

# CAN and Zigbee Based Distributed Control Architecture for Electroplating Applications

Alex W.H Choy<sup>1,2</sup>, B.L. Luk<sup>1</sup> MInstMC, Louis K.P. Liu<sup>1</sup> InstMC, S.Chen<sup>3</sup>

<sup>1</sup>MEEM Department, City University of Hong Kong

<sup>2</sup>Industrial Center, the Hong Kong Polytechnic University

<sup>3</sup>Department of Electronics and Computer Science, University of Southampton

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## Abstract:

In this paper, the application of the distributed control architecture using low-cost hybrid wired/wireless control network in the electroplating line control system design is described. The feasibility of implementing condition monitoring under this proposed control platform for increasing the system reliability and reducing the scrape rate is also discussed.

**Keywords:** Distributed Control, Field Bus, Plating Line Control, Condition Monitoring, CAN, ZigBee

## 1. INTRODUCTION

Electroplating [1] is a chemical process to deposit a metal coating onto a substrate. One of the common applications of electroplating can be found in the PCB (Printed Circuit Board) manufacturing. The electroplating process starts by clamping the plating article in plating racks and immersing them in a series of chemical baths. Due to the demand of product quality and increasing in labor cost, almost all large scale plating manufacturing facilities are automated [2]. A typical electroplating line as shown in fig. 1 consists of multiple hoists for carrying the plating articles and various process control equipment for process conditioning, such as heating equipment for temperature control, rectifier for electroplating and chemical conditioning equipment for regulating the chemical bath concentration.

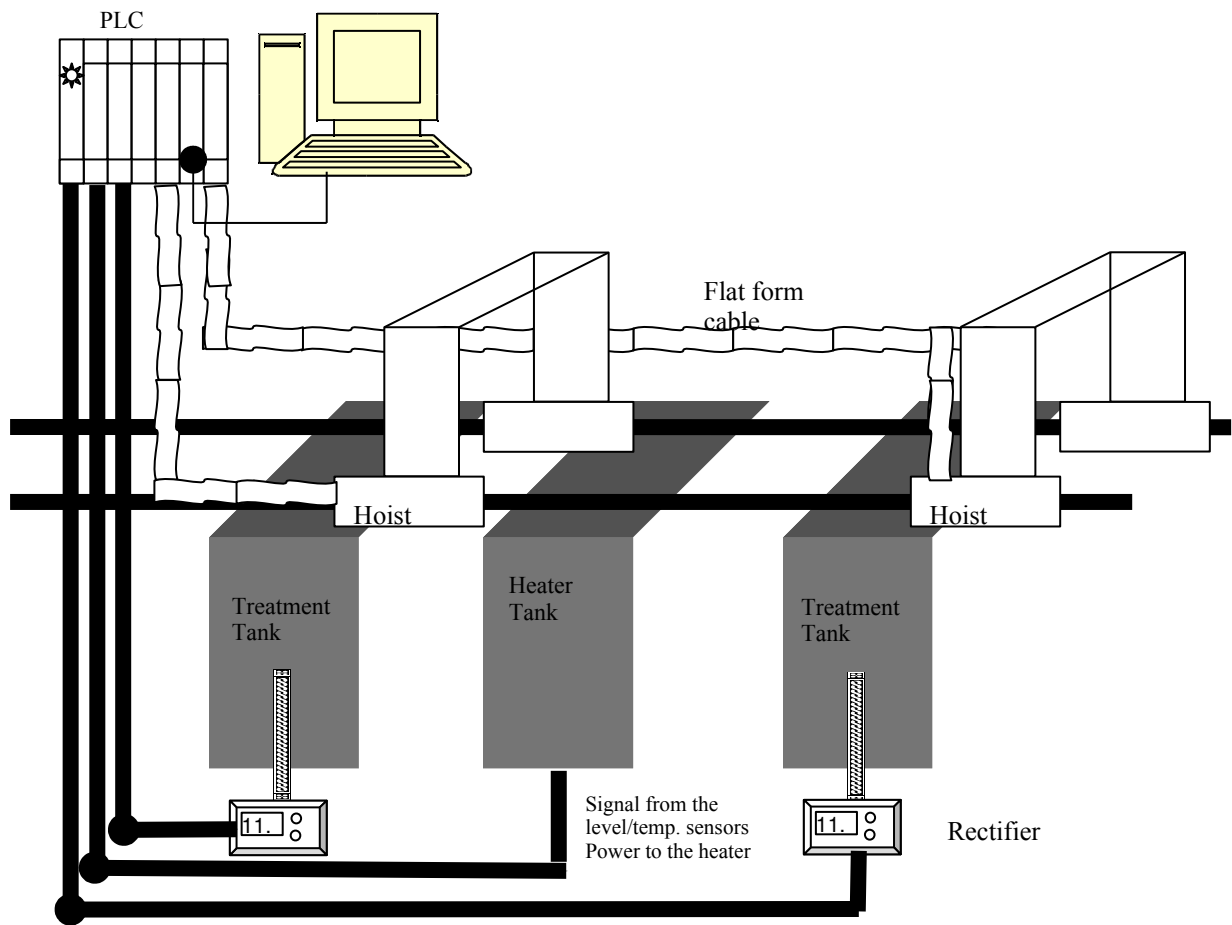


**Figure 1.** An electroplating line with two hoists

For an automatic electroplating line, the control system will interact with the control elements to perform control functions. Most of the current electroplating lines in the market are still employing the centralized control architecture as illustrated in fig. 2 with PLC (Programmable Logic Controller) as the main system controller.

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<sup>1</sup> Correspondence Author's email address is mebluk@cityu.edu.hk



**Figure 2 Illustration of traditional centralised electroplating line control system**

Under this architecture, the various sensory input signals and the actuator output signals are directly connected to the PLC via cables. Despite the simplicity of the architecture, this approach does suffer from certain limitations:

1. High cost for cable installation and future maintenance
2. Signal loss of input/output signals during long distant transmission;
3. Failure of the central computer will fail the whole system.

Furthermore, due to the high cable cost and the fluctuating copper price, the engineer will tend to keep the number of signal wires for connecting the control equipment to a minimum for fulfilling the basic control and monitoring function only. However, the limited feedback information will restrict the feasibility to implement more advanced monitoring and diagnosis functions for the system.



**Figure 3 Flat form cables for the hoist**

An obvious example can be found in the hoist control system of electroplating line. As the hoist is moving along a fixed rail, special flat-form multi-cord cables as indicated in fig. 3 are usually used to provide control signals and power to hoist. The flat-form cable is designed to be used in conveying and hoisting equipment and is for connecting moving machine components. These cables are highly flexible and designed to be subjected to heavy and frequent bending. However, it is expensive and heavy. For a simple hoist configuration, it needs at least five flat-form cables per hoist for connecting power source, various control push buttons for manual mode control, proximity sensors for the hoist positioning, acceleration and deceleration sensors, vertical positioning sensors for the lifting mechanism, and protective limiting switches. Also, a typical electroplating line is normally over 60 meters

long. Under this circumstance, it is difficult to include any additional flat-form cable for accommodating extra feedback signals for monitoring and diagnosing the working condition of the hoist. As such, the system maintenance engineers can only adopt the time-based maintenance scheme to reduce production downtime. However, many failures occurred in electroplating process are not necessarily related to the aging effect of the equipment or the utilization rate of the machine. Therefore, the time-based maintenance scheme can only prevent part of the failures but not all, and a significant amount of failures may possibly occur during operation. Worst of all, it leads to a significant delay in revealing such faults, and the failure occurrence during production operation may cause a huge loss in term of wastage of productivity, energy and raw materials. Thus, there is a great demand on a sophisticated condition-monitoring feature in the plating line systems so that it can signals an early warning and minimize the equipment downtime. However, with the ever-increasing complexity of the electroplating processes, the size or length of the plating line also increases. Therefore, it would be very costly to add many sensors to the system under the current centralised control architecture for conducting system monitoring and diagnosis. So, the distributed architecture [3] seems to be an obvious choice for improving the current system. Also, each node in the distributed control architecture should have enough computing power to provide both control and diagnostic functions for the machine parts under its control. As the communication is a critical part of the distributed control architecture, it is therefore essential to find a robust and yet convenient-to-use communication network for the proposed applications. Since both wired and wireless network technologies have their own strengths and weaknesses, a sensible approach will be adopting both wired and wireless technologies in the proposed distributed system so that both technologies can mutually compensate each other's weaknesses

Although there are many wired fieldbus technologies such as Lonwork and Profibus in the market for industrial and building automation applications, many of them are either too expensive or not suitable for the proposed application. Among the various wired fieldbus technologies, CAN (Controller Area Network) bus [4] has been identified as the most appropriate wired bus technology for the proposed application. The technology was originally designed for automotive industry. Hence, it is low cost, and robust for hazardous applications. With prioritised arbitration mechanism, CAN is very suitable for many hard real-time applications. In addition, CAN hardware and microprocessor implementations are widely available in the market. For example, ARM [5] and AVR [6] microprocessors have included direct CAN hardware support. Because of these, the technology is not just limited to automotive applications but has been successfully applied to many other industrial applications, which require reliable wired bus communication. These applications include Small Aircraft Transportation System (SATS) [7], Low Earth Orbit (LEO) satellites [8], instrumentation for OPERA long-baseline neutrino experiment [9], and wind diesel hybrid systems [10].

Wireless technology has the advantages of flexible deployment, easy-to-use and easy-to-install as compared with wired technology. These features are particularly useful for system diagnostic and monitoring applications, especially when the wired network is physically damaged or oxidized. Among the various wireless technologies, ZigBee [11][12] is an emerging wireless technology designed for low-cost, high-reliability sensor networks. It is focused on an area not yet covered by any other standard wireless technology, such as WiFi, WiMax and Bluetooth. It offers low-cost, long-battery-life, and large sensor networks [12] (up to 65,000 nodes). ZigBee also addresses other important considerations, such as high security to prevent wireless tampering and eavesdropping. Initial applications of the technology are mainly in the area of home and building automation[11]. As many companies are now aware of the advantage of the ZigBee technology, they are developing many other applications such as marine instrumentation [11], vehicle identification [13] and access control [14]. A research [15] has reported that the Zigbee technology is not adequate for closed loop control applications but well suited for system monitoring applications.

This paper presents a novel distributed control architecture with low-cost hybrid wired and wireless control network for electroplating line control application. Also, it discusses the feasibility of implementing condition monitoring under the proposed control platform with Zigbee wireless network for increasing the system reliability and reducing the scrape rate.

## **2. A DISTRIBUTED ELECTROPLATING LINE CONTROL SYSTEM**

The de-centralised (distributed) approach [3] has been proposed to address the limitations which have been discussed in previous section. In our distributed electroplating line processes control prototype system (fig. 4), several low-cost distributed ARM [5] based controllers have been developed and installed to control various local processes, such as rectifier control, temperature control and hoist control. The distributed controllers are connected to a gateway through a CAN wired network. The gateway is the system's main connection point with the outside world. It interfaces to an HMI (Human-machine interface) device as shown in fig. 5 to allow operators to control and configure the electroplating line system, and to a DMS (data management system) for recording essential production and system performance data. In addition, a low cost ZigBee wireless network is used to facilitate the system diagnosis.

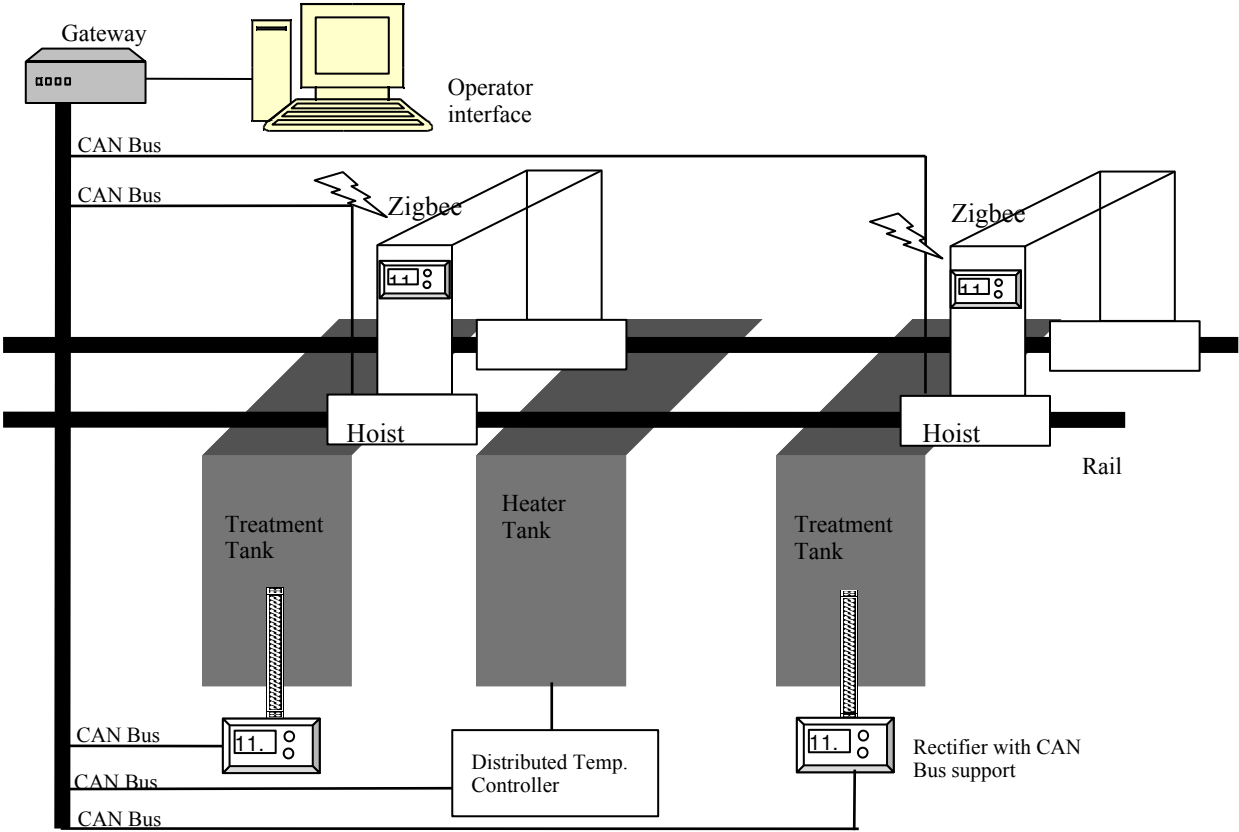


Figure 4 Illustration of a Distributed Electroplating line control system

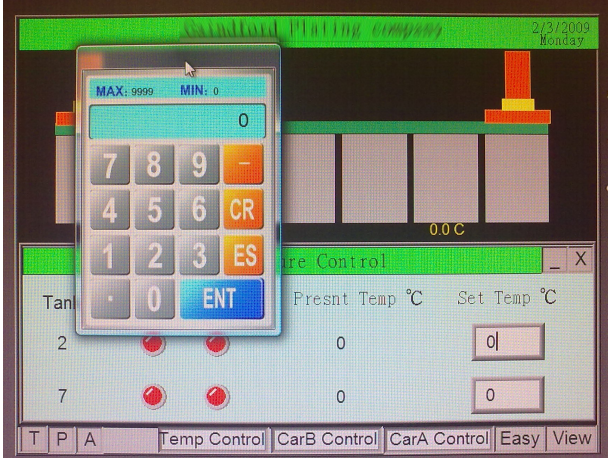
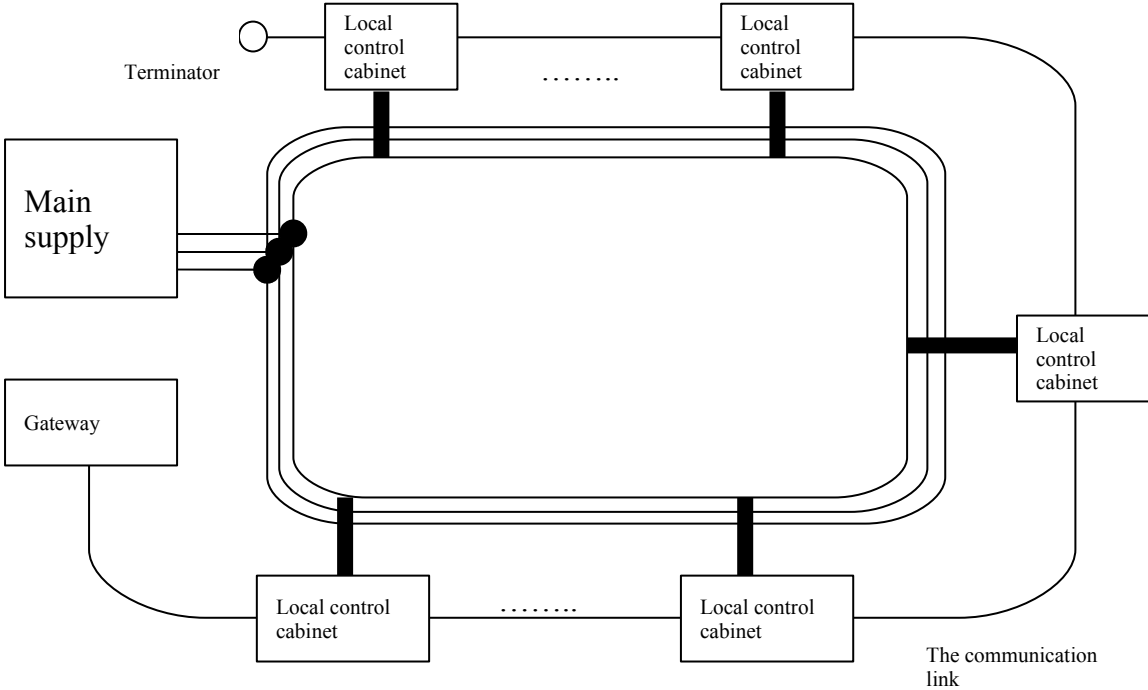


Figure 5 HMI for the new distributed electroplating control system

In our prototype system, two CAN wired networks are used to ensure system robustness and performance. One CAN network using standard CAN cable is for connecting all fixed installation, such as temperature controller, rectifier controller and filter pump controller etc. The fixed installations are powered by a three- phase ring circuit as illustrated in fig. 6.



**Figure 6 the controller network topology**

The second CAN network using the flat form cable is for connecting the movable hoists. Although the movable hoists are still connected and powered via the flat form cable, the number of flat form cables per hoist is reduced to one instead of five as in the traditional centralised control. All distributed controllers have similar hardware design but with different firmware installed for different control applications. The firmware is designed in the form of application profiles according to different applications. Some features are shared among different application profiles, such basic communication protocol, and Input/Output management. Specific control functions are implemented for each particular control profile. The distributed controller is deployed close to the process under its control with the appropriate power control circuitry. Therefore the length of power cable to the control element, such as heater and motor, or the signal cable from the sensor, such as temperature sensor, current and voltage sensors from the rectifier, will be kept to a minimum.

Moreover, a Zigbee wireless communication network is available as part of the distributed control system. It enables the remote debugging function for the movable hoists via command line interface provided by the operating system of the distributed controller. The engineer can examine the internal status of the controller with this command line interface. It offers further support for system maintenance and debugging.

In summary, certain benefits are derived for our new control system implementation from this distributed approach:

1. Reduced wiring.
2. Fast response - dedicated controller for the local processes
3. Higher system reliability / availability
4. Easier expansion in function and capacity.
5. Easier to setup and install

### 3. APPLICATION OF FIELDBUS TECHNOLOGY IN THE DISTRIBUTED ELECTROPLATING LINE CONTROL SYSTEM DESIGN

CAN (Controller Area Network) [4], one of the most popular field buses in industry, is used as the main communication link among the gateway and distributed controllers. CAN is an ISO defined serial communication bus that efficiently supports distributed real-time control with a very high level of security. It was originally developed for applications with high electrical interference and environments of extreme temperature. A typical CAN configuration is shown in fig. 7 below.

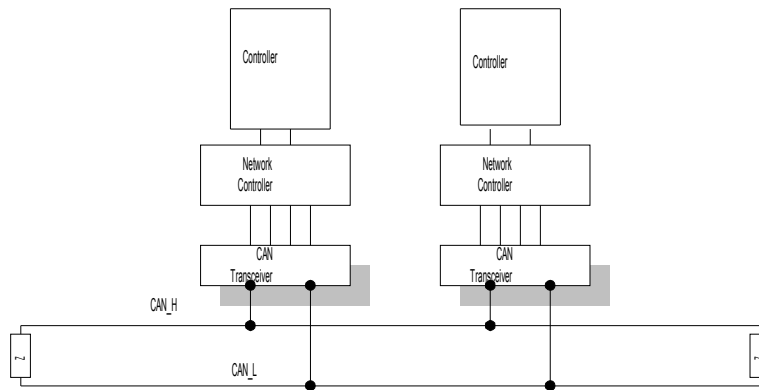


Figure 7 A CAN Network

CAN is a connectionless bus topology that uses CSMA/CD (Carrier Sense Multiple Access with Collision Detect) with non-destructive bit-wise arbitration for bus contention. With the bit-wise arbitration scheme, the frame with higher priority always gains access to the network during collision. Just consider two controllers start to transmit at the same time, they will watch the bus value and compare it with the value they transmitted. If a dominant value is received as they transmitted a recessive bit, they will stop transmission immediately and continue to listen to the bus. Since no two frames with same frame ID are to be transmitted at the same time, it guarantees no data corruption occur during the collision. This is an important advantage over other the protocols also employing CSMA/CD such as Ethernet.

The basic CAN transport protocol is supported by the CAN network controller, which provides following error detection functions to ensure the data integrity.

- *Bit error*, as a unit sending a bit on the bus also monitors the bus, the bit error is detected when the bit value monitored is different from the bit value that is sent.
- *Stuff Error*, the stuff error is detected for 6<sup>th</sup> consecutive equal bit level in a message field as the 6<sup>th</sup> consecutive equal bit should be coded by the method of bit stuffing,
- *CRC error*, the error is detected when the calculated result is not the same as the received in the CRC sequence.
- *Form Error*, the error is detected when a fixed-form bit field contains one or more illegal bits.
- *Acknowledgement Error*, the error is detected by a transmitter whenever it does not monitor a 'dominant' bit during ACK SLOT

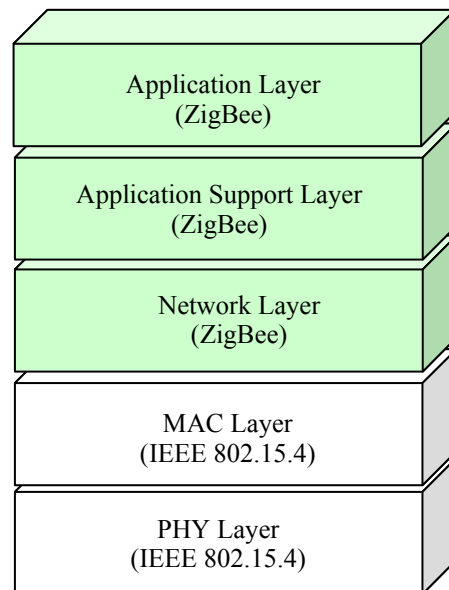
If any error is detected, the CAN controller will transmit an Error flag. The transmitter can recognise such error flag and initiate retransmission of the corrupted message. With the mechanisms described above, the system provides a reliable transport means to delivery the basic CAN packet (8 Bytes data per single CAN packet). Furthermore, a higher level protocol for electroplating line applications has been developed by the authors on top of the basic CAN packet delivery mechanism. With this higher level protocol, the communication system will provide further support on

- Network management: The network can start / stop the operation of individual node; the master can monitor the operation of node in the network.

- Support single packet and multi-packets data transfer: as the basic CAN transfer mechanism is to delivery a single packet with maximum 8 Bytes data. The higher level protocol is designed to transfer a data message by segmenting it into several CAN packets for delivery and to receive and assembly the message at the end point. The higher level protocol also includes an error detection and retransmission mechanism to recover the data corruption for this multi-packet transmission.
- Device profile and automatic configuration support: a standard device profile configuration function is supported by this higher level protocol with the standard inquiry functions for the device specific configuration information and remote setting of the device operation parameters.

#### 4. APPLICATION OF WIRELESS TECHNOLOGY IN THE DISTRIBUTED ELECTROPLATING LINE CONTROL SYSTEM DESIGN

Beside the structural communication for command control and status feedback with wired field bus, the wireless communication is also employed for irregular communication, such as system diagnosis and online debugging of the controller operation. It is particularly sensible for the moveable platform, like hoist controller. The IEEE 802.15.4 (Zigbee) [12] technology was used for this remote monitoring and diagnosis application. The IEEE 802.15.4 is a targeted for a low cost and low power short range communication, such as wireless sensors, home automation or remote control. The IEEE 802.15.4 defines the physical layer (PHY) and the media access controller (MAC). ZigBee defines the network, security and application layer as illustrated in fig. 8.



**Figure 8 ZigBee/ IEEE 802.15.4 Protocol Stack layering structure**

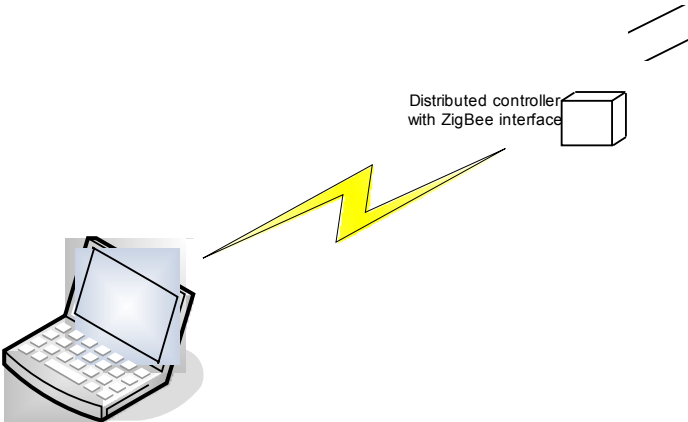
IEEE 802.15.4 employs CSMA-CA (carrier sense multiple access with collision avoidance) for the channel access. The PHY layer of IEEE 802.15.4 supports channel frequency selection, collision avoidance, data transmission and reception. The MAC layer is responsible for all access to the physical radio channel and maintaining a reliable communication between two MAC peers. It supports a guaranteed time slot (GTS) mechanism for high priority communications. Furthermore, device security and PAN (personal area network) formation are also supported by the MAC layer.

Due to the nature of this application and the constraint in memory and processing power of our ARM distributed controller, a simple packet protocol on top of the SMAC protocol stack [16][17] from Freescale is implemented for the distributed control system. The SMAC protocol supports point-to-point and broadcast mode communication. Under the coordination of the SMAC protocol, a packet with maximum 125 bytes data is delivered by transceiver support the IEEE 802.15.4 communication. The transceiver will ensure the data integrity of the packet. A summary of the IEEE 802.15.4 Packet Structure is shown in fig. 9 below.

Preamble	Start of Frame Delimited (SFD)	Frame Length Indicator (FLI)	Payload Data	Frame Check Sequence (FCS)
4 Bytes	1 Byte	1Byte	125 Bytes	2 Bytes

**Figure 9 IEEE 802.15.4 Packet Structure**

Under existing configuration, only interactive diagnosis between the distributed controller and remote diagnostic console is supported. The concept of the remote monitoring and diagnosis with ZigBee communication is shown in fig. 10 below.



**Figure 10 Remote monitoring and diagnosis with ZigBee communication**

As shown in fig. 11, the control message of the distributed control system will be embedded within one SMAC packet. For the provision of further expansion of the ZigBee link in condition monitoring, the definition of the control message includes the device addressing and the support of an ACK/Retransmission mechanism. The message consists of the header and payload. The header contains the source address and the message ID. The payload contains the data to be carried inside the message.

Relay Indicator (1-bit)	Source Address (7-bits)	Ack Indicator 0 – data	Original -0 Re-tx -1 Indicator	Message ID (6-bits)	Payload 96 Bytes
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**Figure 11 a normal control message**



For interactive operation, the retransmission mechanism can be disabled. For multi-packet data transmission, the simple ACK/Retransmission mechanism ensures the reliable communication between two parties. Under this mechanism, the receiver returns an acknowledgement (ACK) packet with the message ID to the sender indicating the successful reception of the packet. In case of any interruption occurred during a packet transmission, which is detected by the ACK time-out timer, the sender will retransmit the packet again.

## **5. ADDITIONAL DIAGNOSIS SUPPORT BY THIS DISTRIBUTED CONTROL ARCHITECTURE**

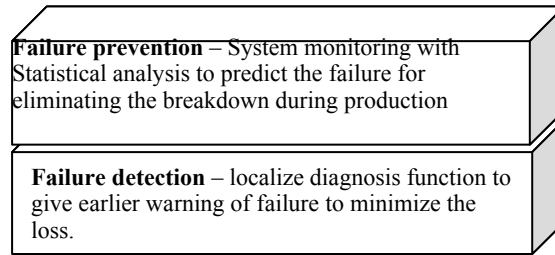
It is important for the electroplating line control system with built-in diagnosis function to detect any abnormality of the system in operation before causing any catastrophe consequence. It is also a demand from the customer to reduce the downtime in case the malfunction of the system. The earlier detection of the system failure will reduce the downtime and hence minimize the loss. However, this is not sufficient for some of the customers especially for those making high-end products such as medical equipment. In fact, a more demanding request for predicting and preventing the system breakdown during production has been made by high-end product manufacturers in order to eliminate the wastage caused by scrape product. Condition Monitoring [18] is proposed to address this issue. The basic idea of Condition Monitoring is to monitor the system performance continually in order to measure the system degradation. Condition Monitoring uses different measurement methods to monitor the machine conditions. Various statistical techniques will be used to evaluate the historical data to measure the deterioration of the machine.

For practical implementation, the system designer under the centralized control approach is likely to limit the number of sensory feedback signal to the central controller as the cost of wiring is substantial. Besides, due to the restriction of input/output and processing power capacity of the central controller, it is not feasible to implement very complicate diagnosis algorithm. In respect to the implementation of Condition Monitoring for the electroplating line, the most critical units suffering from mechanical wear are the movable units, such as hoist, filtration pump for the treatment tank and mechanical agitator. The breakdown of such critical units may cause shutdown of production of the plating line for several days. Therefore, the objective is to predicate the end of life of the critical components and replace it before the breakdown of such units. The most commonly used condition monitoring techniques for the machine with dynamic components are vibration analysis and the actuator condition analysis [18]. For the purpose to evaluate the network throughput, it may assume the proposed condition monitoring unit with 4 channels of 16 bits A/D signal input (two accelerometers and one microphone for vibration analysis and one motor circuit feedback for actuator condition analysis) with 15 kHz sampling rate, the sampling length about 2 seconds and 10 times per hour [19, 20], the data volume from one monitoring unit per hour is about

$$2 \text{ bytes} \times 15 \text{ kHz} \times 2 \text{ seconds} \times 10 \times 4 = 2.4 \text{ MB / hr}$$

Therefore, with the experimental electroplating line control configuration, there are total six monitoring units (two hoists, one mechanical agitator and three filter pumps). The total data volume is about 14.4 MB / hr. It is a considerable data volume for a system to process the data, it particularly difficult to implement this feature in a single centralized controller.

Comparing with the difficulties mentioned before, the distributed control architecture has relative merit to address this issue. Firstly, as the distributed controller is installed close to the controlling element, it is not difficult to install additional feedback sensors to monitor the system operation. With additional feedback signals, it is practical to implement the diagnostic function giving earlier warning in case any failure of the system. In considering the huge data volume generated from the acquired data from the units under monitoring, it would be manageable under the distributed approach (the detail analysis will be given below). The distributed control network of this electroplating line control prototype system will serve as the platform for implementing the Conditioning Monitoring features. In our distributed plating line control system implementation, a two levels system failure monitoring architectures is proposed.



In the Failure detection level, the particular self diagnostic functions are built-in for corresponding device profile. For example, the temperature controller has the built-in function to detect the level sensor, temperature sensor and heater failure by

- comparing the level sensor pattern,
- verifying the feedback of heater current rating and
- evaluating the temperature rising time etc.

Moreover, any detected failure from distributed controller will inform the gateway to alert the operator and activate the error handling function of the gateway. At the same time, the maintenance personnel can use the mobile terminal to plug into the CAN network or the Zigbee network to examine the fault code of malfunction device in order to fix the problem. While the controller, the electrical control circuit, actuator and sensors are adjacent to each other, it will make the trouble shooting to become more effective. As a result, it will reduce the downtime of the system and minimize the loss in productivity, material and energy.

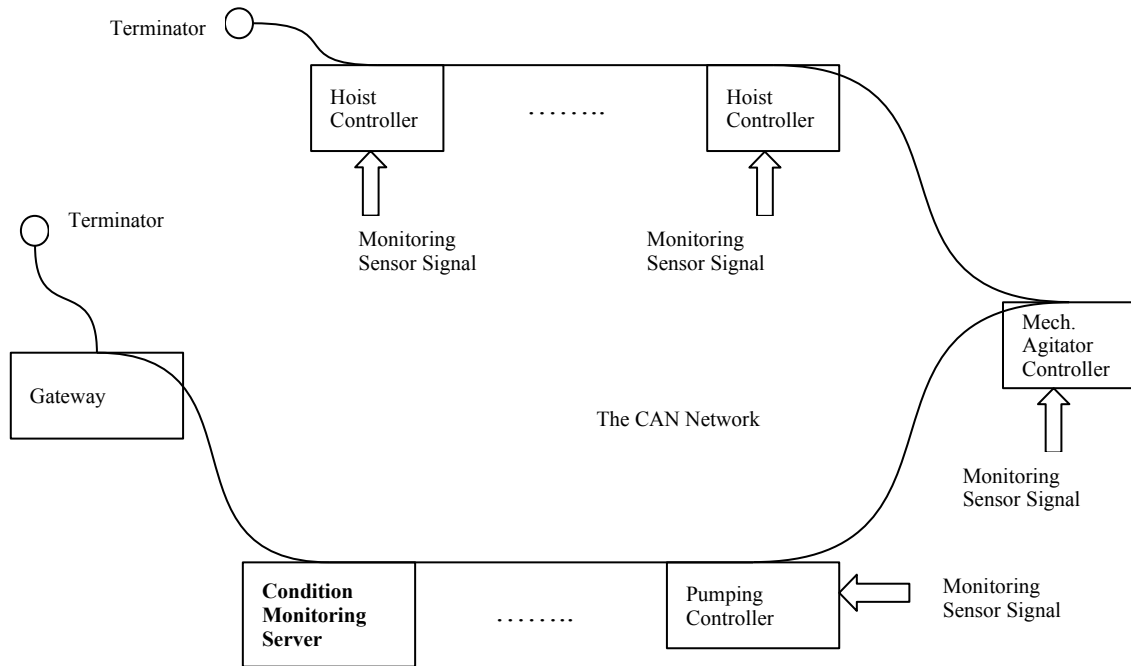
For the failure prevention level, a Condition Monitoring configuration is proposed for the distributed control network. In the proposed configuration (fig. 12), a dedicated server is assigned for the condition monitoring. The analysis algorithm is implemented for the dedicated server to monitor the condition of the machines. Every local distributed controller equips with a data buffer to store the captured data. The C.M (condition monitoring) server will collect the data from the local controller nodes in a fixed time interval. The required throughput of the sampling data over the hour is about  $14.4\text{MB} / 3600\text{s} = 4000 \text{ B/s}$ . The bandwidth of a single CAN network is about  $125 \text{ kbps} \approx 12000 \text{ B/s}$ . As the utilisation for transmitting the sampling data is about 30% of the available bandwidth, therefore it is reasonable to expect the condition monitoring can be implemented over the existing control network.

Furthermore, with the CAN frame ID arbitration feature [4], the normal control message will assign a high priority CAN frame ID and the high volume sampling data will transmit with low priority CAN ID packet. It will guarantee the delivery of real-time control message.

## 6. CONCLUSION

This paper describes the application of a novel hybrid wired and wireless distributed architecture for electroplating line control application and the advantages of the proposed distributed control system over the traditional centralised approach in this application. The advantages include

- the saving in material and labour cost during the installation stage,
- improvement of system performance
- Ability to implement self-diagnosis features to provide earlier warning of system failure and provide addition support of trouble shooting in order to minimum the downtime. It is helpful to reduce the wastage of material and energy caused by the undetected failure.



**Figure 12 the proposed condition monitoring system configuration**

In addition, a condition based monitoring maintenance scheme implemented on the above distributed platform has been discussed. Based on the evaluation result, it is feasible to implement the condition based monitoring feature under this distributed control framework. The proposed scheme can reduce the loss in material and energy caused by the breakdown of system during production. With many low cost hardware components available in the market to support the proposed architecture, the proposed architecture would be able to provide many features requested by end-users or customers without the need of increasing the cost of the product. As a result, it is believed that more and more plating line end-users or customers, previously deterred by high cost, will opt for this hybrid wired and wireless distributed control system instead of the old centralised system.

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