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Design of a Low-cost IoT Enabler System

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***Abstract*—IoT devices are dominating the technology market in areas such as home, industry automation, and entertainment, among others. Hardware companies are offering multiple options for IoT devices that include different types of sensors such as temperature, humidity, atmospheric pressure, air quality, distance, speed, acceleration, and position. Some IoT devices also include actuators such as include electric DC motors, stepper motors, servo motors, and hydraulic or pneumatic actuators such as valves, pistons, and solenoids. These IoT devices are the base for enabling remote manipulation or control of equipment, monitoring of goods in warehouses, or product transportation via ground, air, or water. Companies called IoT enablers provide the networking and communications infrastructure to support the operation of these devices. They rely on the use of IoT communication protocols such as HTTP/HTTPS, WebSockets, Constrained Application Protocol (CoAP), and MQTT. Some of these protocols provide high throughput, lightweight messaging between IoT nodes and servers, security, reliability, and interoperability. This paper presents the architecture and design considerations of a low-cost, modular, and customizable IoT system. This paper also presents a market analysis of IoT devices and IoT cloud service providers.**

***Index Terms*—Internet of Things, Low-cost devices, Cloud Computing, Edge Computing, MQTT.**

I. Introduction

In today's world, a great demand exists for device automation, remote control, and monitoring. Facilitating the implementation of smart systems is one of the goals of modern engineering. This includes the development of innovative Internet of Things (IoT) solutions designed to transform the workplace, production plants, warehouses, and living spaces into smart places.

Currently, companies such as Intel, ARM, Qualcomm, and Silicon Labs have started offering generic System-on-a-Chip (SoC) solutions to develop IoT systems. In addition, Particle, Sierra Wireless, and Telit are developing modules and connectivity services for IoT systems [1], [2]. These devices require specific technical knowledge to develop IoT nodes using their platforms. The required knowledge includes embedded system development skills, as well as programming and networking knowledge to create a functional IoT system.

Providers of IoT cloud platforms such as Amazon, Google, Microsoft, and Telit, among others, offer cloud support for IoT devices, facilitating communication and data visualization [1], [2].

With the use of user-friendly software interfaces and advanced technology in electronic components, telecommunications, and networking, it is possible to offer customers a solution that includes an IoT cloud service together with customizable IoT hardware enabler devices that can be integrated into multiple artifacts to effortlessly enable monitoring and control features.

This paper presents the architecture and design considerations of a low-cost, modular, and customizable IoT system. The remainder of the paper is organized as follows. Section II presents a market analysis of IoT devices and IoT cloud service providers. Section III presents a proposal for an integrated hardware solution that can be customized with different sensors and processing capabilities. In Section IV the architecture of the system is presented, including IoT communications, device management, and reporting. Finally, Section V presents the discussion and future work.

II. Market Context and Existent Products

The market for IoT devices and services has been growing during the last decade to a current market value in 2024 of around US$400 billion [3]. It is expected that IoT will continue at its current growth rate of 30% per year. In terms of devices connected to the Internet, it has been reported that more than 18 billion devices will be connected by the end of 2024 [4].

The three main fields in which IoT systems have the largest inclusion are the consumer field, the electricity, gas, steam, and A/C industries, and retail and wholesale. The consumer industry, in the smart home arena (monitoring and control of temperature and lights) has more than 10 billion devices connected. The field composed of electricity, gas, steam, and A/C has more than 1.7 billion IoT devices. The third, retail and wholesale, has more than 1.2 billion devices [4]. Other fields where IoT systems have been included are agriculture, manufacturing, mining, water supply and waste management, construction, transportation, storage, government, and health, among others, as shown in Figure 1.

The commercial and consumer field is the most mature category with several manufacturers and suppliers of smart devices such as wearables, cameras, voice assistants, thermostats, and "smart" everything; smart TVs that have access to the favorite TV shows and movies of the owners, smart refrigerators that can alert the customer when the food is going to expire and even order the groceries, and smart washing machines that can be started remotely, among others. However, the enabling

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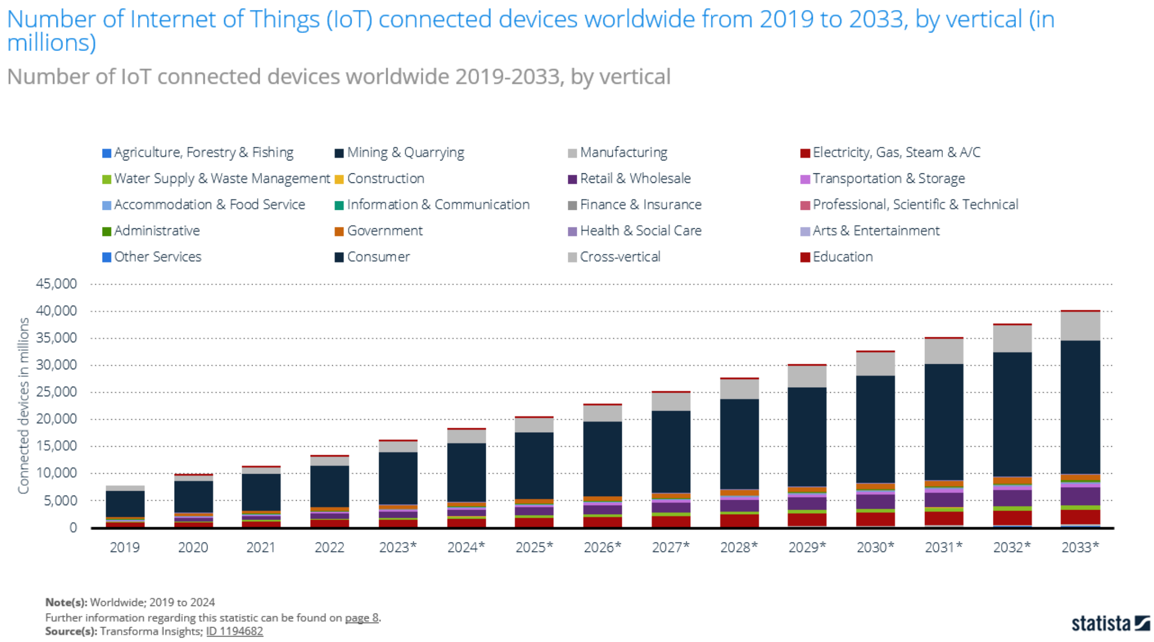

Fig. 1. Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2033, by vertical [4]

platforms and cloud computing for collecting, storing, and data processing, are still in the process of development and better inclusion [6].

A. Existing Products

1) Intel: Intel develops processors and software that help in intelligent computation, now including artificial intelligence (AI) and powerful cloud computing resources. Their solutions also include computer vision, which enables the addition of video to IoT systems. Computer vision adds the possibility of better analytics and decision-making according to the environment [7].

2) ARM: ARM is working in conjunction with the Matter protocol to enable the deployment of secure endpoint-to-cloud solutions. ARM develops Mali graphics processors for Smart TVs, and Cortex-A processors for industrial autonomous systems and safety-critical applications such as robotics [8].

3) Qualcomm: Qualcomm produces processors that combine robust computing optimized with AI and powerful video and graphics processing units. They also work with software providers to offer a complete bundle of resources to enable easy-to-deploy and reliable IoT systems [9].

4) Silicon Labs: Silicon Labs offers hardware (microcontrollers, sensors, and power management) and software that can interact with different communication protocols (Wi-Fi, Z-wave, Thread, and Zigbee) and has solutions for secure key storage, secure boot, and secure update. Their solutions can be implemented in smart homes (door locks, appliances, lighting, cameras), smart retail (electronic shelf labels, loss prevention, direction finding), industrial IoT (factory automation, process automation, human-machine interface, asset tracking, access control), and smart cities (metering, street lighting, energy production and storage, agriculture and smart buildings) [10].

5) Seeed Studio: Seeed Studio provides IoT hardware products and technical support to companies that want to implement IoT systems. Seeed Studio produces, does research in hardware for IoT and smart sensing, and also sells hardware from other companies, such as Raspberry Pi, Arduino, and NVIDIA among others [11].

6) Particle: Particle provides an IoT Platform-as-a-Service (PaaS) for the companies. The platform is composed of software to develop and manage applications, cloud connectivity, and security through encryption. They support the integration with Single-board computers, System-on-Module, and development boards, for the industry and consumers [12].

7) Sierra Wireless: Sierra Wireless offers services for IoT connectivity through a SIM that gives access to around 600 networks in 190 countries, device and data management to monitor, control, and update modules, devices, and data to avoid downtime and support for IoT deployment to companies and customers [13].

8) Telit: Telit Cinterion offers IoT modules, cellular data plans, integration with AI, and custom solutions to different companies. The smart modules allow developers to design and implement their own IoT systems and applications having Wi-Fi, Bluetooth, and cellular connectivity [14].

9) Amazon: Amazon AWS provides services to collect, store, and analyze data from IoT systems. Amazon also offers an operating system (FreeRTOS) for microcontrollers, customizable applications, video processing, and a series of hardware devices through partner companies. Amazon data analytics allow customers to use AI and tools like MATLAB and Octave to process and report the data collected from the IoT system [15].

10) Google: Google with the Google Cloud Platform supplies a suite of cloud computing services such as computing, data storage, data analytics, AI integration, and development tools with Apps and Admin Application Programming Interfaces (APIs) [16].

11) Microsoft: Microsoft's Azure offers a suite of services for IoT applications and systems. These services include Azure IoT Hub for managing device connections, Azure IoT Edge for running cloud intelligence on edge devices, and Azure IoT Central for building and managing IoT solutions with a user-friendly interface. [17].

Table I presents different IoT hardware manufacturers, customizable IoT system vendors, and IoT Cloud providers.

TABLE I
COMPARISON OF COMPANIES' SERVICES IN IOT

Company	Hardware	Software	Cloud Service	Communication	Security	Price
Intel	processors	AI integration	Intel® Tiber™ AI Cloud and Google Cloud	Not specified	Hardware isolation, compression and encryption	The price for the hardware and service is available by quote
ARM	processors	AI integration and open source software	Not specified	Not specified	Hardware isolation, security APIs	The price for the hardware and service is available by quote
Qualcomm	processors	AI integration	Not specified	Wi-Fi and 5G integration	Not specified	The price for the hardware and service is available by quote
Silicon Labs	microcontrollers and sensors	software development kit (SDK)	Not specified	compatibility with Wi-Fi, Z-wave Thread, and Zigbee	Secure key storage, secure boot, and secure update	The price for the hardware and service is available by quote
Seeed Studio	microcontrollers, sensors, and accessories/actuators	AI integration	Not specified	LoRa, BLE, and Wi-Fi	Not specified	Hardware components prices depend on the manufacturer. The price for the service is available by quote
Particle	Not specified	Device firmware and custom applications	Partners with Amazon AWS, Google Cloud, and Azure	Wi-Fi, satellite, cellular and LoRAWAN	Encryption	Basic (For simple IoT products with limited data automation) US$299 per block* per month, Plus (For IoT products with powerful data automation) US$599 per block per month and For professional and enterprise is by quote
Sierra Wireless	Not specified	Device and data management	Not specified	Cellular	Encryption	US$2.5 per SIM and price for complete service is available by quote
Telit	Smart modules development kits	AI integration and APIs	Telit deviceWISE Cloud an AWS hosted service	Cellular, Bluetooth, and Wi-Fi	Encryption, VPN, and Security rules for access	Cellular connectivity starting at US$0.89 per month
Amazon	Through third parties	FreeRTOS OS, IoT applications and AI integration	AWS	Not specified	Access control, encryption, and SSL/TLS certificates	The price for the services is available by quote
Google	Not specified	AI integration, Apps APIs and Admin APIs	Google Cloud	Not specified	Access control through rules and credentials, TLS encryption	The price for the services is available by quote
Microsoft	Not specified	AI integration, databases (SQL)	Azure	Not specified	Microsoft defender	Pricing depends on tier needed (range between US$10 and US$2,500 per month)

*a block in Particle, defines the number of devices and data operations included in the price.

B. Security Concerns

With this growth of IoT devices and systems, some concerns arise in the security side of the devices and systems, due to the inherent use, and sharing of personal data of millions of users that rely on these services.

With the billions of devices that are now connected in cyberspace, attackers have many opportunities to exploit these systems. Most IoT system vendors do not consider implementing security mechanisms in the devices that they produce, whether it be due to restrictions in cost or limitations in available resources.

Securing IoT systems is becoming a critical task; statistics show that more than 50% of the IoT traffic originates in the manufacturing and retail sectors. Every year, the malware attacks on IoT devices and servers increase by 400% [5].

Given the vast number of internet-connected devices, attackers find IoT applications appealing for exploiting security vulnerabilities. Manufacturers of IoT devices often prioritize cost reduction, targeting a broad market with inexpensive products. Consequently, incorporating security measures becomes a costly consideration that is deemed not worth the investment.

III. Proposal of Hardware Platform for Customizable IoT Enabler Devices

The proposed model includes the creation of a generic IoT node that can be customized by the end user with sensors and actuators and then attached to an existing object to turn it into a smart object.

The node will be capable of WiFi communication to send and receive data to the cloud system. It will have a microcontroller to run both the IoT cloud connection and the data collection/actuation capability. It will be powered by either a USB-C connector or a battery. The battery will be available for purchase separately and added by the end user. The biggest addition/difference of this node compared with other IoT devices will be a set of connectors that the end user can use to plug in sensors and actuators (subnodes).

Each node will have a universally unique identification along with the ability to encrypt and cryptographically sign each message allowing for end-to-end encryption and authentication of all the data.

The processor will automatically recognize a subnode plugged into a connector and send the new capability to the IoT cloud where the user can name it and map it according to what it is attached to and intended to do. Each subnode will have an ID identifying its capabilities.

Each node will have a USB-C connector on one side and subnode connectors every side including the top but not the bottom. This will allow it to sit flat on a surface and have sensors extend in whichever direction is most useful for that particular application. There will be a subnode connector on the same side as the USB connector to allow for a single entry/departure of wiring which is required in some applications.

Each node will also have multi-color LEDs labeled to give current status. This will allow users to see at a glance whether a node is working. They will have the option to turn the LEDs off for power saving or to use the LEDs in other ways that help their particular use case. Each node will also have two buttons that can be used to change the status of the node (turn on/off or to standby) or can be used as an input to the IoT system.

The goal is for each node to cost US$25 and each subnode to cost US$10. The subnodes will vary in price depending on the capability. Subnodes with more expensive parts (i.e. AI enabled IMU vs a temperature sensor) will cost around US$15. The attachable battery pack would cost US$15 and allow the node to run for a week in high data rate modes and a month in mid-level data rates. The battery will be charged when the node USB connector is plugged into power. The battery pack will have a button that will display the current amount of charge using 4 blue LEDs on the battery pack. The battery pack will connect with power, ground, and bidirectional communication so that the node will become a "smart" battery pack. It will be able to tell the voltage, how much power has been used from the battery, and what percentage of the charge is left. Future plans include having different sizes of batteries and possibly a solar power option.

The initial types of sensors and actuators are shown in Table II.

TABLE II
INITIAL SUBNODE SENSORS AND ACTUATORS

Subnode Type	Data Frequency/Period	Price
Ambient temperature	60 s	$7.99
Temperature & Humidity	60 s	$9.99
PIR	15 s	$9.99
Shock/Vibration	5 s	$9.99
Orientation	15 s	$9.99
Movement	5 s	$9.99
AI IMU	5 s	$14.99
Haptic (vibration) motor	N/A	$9.99
Button	On Change	$7.99
Multi-color LED	N/A	$7.99
Light intensity	30 s	$7.99
Light color	15 s	$9.99
Servo controller	N/A	$9.99
Battery	30 s	$14.99
Touch sensor	On Change	$9.99
Sound sensor	1 s	$9.99

The proposed IoT node contains a Wi-Fi-capable microcontroller, a power management module with support for a lithium polymer (LiPo) battery, subnode connectors for the attachment of different sensors, USB-C port connection, push buttons, user and status LED's. Figure 2 presents the physical setup of the IoT node.

The subnode connector will supply power, bidirectional communication, and a signaling line. The communication will be I2C between the node and subnodes.

Each subnode will have three levels of configuration:

1) Default
2) Wizard setup for more details
3) Fully detailed

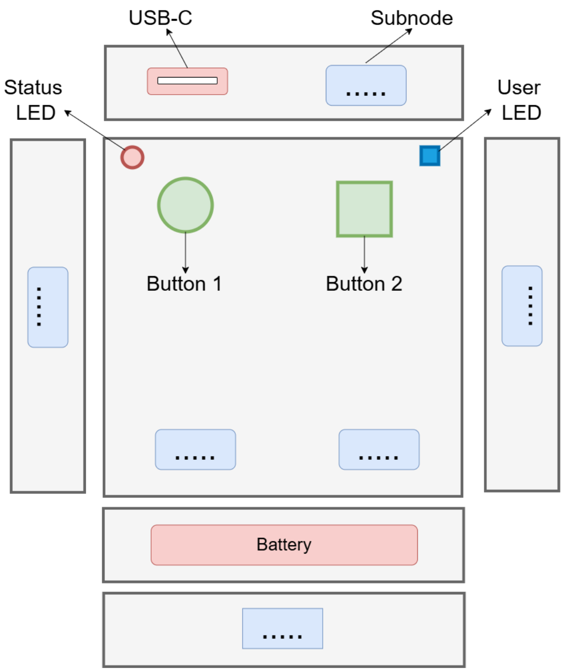

Fig. 2. Proposed node physical setup

The default mode will automatically start recording data to the cloud for sensors at a preset rate determined by the manufacturer. A wizard setup will allow the user to make changes to the how the subnode interacts but in a limited way so as to not be as confusing. The fully detailed setup will let the user to change as many parameters as the system can allow.

Figure 3 shows an example of a test node assembled from off-the-shelf components as a proof of concept. The demo node has two buttons, a joystick, 4 rotary encoder knobs, a pressure sensor, light sensor, a buzzer for output, and an alphanumeric 4-digit display. The goal is to have several nodes like this to test data collection and interfacing to the cloud. The microcontroller can communicate in WiFi, BLE, and 802.15.4 as needed. It also has a cryptographic accelerator onboard.

IV. Software and Cloud Architecture

The communication of the IoT nodes to the cloud server happens directly from the IoT node to the server through Wi-Fi, 4G-LTE or 5G, or through ZigBee, or using Bluetooth BLE between the IoT nodes and an edge internet-capable device. The proposed IoT system will supported by cloud services that allow the monitoring and control of different IoT devices. The architecture will provide the user with an interface to add 'things' IoT nodes to their account, for each of the things the user can configure the sensing parameters such as frequency of sensing, the sensing thresholds, the deferred sensing, the scheduling among others, and customize the data reports, as well as, generation of smart actions based on AI models that can learn from the users and device behaviors.

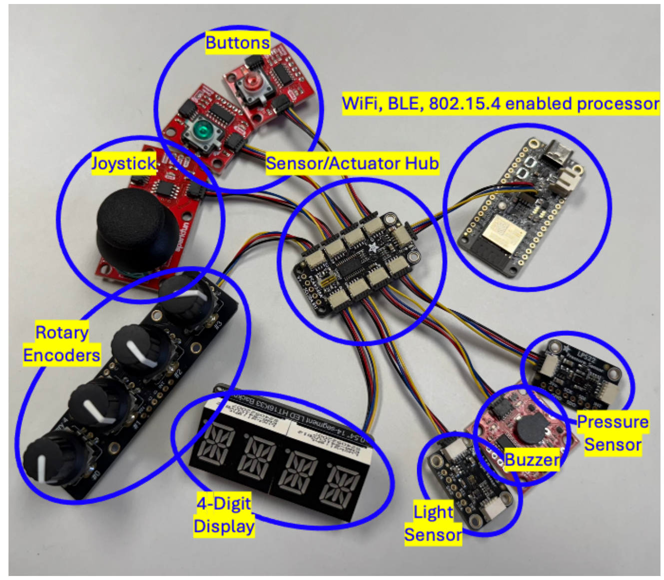

Fig. 3. Example of a test node built from off-the-shelf parts

A. Cloud System Requirements

Table III presents the list of categorized high-level requirements for the IoT Cloud Management System.

TABLE III
High-Level IoT Management Cloud System Requirements

Identification	Definition
HL-101	The system shall support the connection of thousands of users
HL-102	The system shall support the connection of millions of IoT devices
HL-103	The system shall allow the user to easily connect a new IoT node
HL-104	The system shall allow the user to easily disconnect and de-register an existent IoT node
HL-105	The system shall allow the user to easily configure parameters of a new IoT node
HL-106	The system shall allow the user to easily modify the configuration of an existent IoT node
HL-107	The system shall only communicate with authorized IoT nodes from authorized connected users
HL-108	The system shall provide configurable report generation of IoT nodes activity
HL-109	The system shall allow the admin user to add other users with configurable levels of interaction with the system (monitor, reporter, account manager)
HL-110	The system shall allow the users to configure alerts based on nodes sensing values

The IoT Management Cloud System is implemented as a centralized server that provide access to the users Web interface, in this Cloud System users can access their IoT nodes space in which they can access monitoring, configuration, and reporting tools. This system is supported by a database used to

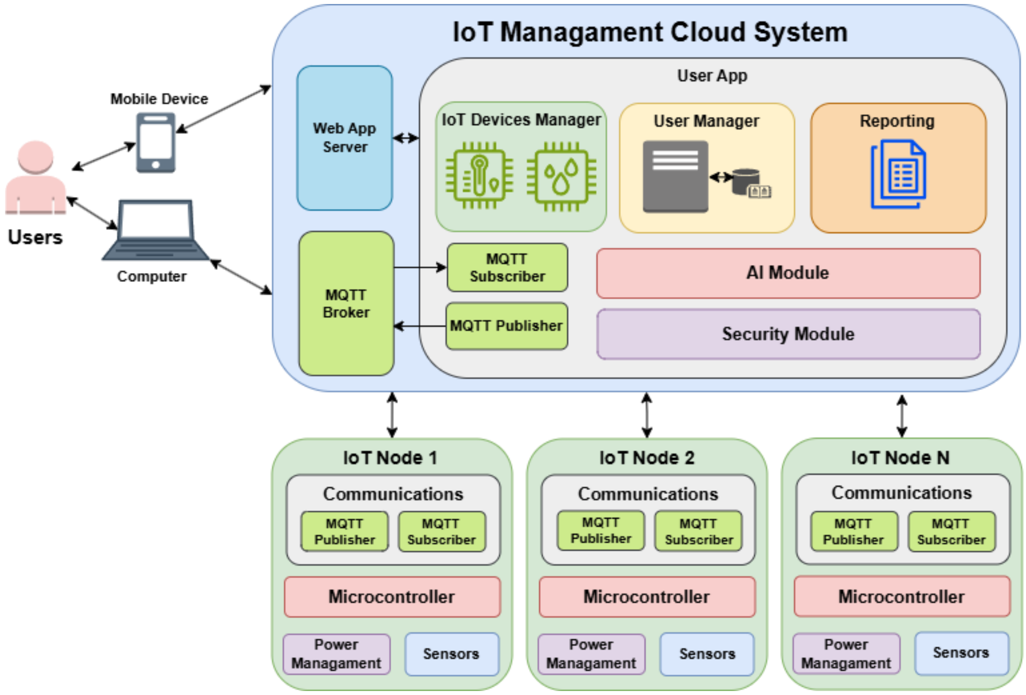

Fig. 4. Architecture of the Cloud-Based IoT System including IoT nodes and server communication modules

store users information, IoT nodes configuration, and historical data.

The server includes the communications module based on MQTT technology, for this an MQTT Broker is deployed and acts as the communications hub for the user's devices and the IoT nodes.

Figure 4 presents the architecture of the proposed Cloud-Based IoT System including IoT nodes and server communication modules.

V. Discussion and Future work

To validate the viability of the proposed product and service in the IoT market, a more in-depth analysis of specific market segments that would benefit from these offerings is necessary.

Additionally, conducting a detailed market and competitor analysis within these targeted segments is crucial to determining optimal pricing strategies for the IoT nodes and associated services. This analysis will also help in accurately assessing the potential return on investment (ROI).

Preliminary research indicates that there is no clear market leader offering a comparable solution—specifically, a generic IoT node integrated with a secure and user-friendly cloud service, positioning our product as a unique opportunity in the marketplace.

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