Embedded Controller for Production Monitoring System Based on Overall Equipment Effectiveness Using FPGA

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ABSTRACT
A Production Monitoring System (PMS) is used in manufacturing and production lines to keep track of machine and man-power efficiencies. Efficient use of resources and facilities contributes in generating high revenues. A real time PMS collects real time data off a production line and displays them on display panels. The collected data was then manually recorded and processed based on Overall Equipment Effectiveness (OEE) concept. OEE is a simple and practical tool to improve the operation line efficiency. This project is to develop an automated real time PMS system on a Field Programmable Gate Array (FPGA) chip. The FPGA chip will be used to collect data and automatically send a control signal to a display panel as well as to a computer for further processing. On the FPGA chip, circuits are developed by using Very-high-speed integrated circuit Hardware Description Language (VHDL). Describing the circuits in hardware description language helps to reduce the system hardware, physical size and cost, while improving the data processing efficiency.

The collected data will be processed using a Visual Basic (VB) 6.0 program. It will determine OEE indicator (%) and its parameters namely Availability (%), Performance (%), and Quality (%). The VB is also linked to Microsoft Excel spreadsheet for data and results recording. The whole automated system for data acquisition, processing and recording will minimize human intervention and improve the data reliability and accuracy.

Keywords – Production Monitoring System, Overall Equipment Effectiveness, Field Programmable Gate Array, Very-high-speed integrated circuit Hardware Description Language, Visual Basic 6.0.

I. INTRODUCTION
A Production Monitoring System (PMS) is a set of equipment placed on a production line to monitor the status of a process or working line. It collects, process, stores and displays production information such as production rates and efficiencies, machine and operator performance, and process variables [1]. The information can help the management team, maintenance and engineering personnel, as well as line operators to benchmark and evaluate the latest performance, maintenance scheduling and prioritizing process improvements towards achieving a targeted production output or yield. Production line status such as production rate, amount of goods produced, amount of rejects and downtime occurrences can be displayed on display panel units. Machine breakdown or downtime occurrences can be warned by using Light Emitting Diode (LED) indicators and buzzers. System statistics such as production rate, performance, utilization and yield are stored and can be presented by using an intuitive graphical user interface (GUI)-based end user applications. Graphical and numerical data report can provide better understanding and analysis in an objective form. Despite all that, as with any data collection tool and reporting system, the PMS must be economical, easy to set up on a production line, and provides reliable and accurate data [2]. Real time PMS was developed by [2] consisting of two sets of Programmable Logic Controller (PLC) as controllers, sensors from machines to provide input signals, and display panel boards, indicators and buzzers as the output devices. It had managed to perform an automated data collection and display real time data on display panels. Indicators and buzzers are used to signify disturbances, small stops or machine breakdowns occurred on the operation line. The development cost was high. The control unit consisted of 2 sets of PLC. The circuitry required 7 printed circuit board (PCB), each sized as an A4 sized paper, to accommodate more than 40 integrated circuit (IC) chips. The whole circuitry and display panels were encased in a chassis with a size of a computer central processing unit (CPU). Meanwhile data processing and recording were still done manually. All collected data were compiled and keyed in to a spreadsheet or paper reports by the line supervisor. Manual data compilation leaves room for both inconsistencies and inaccuracies [3]. Processing and recording a big set of data manually would be a problem
because it is crucial to produce an accurate and reliable report for management use. Automation is needed in data collection, processing and recording to improve data accuracy and reliability. An automated system improves the accuracy of production reports as well as reducing the cost to produce the reports [3]. This project is to simplify the physical hardware and reduce development cost used in the real time production monitoring system developed by [2]. The physical size of the system can be reduced significantly by integrating the system circuits onto a single Field Programmable Gate Array (FPGA) chip. Apart from that, the project will also automate the data processing and recording. This can be done by connecting the FPGA chip to a computer.

II. MATERIALS AND METHODS

The design of this project involved both hardware and software development. The idea of the project was to embed all of the electronic circuits related for the PMS into a single FPGA chip to reduce its physical size, cost of development and increase the possibility of mass production.

2.1 VHDL and Logic Circuits

As shown in Fig. 1, logic circuits that were embedded on the FPGA consist of three units each of up-counters, decoders, multiplexers and display drivers, two units of single pulser, one unit of baud generator, a buffer register and an asynchronous transmitter.

This project used Altera Quartus II 10.0sp1 web edition for design entry, design analysis and synthesis. ModelSim-Altera 6.5e Starter edition simulator was used for design simulation, and a 9 pin RS-232 cable was used for connection to a computer. The finalized design programs were later downloaded into a PLUTO-III FPGA board. Simulations were used to determine whether the obtained design meets the required specifications. A form of stimulus was needed to provide as an input to the design for a simulation. The behaviour of the designed system was verified by analysing the output signals with reference to the given input.

2.2 Hardware

After the simulation indicated a successful design, the next step was to construct a complete physical prototype. The VHDL codes were synthesized by Altera Quartus II, to translate the codes to a circuit description that specified the required logic circuits and the interconnections between them. Synthesized design was then downloaded into an FPGA chip by using an RS-232 9 pin cable. A display board was constructed by using a double-layer printed circuit board (PCB) as shown in Fig. 2 and Fig. 3. The display board consisted of one FPGA chip, 18 units of 7-segment display, 18 units of Motorola 2N3906 PNP transistor, 18 units of 1kΩ resistor, and 21 units of 100Ω resistor. The display board was then tested by connecting it with switches to generate input signals, a 5V power adapter DC supply and an RS-232 9 pin cable. Three 3-pin rocker switches were used to generate input signals. One switch each to generate actual production input signal, reject signal and downtime input signal.
Fig. 2 shows a PLUTO-3 FPGA board was mounted on the top layer of the prototype board. There were also 7-segment displays, 6 units each for Actual production counter, Rejects counter and Downtime counter. A multi-colour TXDI cable was used to connect the FPGA board with a TXDI board. The black wire was for GND connection, red wire for DC +5V to +10V, yellow wire for transmitter TxD, and white wire for receiver RxD, directly fed from a computer RS-232 TxD line. Meanwhile, the TXDI board combined a RS-232 connection and the power connection into one cable.

Data sent from the FPGA chip were also displayed on a computer screen. A Visual Basic (VB) 6.0 program was developed not only to display the data but also to process them based on the OEE calculations. There were three tasks that the VB program had to do at every one hour interval. The first task was to process the input data to determine the OEE indicator and its parameters then display the results on the VB screen display as shown in Fig. 4. The second task was to plot the input data on the Line Production Activities as shown in Fig. 5. The third task was to record all the input data and the results to a Microsoft (MS) Excel spreadsheet as shown in Fig. 6.

2.3 Overall Equipment Effectiveness (OEE)

OEE is a simple and practical method to monitor and improve the efficiency of a manufacturing process. It takes the most common and important source of productivity loss in its calculation. Then it produces a set of metrics as key indicators of progress on the Lean journey [4].
The most common cause of efficiency loss in manufacturing can be categorized into three OEE Loss Categories namely Down Time Loss, Speed Loss, and Quality Loss [5]. Downtime loss is occurrences such as breakdowns and setup/adjustments on a production line. Events considered as breakdowns include equipment failures, tooling failures and general breakdowns. Setup or changeover time, operator/material shortages, major adjustments and warm-up time, are usually discussed in setup time reduction programs. Speed loss events such as equipment wear, operator inefficiency and rough running reduce the speed of the process away from its theoretical maximum speed. Small stops such as sensor blocks and component jams are usually addressed immediately and do not involve attention from maintenance personnel. Quality loss is about amount of rejected products out of the total amount of production. Rejects made during warm-up and steady-state production are called start-up rejects and production rejects. They cover scrap, in-process damage, rework, and incorrect assembly etcetera.

The main purpose of OEE is to reduce or eliminate efficiency loss. Calculations to determine OEE factors are described as follows[5]:

\[
\text{Planned Operating Time} = \text{Plant Operating Time} - \text{Scheduled Downtime} \quad (1)
\]

The total shift length called the **Plant Operating Time** is the amount of time the operating line is opened and available for operation. **Scheduled Downtime** includes all events such as breaks, lunch, scheduled maintenance, and periods when there is no intention of running production. These events should be excluded from efficiency analysis.

\[
\text{Actual Operating Time} = \text{Planned Operating Time} - \text{Unscheduled Downtime} \quad (2)
\]

**Planned Operating Time** is the total time for the line scheduled to operate without interruptions. This is determined during planning or before the operation starts. **Unscheduled Downtime** includes all breakdowns occurred during the production such as equipment failures and material shortages. This is called Downtime Loss.

\[
\text{Net Operating Time} = \text{Actual Operating Time} - \text{Speed Loss} \quad (3)
\]

**Actual Operating Time** is the total operating time available to produce products. It is calculated after Downtime Loss events occurred during the operation.

**Net Operating Time** is determined by considering events that reduce the speed of the process such as operator inefficiency.

\[
\text{Fully Productive Time} = \text{Net Operating Time} - \text{Quality Loss} \quad (4)
\]

**Fully Productive Time** is the total remaining operating time after removing Downtime Loss, Speed Loss and Quality Loss. OEE factors are then determined by using these formulae:

\[
\text{Availability} = \frac{\text{Actual Operating Time}}{\text{Planned Operating Time}} \quad (5)
\]

**Availability** is a ratio of Actual Operating Time over Planned Operating Time. It is affected by the amount time of Downtime Loss. Increase in Downtime Loss cause in reduction of Availability.

\[
\text{Performance} = \frac{\text{Actual Operating Time}}{\text{Ideal Run Rate}} \quad (6)
\]

**Performance** is the ratio of the actual production rate over an ideal run rate. Every machine is specified to operate at its best rate or ideal run rate and is expected to perform as specified under ideal condition. Efficiency loss reduces the speed of the process. Actual production rate is the ratio of total actual products over actual operating time.

\[
\text{Quality} = \frac{\text{Fully Productive Time}}{\text{Net Operating Time}} = \frac{\text{Good Products}}{\text{Total Actual Products}} \quad (7)
\]

**Quality** is the ratio of Fully Productive Time over Net Operating Time. It is affected by the amount time of Quality loss. Quality is also a ratio of total good produced over total production [4]. This implies that increment in rejects caused reduction in Quality. Lastly the **OEE indicator** is calculated by multiplying Availability, Performance and Quality. A higher OEE value indicates a better performance and efficiency. A world class OEE is considered to be 85% or better [5].

\[
\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \quad (8)
\]

### III. RESULTS AND ANALYSIS

#### 3.1 VHDL Simulations
The simulations were done by using ModelSim Altera simulator. A testbench code was used to generate stimuli signal for every logic circuit. Fig. 7 and Fig. 8 show the simulation results for the whole logic circuit.

Fig. 7 shows that after 13 seconds of simulation time, there were 4 input pulses acted as Actual production inputs, and 2 input pulses of Rejects. Fig. 8 shows there were 2 downtime input pulses generated. The first downtime input was started at 0.7 sec and lasted for 4 seconds, while the second pulse started at 6.7 sec and lasted for 3 seconds. The total downtime input then was 7 seconds. The zoomed in results at 13 seconds of simulation time are shown in Fig. 9, Fig. 10, and Fig. 11 respectively.

Fig. 9 shows the simulation result for the Actual Production counter. At 13 seconds of simulation time, when the first display unit for actual counter was activated by a bit 0 (active low common anode display), segment ‘b’, ‘c’, ‘f’ and ‘g’ were activated (active low cathode pins) to display a number 4 on the display board. When the 2nd display unit was activated, segment ‘a’ to segment ‘f’ were activated as well and segment ‘g’ was put on high, to display a number 0 on the 2nd display unit. The same went for the 3rd, 4th, 5th, and 6th display units. Each unit displayed a number 0 when they were activated alternately. All of their segments from segment ‘a’ to segment ‘f’ were activated (active low), except for segment ‘g’ which was high. Fig. 10 shows the simulation result for Rejects counter. At 13 seconds of simulation time, segment ‘a’, ‘b’, ‘d’, ‘e’ and ‘g’ on the first display unit were activated, to display a number 2 on the display board. The rest of the display units showed a number 0 each on the display board when they were activated alternately. Segment ‘a’ to segment ‘f’ were activated and segment ‘g’ was put on high. For the downtime counter, Fig. 11 shows the first display unit displayed a number 7 when it was activated. Only segment ‘a’, ‘b’ and ‘c’ were activated for the first unit. The rest of the display units displayed a number 0 each when they were activated alternately.

3.2 System Tests and Results
A signal generator was designed and programmed onto the FPGA chip to generate a set of data; Actual Production, Rejects and Downtime input signals. The production line runs at normal shift 8 hours. The total
scheduled breaks for meals and short breaks is 1 hour, and the production line runs by machines with an ideal run rate at 1 piece per minute. The signal generator was programmed to generate 252 actual production input pulses, 49 rejects input pulses and 6 minutes downtime input pulses. After 8 hours of simulation, the output displayed on the display board and the screen displays were observed to check whether the system showed the right data as programmed. Fig. 12 shows the displays on the display board.

Fig. 12 shows the first row of display unit displayed 00 06 00 to denote a 0hr 6min and 0sec. That was the total downtime. The second row displayed 252 pieces of total actual production, while the third row displayed 49 pieces of total rejects. The displayed data matched with the programmed input.

Fig. 13 shows the screen display on a computer. It shows the total actual production was 252 pieces, 49 pieces of rejects and 6 minutes of downtime as well. The OEE (%) calculated by the VB program was 48.33%, Availability as 98.57%, Performance as 60.87% and Quality as 80.56%. It shows that the VB program was successfully able to automatically calculate the OEE indicator together with its parameters. Fig. 14 shows the Production Line Activities graph for the 8 hours shift.

Fig. 14 shows the production line was experiencing downtime in between the 5th and 6th hour of operation. Fig. 13 shows the total downtime experienced was 6 minutes. The total rejects was increasing slowly, while the total actual production was way behind the ideal production rate. There were many possibilities that could have caused the slow production. Shortage of input materials, misfeeds or the slow performance of the machines and man-powers needed to be checked and solved in order to bring back the actual production rate as close as possible to the ideal production rate and hence improve the production yield. This implies that a counter measure might need to be considered in future plans to improve the line activities. Line supervisors and managers could analyze the production line’s data record to check the production activity pattern whether a slow production rate was a common or should be treated as an individual case.
Fig. 15 shows the recorded data and results every 1 hour interval during the production shift. The OEE (%) indicator for the 8 hour morning shift was 48.33% with availability 98.57%, performance 60.87% and quality 80.56%. The low OEE indicator was mainly due to the poor performance or slow production rate.

The system designed had managed to capture, process and record all the data and results automatically without human intervention. Users such as managers, line supervisors, engineers, quality personnel and operators could spend more of their time focusing on the production activities, analysis or plans for further improvements and maintenance. It also helped to minimize, if not eliminate, errors due to manual data compiling. Data accuracy and reliability was also improved by using an automated data collection, processing, and recording system.

IV. CONCLUSION

A Production Monitoring System (PMS) is a tool to collect, process and record data for the use in a production line. It displays production information such as production rates and efficiencies, and machine/operator performance to help manufacturing team to achieve a targeted production output or yield. An automated PMS system is crucial to produce reliable and accurate data and reports. It minimizes or eliminates human intervention and errors due to manual data collection, processing and recording. Advancement in FPGA technology can benefit many areas including manufacturing. An FPGA can be programmed to perform automated data collection, processing, data managing and reporting which significantly improve the accuracy and integrity of the source of data.

This Embedded Controller for Production Monitoring System project has successfully developed an automated system on an FPGA chip. Data acquisition, processing and recording are done automatically as compared to the existing real time monitoring system where data processing and recording are still done manually [2]. The FPGA chip has managed to collect real time input data and presented the output on a display board using 7-segment display. The collected data then automatically processed on a computer by using a VB program, based on OEE application concept. The processed data were then displayed on a VB graphical user interface which includes a Production Line Activities graph. All data and results are automatically recorded on a Microsoft Excel spreadsheet.

The physical hardware size is small. It requires only 1 A4 sized PCB to accommodate 1 FPGA board, 21 units of 100Ω resistors, 18 units of 1k Ω resistors, 18 units of Motorola 2N3906 PNP transistors and 18 units of LiteOn LTD-482P common anode 7-segment LED display. The physical size has been reduced significantly as compared to the existing real time PMS circuitry [2], which uses more than 40 IC chips, mounted on 7 A4 sized PCB and encased in a chassis with a size of a computer CPU. The development cost for this project is approximately RM 800. This cost can be further reduced with mass production. In conclusion, this project is not only useful and fully automated but is cheap, portable, accurate, reliable and affordable by many industries.

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