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Building IoT Systems - Challenges and Insights from a Pilot Case Study

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Abstract: ***Applications of the IoT are being continuously developed in various areas to create new businesses. In its typical form, an IoT application comprises a data-censoring device, a communication channel, data processing, and an end user application. In this paper, we investigate the different components of an IoT system and explore their related technological and implementation options. Using a case study of an automated bicycle-monitoring and navigation system in the northern part of Okinawa Island in Japan, we look at the challenges that building an operational IoT system according to the needs of the users entails. We examine various scenarios to select and implement different parts of the IoT system. Although there have been many advances in Internet accessibility and emerging IoT technologies, however, the ability to build and deploy an efficiently operating IoT system for a particular environment and requirements faces several challenges. We find that still there are challenges to deal with in practice; these challenges may involve the power supply, power consumption, operation cost, coverage, and the range of the connectivity, in addition to the ease of deployment. All of these factors should be considered when an IoT system is being built for specific application requirements.***

Keywords: Bicycletraffic, Edge computing, IoT, LPWA

1. Introduction

With the advent of digital communication, networks have expanded and opened up to include more connection points, allowing various devices or things to become part of the Internet. Starting in the early years of this millennium, the convergence of several technological advances began to enable the buildup of the Internet of Things (IoT). These technologies and advances include wireless and mobile connectivity, nanotechnology, and smart sensors [1].

These advances enabled millions of devices, such as automobiles, smoke detectors, motion detectors, watches, and webcams, to be connected to the Internet. Such an unpreceded level of connection not only enabled remote monitoring and control but also produced always-active devices that bring floods of data into the Internet. Moreover, this has opened the door for the development and deployment of many and a variety of IoT-based applications and systems that have spread throughout various domains of daily life. The innovative intervention of the IoT is helping to solve problems and improve services and applications in many situations and fields. These fields include the industrial, biomedical observation, agriculture, smart city, and environmental monitoring fields, to name a few [2] [3].

Advances in communication technologies and sensors had setup the foundations for development of IoT systems [4][5]. Furthermore, advances in cloud computing, and artificial intelligence have contributed significantly to advances in the development of efficient IoT systems [6] [7] [8] [9].

Wireless communication technologies are an essential part of the IoT. A diverse set of wireless technologies is currently available for different rural communication scenarios. Shafique et al.(2020) gave a summary of the use of Wi-Fi and 5G in the smart industry, home, health, and transportation fields, among others [10]. In [3], F. John Dian et.al had studied use of Cellular IoT in wearable devices in areas such as in health, sports and human safety, and reported its advantages. A good review on Radio frequency identification (RFID) and wireless sensors networks (WSNs) can be found in [11]. Bluetooth is suited to short-range, point-to-point, personal-device communication. Wi-Fi dominates short- and medium-range private networks that cover local facilities. Fixed wireless access can be extended using backhaul to remote locations. Bluetooth Low Energy and ZigBee are designed for short-range, low-energy applications, while LoraWAN and certain specialized communication networks for the Internet of Things (e.g., SigFox) are for low-throughput, long-range, low-energy applications. Cellular and satellite networks, due to their accessibility, are the de facto options for Internet in remote regions, but they have relatively high service costs. Private wireless networks, including long-range/mesh Wi-Fi and private 5G networks may be more competitive in the long run in some cases [12].

In an IoT environment, sensors and monitoring cameras are essential. Sensors play an important part in the automation of the generation of data in various IoT applications by detecting changes in physical things and acquiring data for the IoT system [5]. The authors in [5] presented various types of IoT sensors, such as proximity sensors, temperature sensors, humidity sensors, chemical sensors, position sensors, motion sensors, and pressure sensors. On the other hand, video surveillance cameras are widely used today to monitor and capture events.

In order to reduce the volume of data, artificial intelligence (AI) techniques and deep learning models are adopted in many IoT applications [8]. AI techniques bring efficiency, extended abilities, and introduce intelligent learning to be a key enabling technology of the IoT [9].

Data produced by IoT terminals, in addition to being massive in size, are not usually useful without analysis [7]. Edge computing brings computation and storage to the edge of the network, near the place where the data originate, and hence it provides a reduced network load and better system performance [13].

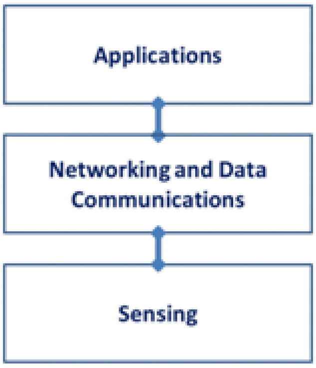

Figure 1: IoT system structure, as depicted in a 2014 publication [18]

Given the wide range of scenarios, there is no one-size-fits-all solution. At the present time, in most situations, case-by-case analyses are needed to choose and create the mixture of current and emerging technologies that will best balance the desired application trade-offs. Rural wireless access will play a vital role, especially for last-mile networks, allowing them to reach end-user devices and potentially making it possible to set up backhaul at a lower cost in regions with difficult terrain [14]. Furthermore, an abundance of applications is the main factor that will ensure stable rural broadband development. Given the close relationship between wireless technologies and IoT applications, advances in rural wireless research could accelerate application innovation and incubate profitable business models for outdoor and rural network deployment.

2. Research Motivation and Objectives

As part of funded research, we had been looking into the collection of data concerning the intensity of automobile and bicycle traffic in some of the streets and lanes in the Yanbaru area in the northern part of Okinawa Prefecture, Japan. We took the opportunity to investigate building and describing the components of an IoT-based smart system to make it easier to perform such a survey. In this study, we revise the structural components of a practical IoT system and consider the technological options that can be used to build such a system. We explore and analyze different application fields and scenarios and provide insight into building an IoT smart system with different orientations of communication modules and with AI-enabled object recognition for an automated bicycle traffic survey. The challenges that we faced while building the systems are discussed.

3. Literature Review

There have been various definitions of the IoT since its emergence about twenty years ago. One of the earliest definitions was stated by Kevin Ashton of MIT [15].His definition emphasized the connectivity of the physical world to the Internet via sensors. He stated that the IoT is a "system where the Internet is connected to the physical world via ubiquitous sensors." In its 2005 report, the International Telecommunications Union (ITU) defined the IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"[16]. This ITU definition focused on enabled services that were made possible by the IoT technologies and developments in digital space.

In its 2008 report, the US National Intelligence Council (NIC) included the "information technology devoted to increased connectivity of people and things, " or the Internet of Things, as one of the six disruptive civil technologies that would affect the power balance of the world over the next fifteen years, out to 2025 [17].

The IEEE, in its 2014 special report on the Internet of Things, described it as "a network of items -each embedded with sensors-which are connected to the Internet." In its earliest IoT architecture considerations, the IEEE report described the IoT as having the following three tiers: application, networking and data, and sensing [18], as in Fig.1.

The National Institute of Standards and Technology (NIST), in its 2020 glossary of the web publication, stated that connection and processing, as well as information exchange, are essential elements of the IoT. The NIST defined the IoT as "the network of devices that contain the hardware, software, firmware, and actuators which allow the devices to connect, interact, and freely exchange data and information" [19].

As being an immensely important part of the industry, the Internet Engineering Task Force (IETF) stated in 2022 that the IoT is a network of things, software, and connectivity that enables objects to exchange data with the manufacturer, operator, and/or other connected devices. The Internet of Things (IoT) is the network of physical objects or "things" that are embedded with electronics, software, sensors, actuators, and connectivity to enable objects to exchange data with the manufacturer, operator, and/or other connected devices [20].

As it evolved, the IoT was improved by then-cutting-edge technologies, such as wireless sensor networks (WSNs) and radio frequency identification (RFID), through the use of sensing devices with embedded intelligent processing capabilities that supported effective decision-making [21]. Wireless communication technology is one of the core enabling technologies that contributed greatly to the IoT. These technologies have different speeds and ranges. Fig. 2 shows different categories of such technologies.

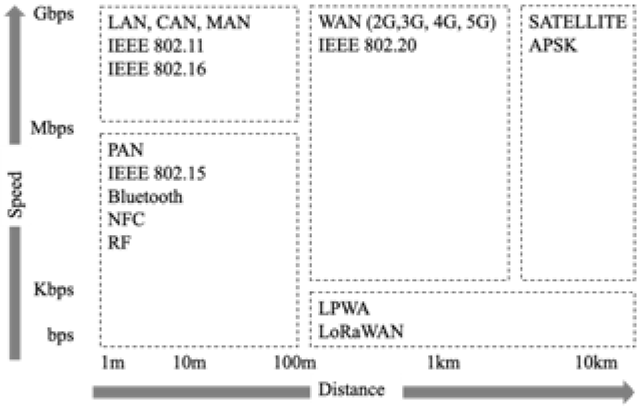

Figure 2: Wireless technologies grouped according to the coverage range and data rate.

While the world is becoming increasingly connected, newer and more numerous devices continue to appear in daily life, helping to make our homes, offices, and cities smarter and more convenient. Meanwhile, the connected devices generate an enormous amount of data every day, putting pressure on network infrastructures. Allowing the data to always travel between end devices and cloud data centers would exhaust bandwidth capacities and lead to high latency and lower performance [22][23]. Networking communications and computing capacity need to be put closer to the locations of data generation to alleviate the stress on the cloud and to ensure more efficient and intelligent ways of managing and processing data; this has given rise to edge computing. Edge computing is the storage, processing, and analysis of data closer to end devices that are at the "edge" of the network. The proximity to users and the low latency achieved as a result are key characteristics of this emerging edge computing technology [24].

3.1 IoT: Application, Market, and Stakeholders

At the present time, IoT applications cover almost every aspect of life, including the manufacturing, mobility and transportation, logistics, media, healthcare, home and buildings, retail, and energy domains (Fig.3) [18].

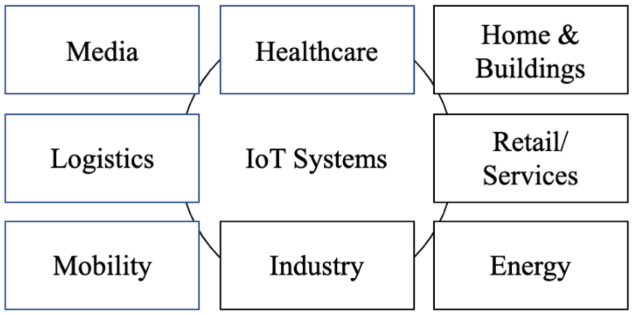

Figure 3: A variety of application fields and domains of IoT systems [18].

Last-mile or, synonymously, first-mile Internet connectivity is a term used to describe where the Internet reaches end users, and it includes the local access network, which consists of the local loop, central office, exchanges, and wireless masts. The access network reaches end-user devices, which are typically basic phones, smartphones, laptops, tablets, computers, and other Internet-enabled devices. For an IoT system, we use the term "IoT last mile" to refer to the connectivity available for an IoT gadget that allows it to reach the main Internet or middle-wide network.

Cellular wireless communication technology, along its evolution through 2G, 3G, 4G, and most recently 5G versions, has contributed much and provided a core connectivity option for deployment. This technology has become the key enabler for the ubiquitous deployment of IoT technology [10].

Instead of seeking higher data rates, a low-power wide-area network is meant for battery-powered sensor nodes and devices that require reliable communication for a prolonged period of time. Recently, the long range (LoRa) technique has become a popular choice for IoT-based solutions [11].

4. Pilot Case Study of an IoT System

4.1 IoT: Components of IoT System Revisited

In this study, we defined three technology domains for the IoT system, which are illustrated in Fig. 4.

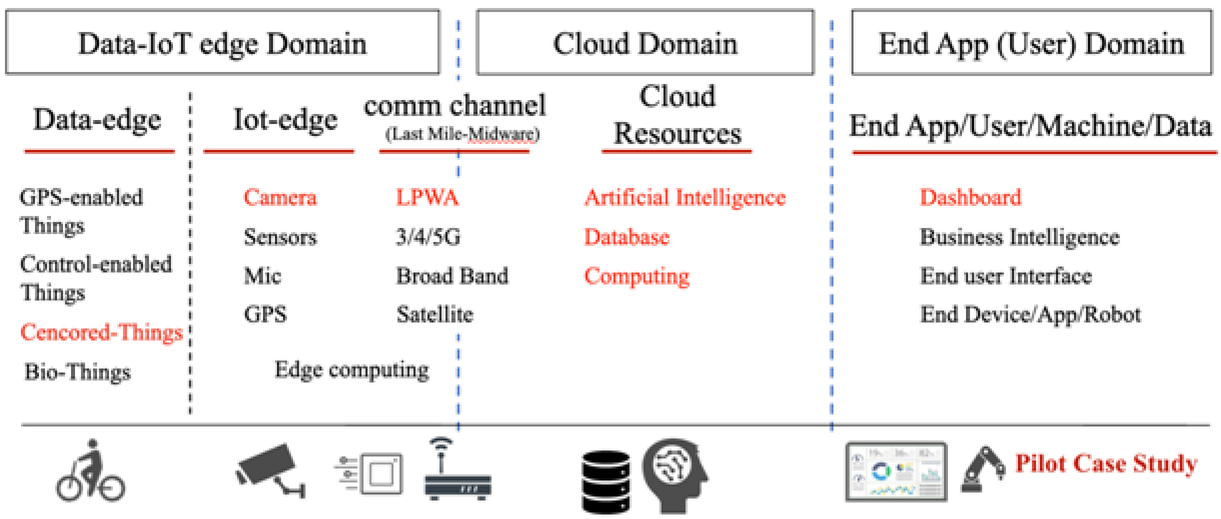

Figure 4: Structure of the IoT system

The first domain is the data-IoT domain, which has both the data edge and the IoT edge. Representative technologies in the data-edge area include GIS technology that uses GPS devices, recording technology (logs), identification technology that uses sensors, such as cameras, sensors, microphones, and GPS devices, to collect data directly from the environment, and technology for recording physical changes or biological reactions [25].

Technology in the IoT edge usually includes some edge-computing modules, in addition to communication technology. The communication technologies include cellular technologies, which include 2G, 3G, 4G, and 5G technologies, and low-power, long-running LPWAN and satellite communication technologies. Using these communication technologies, data collected from the data-IoT area is transferred to the cloud domain.

The second domain is the cloud domain, which uses Internet cloud resources. In the cloud, data are accumulated, filtered, and analyzed. AI algorithms and computational power can be used to extract data, information, and knowledge. Various cloud services offer a range of storage options, analyses, and gateways that make it possible to offer specific services to the end user and applications.

The third domain is the end app (user) domain. Raw data collected from the real world are repeatedly processed and combined, and they can be used by analysts for business intelligence systems such as dashboards or for other decision-support systems; they can also be supplied to end applications and devices. The results are not necessarily used only for business; they are also used in services that are useful to people in the world of mobility and in revolutions in the robot industry, or Industry 4.0.

In this study, we conduct empirical research by using different technology options to enable the building and deployment of the IoT application for a specific use in a specific region in Japan. A pilot study of an automated bicycle-monitoring and navigation system was built, tested, and evaluated.

4.2 IoT: Data-IoT Domain

In the data-IoT domain, which is the first area of the IoT system, as defined in this research, the components used included sensors, cameras, an edge computing platform device, and technologies for data communication between the data-IoT end and the cloud. We have built a module that is composed of three parts: a web camera, an edge processing unit, and a data communication device, as illustrated in Fig. 5.

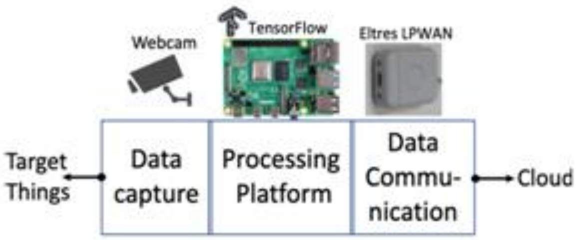

Figure 5: Components of the data-IoT module, built in this research

The module components are housed in one box and are called the IoT gadget. Fig. 6 shows the IoT gadget that was built and used in this research project.

4.2.1 One-Chip Computer: Raspberry PI

The Raspberry Pi is a low-cost, credit-card-sized computer. It can be plugged into a computer monitor, television, keyboard, mouse, flash drive, etc. The Raspberry Pi has built-in software such as Scratch, which enables users to program and design animations, games, or interesting videos. In addition, programmers can also develop a script or program using the Python language; it is the main core language in the Raspbian operating system [26]. The Raspberry Pi B+ is an evolution of the Raspberry Pi Model B. The Python language has been used in this work to write the script for client/server communication.

4.2.2 Web Camera

For the camera, instead of using a built-in camera, we used a USB-type web camera that can be connected to the Raspberry Pi via a USB cable, with night vision to enable it to function well under lower light conditions.

4.2.3 Tensor flow Lite on Raspberry PI

TensorFlow is a strong computational tool for machine learning models that was originally created by Google researchers, and it is one of the most popular machine learning tools, with rich libraries for the application of neural network models [27]. We used TensorFlow with the Python API and object detection library, and YOLO (You Look Only Once) is employed as a real-time object detection algorithm. The objects that can be detected using these methods are numerous; they include cars, bicycles, people, computers, and smartphones [28].

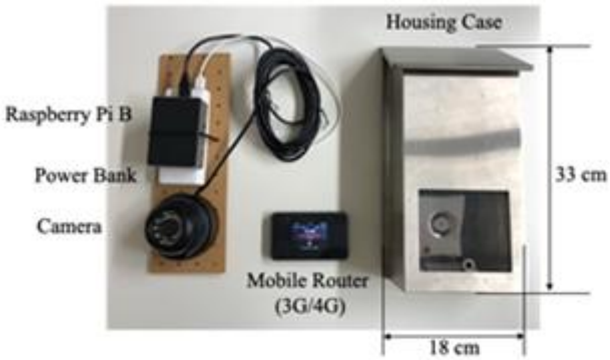

Figure 6: IoT gadget setup for moving object detection and data collection.

4.2.4 LPWAN (3G/4G/5G)

There are various technologies for Internet connectivity with a variety of coverage ranges, power levels, costs, and data transmission rates or speeds (Fig. 7). In this research, we examined both LPWA and broadband, in addition to local area Wi-Fi.

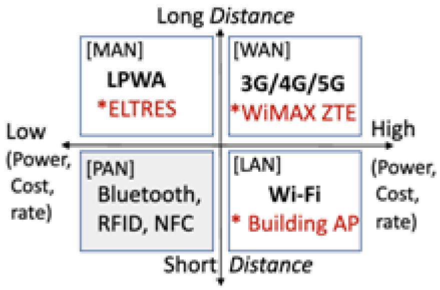

Figure 7: Technologies for Internet connectivity grouped according to their range, power, cost, and speed.

The power requirements for the IoT system and the cost of last-mile communication were critical for choices concerning last-mile connectivity to the cloud. The speed and bandwidth are other factors to consider at the design stage. In our experiment, we set up the system on campus using a local network connection. For the outdoors and the outskirts of the city, we tested two settings. For one setting, we used a WiMAX adapter with 3G, 4G, and 5G service. In the other scenario, an LPWA device was used.

LPWA is a specification that can send only a limited volume of data to the cloud; if the frequency of real-time detection is high, the transfer volume of the cloud transfer line will be a certain amount. Therefore, in this research, we utilized 4G and 5G. The IoT gadget was composed of the web camera, the Raspberry Pi box, and a power bank supply, in addition to a communication module that included a WiMAX mobile router (ZTE 802ZT) and an LPWA adapter (Sony ELTRES) with a mobile power bank unit.All of these components were contained in a steel mailbox as one IoT gadget, which was designed to be set outside and designed to withstand outdoor conditions (Fig. 6).

Figure 8: ELTRES, the LPWA wireless adapter.

ELTRES is a low-power WAN communication device developed by Sony (Fig. 8). According to a publication on the official site for ELTRES, it was designed for long-distance, low-power, high-speed mobile transmissions; it has low power consumption and follows European Telecommunications Standards Institute (ETSI) standards. ELTRES also has an embedded GPS chip[29].ELTRES comes with a payload of 128 bps. It can be set to send data every minute or at less frequent intervals. It uses the MQTSS protocol to send data to the cloud server.

4.3 Cloud Domain

Python and TensorFlow were installed on the Raspberry Pi OS, and each object detected using YOLO, a real-time object detection algorithm, was recorded in a CSV file with a timestamp and object name. Each file was saved on the main body of the Raspberry Pi and transferred to the cloud environment (Microsoft Azure and GitHub) via a mobile router (4G/5G) that was prepared for the experiment.

4.3.1 CLOUD RESOURCES

In the data transfer test to the cloud environment, we also tried transferring to Google Drive, but we used PostgreSQL, an open-source database management system. The cloud environment was built, along with the business intelligence dashboard. The transfer program used the Message Queuing Telemetry Transport (MQTT) protocol, a TCP/IP Pub/Sub data-delivery model.

4.4. End App (User) Domain

In this research, we used Hexagon M.AppEnterprise for business intelligence to visualize and display information based on the data acquired from the data-IoT edge domain and to enable easy data reference and analysis. M.App Enterprise is a cloud platform for creating geospatial apps [30]. M.App can plot map data by loading it from the accumulated database, and visualized data can be rearranged while data are selected interactively.

5. Using The Proposed IoT Gadget for Traffic Object Detection

The components of the whole process of data acquisition, processing, storage, and display are shown in Fig. 9. The IoT system assembled for the purpose of the research was tested on the detection of bicycle traffic in three locations in the Yanbaru area, which is in the northern part of Okinawa Prefecture. The northern part of Okinawa is a tourist area, where the local government has paved bicycle lanes in many areas of the city [31] (Fig.10).

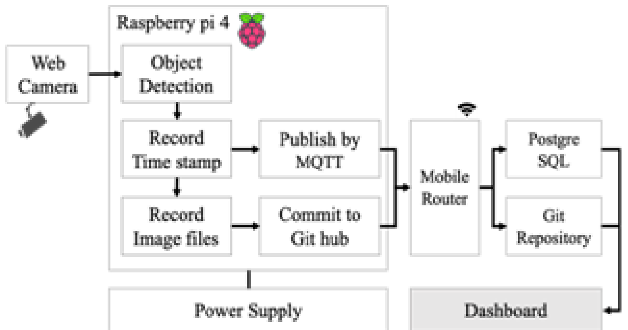

Figure 9: Components of the whole process of data acquisition, processing, storage, and display

Figure 10: Bicycle lanes paved in Nago City, Yanbaru, Japan

Figure 11: Detection of bicycle among traffic at three locations in Nago city and its outskirts, using the IoT gadget

For the outdoor setting of the IoT kit, we considered two options for Internet communication. One was a low-rate, low-power (LPWA) adapter, namely SONY ELRAS, and the other was a WiMAX mobile router (YMobile ZTE 802ZT).

Fig. 11 shows three locations in Nago city and its outskirts, we tested the detection of bicycle traffic and connectivity.

Fig.12 and Fig. 13 show the coverage of the LPWA and WiMAX network services, respectively, in the northern part of Okinawa, where the data collection experiment is meant to take place. The cellular signals have huge coverage, while the LPWA coverage is very limited in the region. Some mountainous uninhabited areas have no communication signals at all. According to the coverage map (Fig. 13), even the cellular service coverage does not always extend to mountainous and to some remote rural areas in the northern part of Okinawa Prefecture. In such environment, we considered off-line operation, where the summary of detection and collected data could temporarily be saved onboard the edge device, and then transmitted later once the Internet connection signal was obtained.

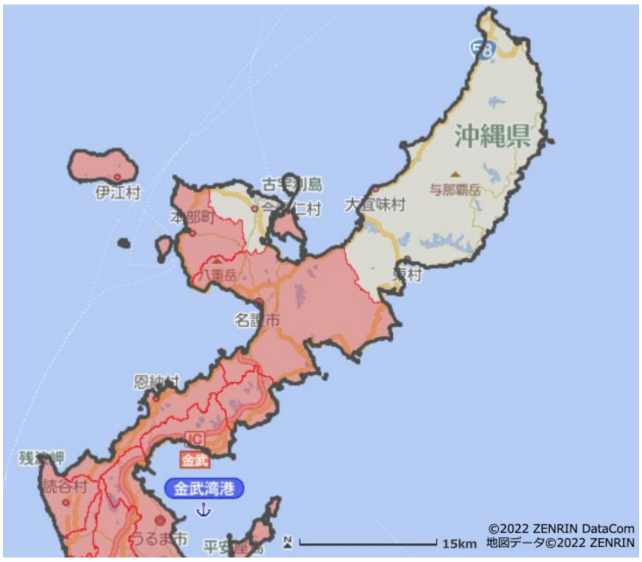

Figure 12: Coverage of ELTRES LPWA network. The northern part in particular is not in the coverage area (yellow).[Source: SONY ELTRES Web Page].

For 3G/4G/5G connectivity, we experimented with a mobile WiMAX router provided by the YMobile Telecommunication carrier in Japan. It provides a speed of 46Mbps upstream and 838Mbps downstream. It comes with a 3000mAh battery with a 12-hour continuous operation time.

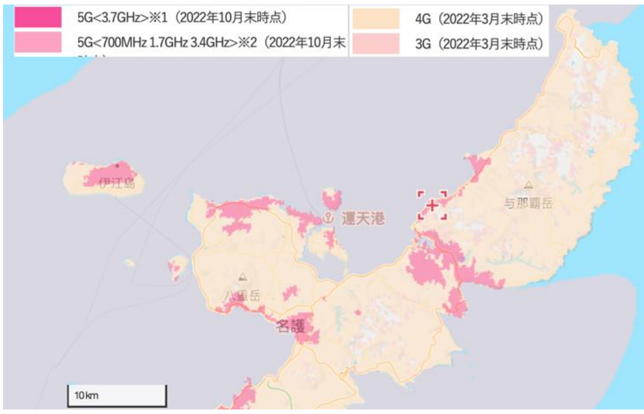

Figure 13: Coverage of the cellular network service provided by the YMobile mobile router (in color). Few scattered small areas (in white) appear to be out of range, as of October2022. [Source: YMobile official web page].

6. Discussion and Summary

We have tested the IoT gadget and system on campus and on city streets. Fig.14 shows the sample detection process during sessions on campus (a) and on the street (b). The detection worked fairly well, with a high detection accuracy. The IoT gadget setting was in a range of 2~20 meters from the target street spot. The detection process missed some objects in cases when two bicycles overlapped in the view frame of the camera.

(a)

(b)

Figure 14: Detection was possible on campus (a), as well as on the street (b), using the IoT gadget.

During this research, we encountered some challenges, which included the power supply for the devices, the cost of usage for the cloud services, a WiMax mobile router, and cloud-related resources. Also, we had to deal with securing and keeping the IoT gadget safe while installing it outside. Additionally, we had to comply with privacy regulations in terms of procedures as well as in technical aspects. The coverage of the signal for communication where the IoT gadget is set up is something that cannot be compromised.

LPWA ELTRES works with a coin battery and has a long operation time. On the other hand, it has a limited transmission rate. It also requires the use of the cloud storage and delivery service for a monthly cost.

We subscribed to the WiMAX router service for two months; in addition to the monthly charges, we had to buy the router itself. The battery of the mobile router could operate for a maximum of 10 hours, so it needed to be recovered and recharged on a daily basis.

We had to deal with environmental conditions such as heat and rain in order to keep the IoT gadget box and the instruments inside it safe.

For compliance with research ethics and regulations, as well as the rules set by public authorities for monitoring and data collection, we had to prove that the developed system abides by the regulations technically and operationally. From a technical perspective, we had to blur faces and number plates so that we could keep some limited number of the images for the purpose of checking the reliability and accuracy of the detection process and the data collected.

In our experiment, we used a Raspberry Pi kit for edge computing and for setting up other devices and liaison operations on the data-IoT level. The Raspberry Pi needed a permanent power supply. We used a power bank that could supply power for up to 10 hours. In case of the interruption of power supply, the continuity plan was limited to recovering the saved data and integrating these data with the automatic collection, processing, and statistical methods.

7. Conclusion

In this research, sufficient detection ability was demonstrated, and the implementation and deployment of all stages were demonstrated.

In this paper, we revised different stages and domains for an IoT system. Alongside building an IoT gadget for detecting and reporting moving bicycle traffic, we have considered different implementation and technology options for various domains of the IoT system. An edge-computing scenario was implemented using a TensorFlow Lite library for moving object detection and classification. The computation is done on a Raspberry PI, which used a USB web camera and communication protocols to connect with a last-mile device for Internet connectivity. It is shown that both LPWA and cellular IoT have their own advantages and disadvantages for different implementation environments. The power supply, power consumption, operation cost, coverage, and range of connectivity, in addition to the ease of deployment, are factors to consider when an IoT system is being built for specific application requirements and a specific geographical area.

In general, we find that LPWA technology is available, but its service frequently comes with vendor cloud or business-supporting services that require the acceptance or integration of such services; however, it was the quite appropriate technology for our specific application and operation area. Each application has its specific requirements. For the detection and data collection functions, we conclude that there are excellent AI libraries available that can be integrated easily into IoT systems. Setting up a survey or monitoring devices on campus or in public areas requires permission to be obtained, and various rules must be complied with in order to deploy and operate such systems. Many IoT technologies are being developed at a fast pace, but choosing the best and optimal options for a specific application requires a decent survey and an assessment of the available options.

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