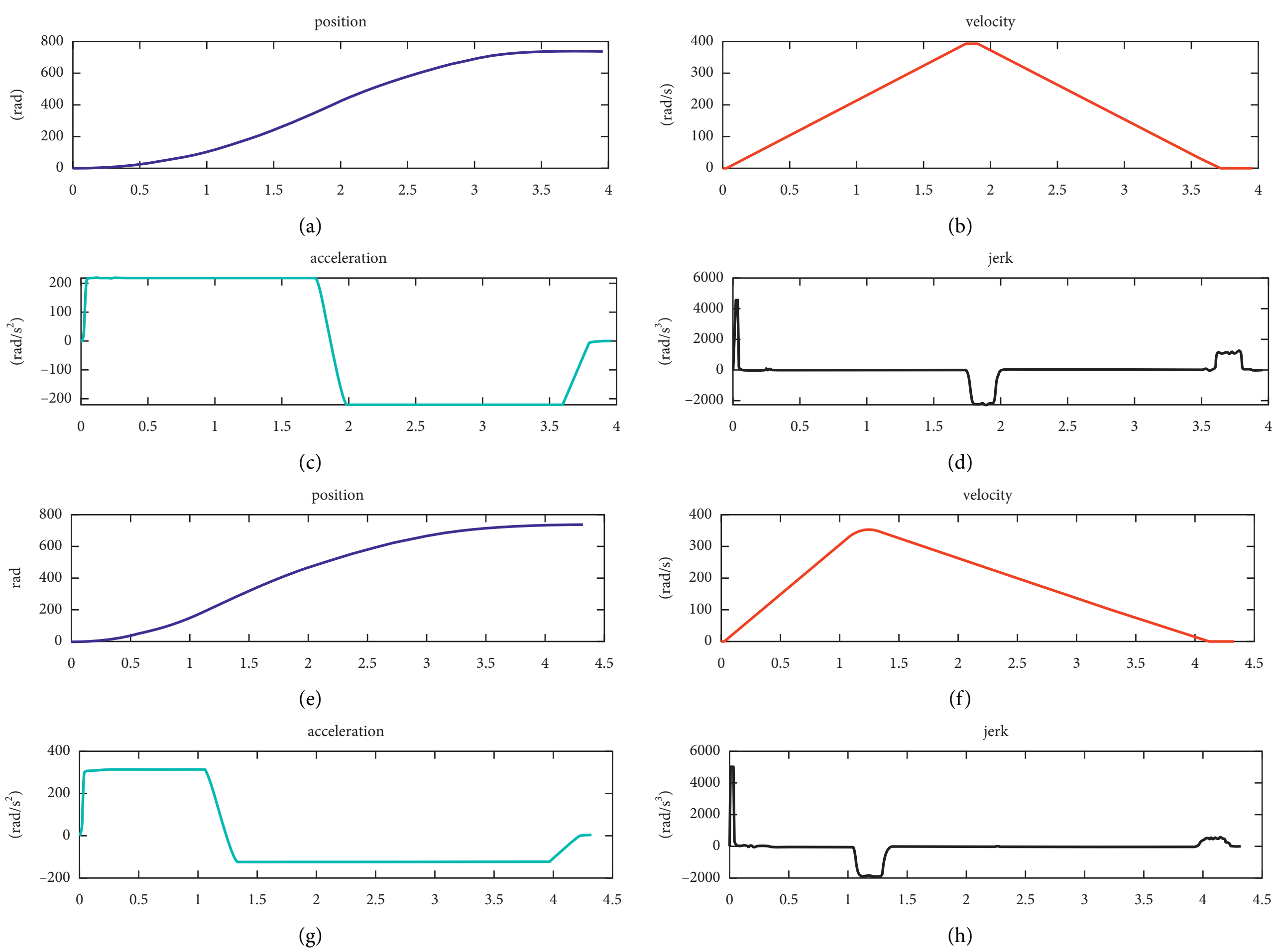

Figure 8: Experimental results of monoaxis control with S-curve profile (left: (a) position, (b) velocity, (c) acceleration, and (d) jerk) and AS-curve profile (right: (e) position, (f) velocity, (g) acceleration, and (h) jerk).

symmetric motion profile could be beneficially achieved since it does not need to decrease so much. At initial stage of asymmetric profile, it must peak as soon as possible, and then it generates the deceleration trajectory. As the abovementioned analysis, the advantageous specifications of asymmetrical S-curve are higher than those of symmetrical one. In the proposed design, the modular controller supports both of them with competitive performance.

Table 3: Descriptions of motion control parameters.

Motion profile	Duration	Command position (rad)	Command velocity (rad/s)	Command acceleration (rad/s^2)	Command jerk (rad/s^3)	Actual position (rad)	Actual velocity (rad/s)	Actual acceleration (rad/s^2)	Actual jerk (rad/s^3)
Symmetric	3.8 s	780	400	200	5000	781	397	200	4596
Asymmetric	4.25 s	780	400	200	5000	780	371	314	5082

5.2. Discussion. The communication cycle significantly impacts on overall performance of the network motion system. It should be considered carefully when designing hardware schematic. This section would analyze and discuss about influence of servo cycle and developing experiences.

To control timing in network, the XINTRX, XSYNC, and XTXTIM pins handle separated tasks. The XINTRX signal would activate when the procedure of receiving frame is completed. If using an external timing signal to start transmitting the frame in the running state, the cyclical trigger signal must send the acknowledgment signal to XTXTIM pin. In this case, the register setting must be needed to switch from the internal timing signal. Reversely, the XSYNC signal is changed logic level when the procedure of transmitting frame starts. In other words, after all slaves receive the data frame in running state, this pin outputs signal in all slaves to synchronize timing pulse. Therefore, it must be ensured that XSYNCs of all slaves are output at the same time as shown in Figure 9.

General speaking, there are four main states in real-time express protocol IC. The initial state starts firstly to reset registers. In the ring config state, network ASIC chip searches for the information of each slave and configures the operation. The result of this period is to store data into the status registers. After checking the correct slave information by comparing with sampled data, the firmware instructs this chip from ready state to proceed to running state. Otherwise, it returns an error message to notify there is no matched data in network. In running state, using TX and RX memory bank, the firmware is communicated cyclically. The transmission buffer memory (TX memory) and reception buffer memory (RX memory) are composed of two banks, respectively. To prevent conflict of data access, one bank is dedicated to the external CPU and another bank is dedicated to the internal communication module. Alternately, the assignment of two banks is switched before reading the received data.

The timing communication during four states is established in Figure 10. To implement rapidly, the duration of internal timer is equalized to communication period. This timer would provide signal to XTXTIM and guarantee that the low or high width of pulse must keep minimum 1 us. In ring config state, a network scan to diagnose slaves which presented in topology should not exceed a period of 2 ms. Once, entering the ready phase, the data transmission has already validated correctly and the registered slave information in master match with up-to-date ones. The transmission speed in running phase is very fast and repeats every cycle. Its speed depends on user's applications and hardware limitation.

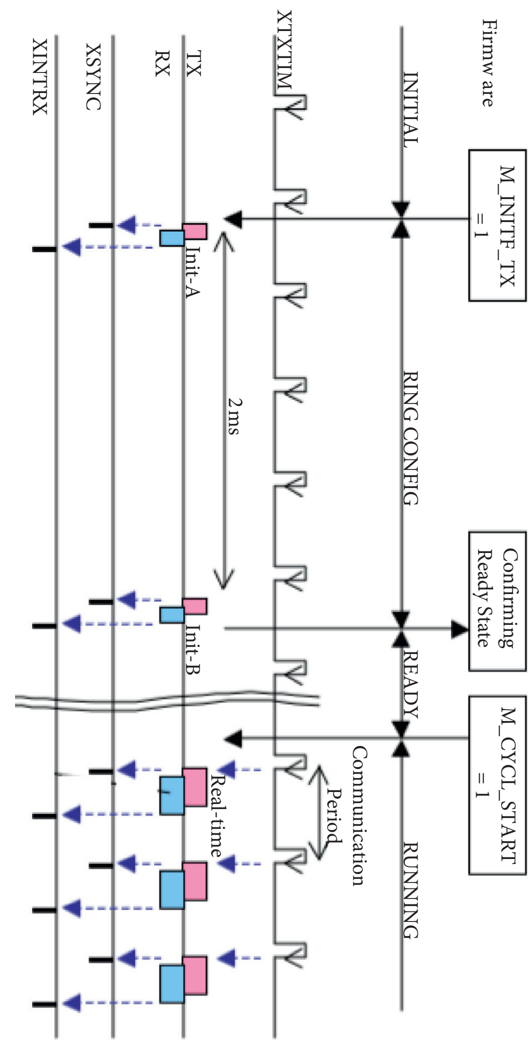

Figure 9: Timing control procedure in transmission protocol.

Furthermore, we verify the effectiveness of our experiment by comparing with the other network protocols such as CC-Link [36] which allows to connect remote I/O function modules, intelligent function modules, specific function modules, and so on. It is an industrial open network that enables communication among devices. In those tests, one Programmable Logic Controller (PLC) master communicates with an external microprocessor by CC-Link protocol. The output performance of our tests is evaluated with CC-Link's test in order to insist on the real-time response in the industrial system. Table 4 summarizes the competitive results between two network protocols when the same operation characteristics are maintained. Examining the data in more detail, the total transmission

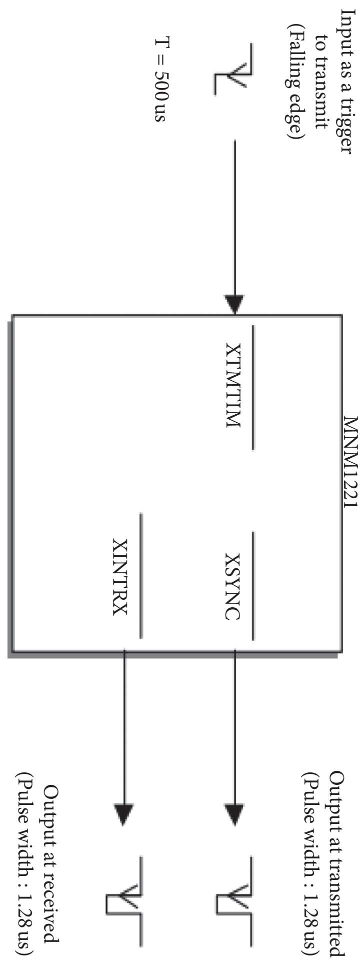

FIGURE 10: XSYNC signal and other peripheral communication.

TABLE 4: Competitive performance between our protocol, CC-Link, and CANopen protocol.

Data frame	Our protocol	CC-Link	CANopen
32 bytes	0.0625 ms	0.258 ms	—
4 bytes	—	—	0.4367 ms

and reception are completed in a cycle time. Therefore, for one data package, our protocol takes 0.0625 ms while CC-Link protocol spends 0.258 ms. Since the transmission rate in those CC-Link tests is only 10 Mbps, our protocol provides the superior performance when data are transferred at 100 Mbps. Once, a popular protocol, for example, CANopen [31], is mentioned again to insist on the excellent response of our approach.

Dissimilar to IT (Information Technology) security, system security for industrial network was not given much attention. The reason might be small number of users who regularly come from industry. Consequently, the vulnerability assessments in the industrial network could be reported and analyzed. In addition, the redundancy or latency in this protocol was not deeply evaluated in some research studies. Context-awareness is also a promising feature that developers expect to integrate in further studies. The advanced schemes such artificial intelligence or machine learning algorithm are embedded to investigate network model that comprise data gathering, parsing, and training.

6. Conclusions

In this paper, a modular design of real-time network controller has been developed successfully. The analyses of network protocol characteristic as well as technical specifications were explained in detail. The testification of circuit schematic and electric connections provides selectable operating mode. In firmware level, the flow of data exchange should be forced to update fluently and continuously. The sampling frequency is 25 MHz same as driving the physical IC.

The contributions in this work are (1) a compact design of module for the network motion controller, (2) both hardware schematic and software implementation using the real-time express protocol, and (3) practical validation in the closed-loop servo system. From laboratory experiment, it can be clearly seen that the proposed module can meet the control constraints in motion system, automation factory, and robotics system.

Future work is a must to achieve the significantly high performance; the embedded system should be upgraded, for instance, more advanced microprocessor that could handle many complex computations. The external bus might be optionally Peripheral Component Interconnect (PCI) port or PCI Extended (PCI-e) port for faster communication. Besides, maximum number of slaves ought to be installed in the ring topology in order to gain the optimal results.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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