Development of Load Moment Control and Monitoring System for Mobile Heavy Load Cranes

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***Abstract*—This study was conducted to develop a fully functional controlling and monitoring device to be used during the actual industrial operation of mobile heavy load cranes. The project aimed to provide a cost effective and user-friendly load moment indicator that meets the requirements of industry safety standards. The control system of the device measures and monitors the main parameters such as boom length, working radius, tip height, maximum load capacity based on crane load chart, actual load, efficiency and (actual load/maximum load) ratio. It was developed using the advanced application of Programmable Logic Controller (PLC) and latest technology of Human Machine Interface (HMI). The interface of Delta PLC and Delta HMI was able to replace the traditional controlling panels which need extensive wiring and the monitoring screen allows the user to complete settings through touchable keys on a user-friendly window. The performance of the implemented load moment control and monitoring system was evaluated and compared to the standard manufacturer rated lifting load chart. A series of tests was conducted and the results attest that the developed device successfully attained its functionality with an average of 99% accuracy on all the readings.**

Keywords—mobile heavy load canes, load moment control and monitoring system, PLC, HMI

I. INTRODUCTION

During the proponent's industry immersion in one of his projects under the Primary Construction Group Inc. at Cebu City with the help of his Project Manager and Primary Construction's Safety Engineers, a certain problem was identified. This problem is to replace the existing expensive LMI system in a second-hand crane. After the problem has been identified, the proponent analyzed the requirements needed for crane safety operation set by the People360 Corporation.

According K. Martinelli, statistical data regarding the main crane-related hazards. Since 2001, accidents involving tower cranes have resulted in 25 serious injuries and 9 fatalities. This highlights that the use of cranes and other lifting equipment at work needs to be aware of the hazards knowing what steps must be taken to reduce the risk ensuring safety [1].

To deal with the problem encountered about the LMI System in second hand cranes of Primary Construction Group, the proponent proposed to develop a load moment control and monitoring system using Programmable Logic Controller as the main controller and Human Machine Interface as the monitoring device of the projected system. The proponent analyzed that it is more practical to replace the existing expensive LMI systems and used the advanced application and controls of a Programmable Logic Controller (PLC) and Human Machine Interface (HMI) than to repair a built in LMI system in second hand cranes.

II. FACTORS AFFECTING MOBILE CRANE SAFETY

According to J.E. Spear, crane capacity to any weight greatly depends upon many factors. The following are the factors to be considered: center of gravity, mobile crane operators controlling skills, anti-two blocking system, extension and retraction sequence, stability, overload protection system, crane load limits, and hand signals [2].

A crane load moment indicator or LMI is a computerized system of sensors that aid the crane operator in avoiding the overturning moment of his equipment. It is a device which is installed on mobile or portal cranes to alert the operator if the lift is exceeding the safe operating range of the machinery. In some cases, the device will physically lock the machinery in circumstances it determines to be unsafe [3].

III. PROJECT DESIGN

Through deep and continuous researches, the potential of combining Programmable Logic Controller (PLC) and Human Machine Interface (HMI) was discovered.

The design model and the block diagram are represented by the Figure 3.1 and 3.2 respectively. The main parts included to the design of the LMI system are: length sensor, angle sensor, pressure transducer, central unit, A2B switch and LMI monitor.

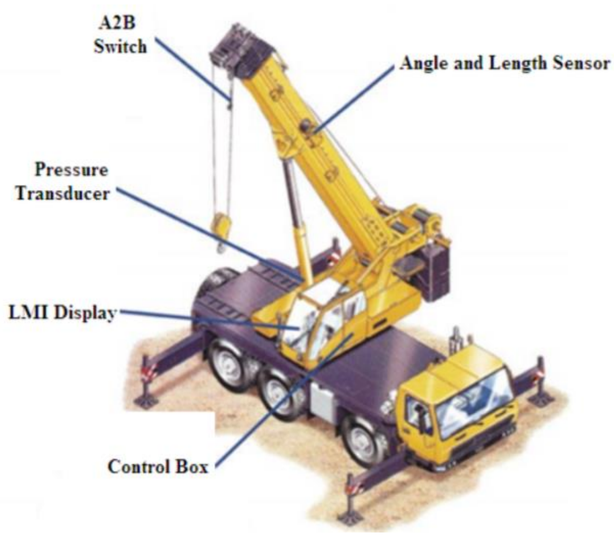

Fig. 3.1 Structural View of the Project Design Model

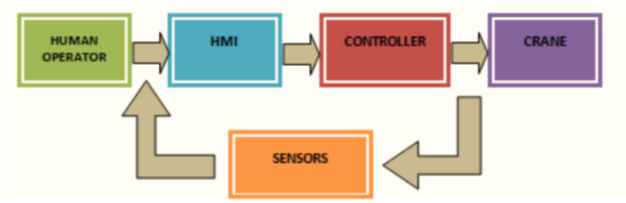

Fig. 3.2 Functional Block Diagram of LMI System

As shown in the block diagram, the operation of an LMI system starts with the manual control of the crane operator as an input. Then, the HMI monitor will indicate the system parameters such as boom angle, boom length, tip height, working radius, maximum load capacity, actual load, anti-2 block indicator, overload indicator, and efficiency. The monitored information from the HMI will be processed using the PLC. Then the processed information will drive the crane hydraulic cylinder and motors. Having a feedback for the closed loop system, sensors such as pressure transducer, limit switches, angle sensor and length sensors will be used to provide an accurate reading.

IV. LMI PROCESS FLOWCHART

Figure 4.1 describes the step-by-step procedure to display the output parameters of the load moment indicator. First, all data must be initialized in the data register of the PLC. The next step is reading of sensors to be able to provide value. The value from the sensors is to be the input program to the PLC for the mathematical formula. Lastly, indication of all the required parameters can be displayed.

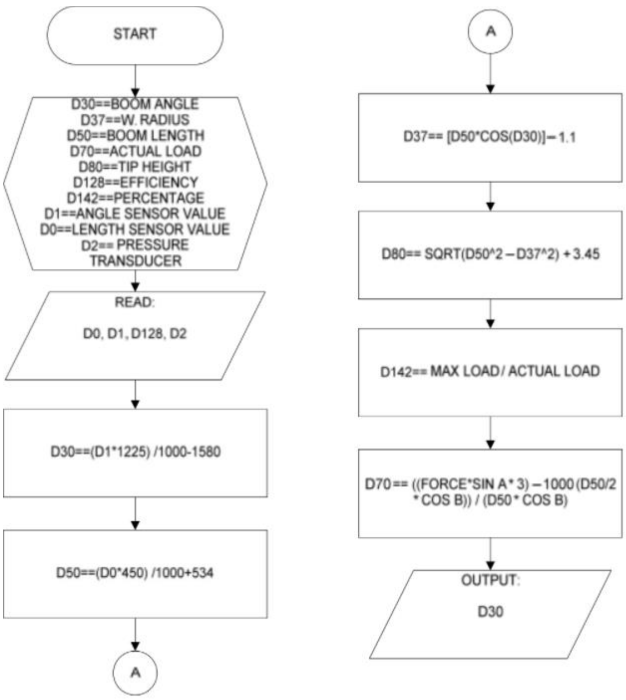

Fig. 4.1 Flowchart to read the parameters

In Figure 4.2, when the crane lifts a load, the cable length sensor and the angle sensor provide signals to the PLC unit. Then the PLC determines the working radius from the center of rotation of the boom to the hook block and proceeds to identify a specific load zone for specific combinations of boom length and working radius. Each load zone has a maximum load lifting capacity associated with it. Thus, the PLC reads the corresponding maximum load lifting capacity from the load chart. Then last is to compare this value to the actual load lifted provided by pressure transducer and indicated in the HMI.

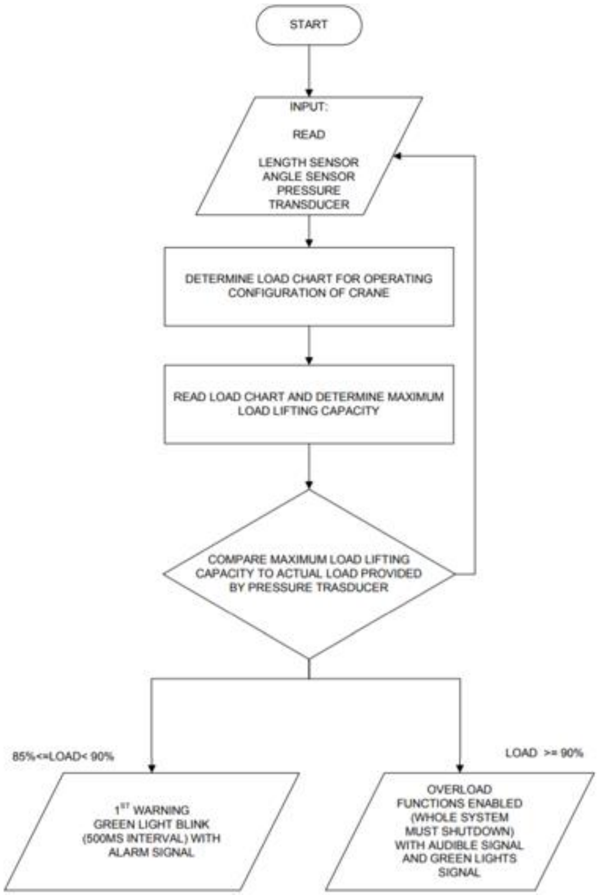

Fig. 4.2 Flowchart for maximum load and actual load

If the load indicated by the pressure transducer less than 85 percent of maximum load lifting capacity the program returns to read the actual load. If the actual load indicated by the pressure transducer is greater than 85 percent and less than 90 percent of the maximum load capacity, a first warning light together with sounding buzzer. If the actual load indicated is greater than 90 percent of the maximum load lifting capacity, the overloading functions are enabled it means, winching the load up and lowering the boom will be disabled.

V. ACTUAL IMPLEMENTATION OF LMI

A. *Software and Hardware Configuration*

Fig. 5.1 LMI system implemented on KOBELCO 45-Tonner Crane

Figure 5.1 shows the actual LMI system installed on the KOBELCO 45-tonner crane during the evaluation of Load Moment Control and Monitoring System. The data before the load has been lifted has an actual load of 0.70 ton and the maximum load capacity is 4.3 tons. On the figure above, the actual load was 4.23 tons, reaching its maximum capacity. It means that the ratio between the actual loads versus maximum load capacity is above 90 percent of the total maximum load capacity that the crane can handle. At that time, the overload protection has been activated and the green light was lit which means that the crane is overload.

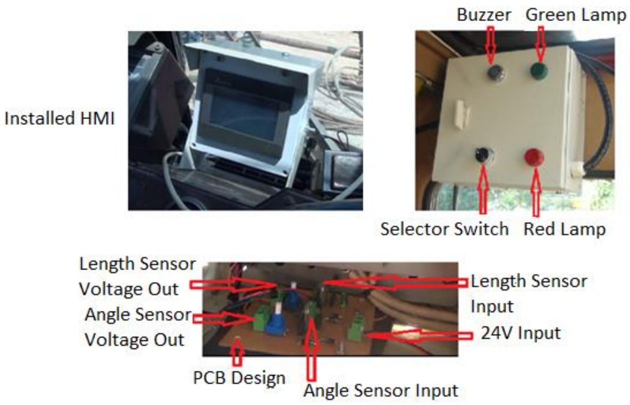

Fig. 5.2 Hardware components

Figure 5.2 shows the installed HMI, control box and the actual PCB design for length and angle sensor. Since PLC Analog Module (DVP-06AD) can only read voltage signal from -10V to +10V and current signal from 0mA to 24mA, this voltage regulator serves as the driver circuit for angle and length sensors to convert its resistance output signal to a voltage signal with a minimum and maximum voltage of 1.25V and 10V respectively.

B. Trials and Testing Procedures

Table 5.1 Boom Angle Going Up (0^o - 82^o) Percentage Accuracy Test

Boom Angle Going Up (0^o - 82^o) Percentage Accuracy Test			
Trial 1	96.26	Trial 4	99.73
Trial 2	98.15	Trial 5	99.70
Trial 3	99.57	Trial 6	99.74

Table 5.2 Boom Angle Going Up (82^o - 0^o) Percentage Accuracy Test

Boom Angle Going Down (82^o - 0^o) Percentage Accuracy Test			
Trial 1	99.79	Trial 4	99.61
Trial 2	97.43	Trial 5	99.61
Trial 3	99.61	Trial 6	99.61

Tables 5.1 and 5.2 show the results of the boom angle test from 0 degree to 82 degrees, and vice versa. A series of trial were made to determine the project design accuracy. Initial test results show a large percentage error found to be due to the angle sensor having no silicone oil. After correcting the problem regarding silicone oil and thoroughly checking and calibrating the voltage regulator circuit, subsequent tests show the percent error decreasing eventually to less than 1 percent.

Table 5.3 Boom Length Percentage Accuracy Test

Boom Length Percentage Accuracy Test			
Trial 1	99.96	Trial 3	99.85
Trial 2	99.96	Trial 4	100

Table 5.3 shows the data gathered in testing the boom length of the crane. Through four consecutive tests by the expert an average of 99.94 percent accuracy was obtained which means that the data indicated in the HMI is accurate and precise.

Table 5.4 Maximum Capacity Test

W. RADIUS HMI	BOOM LENGTH			
	9m	15.5m	22m	28.5m
2.5	25	19.4	12.5	0
3.2	25	19.4	12.5	0
3.6	23	19.4	12.5	8
4.4	21.2	18	12.5	8
4.6	19.4	16.7	12.5	8
5.3	17.8	15.5	11.7	8
5.7	16.3	14.4	11	8
6.3	15.1	13.4	10.4	8
6.7	0	12.5	9.8	7.6
7.2	STOP	10.7	8.7	6.9
8.52		0	7.7	6.2
9.53		STOP	6.8	5.65
10.63			6.1	5.15
11.57			0	4.7
13.53			STOP	4.3
14.65				4
15.53				3.7
16.54				3.4
17.63				0

Table 5.4 shows the data for maximum load capacity test. It is based on the manufacturer's rated lifting load chart using boom length and working radius. It is displayed on the HMI for monitoring. In every load chart there is a maximum working radius that the crane can handle. During testing the crane's boom arm stopped moving downward after obtaining the maximum radius as per requirements of the system based on the Crane Load Chart.

Table 5.5 Working Radius Test

TRIAL 1			
HMI VALUE	Measured	% E	%A
4.95	5	1.01	98.99
12.5	12.7	1.60	98.40
AVERAGE		1.31	98.69
TRIAL 2			
HMI VALUE	Measured	% E	%A
3	3.06	2.00	98.00
15	15.1	0.67	99.33
AVERAGE		1.33	98.67

Table 5.5 shows the data gathered in testing the working radius. During the testing period, the value indicated in the HMI and the measured value using meter tape was compared. The table shows that the proponent was conducted two trials that show an average of 98.68 percent accuracy.

Table 5.6 Actual Load Test

TRIAL 1			
STANDARD WT.(TONS)	HMI VALUE	%E	% A
1	1.07	7.00	93.00
2	2.1	5.00	95.00
4.2	4.23	0.71	99.29
11	11.09	0.82	99.18
AVERAGE		3.38	96.62
TRIAL 2			
STANDARD WT.(TONS)	HMI VALUE	%E	% A
1	1.05	5.00	95.00
2	2.08	4.00	96.00
4.2	4.27	1.67	98.33
11	11.1	0.91	99.09
AVERAGE		2.89	97.11

Table 5.6 shows the comparison between the standard load weights lifted by the crane and the data indicated in the HMI both in unit of tons. It is clearly shown in the table that the average percent accuracy gathered is 96.7 percent.

Table 5.7 Anti-2-Blocking System Test

TRIAL 1				
B. LENGTH	9 METER			
B. ANGLE	HOIST UP	HOIST DOWN	BUZZER	RED LAMP
45 DEG	DISABLED	ENABLE	ON	ON
50 DEG	DISABLED	ENABLE	ON	ON
60 DEG	DISABLED	ENABLE	ON	ON
TRIAL 2				
B. LENGTH	15 METER			
B. ANGLE	HOIST UP	HOIST DOWN	BUZZER	RED LAMP
45 DEG	DISABLED	ENABLE	ON	ON
50 DEG	DISABLED	ENABLE	ON	ON
60 DEG	DISABLED	ENABLE	ON	ON
TRIAL 3				
B. LENGTH	22 METER			
B. ANGLE	HOIST UP	HOIST DOWN	BUZZER	RED LAMP
45 DEG	DISABLED	ENABLE	ON	ON
50 DEG	DISABLED	ENABLE	ON	ON
60 DEG	DISABLED	ENABLE	ON	ON
TRIAL 4				
B. LENGTH	28 METER			
B. ANGLE	HOIST UP	HOIST DOWN	BUZZER	RED LAMP
45 DEG	DISABLED	ENABLE	ON	ON
50 DEG	DISABLED	ENABLE	ON	ON
60 DEG	DISABLED	ENABLE	ON	ON

Table 5.7 shows the data gathered in testing the anti-2-blocking system. It shows different testing procedures that were conducted by the proponent to determine the accuracy and precision of the system. Trial 1 to trial 4 tests the output response of the system under 9-, 15-, 22- and 28-meters working radius, respectively and three different boom angles 45, 50 and 60 degrees in each certain boom length. It is evident that all of the output devices are working properly when the hook hits the sliding weight of the anti-2-block switch. Thus, when the anti-2-block switch was activated, buzzer and red lamp indicator are turned on simultaneously, hoist down of the hook is enabled and hoist up of the hook is disabled. Based on the data gathered, it is proved that the system works accurately and precisely according to the safety standards of the crane.

Table 5.8 Anti-2-Blocking System Test

TRIAL 1	ML	4.3	10.4
	AL	4.26	11
	OPERATION	Overload	Overload
	HOIST UP	Disabled	Disabled
	BOOM EXTEND	Disabled	Disabled
	BOOM UP	Enabled	Enabled
	HOIST DOWN	Enabled	Enabled
	GREEN LAMP	ON	ON
	BUZZER	ON	ON
TRIAL 2	ML	4.3	10.4
	AL	4.26	11
	OPERATION	Overload	Overload
	HOIST UP	Disabled	Disabled
	BOOM EXTEND	Disabled	Disabled
	BOOM UP	Disabled	Disabled
	HOIST DOWN	Disabled	Disabled
	GREEN LAMP	ON	ON
	BUZZER	ON	ON

Table 5.8 shows the actual load (AL) versus Maximum load (ML) response of the of the overload protection device of the system. Based on the data gathered during testing, the overload protection device work accurately and precisely when overload occurs. Hoist up, Boom down and Boom extend are disabled and Hoist down and Boom up are enabled, and also green lamp and buzzer turned on together when overload.

C. *LOAD MOMENT INDICATOR FEATURES*

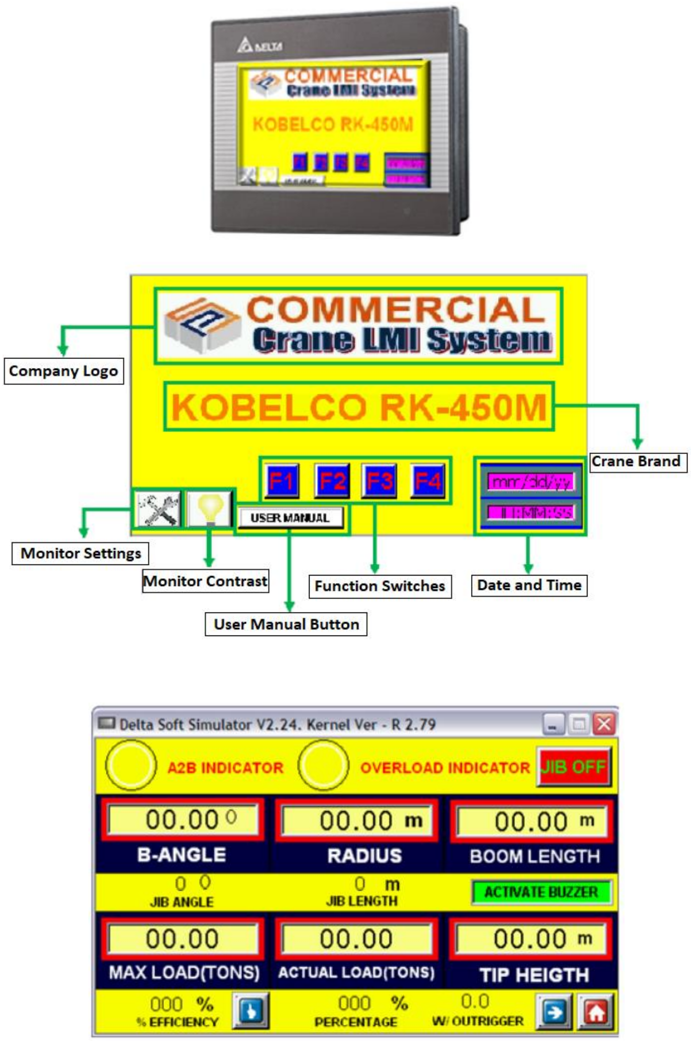

Fig. 5.3 LMI Graphical User Interface

The main objective of this Graphical User Interface design is to produce a user interface that will make it easy, efficient and user friendly to operate the telescopic boom crane in the way which produces the desired results. Figure 5.3 shows the graphical user interface design for load moment indicator.

D. Built-in Mobile Crane Components

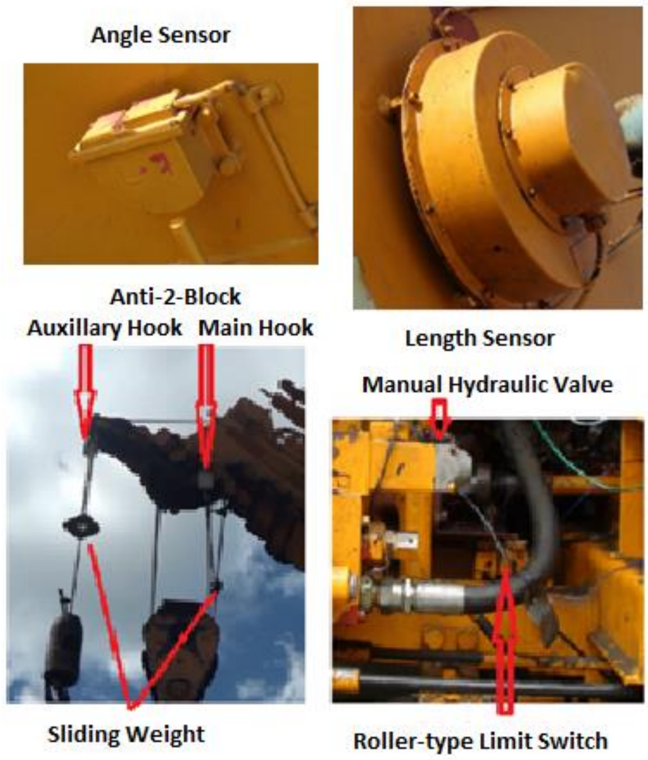

Fig. 5.4 Built-in components in 45-tonner KOBELCO crane

Figure 5.4 shows the built-in crane components that were used in the actual implementation. The angle sensor is used to measure the angle of the boom arm. Length sensor is used to measure the boom length. Limit switch (push button type) is used for anti-2-blocking system to protect the crane in unsafe upward movement of the hook. Roller-type limit switches are installed at the back of the cab near the manual operated hydraulic valve to enable the hoist down motion, boom up motion and boom arm retraction.

E. Project Technical Feasibility

There are three main parts of the design included in this technical feasibility. First is the design of PLC program. This is the most important and crucial in this project, it includes the program to be loaded to the PLC using ladder diagram programming which is based on the IEC 61131 standard and it also includes all the inputs and output devices that were used in implementing the project. The PLC serves as the main controller of the Load moment indicator system. Second is the design of HMI program. It includes the program to be loaded to the HMI and the communication settings between PLC and HMI. It serves as the interfacing device between the operator and the crane as a monitoring device to monitor all the required parameters set by the People360 Corporation. The last but not the least which completes the technical design feasibility is the input/output (I/O) wiring diagram of the entire system. This includes the electrical wiring diagram- the interconnection of input devices, controller and output devices. It also includes the electrical wiring using RS-485 protocol to communicate PLC and HMI.

VI. SUMMARY OF FINDINGS

This project is aimed to design a cost-effective load moment indicator for telescopic boom cranes that assures safety features using the advanced technology of Programmable Logic Controller and Human Machine Interface. Based on the data gathered, the PLC and HMI program were designed to achieve the objectives of the system. Using the ladder diagram programming for the PLC and Graphical User Interface programming for the HMI, it showed that the project design worked effectively and efficiently as implemented. Calculations showed that the total project cost is Php 191,275 which composed of the materials, installation and miscellaneous costs. Benefits and costs were compared and it shows that the project is cost effective compared to the commercially available LMI system. The risk assessment was formulated to give information about the possible technological threat to the system.

VII. CONCLUSION

Based from the findings of this study, the following conclusions were drawn. The proponent has successfully developed a cost-effective load moment control and monitoring system using PLC & HMI for mobile heavy load cranes. The system was designed and programmed to consistently output and monitor the desired parameters while operating the mobile telescopic crane. The system was designed to automatically control the overload protection and anti-2-blocking system of the crane. The requirements of the system were made to be based on programmable logic controller and the human machine interface. The accuracy and precision of the system based on manufacturer rated lifting load chart was successfully attained. The system designed was able to meet the industry safety standards.

VIII. RECOMMENDATIONS

The following statements are some of the recommendations that had been identified. All necessary control hardware may be housed in a single enclosure for ease of maintenance and troubleshooting. Wireless sensor maybe used to do away with cables. Controls of other parts of the crane maybe integrated within the LMI system. Development of a web-user interface for monitoring and data logging.

IX. ACKNOWLEDGEMENT

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IX. REFERENCES

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