FPGA-Based Implementation of SCADA System for Fuel Management

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Abstract

With the emergence of Digital Processors and Logic Design technologies, like FPGAs, the trend of using IC-based plug-and-play modules has been minimized. The focus is commercial off-shelf designing and developing modules and sub-modules on new FPGA technology. Some of the critical factors that make FPGA more suitable include enormous computational power, capabilities to perform logic operations, high-speed clocks, fast memory, and various built-in primitives for computation-intensive arithmetic operations. FPGA becomes suitable for implementing data capturing and processing systems with these characteristics. This paper is about designing and developing an FPGA-based Supervisory Control and Data Acquisition (SCADA) System to monitor and control the fuel level transition between two tanks that generally are designed using PLC. PLC-based SCADA systems are easy to implement, but when discussing performance, PLC cannot replace FPGA. The FPGA chosen is Spartan-3 due to its low cost and meeting the industrial temperature needs. At the same time, it may be translated into any advanced FPGA, producing fewer sources and power consumption benefits. The simulator is Xilinx 14.7 ISE, along with SDK. The implemented system provides the inherent amenities of SCADA along with the benefits of high speed, more accuracy, reduced and predictable delay, and a purely digitized system facilitated by the FPGA.

Keywords—Automation, FPGA, SCADA, SDK, Xilinx

1 Introduction

Industrial automation has become a widely accepted trend today that turns into labor cost reduction [1]. Computer vision is the key to many automated solutions, where it becomes mandatory for items to be grasped or checked [2]. These computer vision systems are generally produced with conventional PCs [3]. Since computers have become more familiar with industrial applications, it is easy to use them for these applications too. When the performance becomes an obligatory factor to consider, the PC (mainly the Central Processing Unit (CPU) inside) is not the right choice [4].

Supervisory Control and Data Acquisition System (SCADA) is an advancement to computer vision system with the inherent characteristics to monitor, supervise, and control any process regularly and intelligently [5]. In today's automation industry, SCADA is considered an essential approach. The SCADA system has become the key to achieving the set objectives of the process plant with intelligent monitoring and controlling [5, 6].

Any generic SCADA system consists of a single central controller and several distributed field devices like sensors and actuators. Communication protocols specifically developed for industrial applications are needed to exchange data between the controller and the field devices [7, 8].

The main parts of a generalized SCADA system are the Master terminal unit (MTU), the Communication module, and the Remote terminal Unit (Fig.1).

The first SCADA-based automation system was reported in the 1960s at Bonneville Power Administration [9]. The key idea was the free-hand monitoring of any process from anywhere. Since then, SCADA has grappled with various applications in monitoring and controlling the operation of wind

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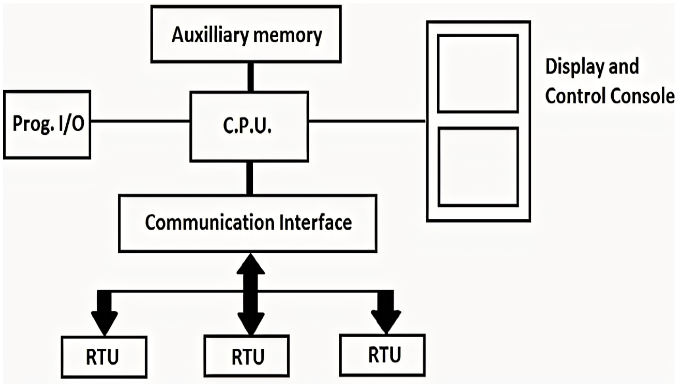

Fig. 1: General block diagram of SCADA system

turbines, refineries, water flow, dams, and industrial processes.

If implemented correctly, SCADA may be more effective in saving time and money by reducing the requirement of physical visits to the site by service personnel for inspection, data collection/logging, or making adjustments to increase process reliability.

In literature, various applications of SCADA have been reported for a few decades. The work in [10] is about SCADA-based Smart Metering systems for water companies. It is reported that SCADA can play a crucial role in sustainable water-energy use. The benefit of SCADA may be seen in stress reduction on the environment, hence promoting the reduction of CO2 emissions and other greenhouse gases in water supply systems.

The work reported in [11] is about an intelligent SCADA system that helps estimate the pollution of various gasses available in urban areas. The work reports the installation of several stations to collect the air pollution and make the prediction that helps people select less hazardous concentration sites.

The presence of SCADA is also reported in the construction domain. The development of SCADA-based operational and control platforms for intelligent buildings is produced in [12]. The work reports various modern technologies integrated to produce information like ventilation control, temperature monitoring, pressure calculations, illumination, etc.

The work in [13] documents a conventional SCADA-based supervisory system's connection with MATLAB software to efficiently handle complex control algorithms with the user-friendly GUI of MATLAB. The SCADA-MATLAB platform produces more reliability and effectiveness in real-life issues and their solutions.

SACAD is also reported in the oil refinery process [14]. Conventionally, the distributed control system (DCS) is used in the oil refinery industry, but once SCAD is used, it is proven faster and more reliable with extensive data storage capabilities.

The work in [15] reports the analysis of the SCADA data for assessing the importance of how wind turbines align in patterns to the wind direction. SCADA data show that non-trivial alignments concerning the wind direction arise, and significant performance deviations occur among the most frequent configurations.

The monitoring of power transfer parameters such as temperature, voltage, load, and bushing condition is reported by an Internet-based Supervisory Control and Data Acquisition (SCADA) system [16]. The work reports unconventional benefits of internet-based SCADA, including reduced running costs by optimized maintenance and schedule and reducing the power transformer's failure risk.

Further, the SCADA system may be implemented for water and wastewater systems management, where the operators can be informed about the design of new techniques and also about upgrading existing systems. Supervisory Control and Data Acquisition (SCADA) has also played a role in the oil and gas industry. The work reported in [17] shows that with SCADA, enhanced monitoring of oil and gas installations such as pipelines, production sites, valve installations, compressor stations, and other remote sites can also be carried out. Besides, more research in this domain is reported in [18-28].

The application of SCADA in fuel management is reported in [29]. The PLC-HMI system for tracking oil product refineries is designed and developed. In the design, PLC automatically displays petroleum product terminals. The proposed design depends on Add on Instructions (AOI) programming along with ladder logic, which results in the best utilization of processor capabilities, which helps add extra program commands in less processor memory, and lower system creation and upgrade costs.

The paper [30] proposes SCADA-based tank management that provides tools for analyzing, reporting, fine-tuning, and monitoring various plant data, including flows, motor currents, temperatures, water levels, voltages, and pres-sure. Besides, Alarms at central or remote sites triggered by abnormal conditions are propagated to the HMI computer for the operator's attention. The literature review justifies that the solution is SCADA if remote monitoring and control of any process are required, along with high speed, reliability, and robustness. The SCADA systems use specific communication protocols sent over the communication links in certain coded

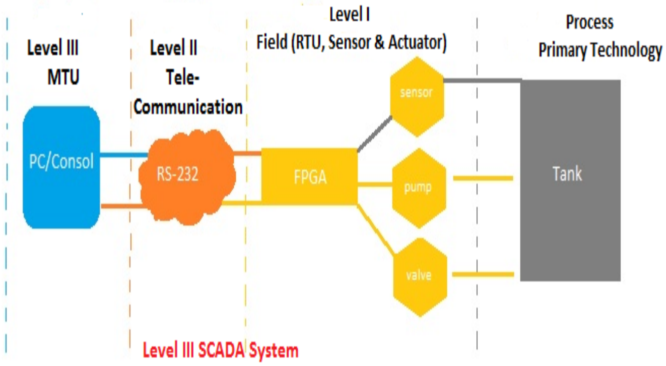

Fig. 2: Proposed architecture of SCADA system

formats. Besides, several advantages of SCADA are observed compared to conventional monitoring and data collection systems, like DSCS.

This paper shows the FPGA-based implementation of the Supervisory Control and Data Acquisition (SCADA) System for monitoring and controlling fuel level transition between two tanks. The FPGA chosen is Spartan-3 due to its low cost and meeting the industrial temperature needs. The simulator is Xilinx 14.7 ISE, along with SDK. The implemented system provided the basic facilities of SCADA with the advantages of great speed, high accuracy, negligible & predictable delay, and a purely digitalized system facilitated by the FPGA. The paper proceeds as follows: Section two presents the proposed architecture of an FPGA-based SCADA system. Section three shows the proposed design's FPGA-based implementation, and section four offers results and a conclusion.

2 Proposed Structure of FPGA-Based SCADA System

The proposed architecture of the FPGA-based SCADA system is shown in Fig.2. There are three levels which include the Master Terminal Unit (MTU), Telecommunication Unit, and Remote Terminal Unit (RTU). The details of these are given in the proceeding section.

- **Level III: MTU** The Master terminal unit, as the name indicates, is the most essential part of SCADA. It gives user control by providing a console of targeted FPGA on a personal computer. This unit carries all the command and control. This unit remains active from starting of the process till the end.
- **Level II: Telecommunication** Level II provides communication between MTU and RTU to monitor and acquire real-time data from the process plant through serial communication. In the proposed design, the RS-232 protocol is used for serial communication.
- **Level I: Field (RTU/sensors/actuators)** Level I consists of the field devices that constantly need to communicate with the MTU. FPGA works as an RTU and is used for data accusation and control. It sends the violated limits of the acquired data to MTU, and on that basis, the control action is proposed and generated through the RTU.

3 FPGA-Based Implementation and Results

The modern-day industry requires system-level intelligence and very high performance, which is impossible to get with high-grade PLCs. Besides, in most scenarios, the exclusive communication medium is required, from dial-up phone lines to broadband wired/wireless IP, which is again an issue with PLCs. PLC-based systems also have a big issue of reconfigurability and higher maintenance costs than fully integrated units. These factors make PLCs a less suitable choice for modern industry.

FPGA is a more robust and attractive platform for implementing high-performance energy management-related scenarios. It provides flexibility regarding I/Os, CPU, and radio-related configurations. With FPGA, adding more intelligence may achieve a more optimized system. Table 1 compares typical PLC-based RTU with FPGA-based RTU in terms of various features showing the potential difference between the two technologies.

Another comparison between PLC-based SCADA and FPGA-based SCADA is provided in Table 2 [31], showing the robustness of the FPGA-based SCADA system.

A level III system is implemented in the proposed FPGA-based SCADA system design (Fig. 3). Level III SCADA, a single-machine process, includes a single MTU (master terminal unit) and a single RTU (Remote terminal unit).

The LEDS on FPGA tell the fuel level status and on and off of the plant. The SDK-based view of the proposed RTU is given in Fig.4.

To get the FPGA working as the RTU (Fig. 5), the general purpose IOs of the board are set accordingly. The details of the pins are given in the user constraint file. A total of six general-purpose input-output ports are used in the design to start the plant and to indicate the status. Also, the power to create the plant

TABLE 1: Typical PLC Based RTU versus FPGA-Based RTU

Features	FPGA based RTU	PLC based RTU
Integrated Software Environment (ISE)	Yes	No
10/100 Ethernet Media Access Controller (MAC)	Yes	No
Encryption Support	Yes	No
Remote software Diagnostics	Yes	No
Configurable Logic Blocks	Yes	No
Digital Clock Managers (DCMs)	Yes	No
Temperature Range in C0	-40 to +100	-20 to +60

TABLE 2: Typical PLC-Based SCADA System versus FPGA-Based SCADA System

Timing Parameters	Plant PLC Control	Plant FPGA Control
Maximum Frequency	200 MHz	395.0 MHz
Minimum Period	100 ms	1.196ns
Combinational Path Delay	0.9ms	10.170ns
Memory usage	Up to 16 MB	256588 KB

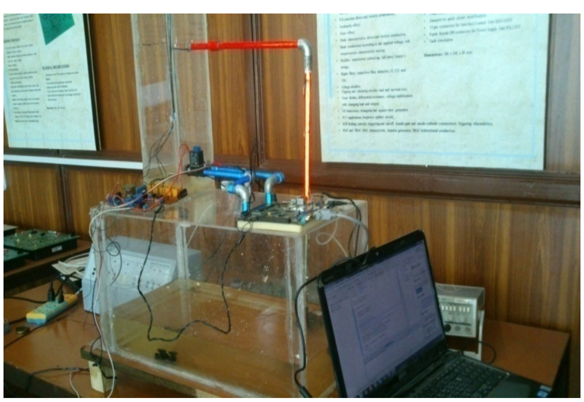

Fig. 3: Prototype of FPGA-Based SCADA system

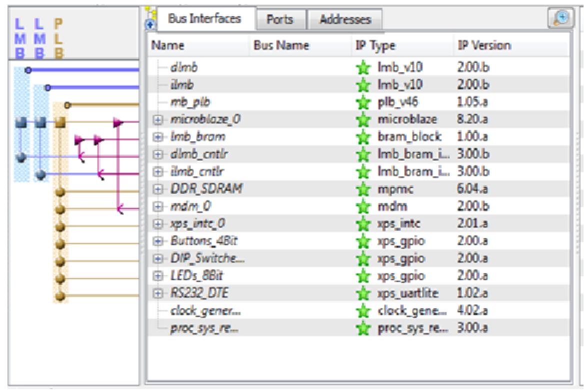

Fig. 4: SDK-based RTU design using FPGA

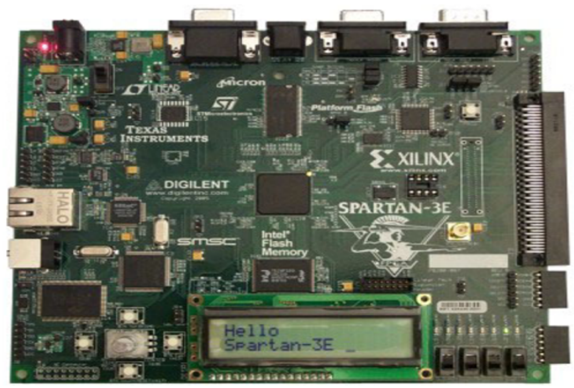

Fig. 5: RTU design using FPGA

is taken from IOs. The IOs on FPGA are connected to J1 and J2 headers.

The JI of Spartan-3 FPGA is shown in Fig.6. it is provided on the right edge of the FPGA boar, which is the topmost 6-pin connector. It consists of a female 6-pin 90° socket. The project's four pins connected to the J1 header are $FX2\_IO < 4 : 1 >$.3.3 the board supplies V and the ground to the header.

The J2 header, shown in Fig .7, is the bottom-

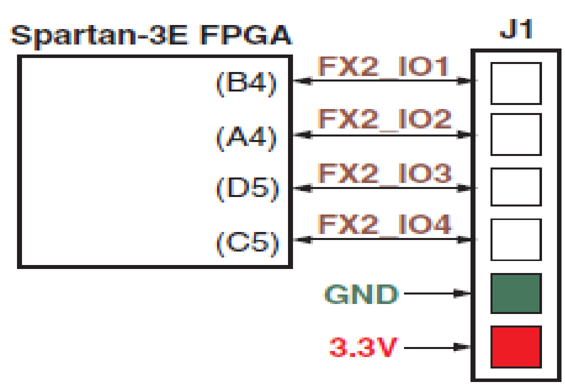

Fig. 6: Pin Configuration on J1 Header of Board

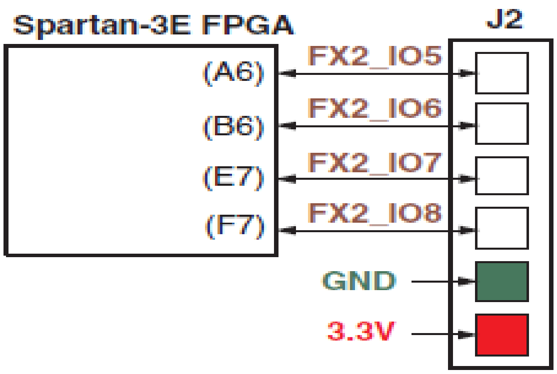

Fig. 7: Pin Configuration on J1 Header of Board

TABLE 3: I/O function of the J1 header

Port	LED on board	Output from board	Action
Header J1	LED3(F9)	o/p_0 (A6)	Initial level
Header J1	LED4(D11)	o/p_1(B6)	Middle level
Header J1	LED5(F11)	o/p_2(E7)	Final level

most 6-pin connector along the right edge of the board. It uses a female 6-pin 90° socket. Four FPGA pins connected to the J2 header are $FX2\_IO < 8 : 5 >$. The board gives 3.3 v and ground to the J2 header.

The user constraint file for J1 and J2 header connections are shown in Fig. 8 and Fig. 9, and the pin locking for the pins used in the project is given in Tables 3 and 4.

The proposed SCADA system starts working by passing the message to the console by serially communicating with the RS-232 protocol (Fig. 10). Once activated, the DIP switch on FPGA is pressed to turn on the water pump and gets the fuel flowing in the lower tank from the upper tank. The LED1 on the FPGA also gets turned on to show the start of flowing. The FPGA processor processes the presence of voltage on the output LED1, and the status of the plant is displayed on the console accordingly (Fig. 11). If some interruption is observed, the output voltage level at LED1 would be reduced, and the plan would work.

When the water level reaches the middle class of the tank, the outlet control valve is opened, LED2 glows, and the message appears on the console. If, in any way, the control valve fails to open, fuel continuously flows into the tank till the whole level is reached. When this happens, FPGA automatically switches off the pump. To actuate this mechanical device (control valve), 3.3 V is generated by FPGA at the port of the J2 header, which is further amplified to the required level.

Besides LED1 and LED2, three more LEDs on board are used in the project to indicate the fuel level of tank 2. LED3 is used to indicate the initial group of fuel transfer (Fig. 12). The message is also displayed on the console, showing the data accusation on LED3 output.

Likewise, LED4 is turned on; when the middle level of fuel transfer is acquired, the control valve opens automatically, and the message of turning on the LED4 gets displayed on the console (Fig. 13).

The LED5 gets a glow to indicate the alarming situation of the plant (Fig. 14). This happens when the water tank gets full, and a chance to overflow is produced. With the turning of this LED, a message signal is generated by the controller to turn off the plant automatically, and once received the message the pump gets turned off.

The overall resource utilization of FPGA in the proposed SCADA system is shown in Table 5, which demonstrates that the proposed system is utilizing the resources efficiently. Finally, Fig. 15 shows the schematic design of the proposed scheme.

TABLE 4: Voice recognition EERs, signature recognition EERs, and voice/signature recognition EERs

Port	Input to board	LED on board	Output from board	Action
Header J2	DIP Switch (N17)	LED1 (E9)	o/p_0 (B4)	To turn on/off the pump
Header J2	—	LED2 (C11)	o/p_1(A4)	To turn on the valve

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```
#NET "J1<0>" LOC = "B4" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J1<1>" LOC = "A4" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J1<2>" LOC = "D5" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J1<3>" LOC = "C5" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
```

Fig. 8: UCF file for 6-pin J1 header with four connections that are shared with the $FX2$ connector

```
#NET "J2<0>" LOC = "A6" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J2<1>" LOC = "B6" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J2<2>" LOC = "E7" | IOSTANDARD = LVTTL | SLEW = SLOW | DRIVE = 6;
#NET "J2<3>" LOC = "F7" | IOSTANDARD = LVTTL | SLEW= SLOW | DRIVE = 6;
```

Fig. 9: UCF file for 6-pin J2 header with four connections that are shared with the $FX2$ connector

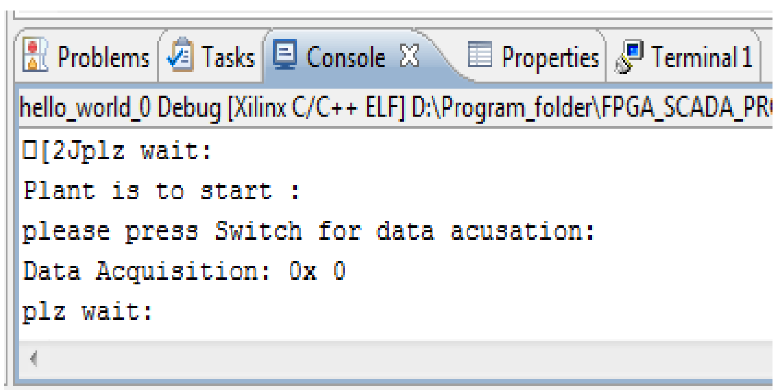

Fig. 10: Console display using RS232 protocol showing the start of the plat

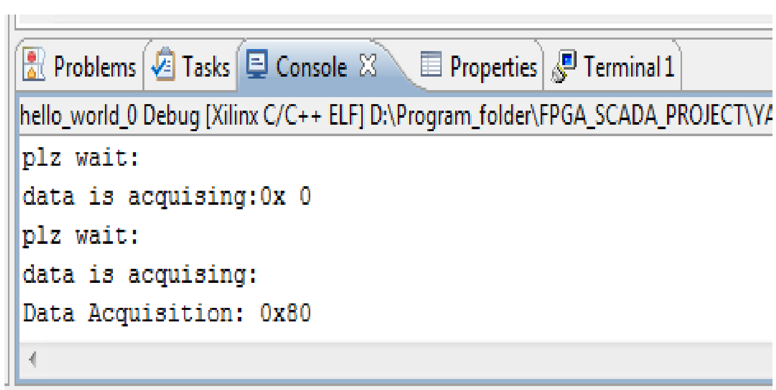

Fig. 11: Console display using RS232 protocol showing data acquisition

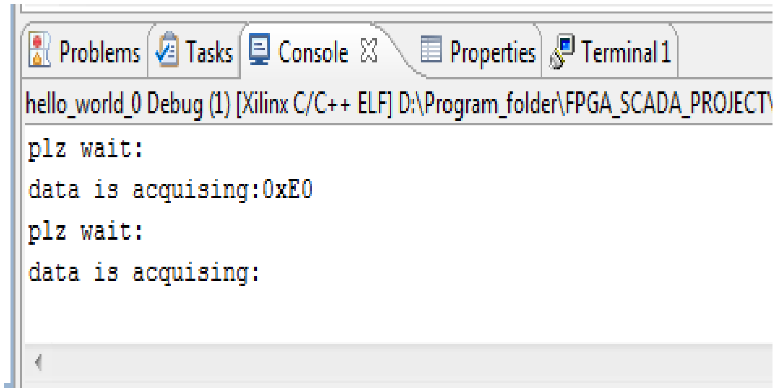

Fig. 12: Console display using RS232 protocol showing data acquisition on LED 3

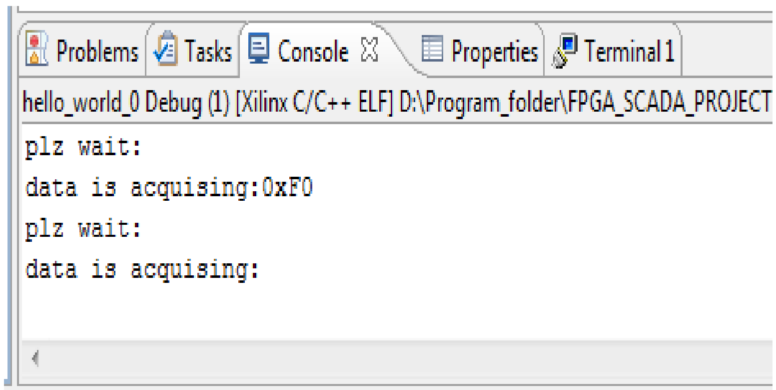

Fig. 13: Console display using RS232 protocol showing data acquisition on LED 4

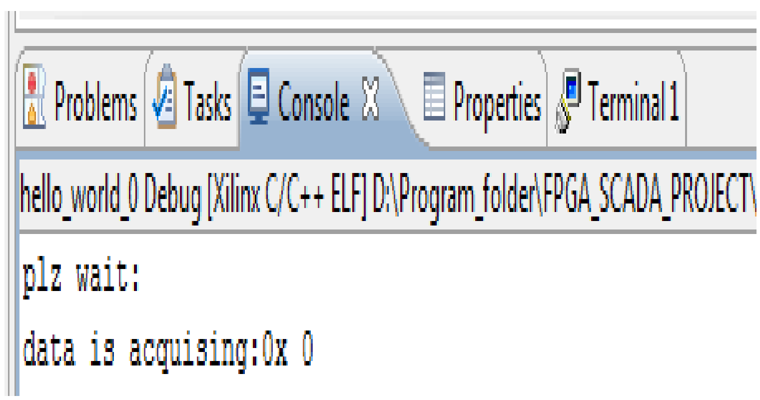

Fig. 14: Console display using RS232 protocol showing data acquisition on LED 4

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TABLE 5: FPGA's resource consumption in RTU design

Resources	**FPGA-Based SCAD System**
LUTs	78
Macro-statistic	# 7-bit adder :2 # 23-bit register:11 # 6-bit register:2 # 32-bit 2-to-1 multiplexer:76
Micro Blaze (RISC)	1
Path delay (ns)	3.59
Logic levels	7
Frequency MHz	278.963

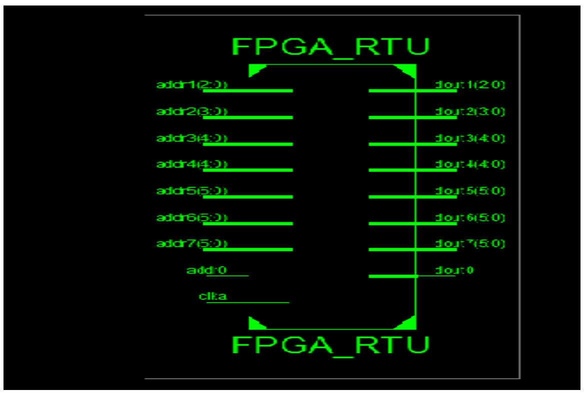

Fig. 15: Schematic diagram of FPGA-based RTU

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