FPGA Design and Implementation of a 5G Industrial Internet of Things Solution for Industry 4.0 Automation and Edge AI Application

5G IIoT, NB-IoT, 5G RedCap

Hossam Fattah
RAN Stack Lead
Lattice Semiconductor
Hillsboro, USA

Rahulkumar Koche
Design Engineer
Lattice Semiconductor
Hillsboro, USA

Karl Wachswender
Principal Architect
Lattice Semiconductor
Austria

***Abstract*— 5G New Radio (NR) has been reshaped in its Release 17 and Release 18 to revolutionize Industrial IoT (IIoT) to modernize industries and catalyze the era of Industry 4.0. As manufacturing processes, supply chains, factories, and industrial operations become increasingly digitized and intelligent, the need for robust, low-latency, reliable, and intelligent communication networks has never been more critical. 5G IIoT introduced new capabilities such as support of a massive number of IIoT devices up to 1 million devices per square Km, extremely low power consumption, ultra-reliability of up to 99.9% uptime, support for Time Sensitive Networking (TSN), and using Edge Artificial Intelligence applications.**

In this paper, we present the Lattice 5G IIoT FPGA solution for Industrial automation. The solution combines real-time control, connectivity, AI, safety, and security. It uses RISC-V® embedded CPU running FreeRTOS along with AXI4, AHBL, and APB buses, multi-channel motor controls, an industry-accepted technique for Motor Current Signal Analysis (MCSA), sensorless Space Vector Pulse Width Modulation (SV_PWM) technique implemented in the RTL of the FPGA, Lattice EtherConnect, a packet-based protocol, very similar to standard Ethernet packet, and 5G IIoT engine. The solution performs AI/ML inferencing models to measure and analyze performance data and enables a predictive maintenance (PDM) system to help identify and replace faulty system components before they fail and interrupt production lines in factories. The solution is fully monitored, controlled, and configured from the cloud. It collects factory motors and equipment data and applies predictive maintenance algorithms and edge AI to determine if the motor is operating properly. The solution meets today's vital industrial interoperability standards while providing best-in-class performance with up to 4X lower power, and 100X lower Soft Error Rate (SER), motor jitter of less than 30ns, and FPGA LUT utilization of less than 80% while reducing the overall system size and cost.

Keywords*— *5G, IIoT, NB-IoT, MTC, RedCap, Industrial, Automation, TSN

I. Introduction

In the dynamic landscape of the Fourth Industrial Revolution, or Industry 4.0, the role of the Industrial Internet of Things (IIoT) in 5G is expanding with unprecedented momentum. The fusion of sophisticated automation, smart factories, smart industries, data exchange, and advanced manufacturing techniques has instigated a paradigm shift, spotlighting the need for more intricate, secure, and efficient wireless communication protocols [1][2].

While established communication protocols have laid a foundational framework for IIoT integration, the evolving needs of Industry 4.0 demand advancements that address the contemporary challenges of security, data integrity, speed, and interoperability [3][4].

5G IIoT is poised to serve the world of supply chain, inventory management, smart factory, and smart industry. IIoT is at the center of this transformation. In simpler terms, IIoT is all about connecting machines and devices in industries, such as cars and food, to collect and share data in real-time. It is taking us from the old days of having to manually check and manage inventory to a new age where much of this work is automated, data-driven, hosted on the cloud with AI/ML engines, and happening in real-time [5].

Cognitive 5G IIoT is promising to make AI/ML part of the story. By infusing AI at the cloud edge, closer to the source of data generation, industrial systems gain the ability to process information swiftly, make autonomous decisions, and adapt to new inputs in real-time. This capability is pivotal in environments where latency is a luxury and bandwidth is at a premium, such as remote oil rigs, automated manufacturing lines, and intricate supply chains.

The infusion of Artificial Intelligence (AI) technologies into the 5G IIoT has catalyzed the emergence of smarter, autonomous systems. The deployment of AI within IIoT (often referred to as Industrial AI) encompasses various technologies, each serving a unique function in enhancing industrial operations. Such technologies include the following:

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- **Machine Learning and Predictive Analytics**: The foundation of Industrial AI is machine learning (ML), where algorithms learn from historical data to make predictions or perform classifications. In IIoT industrial solutions, ML models are trained on vast datasets generated by sensors and devices to predict equipment failure, optimize maintenance schedules, and enhance quality control.
- **Deep Learning for Complex Decision-Making**: A subset of ML, deep learning utilizes neural networks with multiple layers to interpret complex data structures. In IIoT industrial solutions, these networks analyze intricate patterns within large-scale industrial processes, such as visual inspection of products through image recognition, or optimizing energy consumption across a smart grid.
- **Natural Language Processing (NLP)**: NLP allows machines to understand and respond to human language, facilitating user-friendly interactions with 5G IIoT industrial solutions. It enables technicians to query systems using natural language, making it easier to obtain insights or issue commands without needing intricate interfaces or specialized training.
- **Reinforcement Learning for Real-Time Adaptation**: Reinforcement learning (RL) involves training algorithms through trial and error, using rewards to shape the desired behavior. This is particularly useful in dynamic industrial environments where industrial systems must adapt to changing conditions, such as adjusting robotic movements on a manufacturing floor in real-time.

The integration of these AI technologies into the 5G IIoT-enabled industrial solution enables industries to not only process and analyze data at unprecedented scales but also to act upon the insights gained in a timely and effective manner. As IIoT industrial networks grow in complexity, the role of AI becomes ever more integral, driving the evolution of truly intelligent industrial ecosystems.

This paper presents a breakdown of the 5G IIoT industrial solution for the smart factory, smart industry, and Industry 4.0 revolution. The 5G IIoT industrial solution is based on the innovations heralded by the likes of the latest 3GPP Release 17, Release 18, and needed industrial demands and applications.

II. 5G IIoT

A. Message Queue Telemetry Protocol (MQTT)

5G IIoT devices[1] require a special application-layer protocol suitable for efficient data transfer to transmit and receive their data. The widely used application-layer protocol for IIoT devices is the Message Queue Telemetry Transport (MQTT).

MQTT is an application-layer transport protocol that runs on top of the TCP/IP protocol. MQTT is suitable for IIoT devices that have small memory and processing power, are battery-powered, or have scarce bandwidth. MQTT is a lightweight and simple messaging protocol that is best suited for IIoT modems and Machine Type Communication (MTC).

MQTT uses a publish/subscribe model to communicate between a transmitter and receiver. In this model, a one-to-many distribution is provided. A transmitting application or device does not need to know anything about the receiver, including the destination address. Similarly, the receiver does not need to know about the transmitter. The publish/subscribe model is illustrated in Figure 1. In the figure, a single IIoT industrial solution publishes its data to the server while other solutions may subscribe to the server to receive such data from the publisher.

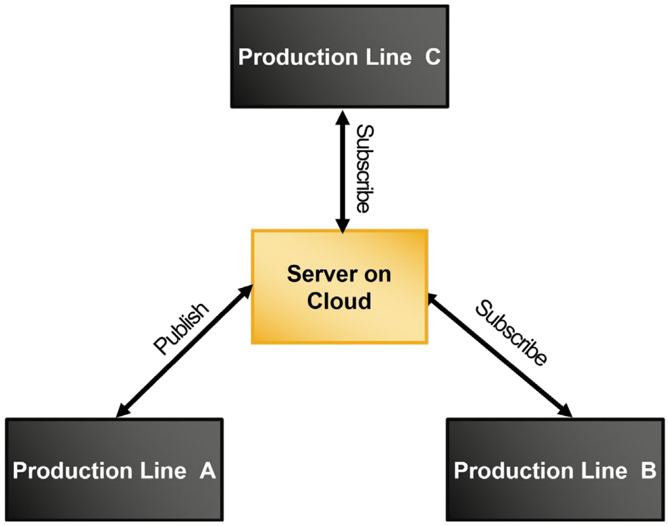

Fig. 1. 5G IIoT publish/subscribe model.

B. Amazon Web Services (AWS) Secure Cloud

Amazon Web Services (AWS) is the cloud offered by Amazon. Amazon cloud is available worldwide and in different geographical regions. AWS offers MQTT service. An MQTT server is hosted in AWS. An IIoT device, acting as an MQTT client, can communicate with the AWS using the publish/subscribe model.

The AWS service for IIoT is called AWS IoT and is available as a service offered by Amazon cloud. AWS allows you to connect a fleet of IIoT devices to the cloud. AWS supports MQTT in a manner designed to minimize the code footprint on IIoT devices, reduces network bandwidth requirements, provides secure and encrypted communication, and is commonly used for IIoT devices.

In the 5G IIoT industrial solution, a 5G IIoT modem, running MQTT, is used to connect to the cloud and fully monitors, controls, and configures the industry automation engine running on Lattice FPGA.

[1] IIoT device or modem are used interchangeably.

The solution connects to AWS by authenticating and providing end-to-end encryption. The solution exchanges data with the cloud after performing authentication. Data is encrypted in both directions. In the cloud, AI/ML engines can filter, transform, and act upon data coming from the IIoT devices on the fly. Data on the cloud can be processed further for visualization.

Figure 2 shows the setup of the 5G IIoT industrial solution. The industrial solution, through the IIoT modem, is connected to a mobile operator network (e.g., AT&T network) and then to the AWS cloud. The cellular IIoT modem communicates with the cellular base station (eNodeB) in the mobile operator network and connects using an Access Point Name (APN) in the mobile operator core network. The APN acts as a router that connects the modem to the cloud.

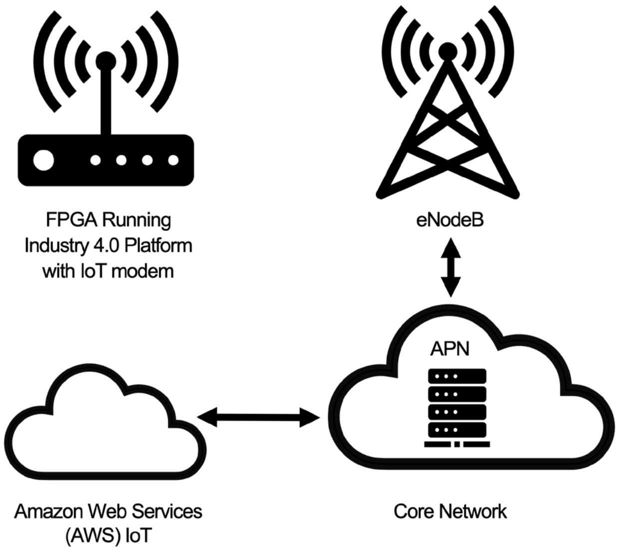

Fig. 2. 5G IIoT industrial solution connected to mobile network and cloud.

Figure 3 shows the industrial solution when using MQTT in a smart factory. It controls production, assembly, or manufacturing lines. It collects insight and uploads the data to an MQTT server hosted on AWS. Data processing and insights are provided on a real-time dashboard where a supervisor or user can interpret the data, generate usage statistics, or control production lines remotely.

C. Data Serialization

Serialization (or deserialization) is the process of translating a data structure or object into a text that is compact and small in size and payload. The compact requirement stems from the fact that IIoT devices are constrained in memory and processing power and run on a battery. Moreover, communication between the IIoT modem and mobile network is limited in data rate and over-the-air bandwidth. For all these reasons, data communication between the IIoT modem and mobile operator network has to use a compact form of data exchange.

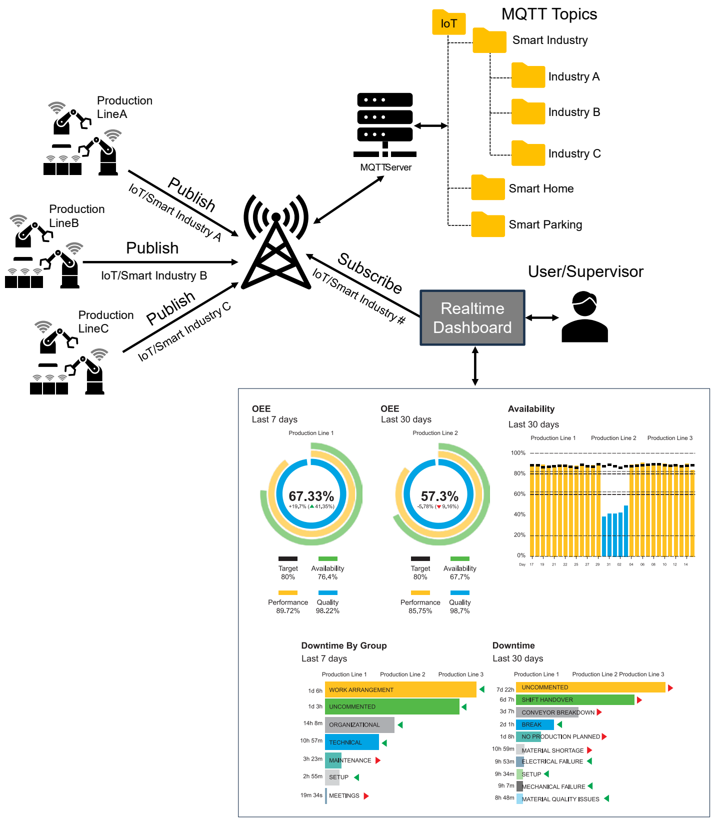

Fig. 3. IIoT industrial solution dashboard. The dashboard shows an MQTT server connected with MQTT clients at multiple production lines. Cloud application on AWS is used as a dashboard to view and collect statistics from production lines.

Concise Binary Object Representation (CBOR) format is a recent binary schema-less data serialization protocol. It introduces several novel concepts such as extremely small and compact message size, support for binary data, and explicit streaming support. IIoT devices transmitting a CBOR message, transmit a binary blob which is compact and consumes a small over-the-air communication bandwidth. CBOR also supports streaming which means that the CBOR encoder and decoder can start encoding or decoding the transmitted or received data without knowing the actual size of the data or the payload yet.

Data between the IIoT industrial solution and the cloud is coded in CBOR format. Data includes commands such as to start and stop a motor, measure the speed and number of running motors, do predictive maintenance, collect motor statistics and measurements, or collect reports about an assembly line.

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D. AT Commands

Attention commands (formally known as "AT" commands) are instructions used to configure, control, and interface with the 5G IIoT modem. In AT commands, every command line starts with "AT" or "at." The starting AT is a prefix that precedes the command. For example, AT+CSQ queries the IIoT modem for the wireless signal strength. The IIoT industrial solution can communicate with the IIoT modem to control, configure, transmit, and receive data through AT commands.

III. FPGA And Software Architecture

Lattice's 5G IIoT industrial solution enables industrial automation, smart factory, and smart industry that includes support for predictive maintenance, real-time motor control, security, AI/ML engine, and cloud edge computing. The solution includes motor control IP implemented in RTL. The solution enables the user to remotely monitor, control, and/or configure multiple motors connected to node systems that are chained using Ethernet cable. The Main System (MS) synchronizes the operations of the Node System (NS). The Node System collects the motor data and sends it over Ethernet to the Main System. The Main System takes this data and processes it by applying the trained neural network implemented using RISC-V and CNN co-processor for predictive maintenance. The entire solution uses the 5G IIoT modem to communicate with the cloud. The solution injects data into the cloud edge where it is used by a central application running on the cloud. The application has a Graphical User Interface (GUI) that allows a user to fully monitor, configure, and control one or more industrial solutions located in different geographical locations or different assembly and production factories.

The cloud application consumes data stored on the cloud, displays the status of the motor, and alerts the user when the motor requires maintenance. The application communicates with the solution using MQTT protocol and exchanges commands and responses between the industrial solution and the cloud. The commands and responses are used to manage the industrial solution and control motors. The entire system with all sub-components is shown in Figure 4.

Figure 4 shows the overall architecture of the 5G IIoT industrial solution. It consists of one Main System with a 5G IIoT modem and multiple Node Systems. The application GUI is running on the cloud, exchanges commands and responses with the MS, and receives motor maintenance data from the system for AI processing. The MS propagates the commands to NS for motor control and gathers maintenance data from NS.

The Lattice CertusPro™-NX FPGA main board supports (RISC-V) CPU IP running FreeRTOS [6] and has the UART interface that communicates with the IIoT modem. The modem is responsible for two-way communication with the cloud. The FPGA runs different software components to process AT commands and exchanges commands/responses from/to the cloud. Triple Speed Ethernet (TSE) MAC, UDP Stack, LPDDR4, and Multiport Extension IPs are used to enable data exchange between RISC-V and an external host PC.

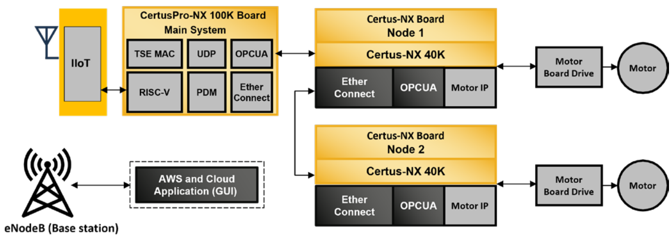

Fig. 4. 5G IIoT industrial solution connected to the cloud.

The NS uses Lattice Certus™-NX FPGA versa board and is used for controlling the motors. The NS acts to control the Motor IP and gets its status as commanded by the MS. It communicates with the MS by receiving commands through EtherConnect. It performs the actions and responds to the MS with interrupts as acknowledgment for the tasks executed. The physical connection between the MS and NS is implemented using Ethernet Cat-5 cables. The physical connection between the first Node System and subsequent Node System(s) also uses Ethernet Cat-5 cables, in a daisy-chain fashion for both chains.

Open Platform Compute Unified Architecture (OPCUA) is a cross-platform open-source data exchange standard developed by the OPC Foundation. It is frequently used in industrial applications for machine-to-machine communication. The MS and NS communicate using the OPCUA protocol (client-server mode) [7].

A. 5G IIoT Modem Architecture

The 5G IIoT modem architecture is shown in Figure 5. It runs ThreadX RTOS on an ARM Cortex CPU. In the kernel space, the following protocol stacks are running inside the modem: TCP/IP, TLS, MQTT, 3GPP IIoT, and baseband and RF. The modem has its serial UART hardware and software that are used to interface with MS. AT commands and control and data messages are exchanged between the MS and the IIoT modem using the UART interface. In addition, the IIoT modem has USB 2.0, I2C, and SPI interfaces which can be used to exchange AT commands, data, and debug messages.

The 5G IIoT modem has an integrated Global Navigation Satellite System (GNSS) that supports Gen8C-Lite of Qualcomm (GPS, GLONASS, BeiDou/Compass, Galileo, and QZSS) and supports gpsOneXTRA Assistance technology [8]. The modem supports standard NMEA-0183 protocol and outputs NMEA sentences at 1Hz data update rate. GNSS is used to build geofencing applications on the cloud. AT commands are used to query the IIoT modem for the current geolocation and read NMEA sentences.

On the modem, the user can build application code, using embedded C/C++ programming, which runs directly on the modem. The application code can utilize a library of APIs that provide access to the different modem software and hardware modules. Pre-existing application codes, running on the IIoT modem, include an AT command interpreter and a communicator with the RISC-V UART on the Main System.

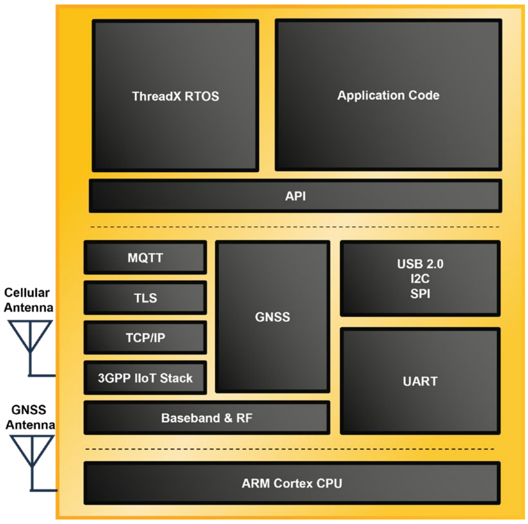

Fig. 5. 5G IIoT modem architecture.

B. *Communication with Cloud*

MQTT is the protocol used to exchange data between the Main System and the cloud through the 5G IIoT modem. The IIoT modem runs the MQTT client, uses the publish/subscribe capability of the MQTT to subscribe to an MQTT topic on the cloud, and receives commands or sends responses to the cloud application.

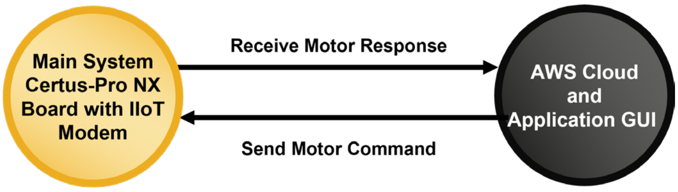

Fig. 6. Command/Response exchange between the MS and cloud.

C. *Main System to Node System*

The Main System acts as the central hub for the system, receiving commands from the cloud application and sending responses back to the cloud application. The Main System interprets these commands, routes the relevant ones to the appropriate node, and responds to the cloud application through responses.

The Node System is responsible for performing operations based on the requests received from the Main System and sending the results back to the Main System for further processing. The Main System receives a command from the cloud, sends a request to the node, and receives an NS response, and then MS sends a response back to the cloud. This is illustrated in Figure 7.

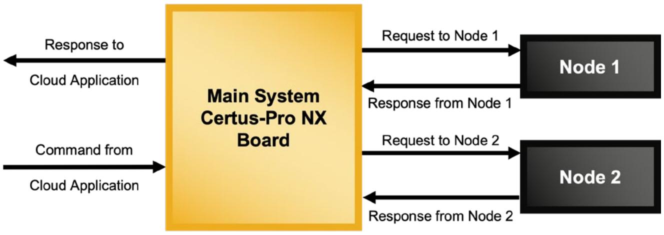

Fig. 7. Command/Response exchange between the MS and cloud and Request/response between MS and NS.

D. *Main System CertusPro-NX FPGA Card*

The FPGA solution for Lattice's 5G IIoT industrial solution is designed to fully monitor and control motors. The CertusPro-NX card features the CertusPro-NX 100K FPGA, which is built on Lattice Nexus™ FPGA platform using low-power 28 nm FD-SOI technology. This FPGA device is able to support a wide range of industry standards such as MIPI, Gigabit Ethernet, 10 GbE, LPDDR4, and PCIe (Gen3). The CertusPro-NX FPGA-based solution enables 5G IIoT modem communication and industrial automation. The card supports the following:

- On-board Boot Flash - Provides 128 Mb Serial Peripheral Interface (SPI) Flash, with Quad read feature.
- Two Gigabit Ethernet ports for ethernet connectivity.
- On-board FT2232H – A built-in download controller for programming the CertusPro-NX device that uses a Dual High-Speed USB to Multipurpose UART/FIFO IC FT2232H to convert USB to JTAG.
- Control Buses – Support various configuration and communication buses such as I2C, UART, and SPI.

In addition, the card supports the following features:

- PCIe x4 Gen3 support for Endpoint and Root Port configuration.
- 2xSFP for 10G Ethernet.
- 2xSERDES channels with SMA.
- USB-B connection for device programming and Inter-Integrated Circuit Bus (I2C) utility.
- 7-Segment display, eight input DIP switches, four push buttons, and 24 status LEDs for customer purposes.

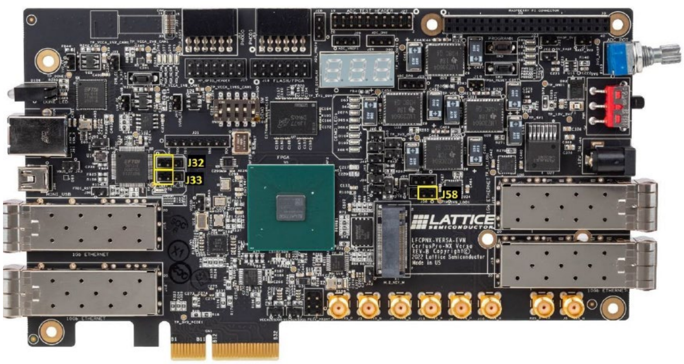

Fig. 8. Lattice CertusPro-NX card for the Main System.

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E. Main System to Host PC OPCUA

The Lattice's 5G IIoT industrial solution uses OPCUA as a data exchange standard for communication between an external PC, running Host GUI, and the Main System FPGA board. The use of Host GUI is to enable control and monitor status of the local industrial solution which can also be accomplished by using the cloud application.

OPCUA is frequently used in IIoT settings. The Host GUI uses the MQTT to send and receive data from the Main System over OPCUA using the publish/subscribe model [7]. The host GUI is connected to the Main System through Gigabit Ethernet cable over SFP. Similar to the cloud application GUI, the host GUI can be used to control the motor, update motor parameters, and control the speed and directions of all the motors.

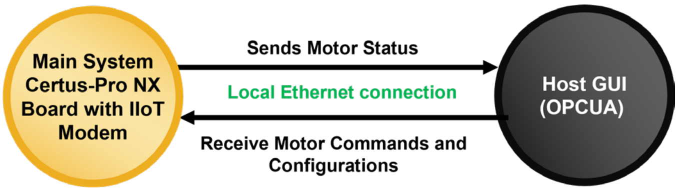

Fig. 9. Host GUI, running OPCUA, connected to the Main System.

F. Main System Firmware

The USB port on the FPGA card is used to flash the firmware to the card as shown in Figure 10. The FPGA card has a built-in download controller for programming the CertusPro-NX card. It uses an FT2232H Future Technology Devices International (FTDI) part to convert USB to JTAG. The USB is connected to a PC with the Lattice Radiant Programmer tool installed and the latter is used to flash and download firmware to the card.

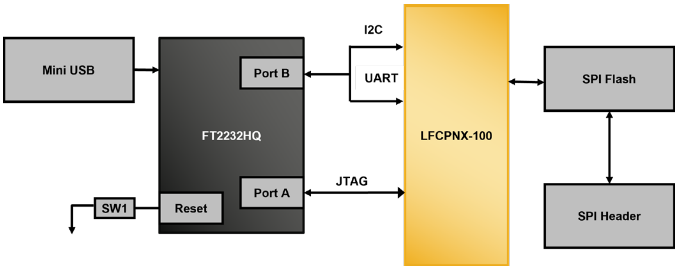

Fig. 10. Lattice CertusPro-NX Main System serial interface.

IV. Industrial Solution User Application

The user interface is running on the cloud for users to control, monitor, and configure the motor behavior remotely. The user interface allows to update motor parameters, control the speed and directions of all the motors, and collect reports and measurements about motors. The following GUI screenshots show a cloud application that sets the target RPM for a motor or views the motor status.

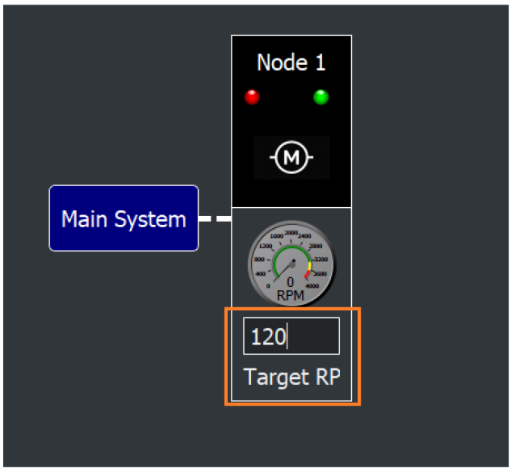

Fig. 11. Application GUI to set the motor RPM.

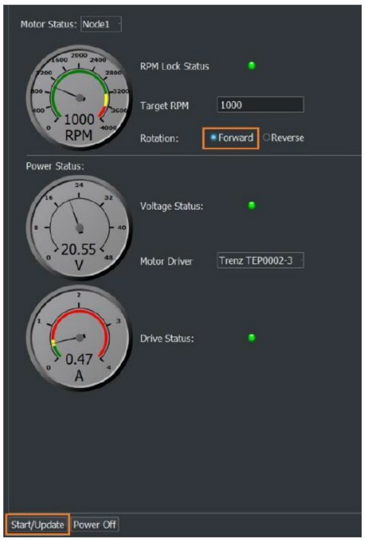

Fig. 12. Application GUI to view the motor status.

For more capabilities and features of the Lattice industrial automation solution, please visit Lattice's website [9].

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