

A Portable and Elastic Edge Computing Network for Disaster First Responders

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Abstract—With the worldwide increase in disaster occurrences and their scale of damage, a resilient Information and Communication Technology (ICT) system that remains available in disaster-affected areas despite Internet, telecom, or mobile service disruptions is strongly desired. In particular, disaster first responders who rush to disaster-stricken areas to carry out investigations, search and rescue operations for people, require tools to collect, share, report, and record disaster information. This paper proposes a portable and elastic edge computing network to support the activities of disaster first responders. The portability and elasticity features enable us to adaptively apply the proposed edge computing network in various disaster situations. In the edge computing node, Artificial Intelligence (AI) functions, such as automatic speed recognition, are equipped to offer hands-free operation and on-site intelligent image processing for first responders. We developed a pilot model of an edge computing node and confirmed the requirements to include AI functionality through experimental evaluation.

Index Terms—Disaster response, edge computing, portable ICT system, speech recognition, support system, wireless LAN

I. INTRODUCTION

The number of natural and man-made disasters, such as earthquakes, typhoons, floods, and landslides, and their scale of damage, have increased over the last couple of decades [1]. Once a disaster occurs, telecom/mobile services and Internet connectivity are often disrupted in the affected areas. Disaster first responders, such as the Fire Department, Police Department, Self-Defense Force, and others, rush to the affected areas and engage in investigating the damage, searching for and rescuing missing people, and performing other activities. They are often forced to work under critical situations, including telecom and Internet service disruptions, which cause inefficiency in their activities and increase the risk of secondary damage. Efficient information handling, which includes the collection, reporting, recording, and sharing of disaster information, as well as bi-directional communication among responders, is recognized as a critical issue to be resolved.

To address this issue, this paper proposes an edge computing network for disaster first responders. It is a portable and standalone system that enables nearby users to handle disaster information locally using their daily-use network devices, such as smartphones, even during network service disruptions.

It also has an elastic networking feature, which makes it possible to adapt the system to various situations flexibly. This paper is organized as follows: First, we present the challenges first responders face in on-site information handling as the background, followed by related work aimed at resolving these challenges. Next, a portable and elastic edge computing network is proposed. The development of a pilot model for the edge computing node and the results of its experimental evaluation are reported and discussed.

II. CHALLENGES OF DISASTER FIRST RESPONDERS

This section provides an overview of disaster first responders and their activities in disaster situations as background. We then focus on the challenges in on-site information handling, which is one of the major activities of first responders. The related works addressing these challenges are then reviewed.

A. Disaster first responders and their activities

A disaster first responder is defined here as personnel or organizations that are among the first to arrive at disaster-affected areas and respond to the situation. The relevant organizations in Japan include the Police Department, Fire Department, Self-Defense Force, Technical Emergency Control Force, Japan Coast Guard, and Disaster Medical Assistance Team. Table I summarizes the activities of the major first responders in disaster situations. In these activities, situational awareness, damage investigation, and information handling, such as collection, reporting, and sharing, are common among first responders and are especially important in the early stages of disaster response.

B. Challenges in the on-site information handling

Table II shows the information handled by first responders and the ways they handle this information. The challenges in information handling, which we identified through interviews with first responders, are also listed. First responders mainly handle disaster information through verbal communication, both face-to-face and over walkie-talkies. When Internet services are retained at the disaster site, social networking services like chat and image sharing are often used secondarily

with members' own network devices. Most challenges in information handling, as shown in Table II, are mainly caused by the risk of network service disruption in the disaster-affected area, which prevents reliance on the latest ICT technologies.

TABLE I
MAJOR DISASTER FIRST RESPONDERS AND THEIR ACTIVITIES

First responder*	Major Activities up to 72 hours after the disaster occurrence	
Police Department	Evacuation guidance, On-site patrol, Traffic control, Identity verification, Crime prevention and control	- Situation awareness - Information collection, report, and sharing - Missing person search - Rescue operation
Fire Department	Patrol, Investigation, Evacuation guidance, Public relations, Fire fighting, Emergency response	
Self-Defense Forces	Life saving, Transportation support, Water supply support, Road clearance	
*: Other than the organizations in the table, Technical Emergency Control Force, Japan Coast Guard, and Disaster Medical Assistance Team are also included in the first responders here.		

TABLE II
INFORMATION HANDLING BY FIRST RESPONDERS AND ITS CHALLENGES

Item	Contents
Commonly handled information	Location/type of damage, On-site situation, Necessity of rescue, Hazards in activities, Damage of road and other infrastructures, others
Way for Information handling	- Face-to-face verbal communication, - Voice communication using Walkie talkie, - Information system of respective organization - Unauthorized use of Social Networking Service
Challenges	- Handling of wide variety of information types (text, voice, image, video). - Support communication types like one-way/bi-directional communication, and multi/broad-casting. - Local/distance communication under the Internet/telecom service disruption. - Ease of information input/output and system operation - On-site use of area information for searching missing person - On-site sharing of information among organizations

C. Related work to meet the challenges

In order to address the challenges stated above, many works have been considered to provide solutions to the problem of on-site information handling in disaster situations. Kishorbbhai et al. [2] surveyed emergency communication systems used during a large scale disaster. The authors highlights various emergency communication networks such as Walkie-Talkie, MANET, Ad-hoc, Wireless Balloon, etc., that can be used to establish communication in disaster situations, their importance and the ongoing challenges in using the reviewed networks. In [3], Usuda et al., introduces SIP4D, a disaster-information infrastructure in Japan that enables disaster-response organizations to share information and collaborate. The SIP4D aims to enhance information-sharing efficiency by reducing coordination and development load. In their work, they emphasize the importance of situational awareness and informed action for effective disaster response. On the other hand, Bharosa et al. [4] addresses the challenges of gathering

and analyzing disaster information at the frontline. They suggested pooling knowledge and resources as a solution to create compatible modules that can be integrated for disaster information management in the future. Similar to this, Kirchner et al. [5], examines the challenges in implementing information systems for disaster recovery and response, stressing the need for a communication system enabling information flow from frontline personnel to central operations. It proposes an integrated disaster management communication and information system, addressing networking, configuration, scheduling, data management, and applications.

Additionally, Damaševičius et al. [6] explores the implementation and potential of IoES in enhancing public safety and crisis management through a coordinated and data-driven approach. They highlight challenges and limitations related to interoperability, data sharing, security, and privacy. The authors emphasized the importance of addressing associated challenges and concerns, thereafter suggested the integration of emerging technologies like AI and blockchain. Matraccia et al. [7] discussed the post-disaster communications and the challenges associated with the enabling technologies, focusing on edge computing to reduce latency and maximize bandwidth. Their work emphasizes the significance of content caching for timely information sharing and proposes a secure caching scheme for backup during disasters. It also addresses challenges in reconciling data from different sources and stresses the need for efficient resource allocation, security measures, and effective communication frameworks. Li et al. [8] also presents a quantitative model for evaluating disaster response effectiveness based on information flow among stakeholders. It includes a conceptual model and a hypothetical example to demonstrate its applicability. The paper also discusses the benefits of the model, including interpretability and identifying critical stakeholders.

Vimukthi et al. [9] reviewed data quality challenges in disaster management, emphasizing the importance of quality data for effective decision-making. They discussed the characteristics of big data in this context and reviewed dimensions of data quality. The paper further highlights the costs of poor data quality and suggests advanced methods to improve decision-making.

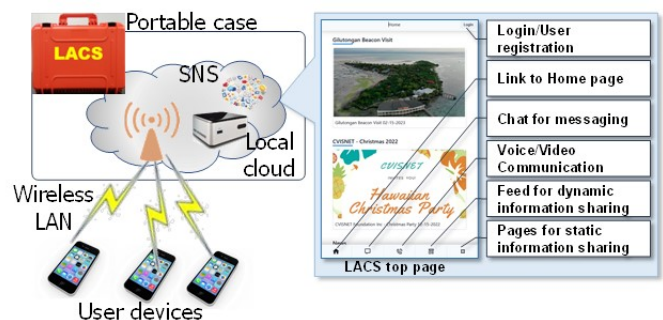


Fig. 1. Overview of Locally Accessible Cloud System (LACS).

Sakano et al. [10, 11] in their paper describes a proposed

network architecture for disaster-resilient networking based on movable and deployable resource units (MDRUs) composed of modularized equipment for networking, information processing, and storage. The authors highlight the challenges faced by the telecom sector during the great east Japan earthquake and tsunami of 2011, emphasizing the urgent need for disaster-resilient network infrastructure that can be quickly deployed and provide necessary ICT services to disaster-affected areas. The MDRU architecture which shows its potential to effectively compensate for reduced network capacity due to devastating disasters was also discussed. Their work further highlights the capability of the MDRU-based disaster-resilient network architecture and how it can effectively meet the critical ICT service demands during catastrophic events.

Furthermore, Sakano et al. in [12] proposed a standalone system called Locally Accessible Cloud System (LACS) as a portable communication tool to fulfill the explosive demand for Information and Communication Technology (ICT) during disastrous situations when the telecommunication or the Internet services are disrupted. Figure 1 shows an overview of LACS. LACS is designed with functions that can host multiple services for delivering, sharing, and exchanging information among local people. The system consists of a portable case, a small server, a IEEE802.11 based wireless LAN(Wi-Fi) access point, a battery, and peripheral devices. They further highlight the importance of filling the gap between supply and demand for ICT services during disasters to save lives and achieve early restoration from damages. The authors demonstrate LACS's performance in real disaster situations and during the COVID-19 pandemic and its usefulness as a communication tool and for providing various services like e-education.

III. PORTABLE AND ELASTIC EDGE COMPUTING NETWORK

With the challenges of disaster first responders in mind, we propose a portable and elastic edge computing network. The features we aim to achieve with this architecture are portability, easy-to-use, standalone operation for local information handling, and flexible or elastic extension of service area coverage through automatic inter-edge computing networking. In our previous work [13], we proposed Front-Line Operation System (FLOS) to aid first responders in disaster response and management. We further extend the functionality and use to include Augmented Reality and this edge computing network proposed in this paper. We call the extended version of our work Extensible Frontline Augmented Communication Exchanger (X-FACE).

A. Architecture

Figure 2 shows an image of X-FACE and its necessary features. X-FACE comprises an edge computing node and user devices that are connected to the node. The node is a portable and standalone system, similar to LACS, which accommodates a small server, Wi-Fi access point, and battery in a portable case, providing local communications and social networking functions for information handling. The first responder team

brings this system when it goes to a disaster site. Each team member utilizes the information handling functions of the system in their activities, including investigation, search, rescue, and direction, by accessing X-FACE using their network devices, such as smartphones and tablets. The edge computing node can flexibly extend its coverage area by connecting to other edge computing nodes, thereby forming a local emergency communication network.



Fig. 2. Architecture of a portable and elastic edge computing network.

The system needs to be simple and easy to operate since first responders usually have to use it under critical conditions, such as bad weather. x-FACE is equipped with a speech recognition function to enable hands-free operation. In addition, intelligent processing, such as auto-correlation of a place (e.g., a broken house) in an acquired image with related information (e.g., the resident member of the house), supports the activities of first responders.

B. Edge computing node

Figure 3 shows the configuration of a portable and elastic edge computing network. The edge computing node comprises a small server and storage, and networking functions for access, inter-node, and wide area networks. The server includes functions for communication and information handling, hands-free operation, and intelligent processing. The network controller manages the networks. All the equipment accommodated in the system operates on battery power.

C. Edge computing network

In X-FACE, three networks are used to form an edge computing network: the access network, wide area network, and inter-node network. Figure 4 depicts an elastic edge computing network. The access network is the network between user devices and an edge computing node, which forms a user network coverage. The wide area network connects the edge computing node to the Internet and other systems. The inter-node network forms a X-FACE network to flexibly extend the geographical coverage of the whole system using multiple edge nodes. The elasticity of the inter-node network enables us to flexibly adapt the edge computing network to the activities of first responders.

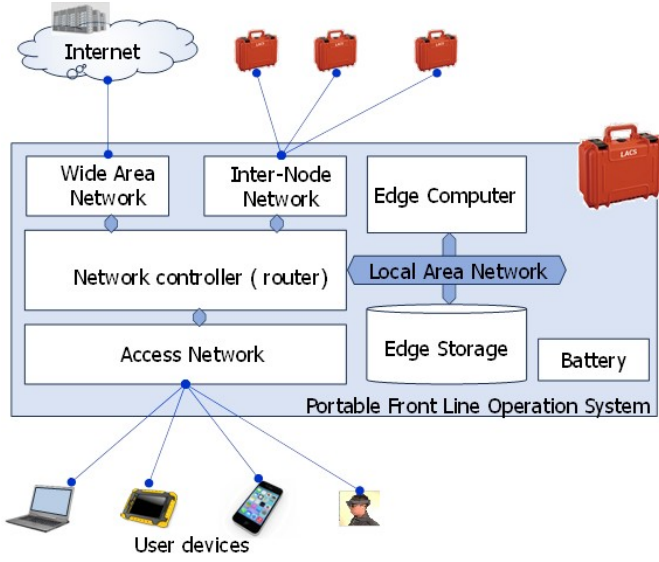


Fig. 3. Configuration of a portable and elastic edge computing network.

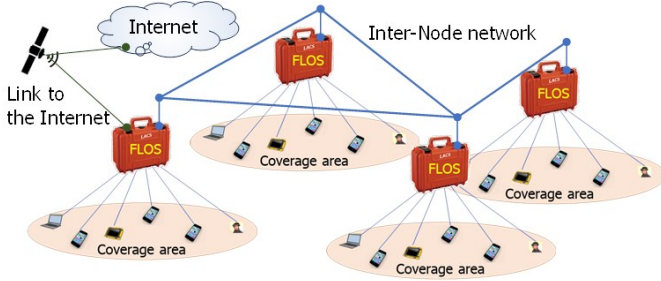


Fig. 4. Elastic edge computing network.

1) Access network:

To make the whole system user-friendly and easy to use, the application of popular user devices is preferable. User devices such as smartphones, tablets, laptop computers, and Mixed Reality (MR) devices are candidates. These devices are widely used worldwide, and most people use them daily to access the Internet over a mobile network service or Wi-Fi. The currently available coverage area of a popular Wi-Fi access point is limited to about a hundred meters at most, even with a direct line of sight. This range of coverage is sufficient for small team activities.

2) Wide area network:

Although the basic role of X-FACE is to support local communication and information handling for disaster first responders, connecting the system to the Internet is desirable to reach and collaborate with other systems. Under conditions of network service disruption, temporarily equipped Non-terrestrial Network (NTN) services [14] would be a candidate for network restoration. Even if Internet connectivity is eventually secured by NTN in the disaster area, the application of edge computing nodes is still beneficial to avoid traffic congestion on the Internet and to realize fast and stable local information handling.

3) Inter edge computing network:

To increase the usability and adaptability of X-FACE, another important feature needed for disaster countermeasures is the ability to scale its performance. One way to scale performance is to increase the modularity of the edge computing node and to form an inter-edge computing node network that flexibly responds to the use case's requirements. Scalability of the service area coverage, such as expanding from a standalone node's 100m area to 1km with a multiple-node network, is a desired feature compared to the scalability of computing power, the number of accommodated users, and storage capacity. To cover this area range and flexibly form and configure the IP (Internet Protocol)-based multi-hop network, Low Power Wireless Access (LPWA) systems like Wi-SUN FAN [15] and 802.11ah [16] are candidate network devices for the inter-edge computing network.

IV. THEORETICAL ANALYSIS OF X-FACE ARCHITECTURE

To quantify X-FACE performance in dynamic disaster response scenarios, we propose two novel metrics: (i) The Disaster Response Resilience Index (DRRI), and (ii) The X-FACE Resource Allocation Model (FRAM). These metrics address the resilience and resource allocation capabilities of our portable and elastic computing network, offering advantages over existing approaches by addressing specific challenges in disaster response.

A. Disaster Response Resilience Index (DRRI)

The DRRI measures system functionality under critical conditions as shown in Eq. 1, where F represents failed nodes, N is the total number of nodes, D denotes cumulative downtime, T represents total operational time, and S is situational severity ($0 < S \leq 1$).

$$DRRI = \left(1 - \frac{F}{N}\right) \cdot \left(1 - \frac{D}{T}\right) \cdot S \quad (1)$$

B. The X-FACE Resource Allocation Model (FRAM)

The FRAM optimizes the resource distribution within the elastic computing network as shown in Eq. 2, where $R_i(t)$ represents resources allocated to node i at time t , $L_i(t)$ is the current load on node i , $E_i(t)$ is the remaining energy of node i , $C_i(t)$ represents connectivity, $U_i(t)$ is task urgency, and coefficients α , β , γ , δ are adjustable weights.

$$R_i(t) = \alpha \cdot L_i(t) + \beta \cdot E_i(t) + \gamma \cdot C_i(t) + \delta \cdot U_i(t) \quad (2)$$

The evaluation of the proposed theoretical framework will be addressed in future work.

V. PILOT MODEL DEVELOPMENT AND ITS EVALUATION

We developed the Extensible Frontline Augmented Communication Exchanger (X-FACE) pilot model and evaluated to determine the requirements for hands-free functionality based on automatic speech recognition.

A. Pilot model development

Figure 5 shows an overview of the developed X-FACE pilot model. X-FACE consist of a small server, a Wi-Fi access point, a router, and a battery were accommodated in a portable case. The dimensions of the case were 336mm x 300mm x 148mm, and the system's weight was 4.7kg. The X-FACE case which is made of a ruggedized plastic is designed in such a way that it is durable and able to withstand the rigorous conditions of a disaster area. In addition, a cooling unit (i.e., heat extractor fan) is included as one of the components of X-FACE to account for the thermal management. While rugged laptops (e.g., the Panasonic Toughbook) are designed for harsh conditions, the choice of a mini-PC as an edge computing node for X-FACE offers several advantages. It allows for greater customization of hardware and software specific to disaster response needs, potentially better power efficiency for extended operation, and more flexible networking capabilities to support the multiple network interfaces required by X-FACE. The modular design also facilitates easier scaling and component replacement. Additionally, the compact and portable nature of the mini-PC aligns with our goal of easy deployment during disaster response, while potentially offering a more cost-effective solution for the specific functions required.

While modern smartphones, including the Panasonic Toughbook, have natural language processing capabilities, X-FACE provides critical advantages for disaster response. It ensures consistent functionality across all devices, operates independently of internet connectivity, and is designed for efficient resource use, which is essential in emergencies. By offering tailored speech recognition and customizable features specifically for disaster scenarios, X-FACE enhances operational effectiveness, making it a more reliable solution than relying solely on high-end smartphones.

Web-based applications for social networking, such as information sharing, text-based chat, and voice/video bi-directional communication, were developed and installed on the server. To enable the hands-free feature, Faster Whisper [17], an automatic speech recognition (ASR) engine, was installed and integrated into the social networking function. Table III presents the specifications of the pilot model. Five CPUs, referred to as A through E, each with different processing capabilities, were prepared as small servers for evaluation purposes.

Users access the applications in the pilot model using devices like smartphones and tablets with Wi-Fi functionality and a web browser. The input/output information to/from the pilot model and other operations are achieved through verbal communication between the user and the system without touching the user device.

B. Preliminary evaluation

The goal of our evaluation of the X-FACE is to address the challenge of realizing hands-free operation while meeting the requirements for ASR functionality in a restricted environment, such as a disaster area. This includes managing limited power consumption from a battery, limited processing

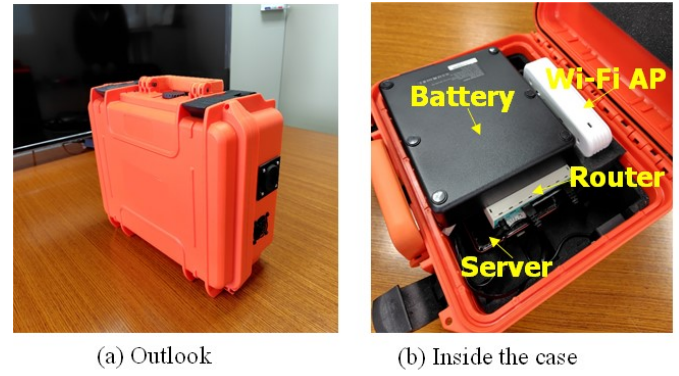


Fig. 5. Outlook of the developed pilot model.

TABLE III
SPECIFICATIONS OF THE DEVELOPED X-FACE PILOT MODEL

Item	Specifications		
	Ref.	CPU number	Speed(single)
CPU (Five kinds of CPUs were prepared for evaluation.)	A	Core i7 1060NG7	1,879 MOps/s
	B	Core i7 7567	2,223 MOps/s
	C	Core i3 N305	2,239 MOps/s
	D	Ryzen 7 5700U	2,596 MOps/s
	E	Core i7 1165G7	2,826 MOps/s
Wi-Fi AP	802.11a/n/ac		
Router	5 GbEthernet ports		
Battery	150 Wh		
Dimension	336mm x 300mm x 148mm		
Weight	4.7 kg		

power of the small server, and maintaining speech recognition performance and speed. Therefore, we measured the performance and speed of the ASR installed in several types of commercially available small servers. Figure 6 explains the conducted evaluation. We first prepared three types of task sets, as shown in Figure 6: the status report task set, the numeral and abbreviation task set, and the proper noun task set, each comprising 100 sentences related to disaster first responders' activities. Although the task set described in this paper is in English, the original task set used in the evaluation was generated in Japanese. The task sets were input to the ASR engine (Faster Whisper) with four types of models, ranging from smaller to larger: base, small, medium, and large-v2. We prepared five small servers to run the ASR engines. Conversion accuracies at the sentence and character levels, as well as processing speed, were measured.

Figure 7 shows the results of conversion accuracy measured using a server. Figures 7 (a) and (b) show conversion accuracies at the character and sentence levels, respectively. No dependency on the servers was found in the measured conversion accuracies. The character accuracy increases with the scale of the model and exceeds 90% for the report and numeral and abbreviation tasks when the model is medium or larger. As for sentence accuracy, the maximum conversion accuracy is around 80%, even when the model is medium or larger.

The measured relationship between the CPU performance of the servers and the real-time factor (RTF), a common metric for expressing the processing speed of an ASR engine, is

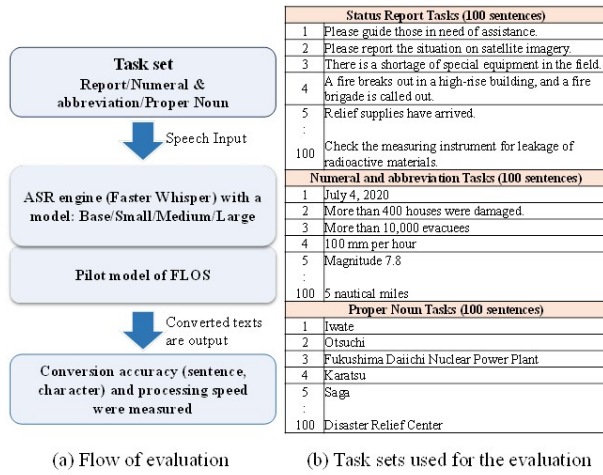


Fig. 6. Flow of the evaluation and the task sets used for it.

shown in Figure 8. In the graph, the horizontal and vertical axes represent CPU performance in arbitrary units and RTF, respectively. The plots in the graph represent the measured RTFs for four models and five CPUs (small servers): CPU-A through CPU-E. The measured RTF tends to decrease with an increase in CPU performance and a decrease in the model's scale. If the applied model is small or base, the RTF becomes smaller than 1.0 regardless of the CPU used. To achieve real-time hands-free operation of an X-FACE, a desirable RTF is said to be around one or smaller. It is therefore concluded that we should select a smaller model or a higher performance CPU than CPU-D with the medium model.

TABLE IV
TYPICAL POWER CONSUMPTION OF PILOT MODELS (WATTS).

Pilot model	A	B	C	D	E
CPU	25	15	10	15	10
Peripheral	5	5	5	5	5
Router	3.5	3.5	3.5	3.5	3.5
Wi-Fi AP	3.5	3.5	3.5	3.5	3.5
Total	37	27	22	27	22

Similarly, the relationship between CPU performance and the system's power consumption was evaluated. Table IV shows the measured typical power consumptions of the pilot models, labeled A through E, which correspond to CPU-A through CPU-E. The measured typical power consumption of a pilot model, including the CPU, peripheral circuit, router, and Wi-Fi access point, ranged from 22 to 37 watts. Figure 9 shows the calculated relationship among the system's power consumption, possible operation time in hours, and battery capacity in Wh. If an X-FACE is configured with a 150Wh battery, the possible operation time for one of CPU-B through CPU-E is 6 to 7 hours. This implies that the X-FACE is suitable for the daily activities of first responders.

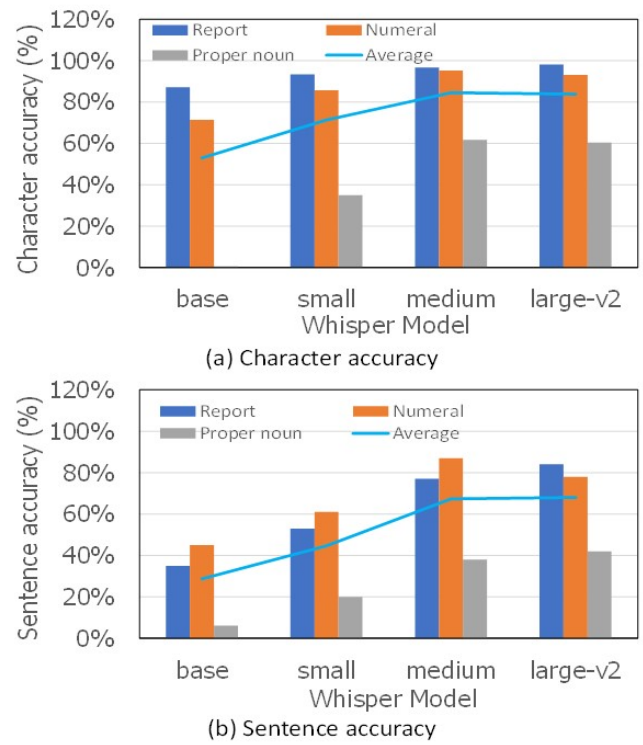


Fig. 7. Measured character and sentence accuracies.

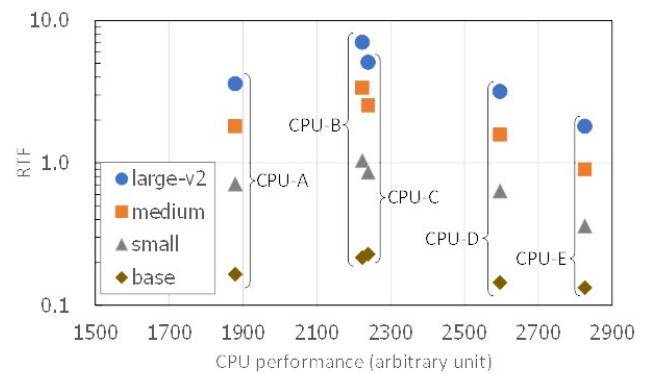


Fig. 8. Measured response time factors (RTF).

VI. DISCUSSION

In the previous section, the development of the pilot model and its preliminary evaluation were explained. Through the evaluation, we confirmed that the inclusion of AI functionality, such as speech recognition, into the edge computing node for hands-free operation is feasible and can run with reasonable power consumption, making it suitable for use in disaster first responder activities. Conversion accuracy, however, should be increased from the current level to at least over 90% to make the system truly feasible. Optimization of the model for disaster first responder applications is key to reaching this feasible level.

Including other AI intelligent functions in an X-FACE is

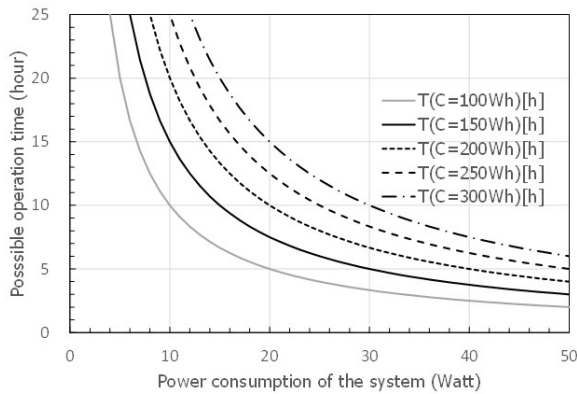


Fig. 9. Relationship between system's power consumption and operation time.

another challenge to unlock the potential of the architecture in disaster operations. This includes a geographical information system (GIS) and a function for automatic correlation and visualization of images captured in the disaster area with related area information.

In this paper, a pilot model of a stand-alone edge computing node is developed and evaluated. Feasibility confirmation of the elastic feature in the proposed edge computing network architecture and the evaluation of the network with various use cases are left for further study. We plan to apply currently available LPWA (Low Power Wireless Access) systems to implement the elastic feature in the next version of the system.

VII. CONCLUSION

In this paper, an edge computing network architecture to support the activities of disaster first responders was proposed. The architecture's portability and elasticity contribute to addressing the challenges that disaster first responders face. The pilot model of the proposed architecture was developed and evaluated. The results suggested that it was possible to use the proposed X-FACE as a real system in a disaster response operation. The ASR engine running on the X-FACE achieved character accuracy above 90% for report, numeral, and abbreviation tasks, while sentence accuracy was 80% when the model was set to medium or large. As part of future work, the detailed development and implementation of the networking features will be addressed as the next step to confirm the elasticity of the architecture.

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