Distributed Remote Input/Output Control Method in Real Time Processing for CNC

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Abstract - Systems for manufacturing using IoT (Internet of Things) solutions attract attention recently. In the IoT solutions, all the relevant elements are connected to internet and all the information are gathered from processes from manufacturing to logistics for data analysis, aiming at the construction of flexible manufacturing systems.

In relation to the network connection and the distributed input/output control method, which are key technologies for IoT, we report in this paper on a pioneering basic technology, which is the input/output control method in real time processing for CNC. We conceptualized and adopted in our products in the 1990s. The basic idea is to define the communication method which is high reliable and suitable for the real time control for the CNC and to achieve modularization and distribution of the components of the CNC. The cumulative number of products shipped with this I/O control method incorporated exceeded 5,000,000.

Keywords: network, Internet of Things, distributed control, CNC, flexible manufacturing systems

1 INTRODUCTION

Solutions using IoT (Internet of Things) technologies attract attention recently. In the IoT solutions, all the relevant elements are connected to the internet, and all the information of the processes from manufacturing to logistics are gathered, aiming at the construction of flexible manufacturing systems based on the analysis of such big data[1]. On the production sites, such IoT solutions are also expected to be incorporated into the manufacturing process. Efforts are made to incorporate all the relevant information into the manufacturing process to facilitate grasping of the current status or each step of the manufacturing process until completion[2]-[4]. The relevant information covers the following: order information provided by the sales department and incorporated into the production system, parts orders made from the purchasing system, manufacturing/production instructions to the production sites, control information for machining or assembly, and in-process product identification information based on sensor technologies. In the field of parts machining, NC machine tools play a central role in IoT, and the use of them makes it possible to establish a link between the parts machining information based on the manufacturing data (including part programs) and the part information obtained from the input/output (I/O) control.

In relation to the network connection and the distributed input/output control method, which are key technologies for IoT, we report in this paper on a pioneering basic technology, which is the input/output control method in real time processing for CNC we conceptualized and adopted in our products in the 1990s. The basic idea for this I/O control method is to define the communication method suitable for the real time control for the CNC[5]. With this I/O control method, a compact, low-cost and safety network can be achieved using serial communication. This method enables to modularize the components of the CNC, connect them through a network, and achieve distribution of the components to build a flexible system suitable for the purpose[6]. The cumulative number of communication modules shipped with this control method incorporated exceeded 5,000,000. It can be said that this control method contributed to the development of the precursor of today's CNC.

2 RELATED TECHNOLOGIES

2.1 Configuration and Functions of the CNC

Figure 1 shows the configuration of the CNC. The CNC consists of the display and operation unit, NC unit, drive units, servo motors, and spindle motor. The display and operation unit is used to create part programs, operate the machine, and display the part programs, machining status, and machine status.

The NC unit is used to analyze part programs, output the machine movement distance to the servo drive units as a movement command, and control the machine movement. The NC unit is also used for sequence control for machining. The servo drive units are used to control the servo motors for the tool nose path control. The spindle drive units are used to control the spindle motor for rotating the tool to achieve the cutting work.

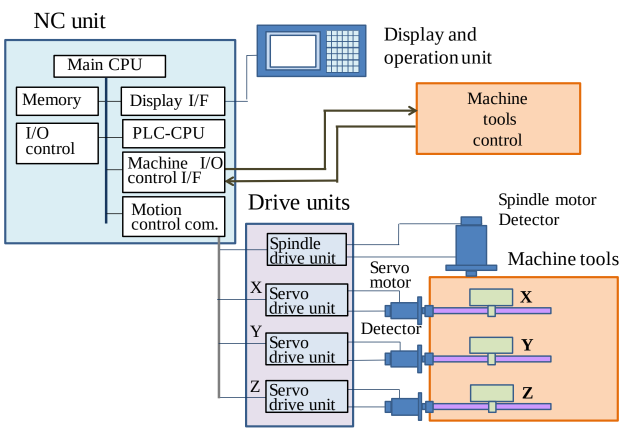

Figure 1: Configuration of the CNC.

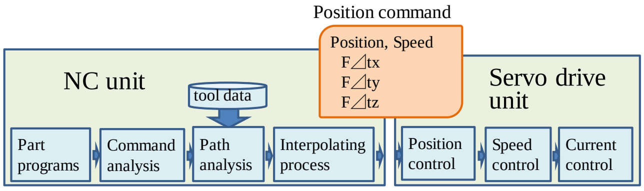

Figure 2: Position Control Processing in the CNC.

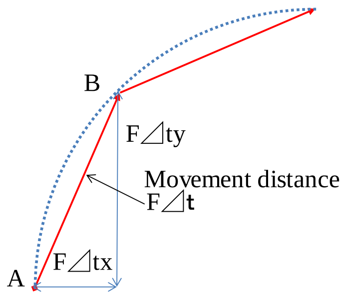

Figure 3: Interpolation Processing in the CNC.

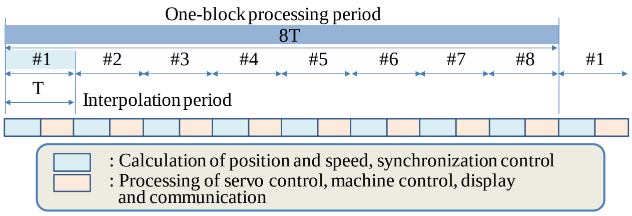

Figure 4: Real Time Control Processing in the CNC.

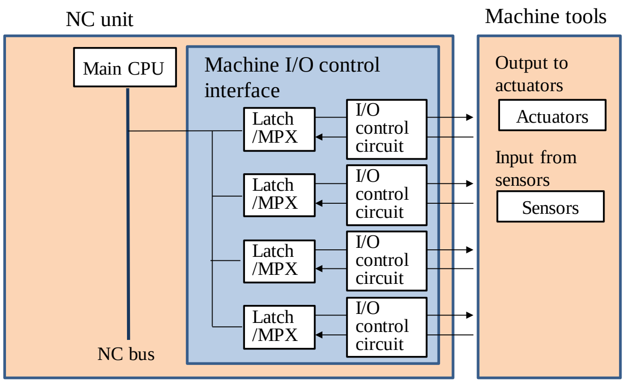

Figure 5: Schematic Block Diagram for Parallel I/O Control.

2.2 Tool Path Control in the CNC

The CNC executes part programs for driving the multi-axis machine tools (for example, X axis, Y axis, Z axis, etc. and the spindle) to move the tool nose position or move a part and cut the part

Figure 2 shows the details of the position control processing. The CNC analyzes the part programs, adds the tool information to the analysis result, and calculates the tool path data. Then, the NC unit calculates the movement distance per unit time for each control axis by an interpolating operation. Figure 3 shows the interpolation processing of the CNC, to control two axes (X axis and Y axis) simultaneously. In Fig. 3, the command for the movement from A to B is generated as follows: at first, the movement distance $F\Delta T$, which is the product of the speed F and the unit time ΔT, is calculated, and then, the distance is decomposed into the x-axis component of the movement distance $F\Delta t_x$ and the y-axis component of the movement distance $F\Delta t_y$.

The position commands calculated in the NC unit are sent to the servo drive units. The servo drive units control the position/speed and the current for driving servo motors based on the position/speed command values sent by the NC unit and the feedback information sent by the detector attached to each servo motor.

2.3 Sequence Control in the CNC

In the sequence control (machine I/O control function), input signals are used to monitor the machine status or to obtain the sensor information, and output signals are used to control the actuators.

The CNC controls the machine tools operations by calculating the movement command values at a fixed time interval and sending them to the drive units, implementing the sequence control of the machining procedure, and indicating status information on the display. In the sequence control, the CNC executes sequence programs. In response to the sensor information input signals sent in synchronization with the control cycle in the CNC, the machine control signals are output. It is essential to ensure real time sequence control processing with an accuracy of 0.1 msec because the processing is synchronized with the positioning control cycle in the CNC.

Figure 4 shows the time division for real time control processing in the CNC. For one axis, CNC calculates a command value and speed, and performs miscellaneous synchronization control in the first half of the interpolation period T. In the second half of the interpolation period T, the system performs servo control, machine sequence control, and data processing for display and communication. For controlling eight axes (at the maximum), the interpolation periods for eight axes are regarded as one cycle for the control operation.

2.4 Conventional Parallel I/O Control Method and Issues

Figure 5 shows the schematic block diagram of the machine I/O control interface in the NC unit. The conventional machine I/O signal control is performed using a parallel I/O function of the NC unit main CPU. In this method, the machine status is checked using the parallel input signal from the NC unit main CPU (ON/OFF control, +24 V/0 V), and the machine operations are controlled using the parallel output signal (ON/OFF control, +24 V/0 V). For this type of I/O control, several tens to one hundred signal wires are connected inside the power panel and externally for the sensor information input and the actuator control.

In the parallel I/O control method, each signal requires a wire connection between the NC unit and the actuator. Thus, the method involves issues such as the degradation of workability caused by the increase in the number of signals and wire bundles, and the lowering of reliability due to noises, etc. caused by the longer wire length.

Also, in the parallel I/O control method, data is directly transmitted between the NC unit and the machines or actuators. Therefore, the NC unit has to have numerous circuits to support the I/O control points according to the machine specifications. The lineup of the NC unit ranges from the high-end model to the general market model depending on the number of control axes and the control performance. In other words, the maximum number of I/O control points is determined for each class of the model. Therefore, there are issues with the NC unit cabinet volume for using the high-end model according to the drive control specifications. In such cases, it is inevitable to choose a NC unit with a large cabinet which supports a lot of I/O control points even when the machine requires less I/O control points. More specifically, the NC unit cabinet volume cannot be selected flexibly without any restraints because the fact that the NC unit has to contain the I/O control circuits prevents downsizing of the NC unit cabinet.

2.5 Conventional I/O Control Method for Serial Communication and Issues

Figure 6 shows an example of the schematic block diagram of machine I/O control for a regular serial communication. The machine I/O control interface in the NC unit consists of the I/O buffer and the communication control part for serial communication. The distributed remote I/O unit consists of the communication control part and the I/O control circuit. By transmitting the I/O signals for controlling the machine tools through serial communication, it is possible to mitigate the issues such as the degradation of workability caused by the increase in the number of wire bundles for signals, and the lowering of reliability due to noises caused by the longer wire length.

In the 1990s, CPUs were in most cases mounted on both the input and output devices to establish serial communication. The master communication control part of the NC unit consists of CPU and memory dedicated to communication and communication control circuit. Likewise, the slave communication control part of the distributed remote I/O unit requires CPU and memory dedicated to communication, communication control circuit, and I/O control circuit. Therefore, there are issues that a large circuit area is required, and the method incurs higher costs as compared to the parallel I/O control method. In addition, the development of software for CPU dedicated to communication is required both in the NC unit and the distributed remote I/O unit.

2.6 Serial Communication Processing by the Main CPU and Issues

To reduce the hardware cost for serial communication, it may be possible for the main CPU of the NC unit to perform serial communication processing instead of the CPU in the communication control part.

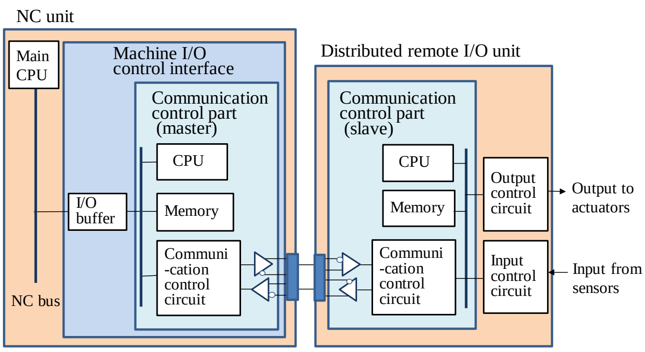

Figure 6: Schematic Block Diagram for Regular Serial Communication.

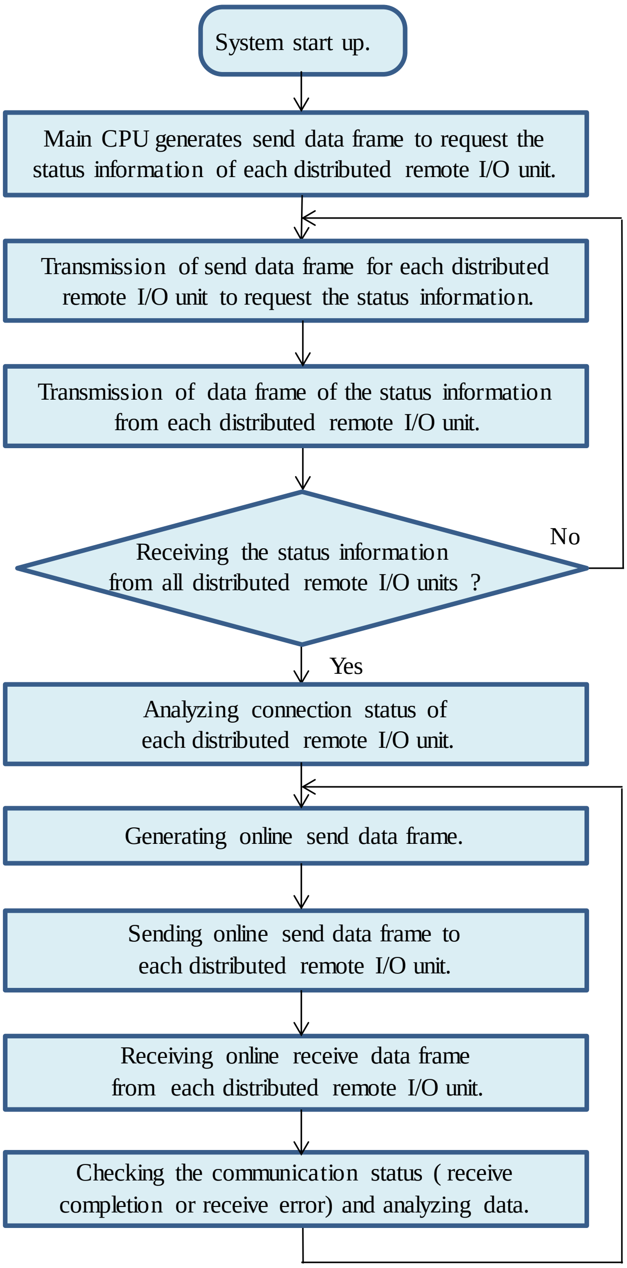

Figure 7: Processing Flow for Conventional Serial Communication.

Figure 7 shows the serial communication processing flow of the main CPU for the conventional serial communication. At power-on, the main CPU sends the data frame to request the status information of each distributed remote I/O unit. After receiving the status information from all units, connection status of each unit is checked. When all distributed remote I/O units are available for the communication, the online communication mode (normal I/O mode) is started. The main CPU generates output data frame and sends the frames to each distributed remote I/O unit. The main CPU then receives data frames sent from each unit. When no error is found with the data frames, the main CPU processes the input data. When an error is found with the data frames, the input data is discarded. These procedures are repeated in the online communication mode.

When software processing of the communication control part of the NC unit is performed by the main CPU, the load for the main CPU is increased. Furthermore, increasing of the distributed remote I/O units causes to increase the load. However, as mentioned in the description for Fig 4, real time processing for the CNC must be performed at a predetermined time period and the drive control command must be completed within a certain time limit. To ensuring the accuracy of real time control, there are issues that a further high-performance main CPU is required, which results in increased cost.

3 PROPOSED METHOD

3.1 Distributed Remote I/O Control Method

The feature of the distributed remote I/O control method introduced in this paper is as follows. In the first place, simplification of communication procedure and reduction of data enable to achieve the communication between the NC unit and the distributed remote I/O unit only by electronic circuits. In the second place, the definition of the supposed failure mode in advance achieves the fail-safe system without performing software processing. This method enables downsizing of the system, lowers costs, improves reliability, and enhances the safety.

Figure 8 shows a configuration of the CNC using the distributed remote I/O control method. In Fig. 8, the machine I/O control interface of the NC unit is used as the distributed remote I/O communication control part. The I/O control circuits are separated from the NC unit and contained in the distributed remote I/O units. The machine requiring numerous I/O control points can be supported by increasing the number of distributed remote I/O units. Consequently, the NC unit cabinet volume is no more dependent on the number of I/O control points.

3.2 Hardware for Distributed Remote I/O Communication

The increased cost is the major issue to perform machine I/O control for CNC using serial communication. Proposals for cost reduction are as follows:

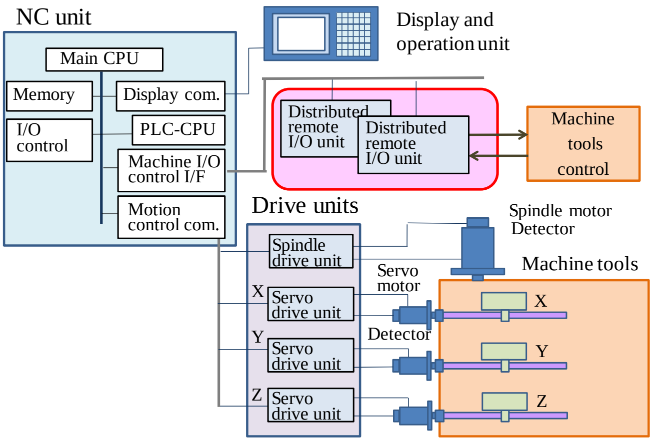

Figure 8: CNC Configuration Using the Distributed Remote I/O Control Method.

(1) Reduction of the number of signal communication wires

A half-duplex method is adopted for serial communication between the NC unit and the distributed remote I/O units. As compared to a full-duplex method, the number of communication wires can be reduced to one, and the wire rod, connector, and cable manufacturing costs can be reduced. In order to establish highly reliable data communication with the half-duplex method, a dedicated time-dividing communication procedure is defined to fit the characteristics of the CNC.

- Adoption of the EIA-485 differential system for the communication physical layer (data communication circuit)
- Adoption of the HDLC communication method
- In order to establish half-duplex communication, the communication cycle order is determined, and data transmission is enabled only during the transmission period.

(2) Elimination of CPU dedicated to communication

The conventional I/O control method for serial communication in Fig. 6 requires using CPU in the communication control part. For elimination of CPU dedicated to communication, simplification of communication procedure is needed. The frame size and data format suitable for the machine I/O control of the CNC functions are defined to minimize the communication processing. The communication pattern is defined to perform periodic communication in automatic synchronization with the CNC internal processing. Furthermore, processing at the time of power-on and processing at error are defined in the process of defining the data format and the communication procedure. These definitions achieve serial communication between the NC unit and the distributed remote I/O units without using CPU.

(3) Integration of the communication control part hardware into a one-chip LSI

With the predetermined frame size, data format, and procedure, the electronic circuits of the communication control part perform communication without using

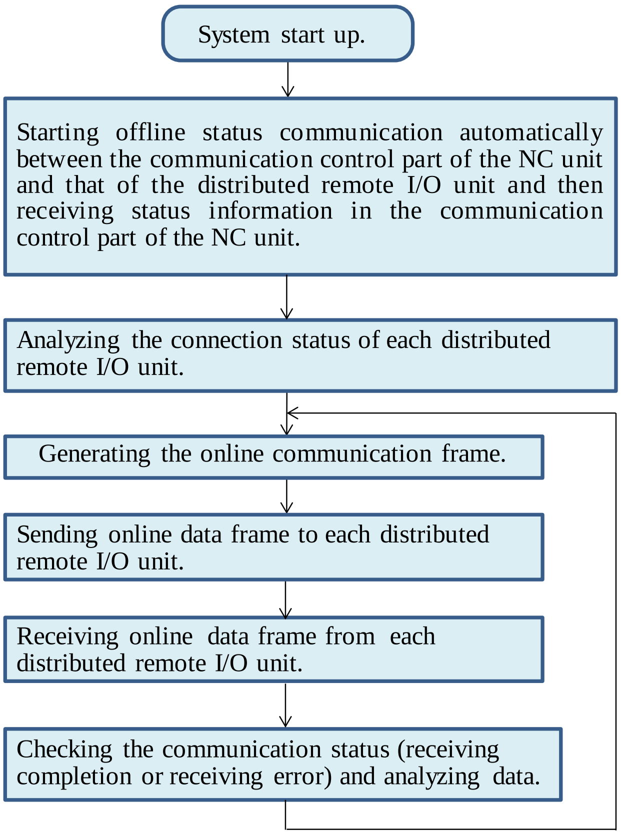

Figure 9: Processing Flow for Distributed Remote I/O Control Method.

CPU. It enables integrating the communication control part into a one-chip LSI both on the NC unit and the distributed remote I/O unit sides, downsizing and cost reduction of the communication control part.

(4) Simplification of the software processing by the main CPU

For I/O signal control processing of the NC unit, the main CPU reads the input data from the I/O buffer and writes the data to the I/O buffer in the communication control part in Fig. 6. These operations are performed either for the parallel I/O control or the I/O control for serial communication. Therefore, software processing by the main CPU can be simplified because the hardware automatically communicates with the distributed remote I/O units as mentioned in (2) and updates the data in the I/O buffers. Software processing to input or output the data can be performed without being aware of using serial communication.

(5) Simplification of processing on the distributed remote I/O unit side

The distributed remote I/O unit has the I/O control circuits which was built into the NC unit conventionally, and the one-chip LSI, mentioned in (3) in the communication processing part.

In remote I/O communication processing for the CNC, data frames are periodically generated from the output buffer at a predetermined time interval and sent to the distributed remote I/O units. The communication processing part of the distributed remote I/O unit receives data frames sent from the NC unit. When no error is found with the data frames, the distributed remote I/O unit outputs the received data as the machine control signal. Then, after the predetermined period of time, the distributed remote I/O unit generates data frames using the data taken as the machine input and sends them to the NC unit. This series of operations are performed without using CPU dedicated to distributed remote I/O unit communication or performing software processing.

(6) Ensuring reliability and safety of the system

To ensure reliability and safety of the system, processing at the time of power-on and at error are defined in the process of defining the data format and the communication procedure. Also, a fail-safe operation is defined for the machine I/O signal control at error.

3.3 Distributed Remote I/O Communication Procedure

In order to perform two-way serial communication between the NC unit and the multiple distributed remote I/O units, the NC unit performs a time dividing communication with each unit. The following two modes are defined for communication: the offline status communication mode, and the online communication mode (normal I/O mode). The two modes can be distinguished by the difference in the frame header pattern.

Based on the status information of the distributed remote I/O units stored in its communication control part, the NC unit generates output data frames in the online communication mode and sends the frames to the distributed remote I/O units. The NC unit then receives data frames sent from the distributed remote I/O units. When no error is found with the data frames, the NC unit processes the input data. When the count for errors found with frames sent from the distributed remote I/O units exceeds a predetermined value, the NC unit determines that a system error has occurred and stops the system.

3.4 Restraints on the Communication Procedure

As a CPU-less approach is used for communication processing in the distributed remote I/O control method, the following restraints apply to the communication.

(1) When the distributed remote I/O units receive the data sent from the NC unit, they send data to the NC unit after a predetermined time period because two-way communication is performed using one communication line.

(2) The NC unit sends data to the multiple distributed remote I/O units in a time dividing manner. Each unit send data to the NC unit only when the header pattern of the received data matches the predetermined station number of the own station.

(3) The two communication modes, the offline status communication mode and the online communication mode, are defined. The mode is switched between those two in accordance with the header pattern.

(4) It is necessary to determine the amount of data transmitted from the distributed remote I/O units to the NC

unit and the number of stations (the distributed remote I/O units) in advance.

4 IMPLEMENTATION SCHEME

4.1 Circuitry to Implement the Distributed Remote I/O Control Method

Figure 10 shows the configuration of the CNC for the distributed remote I/O control method. Eight distributed remote I/O units can be connected with communication network. (In Fig. 10, the distributed remote I/O unit stations from #2 to #6 are eliminated.) Half-duplex communication is used for serial communication. The communication control part (master function) and I/O buffer are integrated into a one-chip LSI in the NC unit. The communication control part (slave function) and control circuit such as multiplexer are integrated into a one-chip LSI in the distributed remote I/O unit. Also, half-duplex communication is established by controlling the communication control signal (RTS signal) to achieve reducing the number of communication signal wires. Input signals from sensors and a setting switch are selected by the switching signal (Mode signal) in the distributed remote I/O unit. In the offline status communication mode, setting switch information of the distributed remote I/O unit is send to the NC unit. In the online communication mode, sensor information obtained through input control circuit is send to the NC unit. Output data received from the NC unit is output to actuators through output control circuit.

The input and output control circuit are separated from the NC unit and contained in the distributed remote I/O unit. When it is required to increase the number of I/O control points, it is thus possible to increase the number of distributed remote I/O units and connect them to the serial communication line.

4.2 Implementation of the Distributed Remote I/O Control Method

In the distributed remote I/O control method, the NC unit state changes among the following: initial operation at power-on, offline status communication mode, and online communication mode. After initialization at power-on, the NC unit obtains information on the type and settings of the distributed remote I/O units in the offline status communication mode. After this, the NC unit mode transfers to the online communication mode. Figure 9 shows the processing flow in the NC unit. Figure 11 is the timing chart for shifting to the online communication mode.

The NC unit sends data frames in synchronization with the clock of the remote I/O communication cycle. After a predetermined time period, the distributed remote I/O units send the data frames to the NC unit. Communication with eight distributed remote I/O units can be performed in one cycle. When the main CPU sends the mode switching instruction signal (MPU-MODE) to change the mode to the online communication mode, the synchronous signal (SYNC-MODE) is output in synchronization with the clock to change the header pattern of the data frame. The communication control part of the NC unit sends the data frames repeatedly until it receives the response of normal reception completion from all distributed remote I/O units. After the NC unit receives the response of normal reception completion from all distributed remote units, the complete signal (STS-FIN) is output to change the mode to the online communication mode. (Figure 11 shows an example of the complete signal (STS-FIN). When no communication error occurs in the first cycle of mode switching, STS-FIN is output at the end of the first cycle. When a communication error occurs in the first cycle of mode switching and the NC unit receives a response of normal reception completion in the second cycle, STS-FIN is output at the end of the second cycle.)

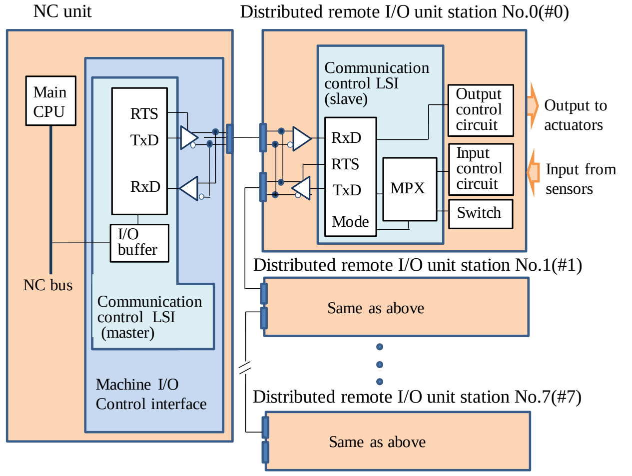

Figure 10: Configuration for Distributed Remote I/O Control Method.

Figure 12 is the timing chart for transferring of communication frames between the NC unit and eight distributed remote I/O units, and shows the data frame configuration. Each communication control signal (RTS) controls a sending data frame either in the NC unit or the distributed remote I/O unit. (In the Fig. 12, RTS signals of the distributed remote I/O unit stations from #4 to #7 are eliminated)
The NC unit sequentially sends data frames to multiple distributed remote I/O units in a time dividing manner, and each distributed remote I/O unit sends a data frame to the NC unit after a predetermined time period. The maximum number of stations is defined in advance for connecting distributed remote I/O units. The NC unit can sequentially send data to each distributed remote I/O unit, and receive the data sent from each distributed remote I/O unit. In this control method, the NC unit can complete the data communication with the distributed remote I/O units within a one-cycle interval. By repeating this procedure, the NC unit can perform the real time processing of the data I/O with a fixed cycle.

Every station is controlled by polling with using half-duplex serial communication. When the number of communication station is increasing, the delay time becomes grater. In the distributed remote I/O control method, the maximum number of station is defined eight on a serial communication line. The communication stations are controlled by polling. To perform the machine I/O control for the CNC, I/O data

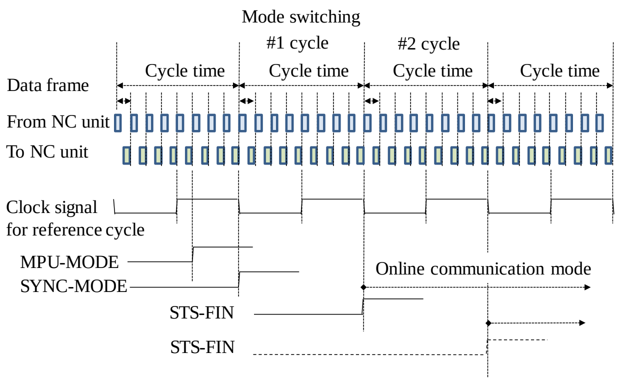

Figure 11: Timing Chart for Communication Mode Switching.

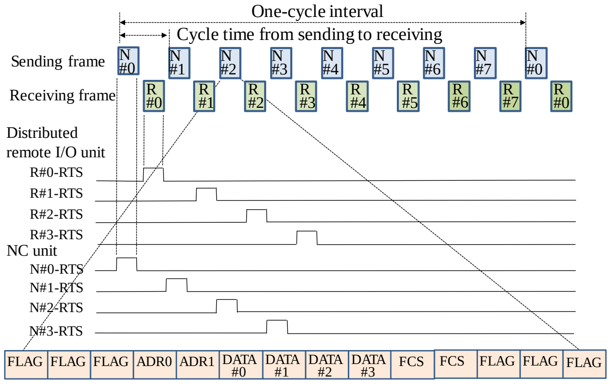

Figure 12: Timing Chart and Data Frame Configuration for the Distributed Remote I/O Control.

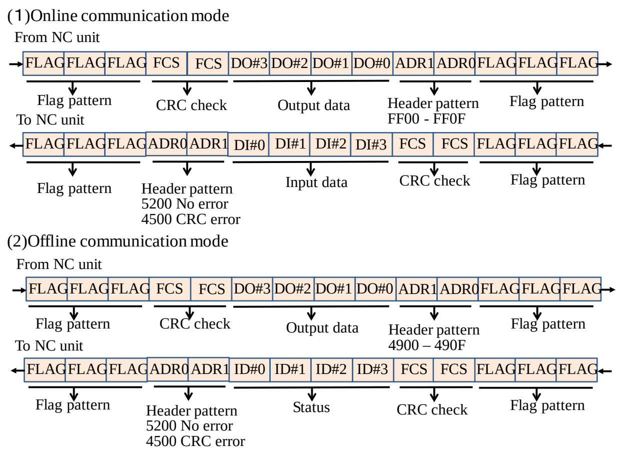

Figure 13: Data Format of Send and Receive Frames.

has to update within a one-block processing period of the CNC as shown in Fig. 4. In the implementation, a communication processing period (as shown a one-cycle interval in Fig. 12) is set to be fast enough to update I/O data more than 10 times within a one-block processing period.

Figure 13 shows the data format of send and receive data frames in each mode. The length of the data frame is fixed 14 bytes. The data frames consist of the flag pattern (3bytes), the header pattern (2 bytes), the data (4 bytes), the CRC check (2 bytes) and the flag pattern (3bytes). A flag sequence is assigned in the first part and the last part of the frame. The flag is a byte in a general data frame of HDLC. In this distributed remote I/O communication, the flag pattern is composed of 3 bytes to prevent malfunction when a flag pattern is misrecognized. The header pattern is used to control communication and to recognize the station number. The length of data is fixed 4 bytes. 32 bits data is small enough to control devices and get information from sensors of machine tools.

(1) These are the send frames from the NC unit to the distributed remote I/O unit and from the distributed remote I/O unit to the NC unit in the online communication mode (normal I/O mode).The header patterns from FF00 to FF0F which consist of 16-bit data are assigned for the online communication from the NC unit to the distributed remote I/O unit. The header pattern 5200 is assigned for the normal response header pattern from the distributed remote I/O unit to the NC unit, and 4500 is assigned for the error response header pattern from the distributed remote I/O unit to the NC unit.

(2) These are the send frames from the NC unit to the distributed remote I/O unit and from the distributed remote I/O unit to the NC unit in the offline status communication mode. The header patterns from 4900 to 490F are assigned for the offline status communication from the NC unit to the distributed remote I/O unit. The response header patterns from the distributed remote I/O unit to the NC unit are the same as the online communication. DO#0-3 are send data (output data) to the distributed remote I/O unit and DI#0-3 are send data (input data) to the NC unit. ID#0 is the identification code on the type of the distributed remote I/O unit and ID#1 is the information on settings of the distributed remote I/O unit. ID#2 and ID#3 are other status information.

Figure 14 shows I/O control circuits of a distributed remote I/O unit for the normal digital I/O control. Each bit of the I/O data has its own meaning. When the NC unit sends data in a data frame to a distributed remote I/O unit, the data is then output from the distributed remote I/O unit as its output signal. Then, when the distributed remote I/O unit takes in an input signal, the distributed remote I/O unit sends the data in a data frame to the NC unit, and the data is then used as the input data in the NC unit.

4.3 Implementation of the Distributed Remote I/O Units

By defining the data format for the distributed remote I/O control method, versatility was achieved for the communication function. Also, the I/O functions of the NC unit are integrated to use the control method through the distributed remote I/O units, and not dependent on the conventional individual interface circuits. Thus, it is possible to configure CNC using the distributed remote I/O units.

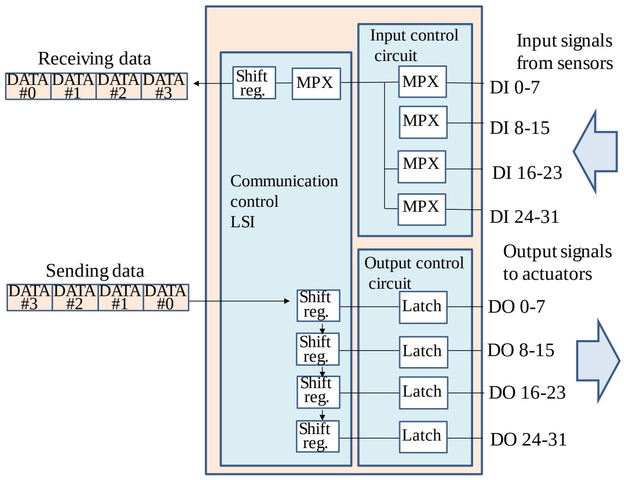

Figure 14: I/O Control Circuits of the Distributed Remote I/O Unit.

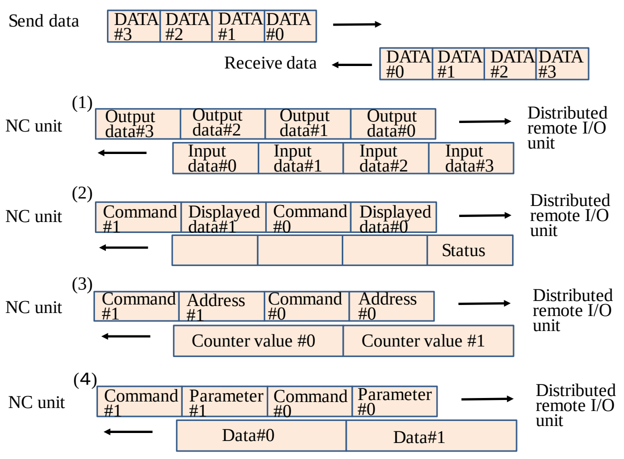

Figure 15: Examples of Communication Data Format for Distributed Remote I/O Control Method.

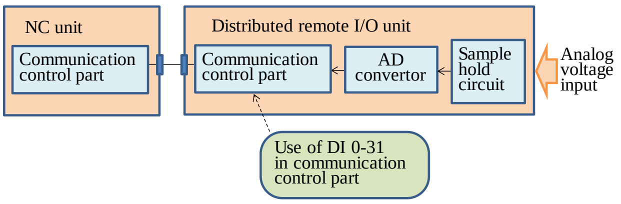

Figure 16: Configuration for Inputting Analog Voltage Information.

In the transmission data format, the data sent from the NC unit can be used as a command or output data, and the data received by the NC unit can be used as input data or status data. Each set of 8/16/32 bits of the data has its own meaning. Figure 15 shows the examples of various types of communication data format for distributed remote I/O. In Fig. 15, the example (1) shows the data format for the operation shown in Fig. 14. Each bit of the I/O data has its own meaning. The example (2) shows the following data formats: one which is sent from the NC unit to the display for combining the command to display data and the data itself, and one which is sent from the distributed remote I/O unit to the NC unit for reporting the display status data.

The example (3) shows the following data formats: one which is sent from the NC unit to the distributed remote I/O unit for sending the command to read the number of pulses generated from the manual pulse generator in a built-in circuit of the distributed remote I/O unit and the address to specify the manual pulse generator's station number, and one which is sent from the distributed remote I/O unit with 16-bit data of pulse number. The example (4) shows the following data formats: one which is sent from the NC unit to the distributed remote I/O unit for sending the command to read analog voltage information and the parameter to specify the station number of an analog voltage input circuit, and one which is sent from the distributed remote I/O unit with 16-bit data of analog voltage information.

In the conventional CNC, the necessary I/O interface circumethod, individual I/O interface circuits are provided in the distributed remote I/O units. Thus, the I/O functions required for the NC unit are achieved by using the distributed remote I/O units. Examples of the functions are as follows: outputting display data sent from the NC unit to the display, outputting the analog voltage command, reading the number of pulses of the pulse generator into the NC unit, or reading the analog voltage information.

Figure 16 shows a distributed remote I/O unit configuration for inputting the analog voltage information to the NC unit when the CNC contains distributed remote I/O units. When the NC unit sends a command to read analog voltage data to the distributed remote I/O unit which has an analog voltage input circuit, the distributed remote I/O unit detects the command in its communication control circuit, performs AD conversion of the analog voltage input through its sample hold circuit, and send the digitalized voltage data as its transmission data to the NC unit. The NC unit reads the analog voltage information at a predetermined time period and provides necessary controls on the real time basis.

4.4 Implementation of the Distributed Remote I/O Communication Procedure

In this section, we explain about the distributed remote I/O processing flow in the CNC unit and the distributed remote I/O units shown in Fig. 17.

4.4.1 Initial Operation at Power-on and Offline Status Communication Procedure

(1) After initialization at power-on, the distributed remote I/O unit reads its own station number from the hardware setting (setting switch). The offline status communication mode is the initial setting for the distributed remote I/O units.

(2) After initialization at power-on, the communication control part of the NC unit sequentially requests each distributed remote I/O unit in the offline status commu-

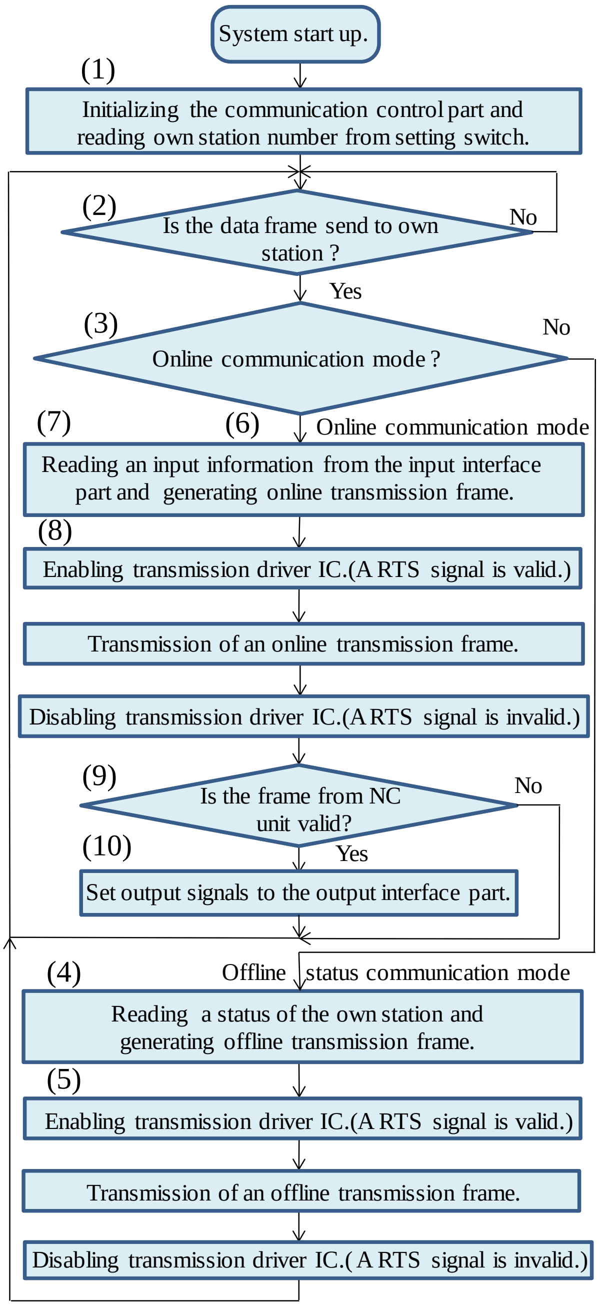

Figure 17: Processing Flow for Distributed Remote I/O Control Method.

nication mode in a time dividing manner to send the type and setting information of the unit. Each unit checks the header pattern (address part) of the data sent from the NC unit, and receives the data only when the header pattern corresponds to its own setting switch.

(3) The distributed remote I/O units distinguish the offline status communication mode from the online communication mode, which is the normal I/O mode, by the difference of the header pattern (address part) of the data frame sent from the NC unit.

(4) In the offline status communication mode, when the distributed remote I/O unit recognizes that the data is addressed to its own station and receives the data, the distributed remote I/O unit generates a data frame which contains the status information of its own station (unit type and setting information) in the data part.

(5) After a predetermined time period, the distributed remote I/O unit determines the communication control signal RTS as valid, and sends the data frame to the NC unit. The communication control part of the NC unit sequentially sends requests to obtain the type and setting information from the distributed remote I/O unit in a time dividing manner, and obtains the information on the number of stations and the unit type for all units connected with the one communication line. Then, the NC unit obtains the status information of all the distributed remote I/O units connected. After confirming the normal status for all of the distributed remote I/O units, the NC unit switches the mode from the offline status communication mode to the online communication mode.

4.4.2 Online Communication Procedure

(6) In the online communication mode, the NC unit periodically sends the data frame to each distributed remote I/O unit which contains the output data addressed to each unit. Each distributed remote I/O unit checks the header pattern of the data sent from the NC unit, and receives the data only when the header pattern corresponds to its own setting switch.

(7) The distributed remote I/O unit receives the data frame addressed to its own station, reads the input data from the input signal interface circuit, and generates a data frame which contains the input data.

(8) After a predetermined time period, the distributed remote I/O unit determines the communication control signal RTS as valid, and sends the data frame to the NC unit.

(9) The distributed remote I/O unit checks the data frame sent by the NC unit for any error.

(10) When no error is found in the data frame, the distributed remote I/O unit determines that the output data in the data frame is valid, and sends the output data to the interface circuit. Thus, the distributed remote I/O unit receives the data sent by the NC unit, and then outputs the data to the machine tools or actuators. When any error is found in the data frame, the previous data is retained as the output data.

(11) By repeating steps from (7) to (10) above, the NC unit performs sequence control for the machine tools.

4.5 Implementation of Safety and Reliability

In the distributed remote I/O control system, communication processing is performed with a fixed cycle in a CPU-less hardware configuration and the following operations are performed to ensure communication reliability and safety of machine tools.

(1) When the distributed remote I/O unit does not detect any data frame sent from the NC unit for a pre-

determined time period or longer, the distributed remote I/O unit automatically resets its own output.

(2) When the distributed remote I/O unit detects an error in the received data frame, the distributed remote I/O unit does not update the output signal. The distributed remote I/O unit changes the header pattern of the data frame and sends the data frame to the NC unit to let the NC unit recognize the data frame error.

(3) The NC unit stops the system when it does not receive the data frame sent from the distributed remote I/O unit.

(5) The NC unit stops the system when the count for errors found with frames sent from the remote distributed I/O units exceeds a predetermined value.

5 EVALUATION

5.1 Downsizing of the NC Unit and the Distributed Remote I/O Units

In the distributed remote I/O control method, a half-duplex communication method is adopted to simplify the communication wiring/circuit configuration. In addition, each electronic circuit is integrated into an LSI in the communication control part either on the NC unit or the distributed remote I/O unit side. Furthermore, the development of the device package technology and the implementation technology enabled electronic circuits to implement on a compact size board. The distributed remote I/O control method enabled to modularize the components of the CNC and connect them with serial communication network. This control method and the development of technologies mentioned above enabled the use of the more compact NC unit and distributed remote I/O units. Figure 18 shows a comparison of cabinet volume by CNC generation.

In the 1st generation CNC, many DIP (Dual Inline Package) devices were used for the electronic circuits. The I/O control circuits were provided in the NC unit. When the machine required numerous machine control signals, numerous circuit boards were required for machine I/O control, which resulted in increase in the NC unit cabinet volume. In the 2nd generation CNC, the device package was changed from DIP to SMT (Surface Mount Type).
Also, the I/O control circuits were separated from the NC unit to the distributed remote I/O control unit. Therefore, the NC unit could be significantly downsized owing to the high integration of the electronic circuits and downsizing of device. In the 3rd generation CNC, the NC unit volume was 20% smaller than the conventional one.

Instead, the I/O control circuits were contained in the distributed remote I/O units. Owing to the integration of the additional circuits into an LSI in the communication control part and downsizing of devices, the distributed remote I/O unit volume was 50% smaller than the conventional I/O control circuit in the 1st generation CNC.

By adopting the distributed remote I/O control method in the products, the system volume of the NC unit and the distributed remote I/O unit in the 3rd generation CNC was 25% smaller than the conventional one, which contributed to the downsizing of the cabinet.

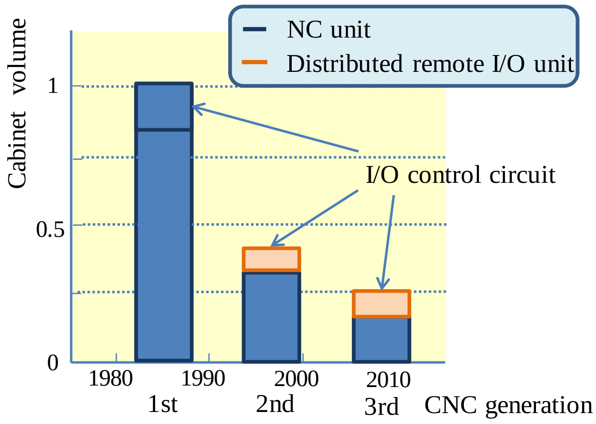

Figure 18: Comparison of Cabinet Volume by CNC Generation.

5.2 System Cost Reduction

5.2.1 HARDWARE COST REDUCTION

In the distributed remote I/O control system, a half-duplex method using a single signal wire was adopted for communication. Therefore, costs involved with serial communication could be reduced for wire rods, connectors, etc. In the 1990s, the development of ASIC which integrated CPU and user circuits was not practical or widely available yet. By simplification of communication procedure, the communication control part was configured using electronic circuits without using CPU and memory. Furthermore, we cloud to develop communication LSIs which integrated the electric circuits into a one-chip LSI, reducing the circuit cost by one-third or more as compared to the conventional communication method. The cost was almost equivalent to that of the conventional configuration for which serial communication was not used.

It was significantly beneficial for cost reduction to configure the communication control part without using CPU. Considering the fact that the LSIs are still used in today's products, it can be said that the use of LSI still achieves high enough cost performance.

5.2.2 Simplification of the Software Processing

After power-on, the hardware-configured communication control part of the NC unit automatically entered the offline status communication mode, and sequentially sent data frames to the distributed remote I/O units, requesting status information. When the distributed remote I/O units connected in the system received the data frame addressed to their own stations, they automatically sent their status information to the NC unit. As the status information was sent to the communication control part of the NC unit, the NC unit only had to check the status of each distributed remote I/O unit during software processing for initialization. Thus, it was possible to simplify the software processing. In the online communication mode, the NC unit writes the control command and parameters in the I/O buffer of the communication control part. After a predetermined time period, the NC unit reads the I/O buffer of the communication control part. It was possible to simplify the software processing because the information of the external devices could be easily read through the distributed remote I/O units without much concern for the serial data communication.

In the distributed remote I/O control method, the simplification was achieved without increasing the load for the main CPU to perform communication processing. Therefore, it was not necessary to replace the main CPU of the NC unit with a high-performance CPU, which enabled suppression of cost increase.

5.3 Flexible System Configuration

The number of I/O signal control points depends on the machine tools configuration. In the conventional NC unit, the number of I/O control points of each class of the NC unit is fixed for its hardware configuration. By adopting the compact-sized distributed remote I/O units in the products and configuring the system using multiple units as required, it was made possible to configure the machine I/O control part of the CNC flexibly to support the number of I/O control points required by the machine tools.

Also, versatility was achieved for the communication function by defining the command and the data as shown in the examples of communication data format in Fig. 15. Thus, it was possible to use distributed remote I/O units with a wider variety of functions as follows: other than for input/output of the normal I/O signals, it was possible to use distributed remote I/O units for outputting the data to the display, inputting the number of pulses and outputting or inputting the analog voltage signal to and from the peripheral devices. The wide selection of the distributed remote I/O units allowed the NC unit configuration to support the I/O type or the number of points of the machine to be controlled, and flexibility of system configuration was further improved. Table 1 shows the distributed remote I/O unit types.

Table 1: List of Distributed Remote I/O Units.

Distributed remote I/O unit type	Digital input	Digital output	Pulse counter	Analog input	Analog output
A	32	32			
B	64	48			
C	64	48			1ch
D	32	32	2ch		
E	32	32		4ch	1ch

The conventional CNC requires wire connections from one power panel to all machine components in the system. By using distributed remote I/O control method, the distributed arrangement of the NC unit, drive units, and distributed remote I/O units are made possible according to the configuration of the machines.

For example, when a machine has a building block structure and auxiliary devices may be added depending on specifications, it is possible to make a power panel for the machine and connect it to the machine, and make dedicated power panels for auxiliary devices and arrange the distributed remote I/O units to be connected to the power panels. Thus, it was made possible to configure a system by connecting the power panel of the machine and the power panel of the auxiliary devices using serial communication. This approach did not need the change on the machine power panel side. The auxiliary devices could be added only by connecting serial communication cables. Thus, it was made possible to reduce additional wiring works, add optional machine tools functions easily, and increase flexibility of the system.

Also, owing to the downsizing of the NC unit, the NC unit can be flexibly placed on various locations, not only inside the power panel as before, but also on the back side of the display part of the display and operation unit, for example.

5.4 Reliability and Safety of the System

5.4.1 Reliability at Power-on

In the distributed remote I/O control method, the CNC is configured by connecting the NC unit and the distributed remote I/O units through communication. We evaluated whether the NC unit recognizes distributed remote I/O units connected to the NC unit, and how the system operates when misrecognition occurs after initialization at power-on.

After initialization at power-on, the NC unit requested information on the type and settings of the distributed remote I/O units in the offline status communication mode. After this hardware information was obtained, the NC unit switched the mode to the online mode. In the above operation, when the actual machine information was not consistent with the NC unit setting information, inconsistency was regarded as an alarm and the CNC operation did not start. As a result, we confirmed that the actual system configuration is checked without fail when the system mode transfers to the normal online mode from the initial status after power-on, and the system is highly reliable in preventing malfunction when a connected device is misrecognized.

5.4.2 Reliability and Safety at Fault Conditions

In terms of communication functions, we evaluated how the reliability and safety of the system can be assured in case of communication failures between the NC unit and the distributed remote I/O units.

Under normal conditions, the NC unit periodically sends data to the distributed remote I/O units and receives data from the distributed remote I/O units after a predetermined time period, following a predetermined procedure. When a communication break or cable disconnection occurred, no data frame was sent from the distributed remote I/O units, the NC unit determined that a communication break or cable disconnection was occurring, and stopped the system.

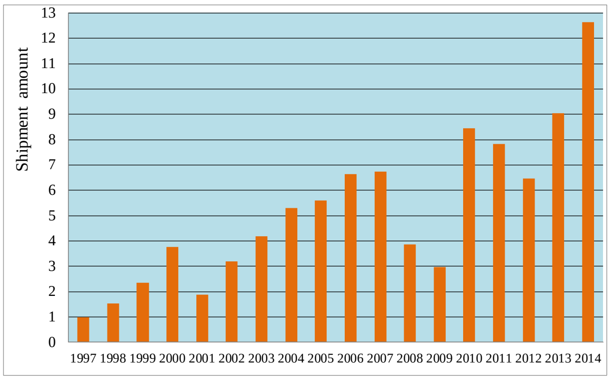

Figure 19: Annual Shipment Amount of the LSIs/IPs for Communication Control Part.

When noise was present and the count for errors in the data frame sent by the distributed remote I/O module exceeded a predetermined value, the NC unit also stopped the system.

We confirmed that the NC unit assures system safety by monitoring the data frame sent from the distributed remote I/O units.

On the other hand, the distributed remote I/O units check the communication status with the NC unit by monitoring the data frame sent from the NC unit.

When an incident such as a cable disconnection or break occurred, the distributed remote I/O unit reset the machine control signal output since it did not detect a data frame sent from the NC unit for a predetermined time period. When the NC unit stopped the system for some reasons, the NC unit detected the system stop with a watchdog using its internal timer, and the signal sent from the distributed remote I/O units was turned off. The distributed remote I/O unit detected that no data frame was sent from the NC unit for a predetermined time period, and reset the machine control signal output. Based on the above, we confirmed that the machine control signal can be reset even when the NC unit enters an error status and stops the system. Also, when the distributed remote I/O unit detected an error in the received data frame, the distributed remote I/O unit held and did not update the machine control signal output.

We confirmed that the above measures ensure the safety of the highly reliable system against abnormal stops of the NC unit or communication failures such as communication breaks.

5.5 Widespread Use of the Distributed Remote I/O

The CNC using the distributed remote I/O control method started to be shipped to the market in the late 1990s. The hardware circuits of the communication control part, a core of the distributed remote I/O control, were integrated into a one-chip LSI in the communication control part. Two types of LSIs were developed: one with a master function is equipped on the NC unit, and the other with a slave function is equipped on the distributed remote I/O units.

Owing to the subsequent development of semiconductor technologies, the LSI of the communication control part is also used as the intellectual property (IP) core of FPGA or ASIC. Figure 19 shows the annual shipment amount of the LSIs for the communication control part with the master or slave function and the IP cores. The annual shipment amount in 1997 when the shipment started is used as reference. The distributed remote I/O control method is now widely available in the market. The most recent annual shipment amount of products is more than 10 times of that of the first year of shipment, and the cumulative number exceeded 5,000,000.

6 CONCLUSION

We reported on the distributed remote I/O control method in the CNC. When serial communication started to be widely available in the 1990s, integrating CPU and user circuits into a one-chip LSI was not practical or widely available yet. Using communication CPUs caused increasing cost and decreasing power of competitive products. Simplification of communication procedure and reduction of data enabled to achieve the communication between the NC unit and the distributed remote I/O unit only by electronic circuits and integration into a one-chip LSI. With this communication control method, we established a compact and low-cost network for machine I/O control of CNC, without compromising the real time performance of the CNC. Thus we modularized the components of the conventional CNC according to their functions and achieved downsizing and optimization of the individual modules. Consequently, we achieved distribution of the component modules of the NC unit and improved flexibility of system configuration while maintaining high reliability and safety of the system. Modularization and distribution of the modules by the distributed remote I/O control method herein was a pioneering solution. The concept of the idea is the origin and the inheritance for the today's CNC.

The basic idea for this I/O control method is to define the communication control method suitable for the real time control for the CNC. Specifying the purpose and simplifying the related information are the key factors to solve issues. We presume that the concept of the idea will also be meaningful in the coming age of IoT. We anticipate further contributions to the development of the new systems for manufacturing in the future.

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