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An efficient industry 4.0 architecture for energy conservation using an automatic machine monitor and control in the foundry

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ABSTRACT

In this article, a machine monitor and control architecture (MMCA) satisfying the industry 4.0 standard is proposed for energy conservation by optimizing the core moulding machine in industrial automation. Since the foundry environment is a fine dust area and is maintained at very high temperatures (around 140°C), the manual operation of machines is more complex and demanding. Moreover, the monitoring and controlling of machines need highly reliable eco-friendly systems. With real-time data logging, the proposed MMCA prototype system has been installed to monitor and control the overall process in a single core shooter machine (CSM). The parameters controlled using MMCA in foundry machinery include pressure, temperature and power consumption. The complete system can be controlled using an intranet or Internet connection without any human intervention in the machinery environment, which operates at a very high temperature. After explaining the architecture and its features, the experimental results are presented on a real-time implementation of the framework to validate the optimal energy management by the proposed MMCA. The experiments were performed on a CSM, which is automated for practical industrial applications. Its real-time implementation ensures that MMCA-based monitoring and controlling is more effective and advantageous than the programmable logic controller-based machine monitoring.

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KEYWORDS
Control system; electronics and communication engineering; industrial engineering; autonomous system; intelligent automation

1. Introduction

In recent days, the automation of equipment or machinery is preferred in industry to speed up the production in an eco-friendly manner and to increase its efficiency. However, the foundry environment and its automation are at an elementary stage. Industry 4.0 is envisioned to evolve a smart factory supported by the Internet of things and computing systems. It conceptualizes a dynamic scenario in industrial automation for data exchange for cost-effective monitoring and control mechanisms. It should be a robust mechanism that ensures the healthy condition of the machinery and its components. The heart of the revolutionary Industry 4.0 is the machine monitoring mechanism, which is mandatory in any real-time industrial environment. Industry 4.0 ensures (i) precautionary measures are taken in hazardous areas during machine operation, (ii) preventive maintenance to avoid sudden equipment failure, (iii) long life for machinery and its components and (iv) less manpower and cost-effectiveness in industrial process. Similarly, one such real-time scenario is evident in industrial electronics; moreover, in the automation industry, monitoring and controlling the equipment or machinery parameters without human intervention is desired. Parameter or data-driven monitoring and controlling are mandatory in any automation process, and many researchers have contributed to the evolution of an environment-friendly industrial automation process.

2. Importance of monitoring in industrial automation

Industry 4.0 is expected to support supply chain management by providing accuracy and transparency, which is cost-effective and leads to optimized operation strategies with greater productivity and efficiency [1]. An energy-efficient light monitoring and controlling architecture that uses Zigbee for an efficient lamp management system can be employed in the outdoor environment of urban and rural areas [2]. For instance, sudden voltage rise in photovoltaic systems has been monitored and controlled using a remote voltage estimation method that uses an on-load tap changer fitted transformer in a low voltage network [3]. But, Cloud4sens is a cloud-based architecture that uses technologies, such as extensible messaging, presence protocol (cross-platform, Apache, MySQL, PHP and Perl; XAMPP) communications and X509 certificates, for controlling and monitoring the sensor parameters [4]. Moreover, the importance of monitoring systems in industries is widely evident for multiple simultaneous measurements using scalable multi-sensor systems

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[5] to monitor the wearing of paper mill blade. In the electrolytic process, proper temperature control and electrolyte circulation flow are essential to detect the flow blockages in an electrolyte effectively. High purity cathode manufactured by the inductive-link system [6] uses lightweight components and ensures battery-free operation in a highly corrosive sulphuric acid environment. Similarly, in industrial machine vision applications, unmonitored illumination will cause a disastrous effect on the sensory data. An autonomous illumination system [7] based on deep reinforcement learning customizes the optimal illumination environment even during the abrupt illumination variation in the zone. Among the renewable energy sources, the wind turbine has a higher failure rate due to unplanned maintenance and repair costs. To address the limitation, a real-time IoT-based holistic monitoring system [8] is suggested for simultaneous condition monitoring and sub-synchronous control interaction detection. Recently in the industrial Internet of things (IIoT)-based heterogeneous optical networks, a heuristic resource optimization method [9] monitors and controls the general-purpose processor, which optimally processes the massive big data via remote radio heads. Similarly, a model for the instantaneous optical resource allocation method [10] for IIoT applications using a convolutional neural network extracts the optimal channel state efficiently with less computational complexity. Hence, the importance of machine monitoring and its subsequent controlling process is mandatory for the automation of industries. Therefore, in this article, we propose a machine monitoring and controlling system for efficient operation of core shooter machine (CSM) to manufacture various kinds of automobile parts including gear, valve, piston, rocker arm and engine outlet body.

3. Machine monitoring and controlling in foundry

The automobile industry relies on spare parts, namely camshaft, rocker arm, piston and gears, manufactured at very high temperatures in a foundry environment. The complicated industrial process of automation is quality-driven and relies on durable manufacturing processes. Several foundries are manually operated, leading to health hazards and making the process more expensive. The limitation can be rightly overcome by automating the entire manufacturing process with more emphasis on the low cost, robustness and efficiency of the resulting system. For this, 16-bit Infineon XE167 microcontroller-based architecture is implemented to control the entire process parameter and monitor it in a separate data log system. The operation of CSM controlled by a programmable logic controller (PLC) with fixed architecture is connected to the local area network (LAN) using RS485 or ethernet. Due to high voltage noise, it suffers high latency and often results in communication failure or malfunction at high temperatures. PLC-based design is energy inefficient (operates at 24 V) due to two temperature controllers and one pressure gauge used to run the CSM [11,12]. Moreover, machine time settings and temperature setpoints are assigned manually, which cannot be restored automatically after power failure. To solve this, the proposed machine monitor and control architecture (MMCA) uses one separate system to control the entire process in a CSM. Infineon XE167 is interfaced with a computer used to manage the machine operation, production, temperature, pressure and power. This system uses Wi-Fi to provide 24/7 monitoring and scheduling the core shooter process in a wireless mode. Altogether the system will enable to estimate the current condition of the machinery or equipment so that any possible failure, in the machining process, thermocouples and the heater coils, can be detected early. The web server can monitor and control the temperature setpoints, time setting and machine operations. A comparative analysis of PLC with MMCA in terms of interfacing mode, operating voltage, temperature and cost is presented in Table 1.

The machine is controlled and monitored by a remote system with Internet connectivity. Since the data collected from the machine are stored, machine troubleshooting becomes simple and effective.

4. CSM

A core shooter is a machine that produces several cores using the required die. The core creates a hollow structure inside a casting like a camshaft, piston, rocker arm and brake lever. The CSM consists of a blow unit with a pressure monitor using a pressure gauge to control the temperature on the left heater box and the right heater box, which can be set and monitored using thermocouples. The required die box is mounted on the heater box [13]; the core shooter is switched ON after the required set temperature is achieved. The sand is filled with appropriate pressure in the die box through the blow air to cure the core at a specific temperature. The coated sand gets cured to obtain the required structure of the core in the die box [14]. The CSM plays a virtual role in the automobile manufacturing; the machine output should be of good quality to get a better casting. The internal block representation of the CSM is shown in Figure 1.

5. MMCA for conserving energy in CSM

The Wi-Fi-based MMCA proposed in the article are presented in Figure 2. The proposed industrial standard MMCA system is presently used in organizations, such as Tata steels, Indo shell cast Private limited and Jindal Steel and Power Limited, for measuring the

Table 1. Comparative analysis of MMCA over PLC.

Criteria	PLC		MMCA
	DELTA SS14	SIEMENS S7-1200	
Mode of communication	LAN, RS232, RS485, CAN	LAN, RS232, RS485, CAN	Wi-Fi, CAN, LAN, RS232, RS485, I2C, SPI
Operating temperature	0°C to 55°C	0°C to 70°C	0°C to 125°C
Execution time	3.4 µs	18 µs	25 ns
Cost	Medium cost	High cost	Low cost
Memory	64 kbytes	25 kbytes	256 kbytes
Real-time	PLC comes with a real-time scheduler, which facilitates running a specific loop at a desired timing interval		Programming based on the user's need gives freedom in looping time intervals
Code library and language	PLCs are usually restricted to IEC 61131 languages, e.g. ladder, function block, etc. These languages are simple to use but have limited functionality and involve complexity during implementation		Embedded systems can be programmed in C, C++, Python, which gives us considerably more power and flexibility. The embedded language supports standardized code across an installed base product due to the object-oriented nature

CAN: Controller Area Network.

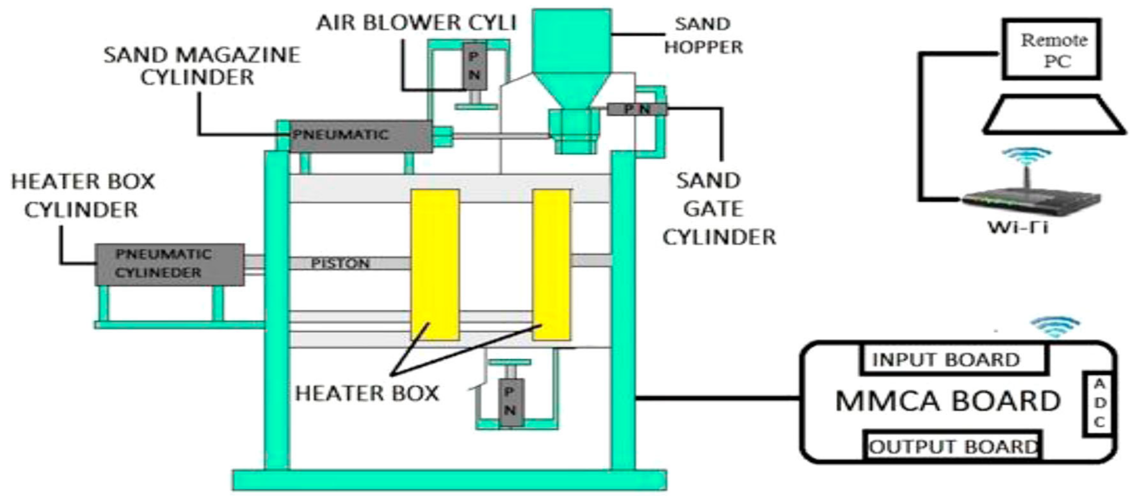

Figure 1. Block diagram of the CSM.

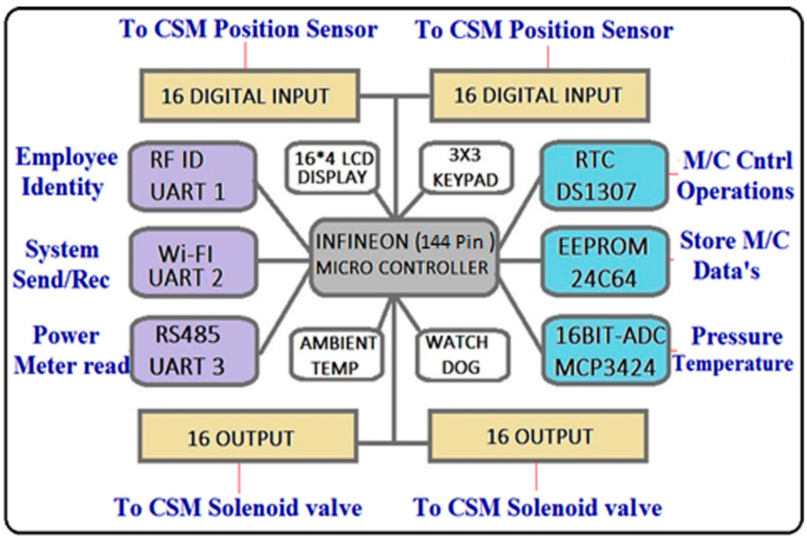

Figure 2. Block diagram of the proposed MMCA.

machine production, temperature and pressure of the CSM. Since the design has to be operated at high temperatures in a fine dust foundry environment, an industry-standard design, components and automotive standard microcontroller, such as Infineon XC167, is used. It is programmed to control the machine input, output logic and all sensor control. The sensor collects the temperature and power consumed details and sends them to MMCA, which further processes the data to schedule the operation of the entire machine automatically. Moreover, the data from the power metre, temperature controller and pressure metre are collected using microcontroller RS485 Modbus Communication [15]. Each machine has a separate IP address for its Wi-Fi (client) module to effectively communicate with XMPP hypertext preprocessor page (PHP) software. Users can

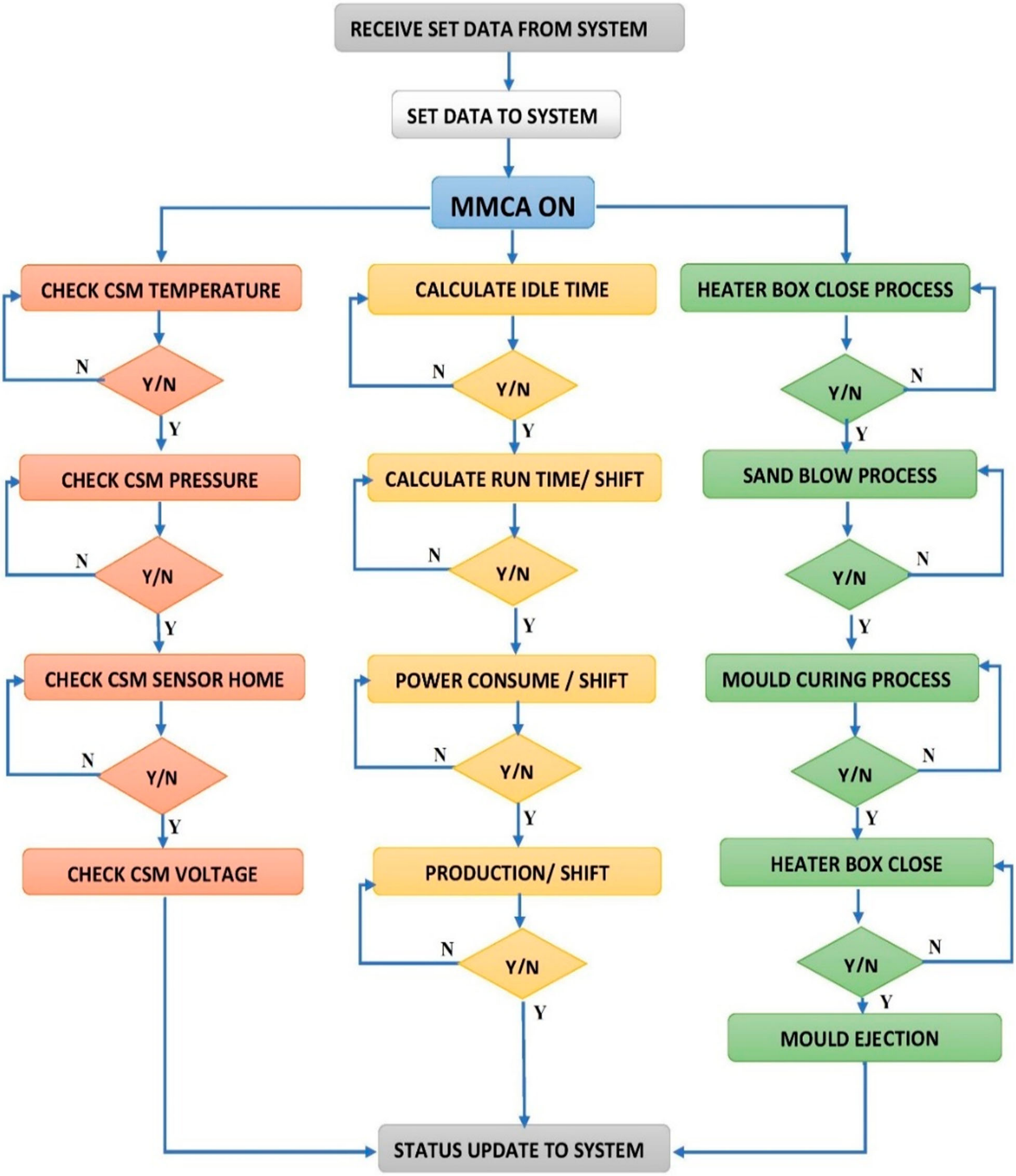

Figure 3. Programming logic for CSM.

change and set the temperature and pressure metre parameter through the microcontroller RS485 communication. The microcontroller transmits the collected data to the server computer using Wi-Fi communication; the web application displays the machine data from the server machine. The user can view and change the set data through the web application. The entire machine data are stored in a separate cloud database so that the data can be monitored in a local or remote host using the internet. The architecture and its operating features in the core shooter monitoring system are elaborated in the subsections. The MMCA printed circuit board (PCB) is fabricated such that every circuit and its component are chosen to meet the industrial standards, as shown in Figure 4. The sequence of steps to be automated in the CSM is represented in the form of a flowchart given in Figure 3.

6. Proposed MMCA in the PCB

The core shooter monitoring system installed in every core shooter module consists of several modules, including thermocouple sensor, pressure sensor, proxy sensor, solenoid valve, power metre, radio frequency

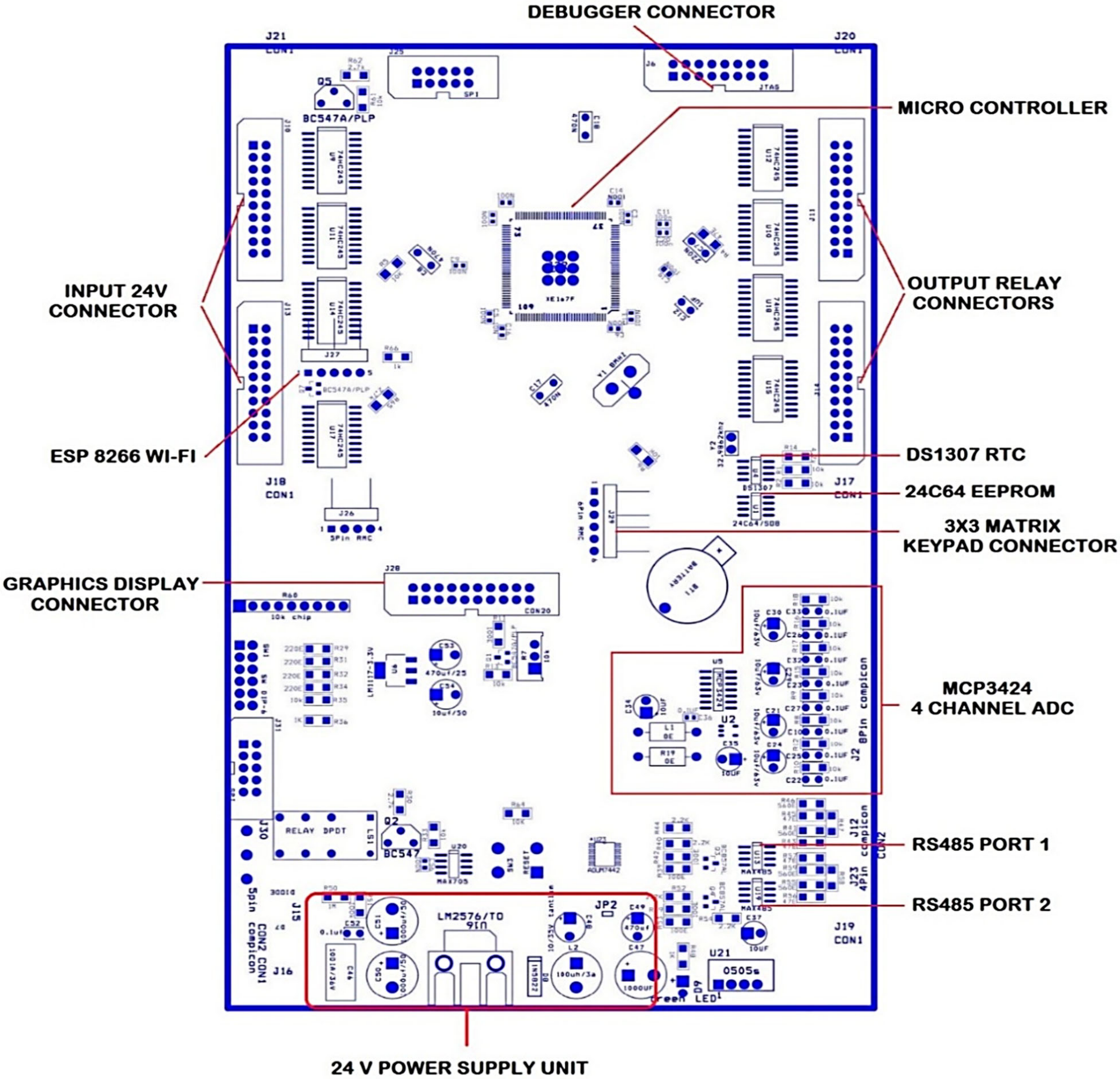

Figure 4. MMCA PCB (front view).

(RF) reader, machine switch input and the Wi-Fi communication module. The thermocouple observes the temperature change in the heater coil and controls it. A pressure sensor monitors the machine line pressure, which operates the pneumatic cylinders for the machine moving part. A proxy sensor is connected to the input unit to control the machine's position. The sensors work in unison to transfer the gathered information to MMCA, which further manipulates the data to regulate the sequence of operation of the entire process. The detailed discussions related to the major components involved in the core shooter monitoring system are given in the subsections.

6.1. Industrial standard microcontroller unit

Choosing a versatile microcontroller for industrial application is more important for the robust and efficient realization of automation processes in the industry. The proposed architecture for the foundry environment uses Infineon XC167, which has "A" Grade (Automotive) and I Grade (industrial) standard microcontroller, as shown in Table 2. It has 144 pins to accommodate more input and output ports to perform the machine functions. It will work in a high-temperature condition. This control is specially used for armed force; it has an on-chip debug interface to JTAG controller and six serial interfaces used to communicate external devices such as RS485, universal asynchronous receiver-transmitter (UART)-based Wi-Fi and Transistor-Transistor Logic (TTL)-based RF reader. It supports the Infineon Dave application including the integrated development environment (IDE) with a graphical user interface and all the required libraries. A bypass capacitor (0.1 μF) connected between the power supply (VCC) and ground

Table 2. Industrial standard 16-bit microcontroller comparison chart.

16-bit microcontrollers	Communication interface	Flash memory	Opera temp	Max pin	Clock speed	Grade	Power
INFINEON XE167	6× UARTs supporting 2× I2S 2× SPI	576 kB flash 32K SRAM 16 kB DRAM	−40°C to +125°C	144	80 MHz	Automotive and industrial	3.0–5.5 V
NXP MC9S12XDP512	4× UARTs supporting 2× I2S 2× SPI	512 kB flash 32K RAM	40°C to +105°C	144	80 MHz	Industrial	3.3–5.5 V
Microchip PIC24FJ1024GA610	6× UARTs supporting 3× SPI/I2S	512 kB flash 32K SRAM 8 kB DRAM	−40°C to +85°C	100	32 MHz	Industrial	2.0–3.6 V
Texas Instruments MSP430F67791IPEU	4× UARTs supporting 2× SPI/I2S	512 kB flash 32K SRAM	−40°C to +85°C	100	25 MHz	Industrial	1.8–3.6 V
Renesas Electronics H8S/2378	4× UARTs supporting 2× I2S 2× SPI	512 kB flash 32K RAM	−40°C to +85°C	144	32 MHz	Industrial	3.0–3.6 V

SPI: Serial Peripheral Interface; UART: Universal asynchronous receiver-transmitter; SRAM: static random access memory; DRAM: dynamic random access memory.

Figure 5. MMCA hardware MAX705 watchdog timer.

(GND) is used to protect the microcontroller from voltage ripple and voltage variation.

6.2. Design of external hardware watchdog timer

The internal timer can be affected by runaway code. An external watchdog is equipped with a separate clock source to better its reliability; if properly configured, it cannot be bypassed or disabled by runaway code. In the proposed design, the MAX705 IC is used for a hardware watchdog timer to generate a reset pulse when the supply voltage drops. Watchdog output goes low if the watchdog input for the microcontroller pin has not been toggled within 1.6 s. When it stops, the MAX705 trigger output is toggled to the controller restart pin. Also, the manual-reset input allows resetting the trigger using a push-button switch. The pin configuration of the MAX705 watchdog timer is shown in Figure 5.

6.3. Design of isolated RS485 Modbus communication

The RS485 serial communication is used to adjust the limits and collect the data from the temperature controller and pressure metre in the CMS machine with the Modbus protocol. In the foundry industrial area, RS485 communication is more effective due to high power line electromagnetic interference and heavy temperature. To protect MMCA from induction and noise due to industrial power lines, the DC to DC 0505s separate power supply circuit is used in this design mentioned in Figure 6. The ADUM1301 automotive-grade digital isolator communicates between the microcontroller and RS485 IC at 125°. Transient Voltage Suppressor (TVS) diode protects the circuit from electrostatic discharge. This system collects the data from long distances in industrial electrical noise and mechanical noise, as shown in Figure 7. The request and response time is 8 ms to communicate with one RS485 enabled device that operates at 5 V and consumes less voltage, as presented in Figure 8.

6.4. Design of sensor input and control output module

This proposed architecture uses 32 input and 32 output ports to control the machine operation. An Opto-coupler is used to obtain the isolated proximetric sensor input from the CSM position sensor to find the CSM pneumatic cylinder position and detect the input voltage range (6.5–32 V) using Figure 8. To control the output, UNL2003 IC is used as a relay driver, which drives several electrical output to control the solenoid valves for changing the CSM position. The input and output logic is controlled by the XE167 microcontroller. The generated high voltage is stepped down to 5 V, while CCMA Opto-coupler provides the isolation between the sensor input (24 V) and microcontroller (5 V); the circuit is shown in Figure 9.

ULN2003 Darlington transistor array IC is employed to drive the relay circuits. It can drive a high current and has voltage capability with a maximum current handling capability of 500 mA.

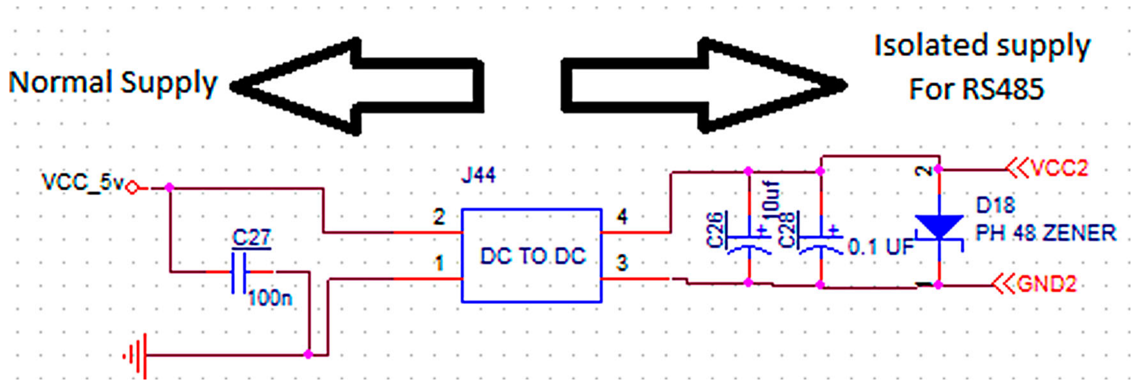

Figure 6. MMCA – RS485 DC to DC isolated power supply.

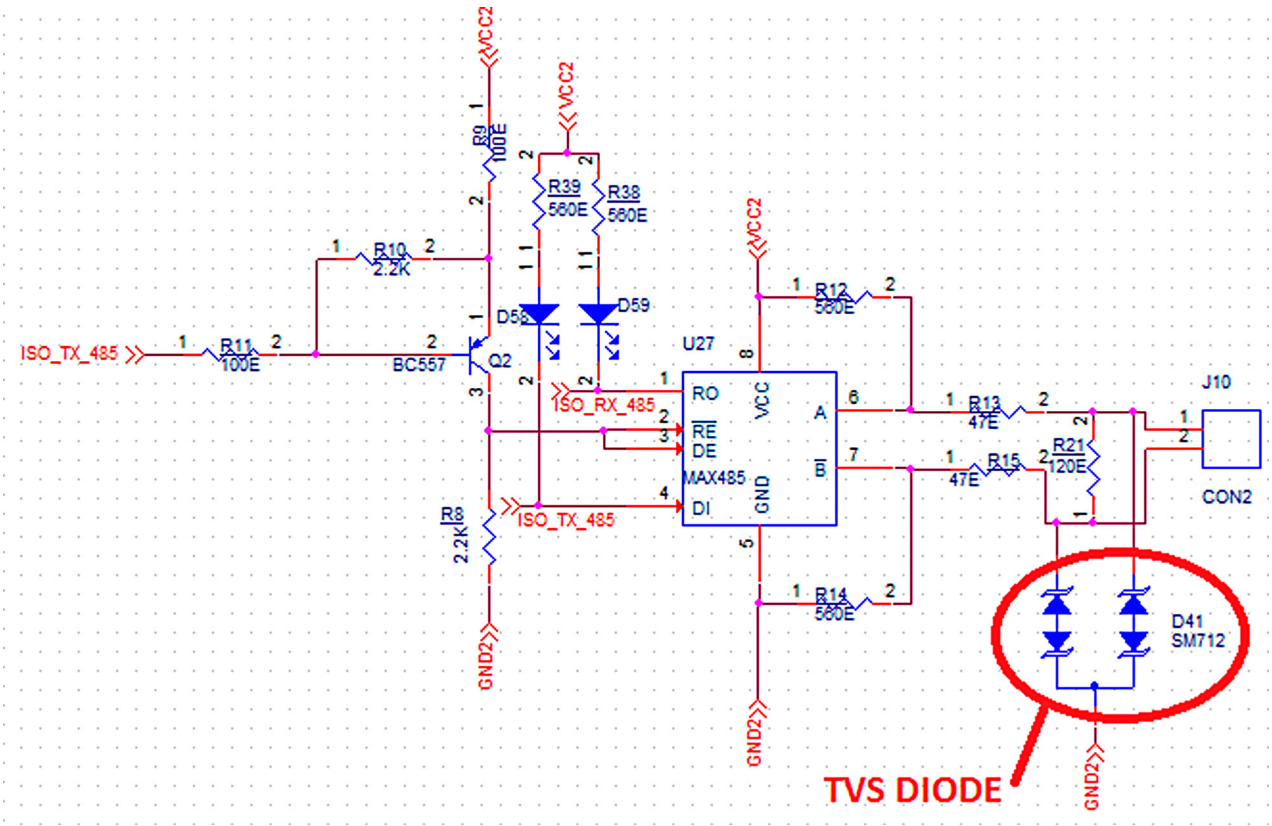

Figure 7. Isolated RS485 circuit and TVS diode.

6.5. Wi-Fi ESP8266 networks

ESP8266 Transmission Control Protocol/Internet Protocol (TCP/IP) stacks with low cost and reduced instruction set computer on-chip memory. Wi-Fi module is controlled by XE167 microcontroller, which operates at a frequency of 2.4 GHz by serial communication using AT commands with 11200 baud rate communication. Wi-Fi in MMCA PCB board is configured as a client and web application acts as a server. For every 1 s, the Wi-Fi sends a hypertext transfer protocol (HTTP) request with the desired machine live data using AT commands to the server, as given in Figure 9. The Wi-Fi transmits and receives using terminal software, and the server response to the machine set parameter for the request (client Wi-Fi) are shown in Figure 10. The AT command for Wi-Fi communication is furnished in

Table 3. Device to Wi-Fi communication.

Wi-Fi command from board	Descriptions	ESP8266Wi-Fi response
AT + RST/r/n	Reset the Wi-Fi	Ok
AT + CWMODE = 1	Station mode selected	Ok
AT + CWJP = "USRE", "PASSWORD"	Station user and password	Ok
AT + CWJAP?	Wi-Fi list	Ok
AT + CIPMUX = 1	TCP selected	Ok
AT + CIPSTART = 1, "TCP", "IP ADD"	Connected to server	Connected ok
AT + CIPSEND = 1, length	Length of sending URL	Ok
GET machine data/01, 03, 02, 04, 05, …	Machine data as URL	$ server response

Table 3. Separate LM1117 3.3 V regulates for ESP8266 Wi-Fi module to protect from external noise.

The AT commands are used to instruct the ESP8266 Wi-Fi module. In this module, an XC167 microcontroller instructs the essp8266, while AT + RST

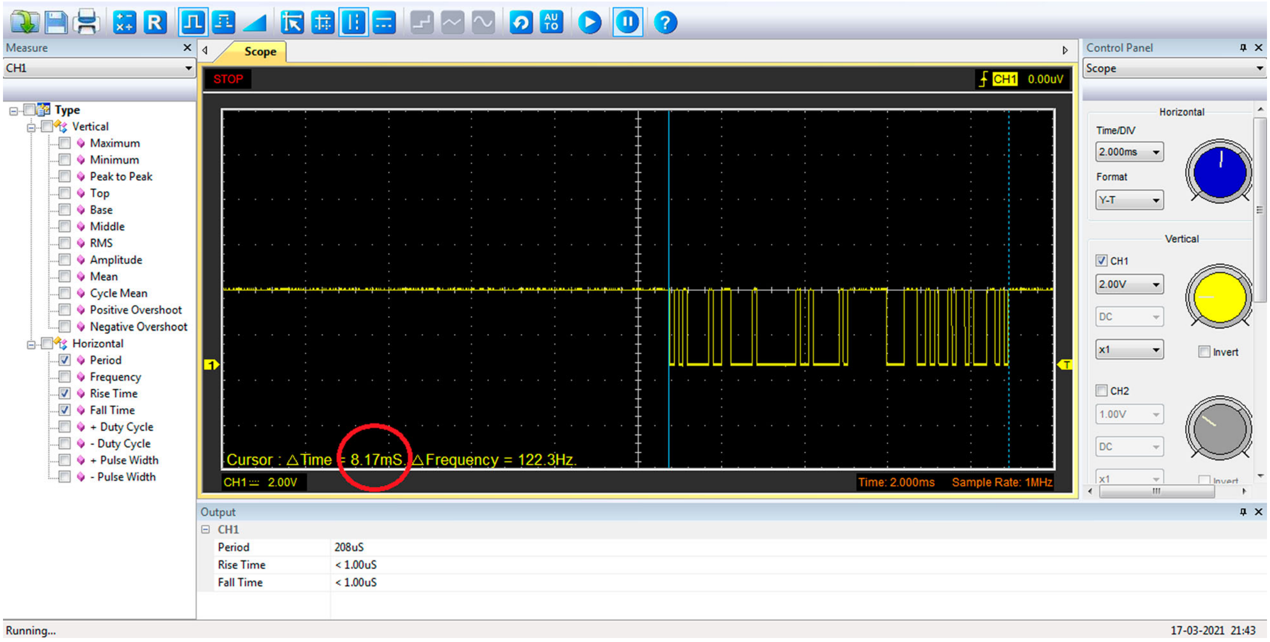

Figure 8. RS485. Request and response time.

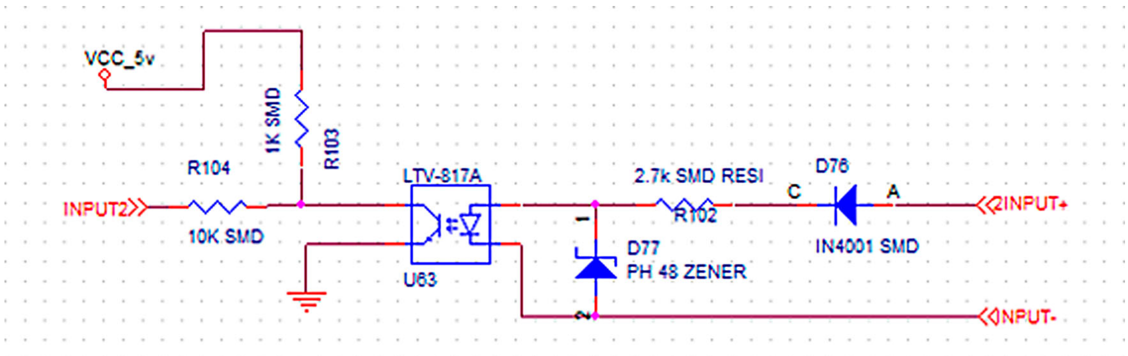

Figure 9. MMCA 24 V input circuit.

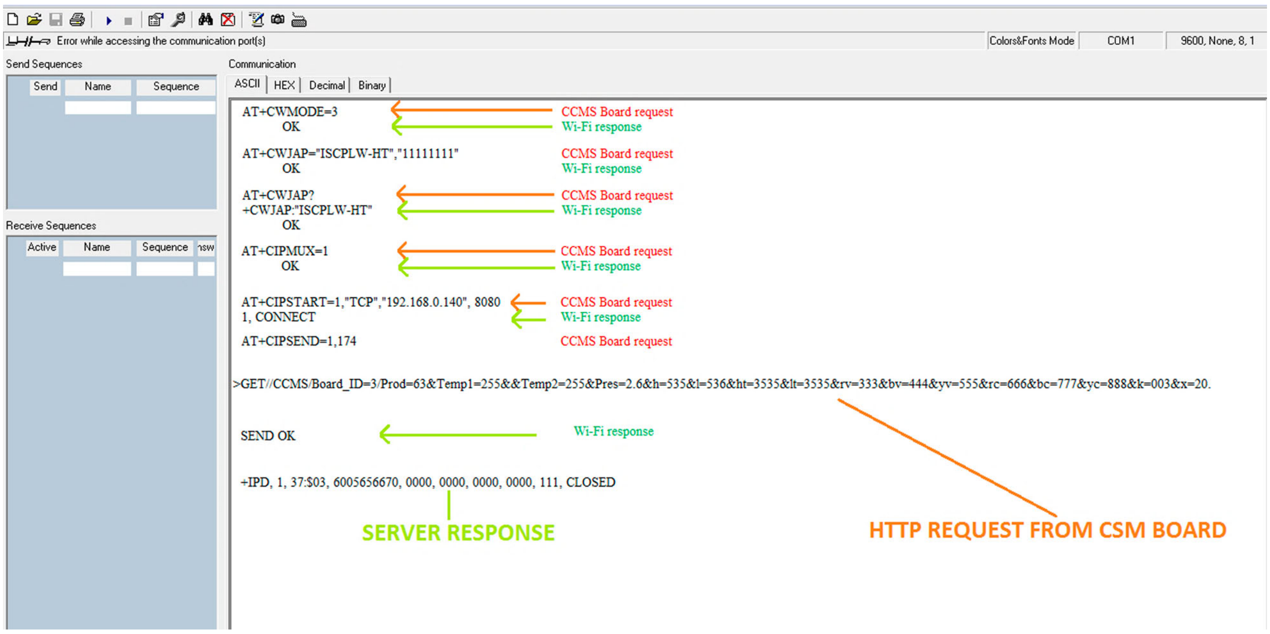

Figure 10. Esp8266 (Wi-Fi) AT commands board request and Wi-Fi response.

Figure 11. Block diagram of HTTP request and response.

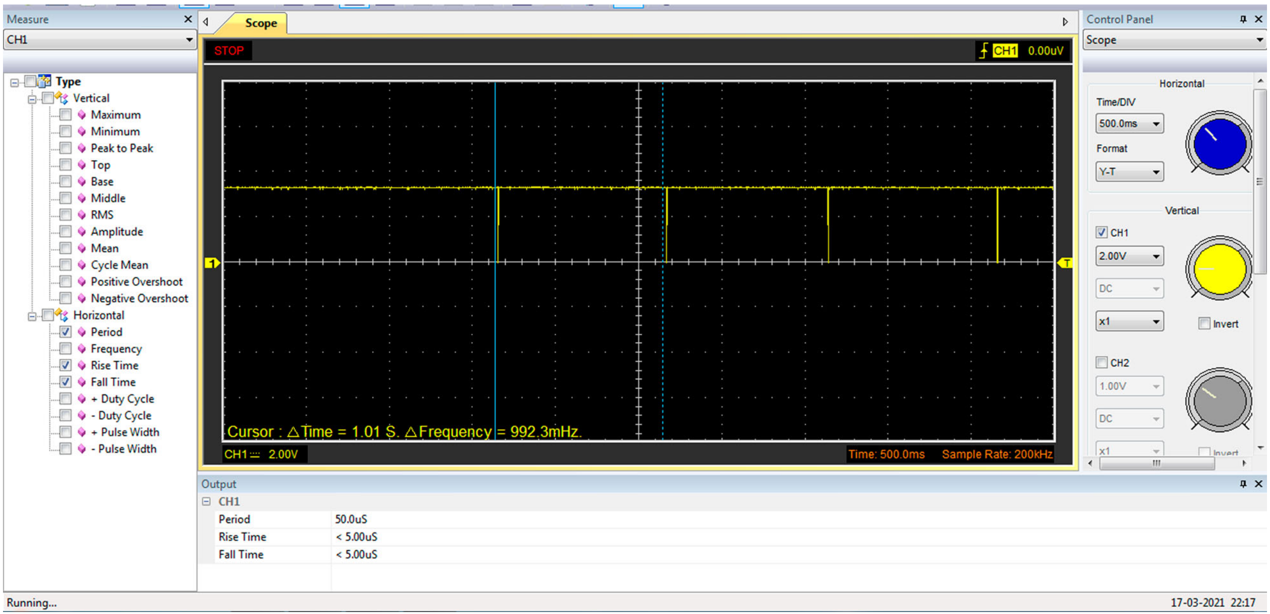

Figure 12. Wi-Fi request and response time (scope view).

command is used to reset the Wi-Fi. AT + CWMODE command is used to select the Wi-Fi as a station mode, to connect between internet router AT + CWJAP = "user name", "password" command is used. Once the esp8266 is connected to the router, the esp8266 is selected as the client mode using AT + CIPSTART = "TCP", "192.168.3.116", 8080 this command. Finally, the number of data and httprequest are sent using AT + CIPSEND and http. The command of ESP8266 and server response is shown in Figure 10.

Wi-Fi in MMCA PCB board configured as a client and web application act as a server. For every 1 s, the Wi-Fi sends an HTTP request with the desired machine live data using AT commands to the server, as shown in Figure 11. The synchronization between the client and server time is 1 s (Figure 12).

6.6. Web application

The XAMPP service application automatically starts the Apache tool to execute the PHP file, and the resulting data are stored in the MySQL database [16]. Apache executes the PHP scripting to run the HTTP server, and MySQL works with PHP to allocate the data in a separate database with the help of web-based application software. The data are separated unit-wise in a local host, as shown in Figure 13. When the communication fails on the machine side, the error is displayed in a dashboard view, as shown in Figure 14. MMCA board triggers the machine data as an HTTP request to the server through the Internet or private LAN, as shown in Figure 14. MMCA board triggers the machine data as an HTTP request to the server through the Internet or private LAN, as shown in Figure 15.

The server responds to the requested client with machine setpoint data, as in Figure 16 and the requested machine data are processed and stored in a server database. The database queries allocate the machine data and display the results in front-end JavaScript. It displays the parameter with data storage, and its processing is controlled by the MySQL database. The database is maintained on the local server or over a remote server through the network. The results of machine gathering data are shown in this web application; the user can view and edit the setpoint of machine parameters setting using a web browser. The software tools used for developing MMCA is given in Figure 17 and the PCB is shown in Figure 18.

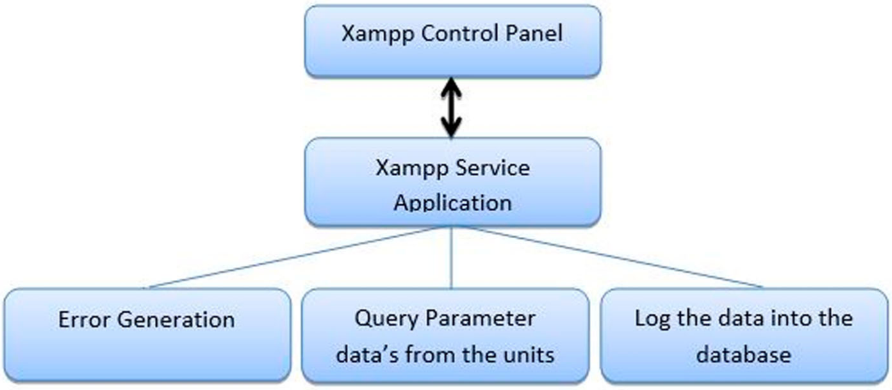

Figure 13. Architecture of system application software.

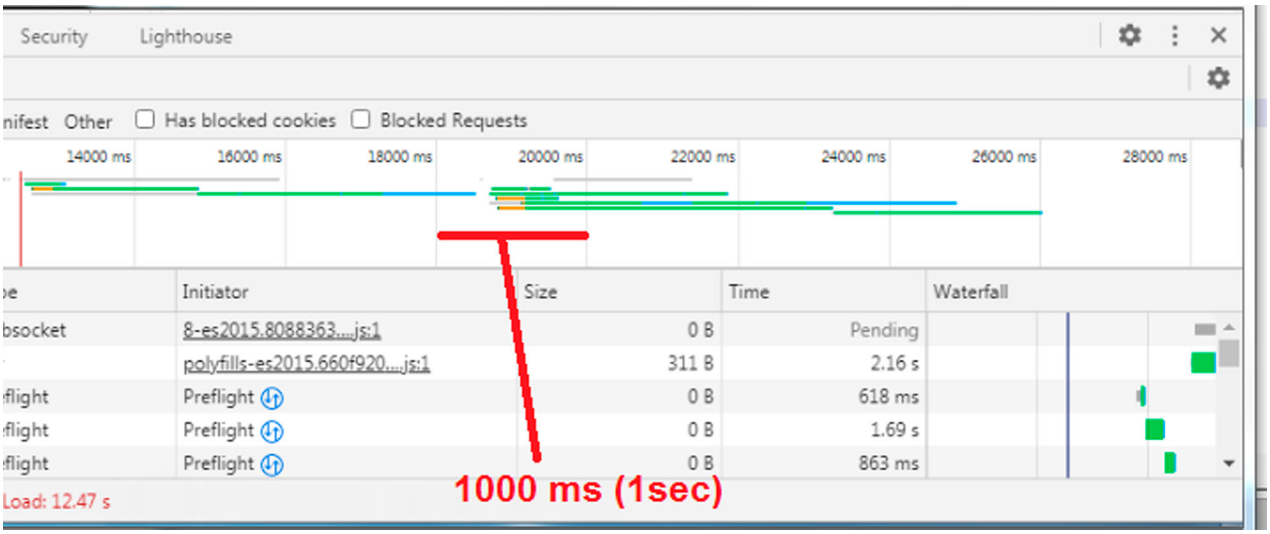

Figure 14. Server response time.

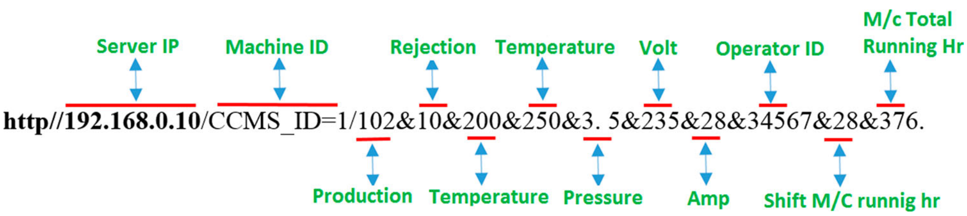

Figure 15. HTTP client request from the board to the server.

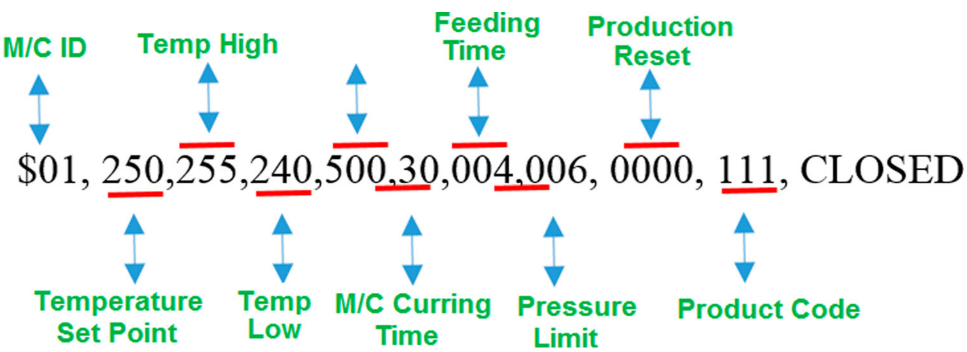

Figure 16. HTTP replay from the server.

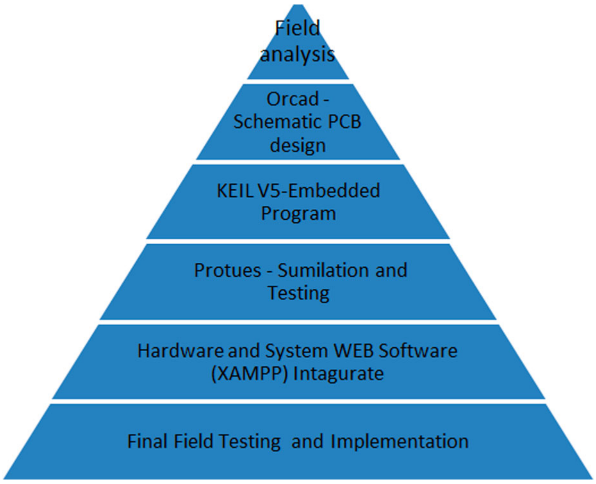

Figure 17. Software tools used to develop the MMCA.

7. Tools used

OrCAD Capture software is used to construct the schematic of MMCA, while PCB Editor is used for placement and routing. The microcontroller XE167 is programmed using Keilu Vision and Mem tool. The µVision Debugger from Keil supports simulation using a PC or laptop and debugging using a target system and a debugger interface. The Proteus Design Suite is used to verify the functionality of the MMCA schematic and the programmed microcontroller. The Keil software is an IDE; it integrates a text editor to write a C/C++ programme. Being a compiler, it also converts C code into hexadecimal. The Memtool is a system application used to flash the programme instruction (hexadecimal code)

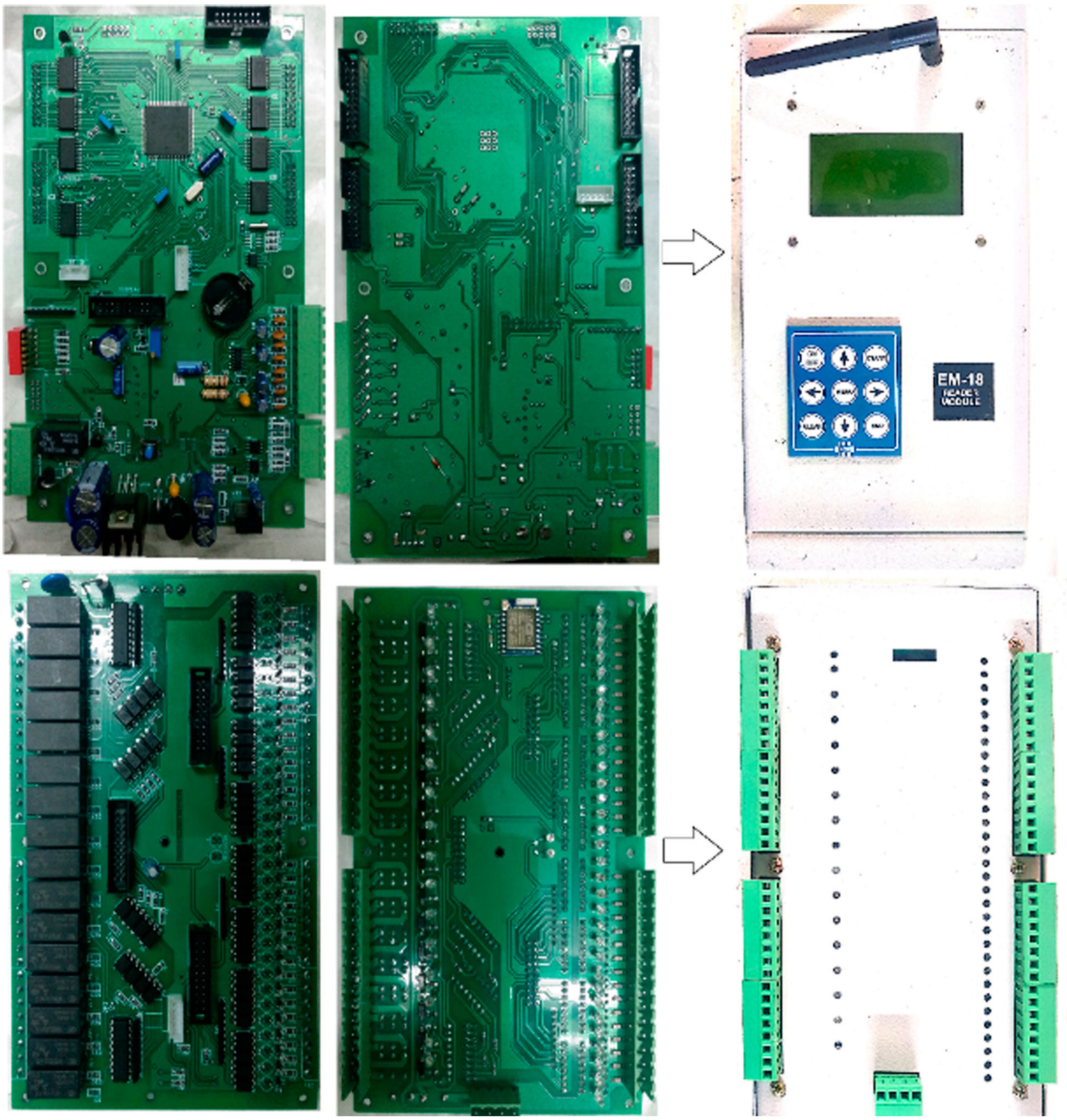

Figure 18. MMCA PCB board.

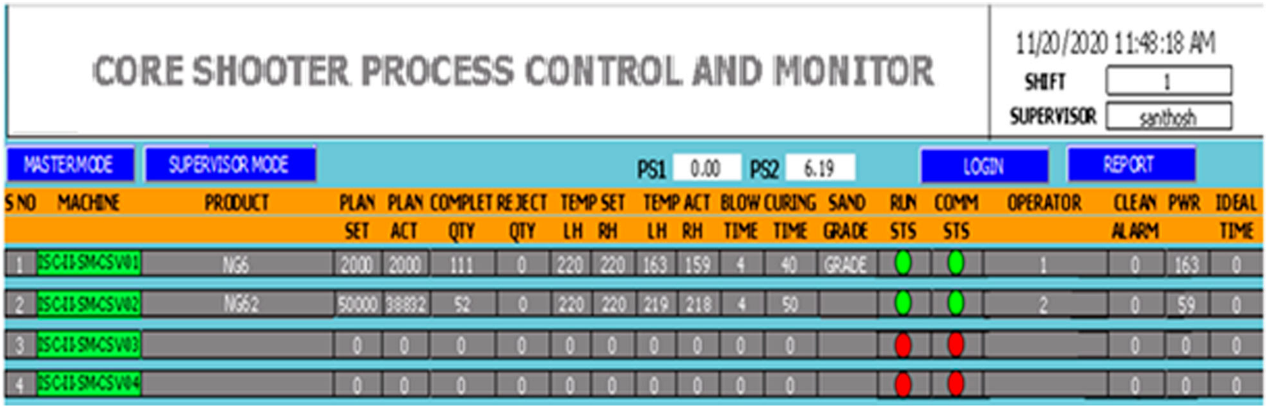

Figure 19. Web application image for monitoring CSM.

and erase the programme to XC167 microcontroller on-chip flash memory.

8. MMCA performance and result analysis

The wireless MMCA prototype is an alternative to the PLCs-based parameter monitoring and controlling system. The prototype is designed for industrial standards, and it enables the centralized monitoring of temperature, pressure, power and machine timings of CSM from a remote location using a Wi-Fi module. PLC has certain limitations like hardware complexity to measure additional parameters; and also, it supports only the Supervisory control and data acquisition (SCADA) application programme for process control.

Since PLC is programmed using ladder logic and it supports wired communication, it is not suitable for artificial intelligence-based machine learning applications. It is inefficient in machinery connected to the LAN, which operates at very high temperatures [17]. The aforementioned limitations are overcome by the proposed MMCA and the manual operation of foundry equipment at high temperatures (around 125°) is avoided. The MMCA can improve the overall equipment efficiency (OEE) by providing secured access to the remote operator for live monitoring and controlling the machinery parameters. The MMCA prototype is operating system independent and can be interfaced with various applications, including web and system applications.

The board is mounted on the CSM unit with the appropriate panels and wirings. The power supply for the board is obtained from the panel already available on the machine. The inputs are wired from the thermocouples mounted in the heater chambers. The Wi-Fi module is mounted on the top of the machine to establish a line of sight link between the server and the client.

The system has secured password access to the parameter settings, and the status of the machine is displayed in the MMCA Liquid Crystal Display (LCD). The board is designed to control the machine even when the server PC fails using a standard keypad. All the parameters can be entered through the standard industrial key. The prototype has been installed and tested to monitor and control the various types of machinery in a foundry. The machinery's status is presented in Figure 19.

The system application is used to continuously monitor the parameter values of all the machine units in the company. The values are logged onto the database at predefined time slices. The history of machine parameters can be logged periodically using a computer. The data logging time can be modified by changing the settings shown in Figure 19. The parameter settings can be changed by an authorized person with password access using the web application.

In this work, low-cost Wi-Fi is used to implement a wireless mode of communication between the machinery and remote user. To control the process parameters of machines, such as pressure, voltage, power consumption, power factor, machine operating time, by employing a suitable number of controllers with appropriate modifications, we can monitor and control the whole plant using the remote servers wirelessly. Login-based entry at the server and machine side improves the system security and reliability. Finally, from the experimental results, the OEE has been significantly improved.

9. Conclusion

MMCA architecture is designed and fabricated in a PCB to optimize power and energy resources in the machines used in the industry. Presently, the MMCA is employed in a real-time foundry environment to monitor the temperature and pressure of machinery. By monitoring the parameters of the defective product, the limitation of the existing architecture, which includes the additional number of controllers, low OEE and possibilities of malfunctions, has been overcome. Hence, the developed robust control mechanism with its lowest cost implementation makes the MMC more suitable for the automation process with significantly less power consumption in small-scale industries and foundries.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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