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Industrial Automation using Embedded Systems and Machine-to-Machine, Man-to-Machine (M2M) Connectivity for Improved Overall Equipment Effectiveness (OEE)

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***Abstract* — Embedded systems in general and microcontrollers in particular are playing a key role in today's industrial automation and remote monitoring era for enhanced productivity and reduced costs. The aim of this paper is to report research at e-Monitoring and e-Management Research Centre (eM^{2}RC) at College of E&ME (NUST) on distributed e-Monitoring and e-Management (eM^2) using Man-to-Machine, Machine-to Machine (M2M) connectivity for industrial automation. The reported system has successfully been developed, tested and implemented in the local Liquefied Petroleum Gas (LPG) industry to improve Overall Equipment Effectiveness (OEE) resulting in an increased overall system efficiency. The research is based on a combination of hardware and software logic in which the hardware implementation emphasizes the role of embedded systems and M2M connectivity for e-Monitoring and e-Management applications. The e-Information is sent to central server and related technicians/managers/executives for immediate decision making to reduce downtimes and improve quality.**

***Keywords*— e-Monitoring and e-Management, OEE, dsPIC Microcontroller, Controller Area Network (CAN)**

I. Introduction *(Heading 1)*

The advancements in technology in the current era have been at an enormous pace. It is now possible for researchers to explore techniques and methods for the design and development of global systems with capabilities of relevance to a wide range of applications. In today's system integration era, the importance of e-Monitoring and e-Management (eM^2) research applications is increasing constantly. These trends are shaping new dynamics in the global automation market. Here "automation" can be defined as "the process of making machines self-acting or self-moving and the technique of making a device, machine, process or procedure more fully automatic thus reducing the need for human intervention" [1]. Embedded systems in general and microcontrollers in particular are the key players in making automation more efficient, reliable and cost effective.

The need for monitoring systems that can be used for different processes and attached resources is being increasingly recognised. Monitoring systems for industrial processes and machines are becoming almost a requirement. These can either be integrated monitoring systems or distributed monitoring systems or a combination of both. The combination of integrated and distributed monitoring systems using the available communication infrastructure makes it possible to reach effective, more reliable and accurate decisions in minimal time. These systems open up the current states of the process to concerned engineers, managers and technicians. This is the area in which embedded systems if used to their best potential can deliver excellent results.

It is widely accepted that the automation and productivity of industrial systems have been on a constant rise since the numerical control was introduced to the industry [2]. Although the use of embedded systems in control applications has been established for some time; their use for monitoring systems has been very restricted, despite their advantages.

The contributions made by improvements in reducing machine downtime may be illustrated using an approach known as Overall Equipment Effectiveness (OEE). The OEE of any system/machine is dependent upon three factors:-

OEE = System Availability Rate *x* Performance Rate *x* Quality Rate [3]

The system availability rate measures any machine system's availability as a whole within the context of an industry. It includes setup losses and downtimes due to failures. The performance rate accounts for overall performance of the system/machine in terms of its efficiency. The quality rate as obvious from the name is related to quality related losses. It has been accepted by the researchers that the OEE of many computer integrated manufacturing systems has been lower than expected [3]. Intelligent Process Monitoring and Management (IPMM) Centre at Cardiff University and e-Monitoring and e-Management Research Centre (eM^{2}RC) at NUST are following a similar research approach in devising

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new methodologies and solutions using eM^2 concept for enhanced industrial OEE [4-7].

II. eM^2RC RESEARCH APPROACH

The monitoring areas generally fall under two major categories namely; process monitoring (i.e. the overall health of the process) and condition monitoring (i.e. monitoring the individual components within the process) [8]. The e-Monitoring and e-Management Research Centre (eM^2RC) at NUST Pakistan is following a research methodology more focused towards process automation, monitoring and its e-Management. The process monitoring systems generally fall under two categories. The first category uses additional sensors for data acquisition and analysis for decision making whereas the second category uses the already available signals from the process to do the same task. It is also worth mentioning that there are systems that use a hybrid approach to achieve the monitoring and management task.

In the past, most of the monitoring systems have used additional sensors for decision making. However; in recent years, the thrust for design of monitoring and diagnostic systems for industrial environment is shifting from direct sensor based to indirect sensor based approaches. The major reason behind this shift in addition to cost is the increase in relevance of these systems to modern industrial environments. Furthermore; the major hindrance towards the design of these systems is the reliability of any decision made from the information retrieved from a source which may not be directly related to the decision making area [9].

The eM^2RC at NUST is following an approach that tackles these issues more efficiently and reliably. This approach addresses the major economic issues of today for third world countries in parallel to system automation and e-Monitoring and e-Management. It is another fact that most of the third world counties are unable to design and manufacture factory machines and therefore; normally import such machinery. Such procedures result in increasing their import bills and resultantly their trade deficits increase. Therefore; there is a dire need for such countries to make sincere efforts to design and manufacture such machinery at their homeland. eM^2RC is following a three tiered approach for tackling these problems more comprehensively. These tiers/salient features of this approach are described below:-

A. Indigenous Design and Manufacture

eM^2RC is following the fundamental principle of indigenous design and manufacture of industrial support systems to reduce the import bills of third world countries like Pakistan and reduce its trade deficit to avoid debt compilation. The indigenously designed and developed LPG filling dispenser with extra capabilities of e-Monitoring and e-Management will be discussed in this paper.

B. Automation in Design

There are two different approaches for automation of industrial systems namely: automation at design phase and automation as an add on. This is an important aspect of any research approach. The current era designs are more focused towards making automation a built in feature. It is widely accepted that the automation should normally be made a part of the system at its design stage rather than being added later on. eM^2RC is following this concept for each new design to make it fully automated with extra features and availability of future expansions.

C. e-Monitoring and e-Management for Enhanced OEE

The implementation of e-Monitoring and e-Management systems is being ensured at the design and manufacturing stage of the systems. Such an approach ensures that signals form each system part/activity are communicated to the monitoring/management consoles at the deign stage with minimal cost and efforts. Although many monitoring systems are still tightly bonded to the place where the industrial process is located. However; the eM^2RC is following a combination of local and remote monitoring and management using Controller Area Network (CAN) approach for local monitoring systems and M2M Connectivity for remote monitoring and management.

III. ARCHITECTURE FOR AUTOMATION AND eM^2

This section discusses the overall design approach and methodologies for building an automated structure for eM2 of an industry. The design is based on the three tier architecture to support automation and eM^2 for enhanced OEE. Using this kind of architecture, the applications are distributed on three levels: processes/machines, Controller Area Networking (CAN) and central server connected using M2M connectivity. This is a very effective approach for today's industrial environments. By combining the IT trend of building distributed applications based on multitier architectures with the latest developments in technology for industrial systems we have developed a distributed application system. This architecture is based on three levels and its block diagram is shown in Figure-1. The levels are:-

A. Industrial Process/Machine Hardware

eM^2RC approach stresses the application of techniques may it be hardware or software at the design and manufacturing level for effective monitoring and management at the later stage. Such an approach saves extra effort and cost that is needed at later stages to achieve similar results. This layer is represented by the process/system itself, monitoring equipment, the embedded system and inter controller communication media. From the monitoring system's point of view, it does not matter what sort of hardware is being used. The system is designed on the fact that the hardware level is able to transform the raw signals into measurements that can be analyzed by the employed system for suitable decision making.

B. Local and Remote Communication

Local communication can be achieved in a number of ways by connected the monitoring embedded system to the industrial system using a Controller Area Network (CAN) or Serial Peripheral Interface (SPI) or Inter Integrated Circuit (I2C) communication protocol. The eM^2RC has tested all these communication protocols for various applications. A comparative analysis was carried out based on the requirements of application environment. It was proven that for the discussed application; CAN is the most reliable media of communication amongst microcontrollers for numerous reasons including speed, reliability, clients and its adaptability in industrial environment. These facts have also been supported by [10-12].

For efficient and reliable remote communication, the concept of M2M has been used. M2M (Machine to Machine or Man to Machine or Machine to Man or Mobile to Machine or Machine to Mobile) is a concept of communication between a device that contains some data and a device which requires that data. The latest advancements in technology, more capabilities and coverage of wireless devices (e.g. cell phones) and reductions in the costs of using satellite data services is making this technology more effective and popular.

The design and implementation of remote data communication for the monitoring systems can be done using a variety of options e.g. WAN and GSM etc. However; the best option for such designs is the use of Global System for Mobile Communication (GSM). This is due to a number of reasons including low cost as compared to preparing a new network and GSM network security. But the most important of these is the wide spread coverage of this network that makes the monitored information available almost every where. Therefore GSM connectivity system for this application was researched and implemented in the design stage.

Focussing on the manufacturing environment the implementation of such a system provides many benefits both in terms of reducing operational costs (e.g. the cost of labour that controls or monitors the machines) as well as saving time (e.g. when machine is far away and the time to get to the machine is long as compared to sending a simple text message). These benefits lead to improved product quality, the reduction of overall operational costs and an increased Overall Equipment Effectiveness (OEE).

C. *e-Monitoring and e-Management*

This is the third tier of the system. It is normally located at a remote place e.g. company head office. The machines/processes and monitoring equipment are networked back to the central server for data analysis and alarm triggering.

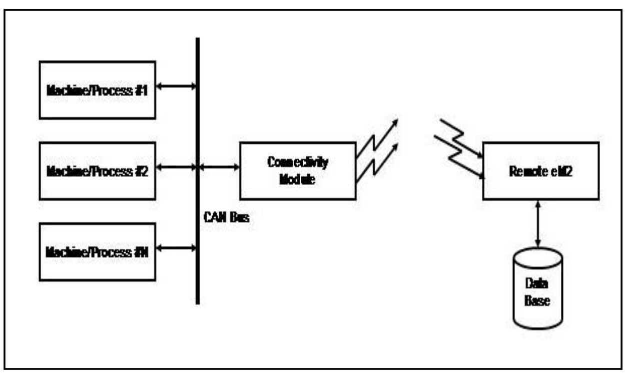

Figure 1. eM^{2}RC Architecture for Automation and Monitoring

The analysts can get the data regularly and analyze it to make swift and effective decisions. These decisions save time and money in terms of both down time between failures and future planning.

IV. LPG Plant Automation and Monitoring

This section discusses the complete system of design and manufacturing of a fully automated LPG filling dispenser, its connectivity to central server and management for eM^2. The system was designed and developed at eM^{2}RC and installed and tested for its reliability in a local LPG company (LORD Gas). The concept of eM^2 was integrated at the design stage. It is a complete factory automation system with automated dispensers connected using CAN and networked back to the company head office using M2M connectivity. The block diagram of the dispenser is shown in Figure-2.

A. *Fully Automatic LPG Dispenser*

Figure-2 shows the block diagram of a fully automatic LPG dispenser. A load cell has been used in the base for weight sensing. The signal from load cell is interfaced to a high accuracy instrumentation amplifier. The used instrumentation amplifier has three precision operational amplifiers and integrated laser-trimmed metal film resistors on a single monolithic integrated circuit for highest possible accuracy.

The output of the instrumentation amplifier is coupled to 24-bit high resolution ADC through a high speed analogue multiplexer/de-multiplexer (MUX). The selection pins of MUX are interfaced to the central microcontroller. Microchip's dsPIC30F6014 16-bit microcontroller has been used for this system design. AD7710 from Analogue Devices has been used for high accuracy Analogue to Digital Conversion (ADC) operation. This is an ideal chip for high accuracy low frequency data conversion applications. The MUX has been used to properly zero the ADC before starting the operation.

The designed system is highly accurate and reliable. The accuracy has further been ensured by zeroing the system before filling each gas cylinder in addition to using the auto-calibration capability of the ADC. This particular action minimises the error. The error reduction is also achieved by:-

- ADC samples the input signal at a frequency of 39 kHz or greater. As a result, the quantization noise is spread over a much wider frequency than that of the band of interest.
- The noise in the band of interest is further reduced by analog filtering in the modulator loop, which shapes the quantization noise spectrum to move most of the noise energy to frequencies outside the bandwidth of interest.
- These actions remove the noise considerably thus enhancing the system accuracy to an acceptable industrial standard.

The communication between dsPIC and the ADC is established using serial link. dsPIC has two onboard serial communication modules. One of these modules has been used to communicate with the ADC that already has a flexible arrangement to allow industrial interfacing. ADC has the capability to act as a master or slave in the system for communication. In this particular design, the dsPIC has been used as a master for establishing serial link.

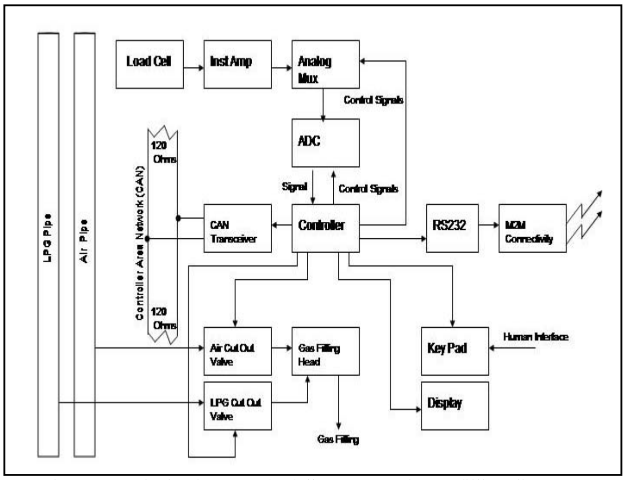

Figure 2. Block Diagram of a fully automated LPG filling dispenser

The designed system has two sub-parts in terms of parallel operations namely digital and analogue. It is imperative to reduce noise for high precision operation in industrial environments. These requirements have been met by designing and integrating two power supplies i.e. analogue and digital. In particular the V_{BIAS} input of the ADC needs to be driven by low impedance to minimize errors due to charging/discharging impedances on the line.

The operator interface has been achieved using a RS keypad. The keypad is interfaced to the microcontroller and operator can operate, check, debug and set the system parameters. A backlit Liquid Crystal Display (LCD) has been interfaced to the microcontroller. The display is used to show every activity to the operator, maintenance manager and plant manager as per their requirements.

The gas and air lines are connected to the cylinder filling head through gas/air cut-out valves. The valves are used to control the flow of gas/air as per requirements of filling. During the operation, as a cylinder is placed on the machine, after necessary calibration and zeroing, the controller opens the air cut-out valve to lock the filling head on the cylinder. There is a short delay of 500 ms to ensure the locking before gas cut-out valve releases the gas flow in the cylinder. The amount of filled gas is continuously fed back to the controller at a frequency of 50 readings per second. This frequency has been selected after necessary calculations to avoid any over/under filling of the gas. In addition, the pressures of gas and air lines are fed to the controller for monitoring and decision making. The controller cuts the gas immediately as the cylinder is filled and after a short delay it cuts the air valve that releases the filling head and ensures to avoid any gas leakage. The amount of gas if any in an empty cylinder (normally called "gain" in industrial language) and the amount of gas filled in each cylinder are stored in the controller for daily report compilation. The report delivery is discussed in the M2M connectivity section.

B. *Controller Area Network (CAN)*

A Controller Area Network (CAN) has been established at the factory area to achieve the local connectivity. The discussed filling dispenser uses dsPIC controller that has an onboard CAN connectivity module. The system has been interfaced to PCA82C250 CAN transceiver that connects the machine to the CAN bus. The same approach is used for each machine to achieve CAN connectivity. CAN bus has the capacity to add more nodes as and when required thus providing "Plug and Play" functionality to the architecture for information sharing.

C. *M2M Connectivity*

The M2M connectivity has been established for efficient e-Monitoring and e-Management. Two sub-tiers of remote connectivity have been established in this application design namely:-

- Connectivity to the central server for record keeping and decision making after analysis of the retrieved data.
- Connectivity to the mobile phones of managers, technicians and executives for immediate decision making.

The Siemens TC35i module for remote communication has been used for M2M connectivity. It has been interfaced to the second onboard serial communication module of dsPIC. The modular programming approach has been used to ensure easy upgrade of the systems and provide plug and play functionality. The controller has been programmed for data communication on following priority levels:-

- Immediate decision making required e.g. low gas pressure, low air pressure, power failure and machine failure.
- These failures are immediately reported and remedial actions are taken to save time and improve OEE of the monitored system.
- Routine reporting e.g. detailed data quoting the amount of gas filled and "gain".

A detailed analysis of an LPG filling plant with and with e-Monitoring and e-Management system was carried out. A comparative analysis revealed an increase in OEE in the range of 11 to 16.7% for various conditions.

V. CONCLUSION

The capabilities of dsPIC controller to be implemented as a heart of the first tier system design along with its communication features on the CAN bus and M2M Connectivity have proven successful for such applications. The use of distributed embedded systems for plant design and automation in addition to eM^2 has been verified for its reliable applicability. It has been identified that such research efforts can lead to successful system designs with multiple capabilities.

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