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Informatics Society

Aims and Scope

The purpose of this journal is to provide an open forum to publish high quality research papers in the areas of informatics and related fields to promote the exchange of research ideas, experiences and results.

Informatics is the systematic study of Information and the application of research methods to study Information systems and services. It deals primarily with human aspects of information, such as its quality and value as a resource. Informatics also referred to as Information science, studies the structure, algorithms, behavior, and interactions of natural and artificial systems that store, process, access and communicate information. It also develops its own conceptual and theoretical foundations and utilizes foundations developed in other fields. The advent of computers, its ubiquity and ease to use has led to the study of informatics that has computational, cognitive and social aspects, including study of the social impact of information technologies.

The characteristic of informatics' context is amalgamation of technologies. For creating an informatics product, it is necessary to integrate many technologies, such as mathematics, linguistics, engineering and other emerging new fields.

Guest Editor's Message

Ryozo Kiyohara
Guest Editor of the Forty-eighth Issue of the International Journal of Informatics Society

We are delighted to have the Forty-eighth issue of the International Journal of Informatics Society (IJIS) published. This issue includes selected papers from the Sixteenth International Workshop on Informatics (IWIN2023), held online from September 1st – 4th, 2023. The workshop was the seventeenth event for the Informatics Society. It was intended to bring together researchers and practitioners to share and exchange their experiences, discuss challenges and present original ideas in all aspects of informatics and computer networks. In the workshop, 27 papers were presented in six technical sessions. The workshop was successfully finished, and precious experiences were provided to the participants. It highlighted the latest research results in informatics and its applications, including networking, mobile ubiquitous systems, data analytics, business and industrial systems, education systems, design methodology, intelligent systems, groupware, and social systems, etc.

Each paper submitted to IWIN2023 was reviewed in terms of technical content, scientific rigor, novelty, originality, and presentation quality by at least two reviewers. Through those reviews, 22 papers were selected for publication candidates of the IJIS Journal, and they were further reviewed as Journal papers. We have three categories of IJIS papers, Regular papers, Practical papers, and Invited papers, each of which was reviewed from different points of view. This volume includes papers among those accepted papers, which have been improved through the workshop discussion and the reviewers' comments.

We publish the journal in print as well as in an electronic form over the Internet. We hope that the issue would be of interest to many researchers as well as engineers and practitioners all over the world.

Ryozo Kiyohara received B.E., and M.E. degrees from Osaka University in 1983, and 1985. Since joining Mitsubishi Electric Corporation in 1985, he had been engaged in developing a machine translation system. From 1989, he had been at the Institute for the New Generation Computing Technologies engaged in the Fifth Generation Computing Project until he returned to Mitsubishi Electric Corporation in 1992. He developed the software updating system and Java processing environments for mobile phones. He received Ph.D. in 2008 from Osaka University in Information Science and Technology. He is a professor of Kanagawa Institute of Technology since 2012. He is a fellow of IPSJ (Information Processing Society of Japan). He is a member of IEEE (Senior Member), ACM, and IEICE (The Institute of Electronics, Information and Communication Engineers).

Regular Paper

Information Delivery System to Maintain Intellectual Productivity in Teleworking

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Abstract - The COVID-19 pandemic highlighted the importance of effective telework environments, particularly in maintaining intellectual productivity. Prior research suggests that productivity is closely linked to environmental satisfaction in the workplace. However, many remote workers lack systems that facilitate optimal conditions at home. To address this, we developed an IoT-based tool that monitors indoor temperature, humidity, and CO_2 levels and provides tailored feedback to support user-driven environmental adjustments. Over a two-month experimental period, the system demonstrated reliable performance and led to observable behavioral changes, such as the proactive use of humidifiers. These findings suggest that personalized environmental information delivery can effectively support productivity improvement in telework settings.

Keywords: telework, IoT, indoor environment, CO_2, productivity

1 INTRODUCTION

Following the initial COVID-19 emergency declaration, many workers in Japan transitioned from office settings to telework. According to a survey by the Japan Business Federation [1], approximately 60% of companies adopted telework systems (Fig. 1 [2], [3]).

While environmental factors such as temperature, humidity, and carbon dioxide levels were initially overlooked, subsequent studies revealed a strong correlation between environmental satisfaction and intellectual productivity [4]. In the United States, improving such environmental conditions is estimated to contribute between $40 and $200 billion in annual economic benefits (Table 1) [5]. Recognizing this, many

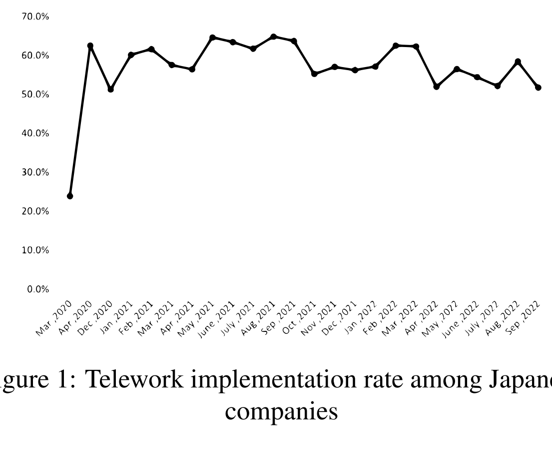

Figure 1: Telework implementation rate among Japanese companies

Table 1: Estimated economic impact of improving indoor air quality in the United States

Source of productivity gain	Estimated annual savings (USD)
Reduced respiratory illness	$6–14 billion/year
Reduced allergy and asthma symptoms	$2–4 billion/year
Reduced sick building syndrome symptoms	$10–30 billion/year
Improved worker performance from changes in thermal environment and lighting	$20–160 billion/year

companies have implemented Building Energy Management Systems (BEMS) and smart office technologies to improve in-office environments.

However, few comparable efforts have been made to support the home workspace. A survey conducted by Daikin Industries found that about 70% of teleworkers experienced dissatisfaction with their home air quality, citing issues such as temperature instability, dryness, and lack of ventilation [6]. Despite growing evidence that thermal comfort influences productivity, centralized solutions for home telework environments remain limited.

To address this gap, we developed an IoT-based system utilizing the “Netatmo Weather Station” to measure key environmental parameters—temperature, humidity, and CO_2 concentration—in the teleworker's environment. Based on the collected data, our system delivers personalized feedback aimed at improving indoor conditions. This paper explores the effectiveness of such a system in promoting environmental awareness and supporting behavioral changes that may lead to improved intellectual productivity during telework.

2 RELATED STUDY

2.1 Telework Situation in Japan

The Ministry of Internal Affairs and Communications defines telework as a flexible work style utilizing ICT to enable more efficient use of time and space [6].

It can be broadly categorized into three types based on location: telework, mobile work, and satellite office work. Since the onset of the COVID-19 pandemic, telework has become increasingly widespread, with many companies adopting it as a standard practice [7].

Telework offers benefits not only for employers and employees but also for broader society. This study focuses specifically on telework, where individuals work from their residences.

2.2 Indoor Environment and Intellectual Productivity

2.2.1 Teaching Bot for Enhancing Indoor Comfort

Hamanaka et al. [8] developed a chatbot integrated with Slack to support indoor comfort. By retrieving real-time temperature and humidity data from a Raspberry Pi 3 sensor, the bot provides users with feedback and visualizations to help maintain optimal environmental conditions. The system enables users to make informed adjustments to their surroundings through simple, interactive queries.

2.2.2 AI/IoT-Driven Intelligent Environmental Control

Nishino et al. [9] designed a system to mitigate drowsiness during desk work using an AI-based alertness detection mechanism. When the system detects reduced alertness via a desk-mounted camera, it automatically adjusts air conditioning to improve worker attentiveness. Evaluated over two seasonal periods with five office workers, the system demonstrated reductions in drowsiness-related productivity losses.

2.3 Novelty of Our Study

Most IoT-based environmental control systems to date have focused on shared office spaces or general home energy usage (e.g., HEMS). However, they often lack consideration for the unique needs of telecommuters working individually from home. Given the diversity of household environments and air-conditioning systems, existing solutions are not readily applicable to home-based telework.

In contrast, our study addresses this gap by developing a personalized information delivery system specifically for telework. The system collects temperature, humidity, and CO_2 data using a commercially available IoT sensor and provides tailored recommendations to help users manage their indoor environment. Unlike systems that automate control, our approach emphasizes behavioral support—encouraging individuals to take actions themselves. To be effective during work hours, the feedback is designed to be clear, timely, and intuitive. The following sections describe the system architecture, experimental methodology, and results demonstrating its effectiveness in supporting productive and health-conscious teleworking.

3 SYSTEM DESCRIPTION

3.1 Overview

The proposed system monitors environmental conditions in home workspaces using strategically placed sensors. It analyzes the collected environmental data and generates real-time notifications aimed at supporting the maintenance or improvement of indoor conditions. Upon receiving these alerts, users can take actions based on the provided recommendations, thereby fostering a more productive and comfortable teleworking environment.

3.2 System Configuration

Figure 2 illustrates the overall architecture of the system. The design is centered on IoT sensors installed across diverse telework environments. These sensors continuously transmit relevant environmental data to a centralized management server. The server not only retains these data in real time but also stores it for longitudinal analysis.

After data collection, the system performs both real-time and historical analysis. This dual-layered processing enables the system to generate personalized feedback—either suggesting improvements or encouraging maintenance of favorable conditions. Once generated, the feedback is sent as notifications to the users.

The following subsections provide detailed explanations of each system component and the logic that governs its operation.

3.2.1 Data Acquisition

The data acquisition module utilizes the Netatmo Weather Station [11] as the primary sensor device. The setup consists of two units: a primary (indoor) module and a secondary (outdoor) module. The indoor module measures variables such as temperature, humidity, and CO_2, while the outdoor module collects contextual environmental data.

The architecture ensures that data from the indoor module is directly transmitted to Netatmo's cloud server via the household's Wi-Fi. The outdoor module relays its data through the indoor module. A key feature of this system is Netatmo ' s account-specific data management, which allows for unlimited storage and access through an Application Programming Interface (API). This makes the system extensible and suitable for integration into custom platforms.

A data management platform developed in our previous work [12] played a critical role in aggregating data from multiple Netatmo devices installed in different households. This was achieved by linking each device to its corresponding user account.

To maintain data freshness and usability, updates are performed every five minutes. The data is stored in BSON (Binary JSON) format using MongoDB, a document-oriented database. The backend is hosted on Heroku, a cloud platform-as-a-service. Table 2 summarizes the development environment.

3.2.2 Information Generator

This module analyzes real-time and historical sensor data to provide personalized recommendations that support a productive indoor environment. It generates four categories of information:

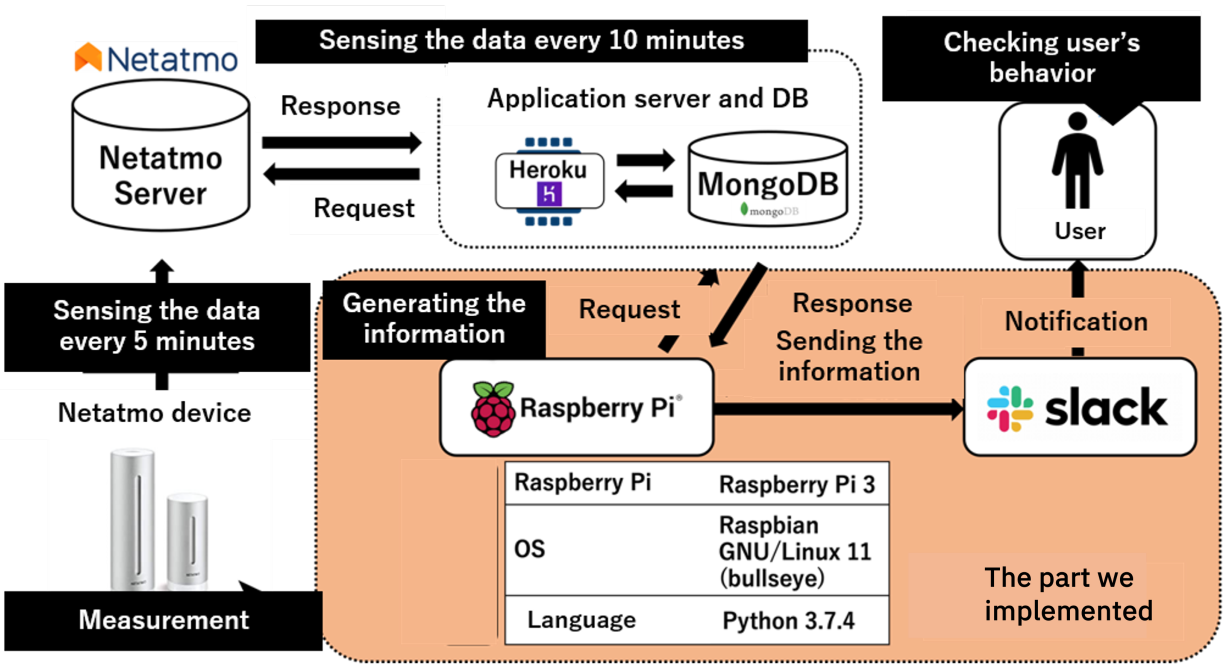

Figure 2: System overview (highlighting the parts we implemented)

Table 2: Development environment of the platform

Component	Server-side	Client-side
OS	macOS	macOS
Language	Node.js (v10.18.1)	HTML, CSS, (SCSS), JavaScript
Library	express, ejs, crypto, Socket.IO	Vue.js, Bootstrap-Vue, Core UI, Chart.js, Axios
Database	MongoDB	–

Table 3: Ideal working environment

Category	Detail
CO_2 concentration	Less than 1000 ppm
Temperature	17–28 ° C
Relative humidity	40–70%

1. **Current Indoor Environment Status:** Real-time values of temperature, humidity, and CO_2, along with immediate guidance.
2. **Daily Environmental Trends:** Graphical representations of fluctuations throughout the day, annotated with explanatory comments.
3. **Historical Analysis:** Suitability rates for the previous day and week, with averages and actionable advice.
4. **Guided Articles:** Informative content to help users maintain or improve their indoor environment.

To determine optimal indoor conditions, the system references Japanese building environmental hygiene standards [10], as shown in Table 3 [13].

Table 4: Definitions of Information Types

Type	Definition
Type 1	Current indoor environment status (temperature, humidity, CO_2) with immediate guidance.
Type 2	Daily environmental trends (8:00–19:00) with annotated comments.
Type 3	Historical adequacy rates for the previous day/week with averages and advice.
Type 4	Informative articles or tips to maintain/improve indoor environment.

Table 5: Conditional branching and comments in humidity (current status)

Condition	Comment
40–70%	Humidity is within the optimal range. Maintain current conditions.
$< 40\%$	Air is too dry. Consider humidification to reduce fatigue and discomfort.
$> 70\%$	Humidity is high. Ventilate or dehumidify to prevent discomfort and mold.

The system evaluates each metric using predefined conditional logic.

Table 4 summarizes the definitions of the four information types used in this study for clarity.

Table 5 and Table 6 show the rule sets for current humidity and CO_2 conditions, respectively.

Information of type 2 provides visualized summaries and commentary on the fluctuation of temperature, humidity, and CO_2 concentration from 8:00 to 19:00. The conditional rules for interpreting these trends are shown in Tables 7–9.

The system also evaluates how well the indoor environment

Table 6: Conditional branching and comments in CO_2 (current status)

Condition	Comment
< 1000 ppm	CO_2 levels are within the optimal range. Good air quality. Keep maintaining ventilation.
1000–2000 ppm	Slightly elevated CO_2 levels detected. Consider ventilating the room soon.
> 2000 ppm	High CO_2 concentration detected. Immediate ventilation is recommended to avoid fatigue and decreased concentration.

Table 7: Conditional branching and comments in temperature (daily trends)

Condition	Comment
18–28 ° C	Today ' s room temperature was optimal. Maintain this range.
< 18 ° C or > 28 ° C	Readings were outside the optimal range. Adjust temperature for comfort and productivity.

met the defined standards, expressed as an " adequacy rate. " Tables 10–12 summarize these assessments.

Every day at 12:00, the system generates and sends summary reports highlighting the relationship between indoor environmental conditions and productivity. These recommendations are grounded in scientific evidence and are intended to raise user awareness and promote behavior change.

3.2.3 Information Notification

The system implements three types of notification functions, all of which are delivered via Slack [14], a chat-based communication tool. Each participant had a dedicated Slack channel, and a bot named "Indoor Environment Notification Bot" dispatched the notifications. The features include:

1. Periodic notifications that deliver the four types of environmental information previously mentioned.
2. Alerts triggered when humidity or CO_2 levels exceed predefined thresholds.
3. Interactive chatbot responses to user inquiries regarding the current environment.

Details of each function are as follows:

Table 8: Conditional branching and comments in humidity (daily trends)

Condition	Comment
40–70%	Humidity levels were ideal today. Maintain this range.
< 40% or > 70%	Humidity was outside the ideal range. Adjust to avoid fatigue.

Table 9: Conditional branching and comments in CO_2 (daily trends)

Condition	Comment
< 1000 ppm	Great condition. CO_2 levels were consistently low. Maintain ventilation.
≥ 1000 ppm	Some elevated CO_2 readings detected. Increased ventilation is recommended.

Table 10: Temperature adequacy and comments

Adequacy Rate	Comment
> 80%	100% adequacy with average temperature of 23.3 ° C. Maintain range.
60–80%	Adequacy rate was 74% (avg: 18.9 ° C). Nearly optimal.
40–60%	Adequacy rate was 50% (avg: 16.2 ° C). Improvement needed.
< 40%	Only 19% adequacy (avg: 13.2 ° C). Adjust temperature to optimal range.

(1) Periodic Information Delivery The system sends scheduled updates during work hours. These are concise to avoid interfering with the user ' s workflow. Figure 3 shows a sample notification of information type 1, where the system delivers current indoor environmental values and simple status messages. Figure 4 illustrates a time-based CO_2 trend graph corresponding to information type 2.

(2) Real-Time Alerts Sensor data are collected every 30 minutes. When threshold conditions are met, the system sends alert messages with brief evaluation and recommended actions.

(3) Interactive Chatbot for PMV Feedback When a user sends a message with specific keywords (e.g., "working environment"), the chatbot responds with a thermal comfort analysis. This analysis uses the Predicted Mean Vote (PMV) index, which reflects human thermal comfort based on six parameters: four environmental (temperature, humidity, air velocity, and mean radiant temperature) and two personal factors (clothing insulation and metabolic rate).

The PMV index ranges from -3 (cold) to +3 (hot), with 0 indicating thermal neutrality. The system estimates:

- Air velocity: assumed 0.1–0.3 m/s
- Radiant temperature: equal to room temperature
- Metabolic rate: fixed at 1.3 METs (sedentary desk work)

Table 11: Humidity adequacy and comments

Adequacy Rate	Comment
> 80%	100% achievement (avg: 50%). Maintain 40–70%.
60–80%	84% adequacy (avg: 44%). Close to target.
40–60%	50% adequacy (avg: 39%). Fatigue may increase. Improve humidity.
< 40%	Only 18% adequacy (avg: 20%). Active humidification recommended.

Table 12: CO_2 adequacy and comments

Adequacy Rate	Comment
> 80%	Excellent air quality maintained (avg: *e.g.* 620 ppm).
60–80%	Adequacy rate was 72% (avg: *e.g.* 1,050 ppm). Satisfactory.
40–60%	Adequacy rate was 50% (avg: *e.g.* 1,400 ppm). Improve ventilation.
< 40%	18% adequacy (avg: *e.g.* 2,100 ppm). Increased CO_2 risk. Ventilation needed.

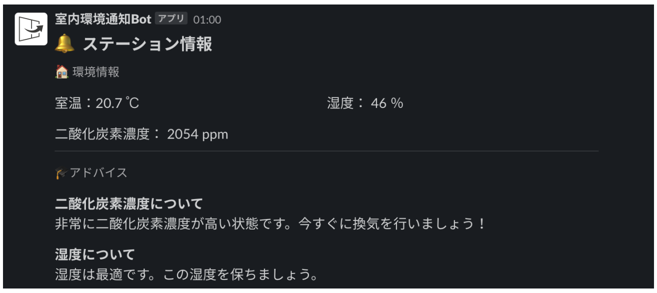

Figure 3: Example of information type 1: current indoor environmental status notification

- Clothing insulation: selected by user from Table 13 [16]

Based on the user's input, the system calculates the PMV value and returns tailored feedback.

4 EXPERIMENT

4.1 Overview of the Experiment

The main objective of this experiment was to evaluate the effectiveness of the proposed system in promoting environmental awareness and behavioral change in telework environments. Using the Netatmo sensor system, indoor environmental data were collected over a period of 33 weekdays between November 10 and December 28, 2022. Based on the collected data, personalized environmental feedback was generated and delivered to participants.

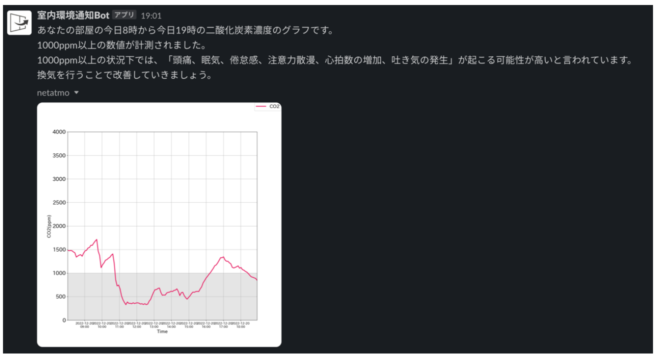

Figure 4: Example of information type 2: CO_2 trend notification

Table 13: Relationship between clothing type and insulation level (clo) [15]

Clothing Type	Clo Value
Collarless short-sleeve shirt and shorts	0.3
Short-sleeve shirt and pants	0.5
Long-sleeve shirt and pants	0.7
Long-sleeve shirt and jacket/sweater	1.0
Thick suit and vest	1.5

Table 14: Participant attributes of the study

Attribute	Participant A	Participant B	Participant C
Age	50s	40s	20s
Gender	Male	Male	Female
Occupation	Engineer	Technical Sales	Office Worker
Residence Type	Apartment	Apartment	Apartment
Workplace Location	Study	Living Room	Living Room
Workplace Size (m^2)	18	22	14

In addition to sensor data analysis, structured interviews were conducted before, during, and after the experiment to assess participants' perceptions of system usability, relevance, and impact on their telework practices.

4.2 Participant Demographics

Three participants residing in the Kanto metropolitan area and engaged in telework took part in the experiment. They ranged in age from their 20s to 50s and represented diverse occupational backgrounds. Table 14 summarizes their demographic and environmental attributes, based on responses to pre-, mid-, and post-experiment questionnaires.

4.3 Experimental Method

This section outlines the procedures used to implement the experiment, including device preparation and participant setup.

4.3.1 Participants

Before the start of the experiment, the following preparatory steps were taken:

1. Creation of user accounts for both Netatmo and Slack platforms.
2. Configuration of devices and association with corresponding user accounts.
3. Delivery and installation guidance for each participant.

Table 15 lists the components included in the experimental device kit.

Participants were instructed to place the indoor module in their telework workspace, and the outdoor module in a semi-protected location such as a veranda or window area, avoiding direct exposure to rain and wind.

Table 15: Contents of the experimental kit

No.	Details
1	Netatmo Weather Station outdoor module
2	Netatmo Weather Station indoor module
3	AC adapter for the indoor module
4	Kit bag
5	Covering letter

4.3.2 Pre-experiment Questionnaire

A preliminary survey was conducted to understand participants' baseline awareness of their teleworking environments and potential areas for improvement. The questionnaire was implemented using Google Forms [17], and was inspired by a similar survey developed by Daikin Industries [18], [19].

Participants were asked about housing type (e.g., detached house, condominium, apartment), environmental conditions (e.g., dust, temperature, humidity, ventilation), and the presence of issues such as mold, stale air, or noise. Additionally, they were asked to indicate which improvements they considered necessary, such as updating furniture (e.g., desk, chair, monitor), enhancing appliances (e.g., air conditioners, humidifiers), or routine cleaning habits.

4.3.3 Questionnaire During the Experiment

Although all participants primarily worked remotely, occasional office visits occurred. Since the study focused on telework, participants were asked to complete a daily survey using SurveyMonkey [20]. The questionnaire recorded their work location, working hours, and their evaluation of both the work tasks and environmental conditions.

4.3.4 Post-experiment Questionnaire

To evaluate the effectiveness of the system and capture any shifts in participants' environmental awareness, a post-experiment questionnaire was administered. Table 16 summarizes the questionnaire items.

5 EVALUATION

The aim of this study was to improve the quality of telework environments. This section evaluates the effectiveness of the proposed system in achieving that goal, based on experimental outcomes.

5.1 System Evaluation

To assess system performance, we analyzed how consistently it delivered information to participants on their work-from-home days.

The system generated four types of environmental notifications, along with alerts triggered by bi-hourly monitoring of humidity and CO_2 levels. It also featured a chatbot that responded to participant inquiries regarding the current environment.

Table 16: Post-experiment questionnaire items

No.	Question
1	Where did you position the indoor module?
2	Where was the outdoor module placed?
3	What are the dimensions of the room where the device was set up? (in square meters)
4	Was the installation process for Netatmo intuitive?
5	Was the notification frequency of once per hour satisfactory?
6	Please elaborate on your answer to question 5.
7	Was receiving a daily summary notification at 19:00 suitable for you?
8	Please elaborate on your answer to question 7.
9	Was the 8:00 AM summary notification (recapping the previous day/week) convenient?
10	Please explain your response to question 9.
11	Was the 12:00 PM informational column notification helpful?
12	Please explain your response to question 11.
13	Do you have further comments regarding the column feature?
14	Which type of indoor environmental data did you find most valuable?
15	In your opinion, did the system improve your work environment?
16	What aspects of your home environment present challenges when telework? (Select all that apply.)
17	Are there tools or devices you are considering investing in to enhance your telework experience?

Table 17 summarizes the number of notifications delivered, separated by participant and time of day (during vs. outside working hours).

We define the "adequacy rate" for a variable (temperature, humidity, or CO_2) as the percentage of measurements that satisfy the standard in Table 3 during work hours (8:00–19:00) on teleworking days:

We define the "adequacy rate" for a variable (temperature, humidity, or CO_2) as the percentage of measurements that satisfy the standard in Table 3 during work hours (8:00–19:00) on teleworking days. It is calculated as the number of measurement samples that meet the standard divided by the total number of measurement samples taken during work hours, multiplied by 100:

$$\text{Adequacy Rate (\%)} = \left(\frac{\text{samples within standard}}{\text{samples during work hours}} \right) \times 100 \tag{1}$$

Table 18 presents the calculated provision rates for each participant and information type.

5.2 Questionnaire Evaluation

Following the experiment, participants were asked to complete a post-experiment questionnaire. This section summarizes the results related to system usability, notification interval preferences, and perceived usefulness of the delivered

Table 17: Number of notifications delivered during the experiment

Function	Type	Participant A		Participant B		Participant C	
		Work hours	Off hours	Work hours	Off hours	Work hours	Off hours
Notification	Type 1	182	296	160	349	82	134
	Type 2	20	20	9	-	-	-
	Type 3	13	14	5	-	-	-
	Type 4	13	14	5	-	-	-
Alert	Humidity	42	149	0	0	0	0
	CO_2	94	7	255	537	7	45
Chatbot	–	0	0	0	0	0	0

Table 18: Information provision rate (system availability)

Type	A	B	C
Type 1	84%	84%	83%
Type 2	83%	83%	83%
Type 3	100%	100%	100%
Type 4	100%	100%	100%

Table 19: Participants ' evaluation of improvements in their work environment (5-point scale)

Information Type	A	B	C
Type 1	4	4	4
Type 2	5	5	4
Type 3	3	5	4
Type 4	4	5	4

information.

5.2.1 Device Installation Difficulty

System usability was evaluated based on the ease of device installation. Participants rated the difficulty on a 5-point scale, where 1 indicated high difficulty and 5 indicated ease. The average rating was 4.5, suggesting that the installation process was generally straightforward and accessible.

5.2.2 Notification Frequency Evaluation

Participants evaluated the frequency of each type of information notification using a 5-point scale, where higher values indicated greater satisfaction with the interval. Table 19 presents the results.

Participants noted that Type 3 notifications, which provided daily or weekly summaries, were helpful in establishing awareness early in the day. However, Type 4 notifications delivered at noon were more difficult to engage with, as they coincided with the lunch period (12:00–13:00).

5.2.3 Perceived Usefulness of Information

Participants were also asked to evaluate the usefulness of each type of information. Ratings were based on a 5-point scale, where 5 indicated the highest perceived value. Types 2 and 3, which correspond to daily summaries, were grouped together. Table 20 summarizes the responses.

Table 20: Perceived usefulness of each information type (5-point scale)

Information Type	A	B	C
Type 1	3	5	4
Type 2 and 3	5	5	4
Type 4	3	5	4

5.3 Improvement of Work Environment

This section examines how the proposed system contributed to improving participants' work environments.

5.3.1 Quantitative Evaluation

Quantitative assessment was conducted using environmental data collected during telework days. Metrics included average temperature, humidity, and CO_2 concentration, along with an evaluation of consistency and stability. Figure 5 visualizes these metrics.

Participant A: Maintained stable temperatures, but experienced fluctuation in humidity. CO_2 concentration remained moderate, though environmental stability was inconsistent.

Participant B: Maintained stable temperature and humidity, but CO_2 levels were unstable across telework days.

Participant C: Demonstrated stable environmental conditions across all parameters.

5.3.2 Qualitative Evaluation

Qualitative insights were derived from post-experiment questionnaires. Table 21 summarizes participants' self-reported actions related to environmental control.

While basic monitoring practices were in place before the experiment, Table 22 reflects improvements in how participants used the data to optimize their work environments.

6 DISCUSSION

6.1 Information Notification System

This section discusses the functionality and effectiveness of the information notification system based on evaluation re-

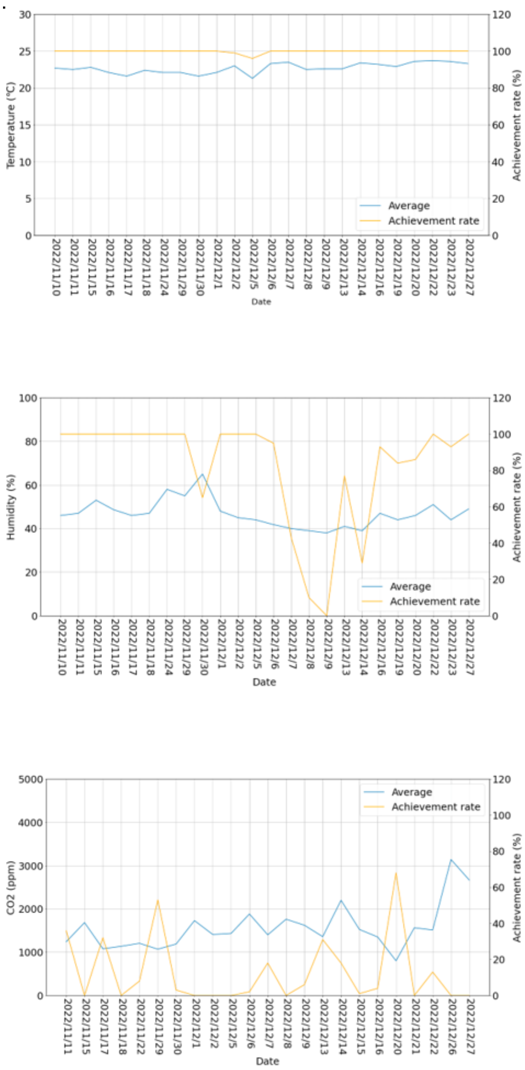

Figure 5: Environmental data of a representative participant

sults.

The system was designed to periodically deliver four types of environmental data aimed at improving participants' work environments. In addition, it included an interactive chatbot feature for on-demand feedback. The system demonstrated stable performance overall, as reflected in high data provision rates.

A notable exception occurred between November 14 and 21, during which the system experienced downtime due to an authentication issue with the Heroku server hosting the backend. This incident temporarily interrupted the delivery of Information Types 1 and 2. Nevertheless, the core functionality of the system remained unaffected and resumed normal operation after resolution.

Despite the inclusion of the chatbot, participants predominantly interacted with the automated notifications. Limited usage of the chatbot may be attributed to work-related constraints or user preferences for passive, rather than active, feedback mechanisms.

Table 21: Actions taken to manage the telework environment

Question	A	B	C
Do you use air conditioning, humidifiers, or ventilation to regulate your telework environment?	Yes	Yes	Yes
Do you monitor room temperature, humidity, and CO_2 concentration using any equipment?	Yes	Yes	Yes

Table 22: Participant evaluation of work environment improvement (5-point scale)

Question	A	B	C
System's contribution to a good work environment	5	4	5
Intent to continue improving the work environment	5	5	5

6.2 Discussion Derived from Questionnaire Results

This section discusses key insights gained from the pre-, mid-, and post-experiment questionnaires.

6.2.1 Information Notification System

Post-experiment responses indicated generally positive impressions of the information notification system. Participants found the four categories of presented information useful, particularly appreciating the clarity and conciseness of hourly notifications.

6.2.2 Improvement of Work Environment

Participants reported increased awareness of environmental conditions due to system feedback. Table 23 presents the nature of work and the total number of workdays during the experiment, based on mid-experiment responses.

For example, Participant A noticed low humidity levels in early December and began using a humidifier after receiving notifications. Conversely, despite frequent CO_2 alerts, Participant B made no changes, citing concerns such as room temperature drops, external noise during meetings, and a tightly packed schedule. These insights suggest that while the system effectively raised awareness, behavioral change was also influenced by environmental and contextual constraints.

Suggestions for automating environmental regulation were noted. However, integrating automated HVAC or ventilation

Table 23: Type of work and total days during the experiment

Type of Work	A	B	C
Office work	0	2	5
Meetings	11	14	3
Programming	12	0	0
Document writing	13	12	3
Thinking	5	5	0
Other	0	0	0

controls may present technical challenges. The primary barrier was information presentation, and improvements in that area (as discussed in Section 6.1) may foster stronger behavioral responses.

6.2.3 Questionnaire Considerations

The questionnaires were useful in evaluating the effectiveness of the system in enhancing awareness and promoting action. While some participants already had awareness of temperature, humidity, and air quality issues, the post-experiment feedback revealed increased motivation to act on this information.

Additionally, daily work-from-home tracking via the mid-experiment questionnaire successfully contextualized behavioral data. Future improvements may include querying participant schedules in advance to deliver more tailored environmental recommendations, such as optimal ventilation timing.

7 CONCLUSION AND REMARKS

Over the course of a two-month experiment, we evaluated a system designed to support behavioral improvements in telework environments through personalized environmental feedback. The results confirmed the system ' s potential utility in raising awareness and encouraging positive behavioral change among participants.

However, certain limitations were also identified. Notably, the use of Slack as the primary communication channel posed challenges, particularly in terms of reviewing historical messages due to its chat-oriented design. These insights will inform future iterations of the system, including potential improvements to information delivery interfaces and automation features.

Acknowledgments

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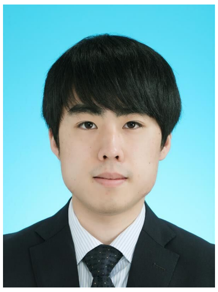

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Regular Paper

Proposal of a Spherical POV Heatmap using Mixed Reality in 360-degree Internet Live Broadcasting

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Abstract 360-degree internet live broadcasting enables viewers to change their point of view (POV) while watching the 360-degree live video and has an issue that the broadcaster cannot check the viewers' POV. To solve the issue, we have proposed a spherical POV heatmap using Augmented Reality (AR) on a smartphone so that the broadcaster can be aware of the viewers' POV. Although the spherical POV heatmap reduced communication errors, the response time increased due to the need to check the heatmap on a smartphone. In this paper, we propose a new spherical POV heatmap using Mixed Reality (MR) through an MR headset. The proposed system displays the heatmap in real space through the MR headset and reduces the response time by eliminating the need to check the smartphone. We implemented a prototype system and found it could reduce the response time through the evaluation.

Keywords: 360-degree Internet Live Broadcasting, Viewers' POV, Mixed Reality.

1 INTRODUCTION

360-degree video frees viewers from the constraints of viewing direction. The viewers can change their point of view (POV) and enjoy all directions of the video. Recently, 360-degree video has also been introduced in internet live broadcasting, where the viewers can typically communicate with the broadcaster via text chat. However, there is an issue that the broadcaster cannot check the viewers' POV in the 360-degree internet live broadcasting. Since the broadcaster does not know what the viewers saw and commented on, it can cause communication errors between the broadcaster and the viewers.

To solve the issue, we have proposed a spherical POV heatmap using Augmented Reality (AR) technology [1][2] (hereinafter called AR spherical POV heatmap). The AR spherical POV heatmap displays a spherical heatmap of the viewers' POV on a QR code using AR technology through a smartphone screen. The broadcaster checks the AR spherical POV heatmap and can know which direction the viewers are watching. Although it can reduce communication errors between the broadcaster and the viewers, it increases the response time to viewer comments due to the need to check the heatmap on the smartphone. The response time should be short to realize smooth communication between the broadcaster and viewers.

To overcome the disadvantage of the AR spherical POV heatmap, we propose a new spherical POV heatmap using Mixed Reality (MR) technology (hereinafter called MR spherical POV heatmap). The MR spherical POV heatmap displays a spherical heatmap of the viewers' POV on top of the omnidirectional camera in real space using the MR technology through an MR headset. Since the broadcaster can check the MR spherical POV heatmap in real space, it is expected that the response time to viewer comments can be shortened.

The contributions of this paper are summarized as follows:

- We developed and evaluated a prototype system of the MR spherical POV heatmap using HoloLens 2.
- We clarified that the MR spherical POV heatmap enabled the broadcaster to reduce the response time to viewer comments.

The rest of this paper is organized as follows. Section 2 describes related work and the AR spherical POV heatmap in the 360-degree internet live broadcasting as our previous work. Section 3 describes an overview of our proposed system. Section 4 describes the implementation of the prototype system. Section 5 describes an evaluation experiment to clarify the effects of the proposed system. Section 6 summarizes this study.

2 RELATED WORK

In this section, firstly we describe the role of eye gaze in human communication and the need to grasp viewers' POV for the broadcaster. Then, we describe the effectiveness of introducing MR technology in remote communication. At last, we show the detail of the AR spherical POV heatmap in our previous study and its issues.

2.1 Role of Eye Gaze in Communication

Many studies have described the importance of the eye gaze in human communication. Roel [3] proposed the GAZE Groupware System which was a study on the eye gaze information in human communication. This research verified the transmission of non-verbal information in a multi-participant teleconference system. He studied whether natural communication can be performed by conducting a meeting with non-verbal information in a virtual conference room. He discovered an issue that it was difficult to present eye gaze information in the system. This study concluded that who talked about what with whom would be analyzable if it was possible to show the eye gaze directions of the communicatees. David [4] also found the eye gaze information was an important factor that affected task performance in cooperative work. From these studies, the eye gaze is important information to express the communicatee's intentions and essential information in remote communication. ClearBoard [5] is a shared drawing medium which realizes a seamless shared drawing space and eye contact to support real-time remote collaboration by two users. They found "gaze awareness" is a most important feature for the collaboration.

The eye gaze information has been often represented on the flat display two-dimensionally. Angelo [6] investigated how remote pairs made use of gaze cursors which tracked their eye gaze on the display during a tightly coupled collaborative task. They found that the remote pairs used the gaze cursor to circumscribe the referential domain and they were also able to coordinate by indicating with both gaze and language to ground on the pieces. Xu [7] designed a hybrid meeting system which used an omnidirectional camera in the meeting room so that remote participants could look around. It also showed local participants where the remote participants' gazes were directed on a display such as a tablet PC under the omnidirectional camera. They found that it could provide powerful social cues, in ways similar to that of real gaze.

Several studies represent the eye gaze information in the real space three-dimensionally. OmniGaze [8] is a method for three-dimensionally displaying gaze information in telepresence. In this method, an omnidirectional camera is covered by a LED matrix display, and the lighting of the LED indicates the gaze information of a remote user. From the results of the evaluation experiment, it was clarified that the light information of the LED display on the sphere surface was effective for presenting the gaze information of a remote user. ThirdEye [9] is an add-on eye display that shows a remote participant's gaze direction. It improves the gaze estimation accuracy compared to the case where the remote participant's face is shown on a flat display. It indicates eye gaze information as 3D information in the real space is more effective than 2D information on a flat display.

Since the viewers' POV indicates directions where the viewers are watching centered on an omnidirectional camera, it has similar roles to eye gaze in remote communication. In this study, the viewers' POV is used for the same meaning as the eye gaze. Moreover, since eye gaze information should be shown as 3D information in the real space for remote communication, we try to introduce MR technology to show the information.

2.2 Effectiveness of MR

MR is a technology that displays holograms of virtual objects in real space and the users can interact with the holograms. Several studies show the effectiveness of MR in remote communication between users.

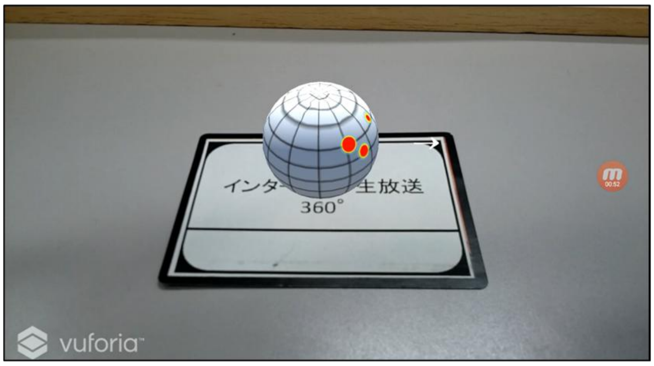

Figure 1: AR spherical POV heatmap through smartphone display

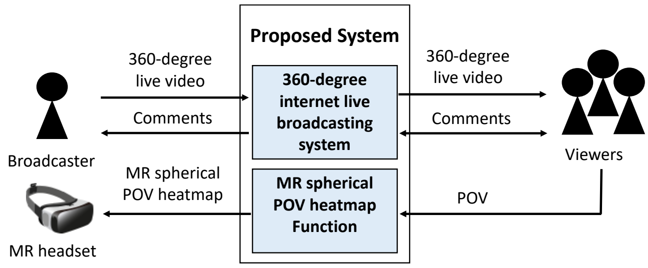

Figure 2: System model of the proposed system

Lee [10] developed an MR remote collaboration system that shared 360-degree live video. In this system, a hologram of the remote user's hand is displayed in real space through the MR device. The hand gestures by the hologram help to understand each other's focus and improve their communication. Johnson [11] studied the effect of MR guidance. An experiment was conducted to understand how to provide explicit spatial information in a collaborative MR environment. From the experiment, the result showed the MR guidance realized effective referencing through deixis.

Several studies also show the effectiveness of the hologram for remote communication [12-14]. From the related work, the improvement of communication between the broadcaster and viewers can be expected by introducing the MR technology to the POV heatmap in 360-degree Internet live broadcasting.

2.3 AR Spherical POV Heatmap

The AR spherical POV heatmap shows a sphere that represents the broadcasting space on an AR marker through a smartphone as shown in Fig. 1. The spherical heatmap visualizes the viewers' POV by displaying the angular coordinate vector on the spherical surface as a heatmap. By synchronizing the direction of the image taken by the omnidirectional camera with the vector of the spherical heatmap, the broadcaster can grasp the viewers' POV in real space simply by checking the heatmap. In addition, the heatmap is easy to visualize multiple data at the same time. It is also possible to check the POV of multiple viewers. By checking the density pattern of the viewers' POV on the

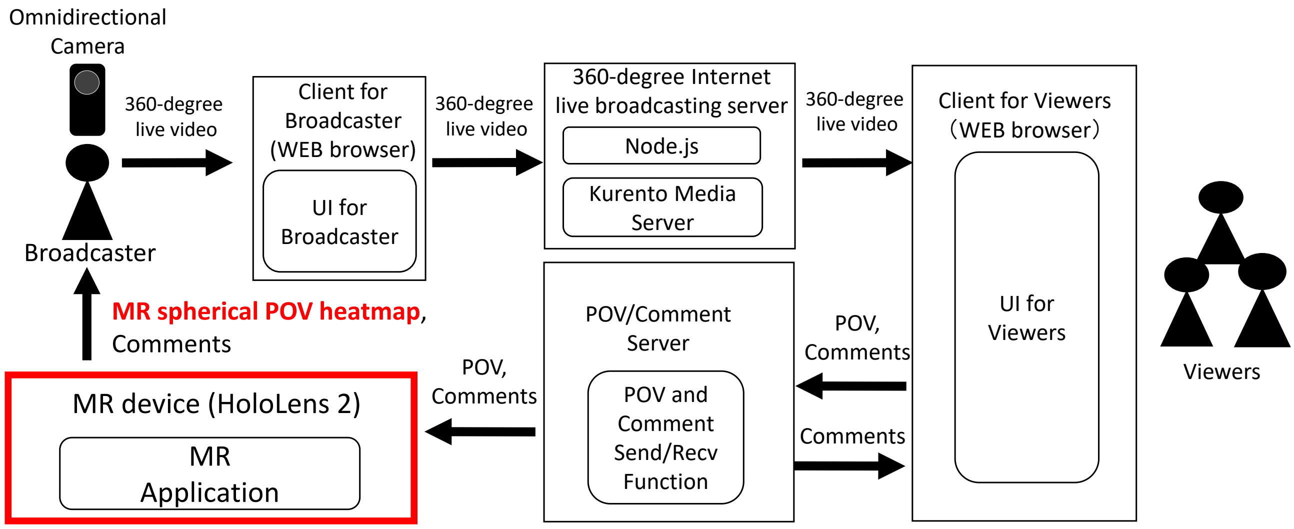

Figure 3: System architecture of the prototype system

heatmap, the broadcaster can grasp where many of the viewers are interested, and where the other viewers of the minority are watching. Therefore, it gives some hints about the viewers' interests and achieves smooth communication between the broadcaster and viewers.

In the evaluation experiments, the AR spherical POV heatmap could reduce communication errors by visualizing the viewers' POV and the speaking timing is easier for the broadcaster to grasp when waiting for the viewers' attention. On the other hand, the time it takes for the broadcaster to respond to the viewer's comment was increased by approximately 10 seconds compared with the broadcasting without the AR spherical POV heatmap. This result was due to the time required to check the heatmap through a smartphone. If the wasted time can be eliminated, the effectiveness of the spherical POV heatmap can be improved.

3 PROPOSED METHOD

In our previous study [1][2], the issue was that checking the viewers' POV was a burden for the broadcaster. This is because the spherical POV heatmap was implemented using AR and forced broadcasters to check their smartphone to see the heatmap. To solve this issue, we propose a system that displays the spherical POV heatmap using MR technology through an MR headset. The proposed system is expected to eliminate the need to confirm the POV heatmap using a smartphone in the previous study. The use of a head-mounted type MR device also solves the issue of both hands being occupied and reduces the burden on the broadcaster in 360-degree internet live broadcasting.

Figure 2 shows a system model of the proposed system. The proposed system consists of a 360-degree internet live broadcasting system and an MR spherical POV heatmap function. The broadcaster sends a 360-degree live video to the proposed system and the viewers watch the live video. The viewers send comments to the proposed system, which are sent to the broadcaster and the viewers. The proposed system receives viewers' POV in real-time and makes an MR spherical POV heatmap. The MR spherical POV heatmap is provided to an MR headset of the broadcaster.

The proposed system is expected to have several advantages by reducing the burden on the broadcaster as follows: (1) the time it takes for the broadcaster to respond to the viewer's comment is expected to be shorter than the previous study with few communication errors, (2) the speaking timing is easier for the broadcaster to grasp than the previous study when waiting for the viewers' attention. The advantages of the previous study will be further enhanced, and the disadvantage is solved by the proposed system.

4 IMPLEMENTATION

We implemented a prototype system of the MR spherical POV heatmap using HoloLens 2. In this section, we describe the architecture of the prototype system and its main application.

4.1 System Architecture

The prototype system was implemented by replacing the AR spherical POV heatmap in the previous study with an MR application for the MR spherical POV heatmap. Figure 3 shows the system architecture of the prototype system. The red square in the figure shows new implementation in this study and the other parts are diverted from the previous study. In the prototype system, we used Microsoft HoloLens 2 as an MR headset for the broadcaster and THETA V as an omnidirectional camera.

A broadcaster can start 360-degree internet live broadcasting using the broadcaster client on a web browser. The 360-degree internet live broadcasting server distributes it to viewers. The viewer can watch the 360-degree live video using the viewer client on a web browser and send text comments to the comment server. The comment server forwards the received comments to the viewers and the

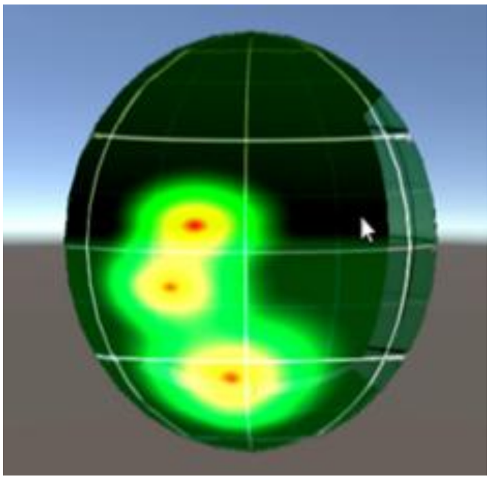

Figure 4: The heatmap when multiple viewers are watching from different POV

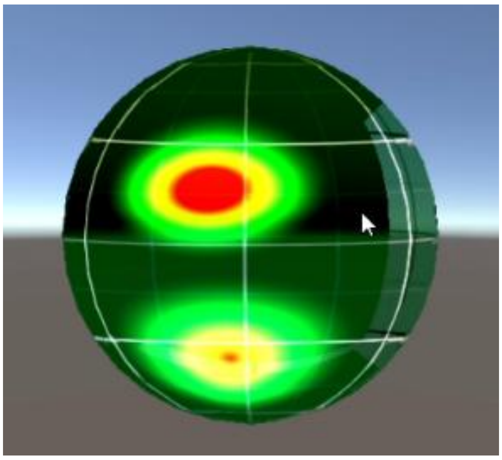

Figure 5: The heatmap when several viewers are watching in a particular POV

Figure 6: The user interface for the broadcaster through the HoloLens 2

broadcaster. The viewers can read the comments on their web browsers and the broadcaster can read the comments on the HoloLens 2. The viewer client also automatically sends the viewer's POV to the POV server every second. The POV is represented by spherical coordinates (r, θ, φ) where r denotes the radial distance, θ denotes the polar angle, and φ denotes the azimuthal angle. The POV server forwards the received viewers' POV to the MR application on the HoloLens 2.

4.2 MR Spherical POV Heatmap

The MR application on the HoloLens 2 is implemented by Unity and it shows a spherical POV heatmap and comments to the broadcaster. The MR application receives the viewers' POV and displays their heatmap on a sphere object which is shown above the omnidirectional camera. Based on a list of the viewers' POV received within a certain period, it creates circles for the heatmap. In this circle, the closer to the center, the higher the heat value, and the farther from the center, the lower the heat value. If a circle overlaps another circle, the heat values of the two circles are added and the overlapping area has a higher heat value.

Figure 4 shows an example of the heatmap when multiple viewers are watching the 360-degree live video from different POV. The broadcaster can see that the viewers' interests are dispersed in different directions. Figure 5 shows an example of the heatmap when several viewers' POV are concentrated. The broadcaster can see that several viewers are interested in a particular direction of the size of the red area.

Figure 6 shows the user interface for the broadcaster through the HoloLens 2. The MR application gets a coordinate and direction of the omnidirectional camera, and it displays the MR spherical POV heatmap which is fixed above the omnidirectional camera. The comment window tracks the broadcaster's sight so that the broadcaster can read the viewers' comments. The MR spherical POV heatmap is updated every second. The broadcasters can walk freely around the room wearing hololens2.

The backside heatmap color of the MR spherical heatmap is not visible unless the broadcaster goes around to the backside. This implementation was chosen because the information on the front heatmap overlaps with the information on the back heatmap, making it difficult to see.

In this study, we implemented this method to verify whether the display method used in the previous study, the AR spherical heatmap, could be improved using MR technology to reduce the effort required for confirmation. On the other hand, another implementation method that could be considered is to display the heatmap directly on the object itself in the direction the viewer is looking. However, issues such as the heatmap being difficult to see when it is outside the broadcaster's field of view were anticipated, so we decided to implement this method in the future.

5 EVALUATION

We conducted an evaluation experiment using the prototype system compared with the AR spherical POV heatmap. In this section, we describe the evaluation environment and the results.

5.1 Environment

The experiment was conducted under the same conditions as in the previous study [2]. The purpose of the experiment

was to confirm whether the MR spherical POV heatmap reduced the burden on the broadcaster compared to the AR spherical POV heatmap.
Each experiment was conducted with one broadcaster and three viewers, for a total of four times. The role of broadcaster was performed by one different participant in the experiment at each time. This number of experimental participants was set because the use case in the previous study [2] assumes a single broadcaster and a small-scale internet live broadcast with less than 10 participants. The broadcasters and viewers are students at Iwate Prefectural University who have experience using computers but little experience using MR applications. The broadcaster and viewers were in different rooms in the experiment. The equipment used in the experiment was one notebook PC for the broadcaster, three laptop PCs for the viewers, one PC for the server, Ricoh Theta V for the omnidirectional camera, and HoloLens 2 for the MR headset.

The content of the broadcast was a chat about objects in the broadcaster’s room. In the room, there were various objects. The viewers commented on objects in the broadcaster’s room freely changing their POV. The procedure of the experiment is as follows:

- [Practice] The broadcaster and viewer practice the operation of the prototype system for 5 minutes.
- [Task 1] One of the viewers sends a designated question comment to the broadcaster 4 times at 3-minute intervals.
- [Task 2] The broadcaster directs the viewer's attention to a specified object and chats about it 3 times at 2-minute intervals.
- [Questionnaire] The viewers and broadcaster are given a 5-point scale questionnaire for each task.

In Task 1, the viewer communicates to the broadcaster by sending a question comment about an object in the room, such as "What kind of animal is this stuffed animal?". The text to be sent, the timing of the comment, and the object to which the viewer is directed are specified in the procedure manual. The broadcaster determines which object the viewer is commenting on and responds to the viewer's comment. If the broadcaster understands what the viewer is commenting on, the time it takes for the broadcaster to respond correctly to the viewer’s comment is expected to be shorter. We measure the time and define it as the *response time*. We also count the *number of communication errors* if the broadcaster makes a mistake with the object the viewers are talking about.

In Task 2, the broadcaster points to a specified object and instructs the viewers "Please look at this". The broadcaster starts chatting with the viewers about the object when their POV are gathered. If the broadcaster is aware of the viewers’ POV, it is expected to be able to start chatting at the same time when the viewer's POV is gathered. We measure the time between the broadcaster's attention instruction to the viewers and when the broadcaster begins to speak. It is defined as the *wait time*.

The viewers and the broadcaster complete a questionnaire after each task. After Task 1, the viewers were asked a questionnaire on a 5-point scale to determine how correctly they felt the comments were conveyed to the broadcaster. After Task 2, the broadcaster was asked a questionnaire on a 5-point scale to determine how well the broadcasters felt being able to capture the timing of when to begin speaking.

Figure 7 shows the location of all objects, the fixed position of the MR spherical heatmap and the initial position of the broadcaster in the broadcaster’s room for Task 1. The MR spherical heatmap is displayed in a fixed position and does not move. The broadcaster can move freely within the area surrounded by desks and stand in front of the target object to speak. Four different types of objects (game consoles, laptop PCs, rackets, and stuffed animals) were prepared. Combinations using dashes, such as A and A', indicate target objects of the same type. For example, they are the same game console but differ in that one is stationary and the other is portable. This is to provide target objects of the same type that are difficult to distinguish when viewers refer to a particular game console. They are placed in different locations so that the same type of object was not in view at the same time. We also prepared other 6 objects (a programming book, a head-mounted display, a projector, a tablet PC, a desk light, and a music CD) in the broadcaster’s room for Task 2 as shown in Fig. 8. The conditions such as

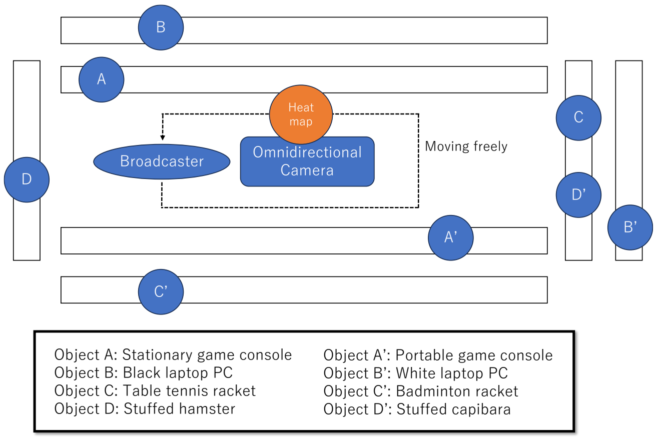

Figure 7: Location of all objects in the broadcaster’s room for Task 1

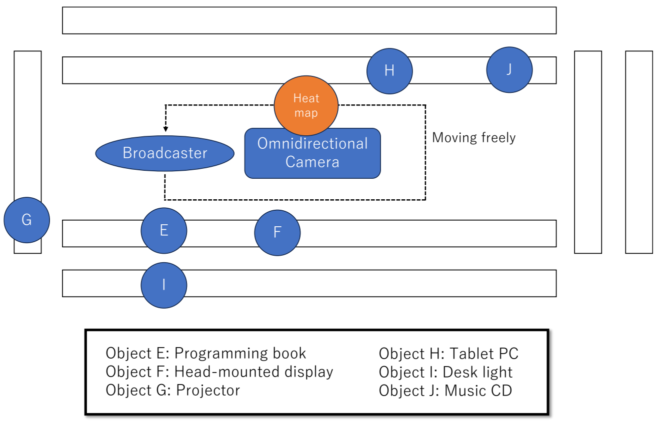

Figure 8: Location of all objects in the broadcaster’s room for Task 2

the initial position of the broadcaster and the fixed position of the MR spherical heatmap are the same as in Task 1.

In this experiment, only the MR spherical POV heatmap was performed, and the environment of the previous study [2] was reproduced and the target objects were used same ones. The evaluation results of the AR spherical POV heatmap are reused from the previous study [2]. Therefore, since the participants in the experiments using the MR spherical POV heatmap and the AR spherical POV heatmap are different, there is no effect of experimental order on learning. Although there is a possibility that differences in results may arise due to the skills of the participants in each experiment, we assumed that there would be no significant differences since the participants in each experiment had similar skills.

5.2 Results in Task 1

Table 1 shows the results of measuring the response time in the evaluation experiment for Task 1 using the MR spherical POV heatmap. Table 2 shows the result of measuring the response time under a similar environment in the previous study. The mean response time was 21.47 seconds for the MR spherical POV heatmap, compared to 30.88 seconds for the AR spherical POV heatmap. In comparison, the MR spherical POV heatmap reduced the response time by about 9 seconds. We conducted a Mann-Whitney U test for the results. There was a significant difference in the mean response time to find ($p = 0.001586 < 0.05$). One of the reasons for this result is that it was necessary to confirm the POV heat map by using an AR application with a smartphone when confirming the POV in the previous study. However, this procedure could be omitted by displaying the MR spherical POV heatmap in real space, and the response time could be reduced.

Table 3 and Table 4 show the results of measuring the number of communication errors using the MR and AR spherical POV heatmap respectively. In terms of the number of communication errors, there were 4 communication errors in the MR spherical POV heatmap, while there was no communication error in the AR spherical POV heatmap. This is because some broadcasters selected the target object without checking the MR spherical POV heatmap at the first time. The number of communication errors could be reduced to zero if checking the MR spherical POV heatmap.

Table 5 and Table 6 show the results of the questionnaire “How correctly you felt the comments were conveyed to the broadcaster?” on a 5-point scale when the broadcaster used the MR and AR spherical POV heatmap respectively. The mean score was 3.7 in case of the MR spherical POV heatmap, while it was 3.56 in case of the AR spherical POV heatmap. We conducted a Mann-Whitney U test for the results and there was no difference between the mean scores ($p = 0.70626 > 0.05$). From the results of this questionnaire, the MR spherical POV heatmap can shorten the response time while keeping the accuracy of the communication with the broadcaster from the viewers’ subjective point.

Table 1: The response time using the MR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object B'	15.34 sec	55.77 sec	16.04 sec	56.18 sec	21.47 sec
Object A'	41.92 sec	7.13 sec	27.16 sec	8.03 sec	
Object D'	14.69 sec	10.61 sec	31.23 sec	7.96 sec	
Object C'	11.61 sec	11.79 sec	16.78 sec	11.25 sec	

Table 2: The response time using the AR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object B'	45 sec	39 sec	46 sec	38 sec	30.88 sec
Object A'	29 sec	26 sec	29 sec	16 sec	
Object D'	35 sec	32 sec	24 sec	32 sec	
Object C'	29 sec	33 sec	13 sec	28 sec	

Table 3: The number of communication errors using the MR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Total
Object B'	0	2	0	2	4
Object A'	0	0	0	0	
Object D'	0	0	0	0	
Object C'	0	0	0	0	

Table 4: The number of communication errors using the AR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Total
Object B'	0	0	0	0	0
Object A'	0	0	0	0	
Object D'	0	0	0	0	
Object C'	0	0	0	0	

Table 5: The questionnaire result in case of the MR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object B'	4	3	5	2	3.7
Object A'	3	4	4	4	
Object D'	5	4	4	1	
Object C'	5	3	5	3	

Table 6: The questionnaire result in case of the AR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object B'	1	5	4	5	3.56
Object A'	4	3	4	4	
Object D'	4	2	5	4	
Object C'	3	3	3	3	

5.3 Results in Task 2

Table 7 and Table 8 show the results of measuring the wait time between the broadcaster's attention instruction to the viewers and when the broadcaster begins to speak in the evaluation experiment for Task 2 using the MR and AR spherical POV heatmap respectively. The mean wait time was 14.78 seconds for the MR spherical POV heatmap, compared to 16.67 seconds for the AR spherical POV heatmap. In comparison, the MR spherical POV heatmap shortened the wait time by approximately 2 seconds. Meanwhile, we conducted a Mann-Whitney U test for the results and there was no difference between the mean wait time ($p = 0.20402 > 0.05$). The MR spherical POV heatmap was not able to reduce the wait time although we expected to be able to reduce the time by eliminating the need to check the smartphone as with the previous result of the response time. One possible reason for this result is that when several heatmap circles were gathered into one heatmap circle, it was difficult to determine how many viewers were in the heatmap. In Task 2, the broadcaster provides an attentional instruction to a target object, and the viewer turns toward the viewing direction of the object. At this time, the heatmap circles are gathered into one heatmap circle, and the red area in the middle of the heatmap circle becomes larger. In the prototype system, when two heatmap circles overlap, the red area is clearly larger than when only one heatmap circle overlaps. However, when the number of overlaps increases from two to three, the red area is not as large as that from one to two, and it is difficult to understand the difference unless the broadcaster is accustomed to the display method. Since there were three viewers in the experiment, it was difficult to confirm that the POV of all the viewers had gathered to the target object, and this placed a burden on the broadcaster. Therefore, we consider that the wait time could not be reduced in the prototype system.

Table 9 shows the results of the questionnaire for the broadcaster, “How well you felt to be able to capture the timing of when to begin speaking?” on a 5-point scale when the broadcaster used the MR and AR spherical POV heatmap respectively. The mean score for the MR spherical POV heatmap was 3.25, compared to 4.5 for the AR spherical POV heatmap. The difference between MR and AR spherical POV heatmap was -1.25. We conducted a Mann-Whitney U test for the results and there was no difference between the mean score ($p = 0.08326 > 0.05$) while there was a trend. A possible reason for the lower score of the MR spherical POV heatmap compared to the AR spherical POV heatmap is that it is difficult to know how many viewers are there when several heatmap circles are gathered into one, as can be seen from the wait time result.

Furthermore, the broadcaster was asked to freely describe what they found advantages and what they found disadvantages about the prototype system. As an advantage point, many participants said that "it is easy to visually understand where the viewer is looking". As a disadvantage point, many participants said that "when the viewers’ POV is focused on one place, the heatmap becomes one circle, and it is difficult to grasp how many viewers are there".

Table 7: The wait time using the MR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object H	32.16 sec	4.8 sec	11.25 sec	9.03 sec	14.78 sec
Object I	14.9 sec	13.6 sec	12.56 sec	9.96 sec	
Object G	34.5 sec	15.2 sec	7.33 sec	12.05 sec	

Table 8: The wait time using the AR spherical POV heatmap

Target Object	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
Object J	10 sec	18 sec	24 sec	22 sec	16.67 sec
Object G	23 sec	15 sec	20 sec	20 sec	
Object F	12 sec	11 sec	13 sec	12 sec	

Table 9: The questionnaire result about the timing of when to begin speaking

Heatmap Type	1st Experiment	2nd Experiment	3rd Experiment	4th Experiment	Mean
MR	4	2	3	4	3.25
AR	4	5	4	5	4.5

There was also an opinion that "the conversation is delayed by one step because we have to look at the POV heatmap before speaking". This is because it is necessary to check the MR spherical POV heatmap above the omnidirectional camera before finding the target object. To solve this problem, instead of displaying the heatmap on a sphere, a method may be effective in which the heatmap is displayed directly on the target object.

6 CONCLUSION

We proposed the MR spherical POV heatmap to reduce the burden on the broadcaster in 360-degree internet live broadcasting, which displayed a spherical POV heatmap on the MR space. We compared it with our previous study, the AR spherical POV heatmap to clarify its advantages and issues. The results of evaluation experiments showed that the MR spherical POV heatmap reduced the response time compared to the AR spherical POV heatmap, and the objects could be found quickly. In addition, the use of the MR headset eliminated the need to check the smartphone and reduced the burden on the broadcaster. On the other hand, the wait time could not be reduced. One of the reasons for this result was that it was difficult to grasp how many viewers were there on the MR spherical POV heatmap. In future work, we will improve the way the heatmap circles are displayed so that it is more intuitive for the broadcaster to know approximately how many viewers are on the heatmap. Moreover, we will implement a method in which the heatmap is displayed directly on the target object.

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Regular Paper

Assessing the Impact of Communication Failures on Disaster Victims using a Communication Emulator

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Abstract - This paper analyzes the prediction of communication failures and their impact on information communication during a flood event using a communication failure emulator. Damage estimates related to communication in the event of a disaster are indicated by the number of disrupted lines. However, this method does not allow disaster victims to know when they will not be able to use the system and what kind of situation they will be in. In these days when information communication has become commonplace, such a situation could have a tremendous impact on the damage. Therefore, we propose a system that emulates communication failures in the event of a disaster and analyzes the impact from the user's perspective. We have performance study for our system with communication failures emulator and discuss its impact.

Keywords: flood disaster, communication failure, federation system

1 INTRODUCTION

1.1 Background

The number of disasters and the number of human casualties is steadily increasing in the world due to the complex intertwining of changes in the global climate system and global warming caused by greenhouse gases[1] [2]. Urban populations are expected to reach over 6 billion by 2050, with 68% of that population concentrated [3] in urban areas at risk of disaster. In particular, flood disasters have the highest number of human casualties, with about 3.39 million affected in 2018 [4], and the projections show further increases in these numbers.

Smart city technology is expected to realize resilient cities. Smart city technology uses Internet of Things (IoT) sensors to collect various data on cities, such as traffic flow, people flow, and weather, and uses AI to determine and predict the supply and demand of people living in cities in real time [5].The aim of smart cities is to create resilient cities that make our lives in cities with high disaster risks better.

Advances in cyber-physical systems, IoT, cloud computing, and other software technologies are actively contributing to the development of smart cities. Smart cities offer the basic capabilities of integrating sensors, actuators, and other devices into the physical environment of the city through a variety of technologies and computational techniques. Especially, simulation technology, one of the basic technologies of smart cities, playing an important role in service demand forecasting in physical spaces and prediction analysis in virtual spaces.

1.2 Motivation

Simulation is a traditional fundamental technology for imitating real-world events. Simulation techniques can be broadly classified into physical simulations (i.e., that physically model actual objects or physical phenomena) and logic simulations (i.e., that approximate state changes with continuous or discrete modeling). Case study application of simulation technologies is contributing to the study of production process management and productivity improvement measures in the supply chain, as well as to the upgrading of agricultural management systems based on weather data in the field of agriculture. These manufacturing and agriculture smart city objectives can be said to be relatively simple simulations and system optimizations. For example, in agriculture, the change in weather can be represented by a physical phenomenon model, and the growth of agricultural products can be represented by a real model given conditions. In other words, these objects and phenomenon can be described by physical simulation.

By contrast, in the field of disaster researches, various types of simulations are required to explain complicated phenomena. The magnitude of disaster damage is determined by the disaster phenomena and the vulnerability of elements, such as urban spatial structure and human behavior, against them. Therefore, in order to extend the smart city to the field of disaster prevention and contribute to realizing resilient cities, it is necessary to handle various physical and social phenomena. The problem is that the simulations of each phenomenon to be handled are modeled with different principles. Disaster phenomena are described by a physical model, and human behavior is described by a discrete model such as a multi-agent model. Conventional simulation technology has evolved such as to be specialized for one certain model. That is, these different models and technologies are represented by different simulations and systems. Therefore, in order to realize a cyber-physical system for disaster prevention, dealing with analysis results obtained from different models and technologies in an integrated manner is a major challenge.

2 RELATED WORK

2.1 Literature Review

One of the simulation techniques is physical simulation for reproducing disaster phenomena; for flood damage, this means a flood analysis simulator that estimates the occurrence of flood damage and its expansion process. This is a simulator that derives the flood water value in several-meter grid units by numerical analysis using input data such as precipitation, land use, building coverage, sewer pipes, and manholes. In addition to flood damage, many simulations have been developed to accurately reproduce various disaster phenomena such as tsunami [6] and wildfire [7]. In these simulations, each generation mechanism is modeled by a physical formula and then reproduced on a computer; these simulations are actually used for risk estimation and damage estimation in many regions.

Another approach is a social simulation that models the behaviors that can be taken by evacuees. An evacuation simulator reproduces evacuation behavior in various situations, such as when a disaster event occurs. There are several approaches to behavior modeling, including an empirical approach and an agent-based approach [8]. A number of models have been developed, including an evacuation model that dynamically selects destinations [9], an indoor evacuation model that considers collisions between evacuees [10], an evacuation model that considers evacuation behavior affected from nearby evacuees [11], and a crowd evacuation model [12]. Nguyen et al. [13] used an evacuation simulation in disaster phenomena, considering the behavior of smoke diffusion during a fire and providing directions to evacuees, and discussed its use in formulating efficient evacuation plans.

A new approach in the concept of the cyber physical system is a simulation that models physical elements of the real space onto the virtual space. Virtual Singapore produces an urban space model that integrates terrain information, buildings, and social infrastructure information throughout Singapore onto a virtual space [14][15]. Furthermore, a simulation environment is being constructed by integrating various real-time data (traffic information, car / people location information, etc.) into that urban space model. Behind these technologies is the evolution of technologies developed for various applications, such as IoT. Cyber-physical systems extend the IoT concept further to facilitate the interaction of the smart city's cyber and physical spaces. Ref. [16] attempted to detect landslide using IoT concept, Refs. [17]-[19] adopted their cyber physical system to disaster response. In disaster prevention, construction of an elaborate urban structure model means that disaster phenomena can be reproduced with high accuracy, which can improve the usefulness of feedback to the physical spaces. This is because the parameters of the physical model used for the physical simulation of disaster phenomena are defined based on the data of the urban space model. Moreover, the collection of real-time data by the IoT has the potential to improve the accuracy of both disaster phenomena simulation and social simulation.

The goal of handling different models and technologies in an integrated manner is achieved by a strategy to develop a large framework that incorporates these simulations and systems as a single function. Integrated Emergency Response Framework (iERF) [20] is such an integrated framework. This was proposed as a framework to integrate various tools used in emergencies such as simulation and visualization. High Level Architecture (HLA) is an approach to standardize different simulators/systems for distributed simulation, used when developing a simulation for a larger purpose by combining several simulations [21]. HLA develops a distributed simulation by providing various services such as data distribution and time synchronization through middleware. Dahmann et al. [22] have achieved the interoperability of various simulations by examining the specifications of a common technical architecture for simulations using HLA. The architecture was implemented as a prototype to interoperate multiple simulators, including evacuation, information provision systems, and emergency operations, in an earthquake disaster [23]. In addition, a distributed simulation platform has been constructed for evacuation simulation in the event of fire disasters caused by earthquakes [24].

2.2 Limitations and Contributions

Although the abovementioned integration strategies provide theoretical support for coordination between different models to represent complex real spaces, there remain several issues to be improved. First, it is necessary to realize information communication environment in virtual space. Considering the feedback of the prediction results, actual information communication needs to be simulated, but this has rarely been discussed in disaster response terms. Second, while ensuring scalability, the cost of system improvement for synchronization with new simulations and systems should be reduced. This is due to reducing obstacles to quickly adopting new observation systems and prediction technologies created by feedback from the virtual space of a cyber-physical system. Third, social simulation depends on information and decision making. In order to reproduce human behavior in a disaster situation more precisely, a cyber-physical system needs to incorporate accessibility to disaster information as a parameter of the simulation.

A federation strategy using the information bus was proposed in our previous paper [25] to solve the problems above. The contributions of the federation strategy are summarized as follows:

- Federation technology is achieved by implementing functions of data exchange and processing timing control between simulations / systems in a cyber-physical system. These functions mean that simulations representing virtual spaces can be integrated together to create a more elaborate physical space. In addition, the components themselves can be exchanged between virtual space and physical space via federation, and application to various test beds can be expected. We named this progressive simulation.

- Our platform also supports the behavior of computer networks that affect the accessibility of information, and it evaluates the damage mitigation effects of that behavior. We define the technique that imitates the behavior of computer networks as computer emulation. Computer emulation automatically verifies computer network outages or destruction due to disasters and can more accurately reproduce physical space events caused by complex factors.

This paper proposes a system that uses this federation strategy to create scenarios that include the impact of communication failures in floods.

3 PROPOSAL OF DISASTER VICTIM IMPACT ANALYSIS SYSTEM

This paper aims to propose a system that uses the federation strategy to create scenarios that include the impact of communication failures during floods. It is well known that communication failures occur during disasters such as floods. Communication failures during disasters include power outages, broken communication systems, and traffic congestion caused by concentrated traffic. In particular, communication failures caused by power outages and physical damage to communication systems occur frequently during floods. In recent years, 70% of floods have resulted in failures due to damage to communication systems. Such physical failures are considered to have a significant impact on the disaster victims because their recovery requires physical system relocation.

Particularly in disasters such as floods, where damage spreads gradually, the accessibility of information to disaster victims is a critical aspect before and during the disaster. Therefore, it is important to consider countermeasures including communication failures in providing and obtaining information. However, preliminary disaster assessments are based on large estimates, such as “X million network access lines will be out of service.” In preparation for network outages, there have been studies on advance deployment of systems that enable early recovery and alternative networks such as delay tolerant network [26]-[28]. On the contrary, we believe that it is essential to consider how the occurrence of such communication failures affects the access to information for disaster victims during a disaster. In the 2020 floods in Kumamoto, Japan, communication failures occurred as the rainstorms progressed, making it difficult to obtain information. Optical fibers at bridge piers were flushed away by the rising river water, and communication was damaged even in areas where no flooding had occurred.

Human behavior during disasters depends largely on what kind of information affected people have obtained. In the current society, which relies heavily on information and communication technology, we should assess what kind of situation the victims’ access to information will be in and how it will affect them by simulating the situation in advance as a strategy for disaster response. Thus, in this paper, we develop a system to create scenarios that simulate communication failures by using our federation strategy, which allows multiple simulators to be implemented in a cooperative manner. The system incorporates multiple factors such as the impact of natural disasters, human behavior, the impact of disasters on communication networks, and information services as a flood

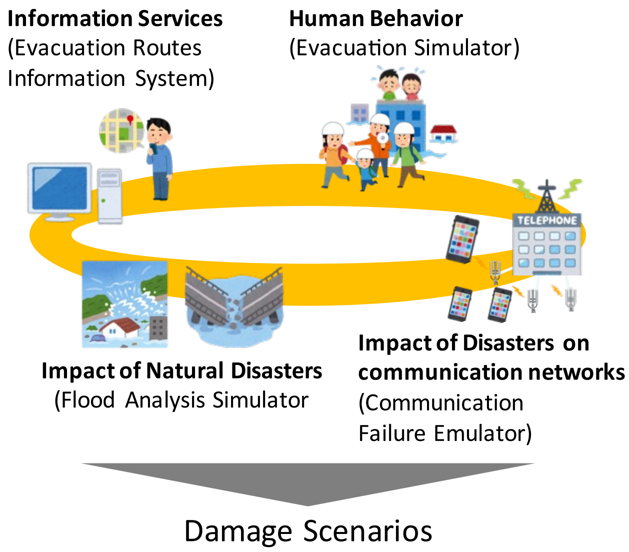

Figure 1: System Concept

analysis simulator, evacuation simulator, communication failure emulator, and evacuation routes information system, respectively, and creates scenarios of human impact by emphasizing the dependencies among these factors (Fig. 1). Using this system, we confirm that it is possible to generate multiple scenarios (optimistic scenarios and worse scenarios) related to communication failures.

4 SYSTEM CONFIGURATION

4.1 Overview

This paper simulates and analyzes human impacts from disaster phenomena simultaneously with information service technology. The incorporation of multiple factors into a simulation model requires complex and massive development efforts, although our federation strategy allows for the cooperative implementation of these multiple simulations, It can also be expected to be used as a mechanism for evaluating the accuracy and usefulness of the information service in a disaster situation.

Our system consists of multiple simulators operating in a cooperative manner. Four simulators / systems (flood analysis simulator, evacuation simulator, evacuation route service system, and communication failure emulator) exchange data with each other considering their operation timing, and progressively compute their own simulations using data from other simulators (Fig. 2).

4.2 Federation Strategy

We describe a federation strategy for four different simulators / systems: a flood analysis simulator, an evacuation simulator, an evacuation route service system, and a communication failure emulator. To achieve this cooperative operation, this system needs to be addressed, including physical data exchange between simulators and systems, processing timing control. We aim to achieve this goal through a federation strategy that develops a larger framework incorporating

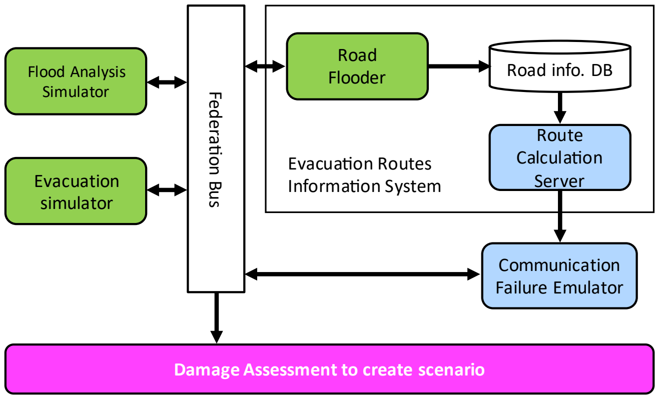

Figure 2: System Configuration

these simulations and systems as a single feature. We aim to achieve this goal through a federation strategy that develops a larger framework integrating these simulations and systems as functions. The process to achieve the federation strategy involves several phases, all of which are provided on a single platform. We have addressed the design and implementation of simple data exchange and processing timing control [25] for pre-verification, and a real-time data exchange and processing timing control [29] for practical service. As a feasibility study on static scenario, this paper uses the simple data exchange and processing timing control shown in [25] to cooperate with simulations and systems. This paper aims to propose a system that uses the federation strategy to create scenarios that include the impact of communication failures during floods.

4.3 Federation Bus

In our federation strategy, the federation bus is responsible for their data exchange and timing control. The federation bus consists of an MQTT broker for Publish-Subscribe message exchange and a federation manager for time synchronized progress management. As the name suggests, the data exchange function is responsible for exchanging data between simulators and systems. The data exchange function is composed of an MQTT broker. Each simulators / systems outputs the calculation results for each step as MQTT messages. Other simulators and systems subscribe to others' MQTT messages based on pre-defined information and use the messages as input data for their respective calculations. Although each of the simulators takes a different amount of time to compute, we achieved the cooperation of multiple simulators/systems by using this timing control manner.

The processing timing control function is a server that manages processing timing. The processing timing control function manages the operation of four simulators / systems as a coordination manager responsible for time synchronized progress management. When starting the overall simulation, this function sends a simulation start order to all simulators / systems. When the first step of each calculation is completed, the simulators / systems publish the MQTT message that the first step of the calculation is completed, as well as the calculation results. Upon receiving messages from all simulators/systems, the processing timing control function determines that the first step calculation is complete. It then sends an order to all simulators / systems to start the second step of the calculation. By repeating this process, the calculation proceeds with multiple simulators/systems working cooperatively. Then, our system creates scenarios by changing the alert timing, and analyzing the behavior of disaster victims and their access to information as calculated by the evacuation simulator.

4.4 Flood Analysis Simulator

Our federation strategy can allow us to use a conventional flood analysis simulator. However, in this paper, we use data from API[1], which performs flood calculations, due to the difficulty of obtaining the input data for the flood calculations. For the scenario area, Hitoyoshi City, Kumamoto Prefecture, we regard the flood data as calculated at specific time intervals and connect it to a federation bus.

Road Flooder progressively calculates the impassable roads, according to the flooded value from the flood data. The calculation result is transmitted to the road management DB through the federation platform, and the road information is updated. Road information management DB stores the road information and the shelter information, which are used for the evacuation route calculation in the target area.

The flood analysis simulator receives MQTT messages for timing control from the federation bus. Upon receiving this MQTT message, it publishes the flood values for each grid for one step.

4.5 Evacuation Simulator

Our evacuation simulator is developed using a multi-agent simulator. At the beginning of simulation, evacuation simulator generates the evacuee agents, according to the population distribution which is set in the map. Determination of each behavior can be set the parameters for each agent as evacuation characteristics. In other words, we can set the evacuation behavioral characteristics of each agent according to age, disaster experience, and ability to access information. Besides, the shelter where to which each agent evacuates is set as the initial value for each agent. The total number of evacuee agents can be set on the evacuation simulator.

The evacuation simulator calculates the behavior of the evacuee agents, depending on the flooded value calculated from the flood analysis simulator. The evacuee agents determine their behaviors on the basis of their own location, walking speed, or information. Evacuee agents have their own smartphones. When local agency sends the evacuation information, evacuee agents move in accordance with their own evacuation behavioral characteristics. For example, an agent who has better evacuation behavior characteristics starts to evacuate to the shelter immediately after receiving information. We configure several types of the evacuation behavioral characteristics; the agent who start the evacuation several minutes after receiving the information, or who start if their surrounding agents start to move.

Evacuee agent consults the evacuation routes information system to determine the safe evacuation route after their deci-

[1]https://suiboumap.gsi.go.jp/

sion, then starts to move to the shelter. During their evacuation, they confirm the flooded value of the surrounding grids at each simulation step. If flood has not occurred around the agent, they move to the next grid on their route. If the flooded value exceeds the threshold, their evacuation routes are flooded; in consequence, they re-ask the other safe route to information system. This threshold is used to set the flooded value as impassable for a given road for each agent.

Evacuee agents search for safe evacuation routes when flooding above a threshold occurs around them at the start of evacuation or during evacuation. After each search, the route calculation server calculates the evacuation route and sends it to each agent's smartphone. If there is a communication failure at the current location of the evacuee agent, the evacuee agent will not be able to receive flood information and cannot access further route searches. In case of search at the start of evacuation, the evacuee agent does not start evacuation. In the case of search during evacuation, the evacuee agent does not update the evacuation route and stops at the location where it cannot move due to flood. The evacuation simulator calculates the amount of damage and data access status in a progressive manner using data from evacuation agents.

The evacuation simulator receives MQTT messages for timing control from the federation bus. Upon receiving this MQTT message, it receives the flood values for each grid calculated by the flood analysis simulator and determines if the evacuee agent can move based on these values. In addition, it receives MQTT messages from the communication failure emulator with the location of each base station, its communication range, and its status. Each evacuee agent calculates its communication accessibility based on its current location. If communication is available, it publishes an MQTT message with its current location and destination.

4.6 Evacuation Routes Information System

Before the evacuation, each evacuee agent searches the safest evacuation route to the shelter using their smartphone. Evacuation routes information system search and provide the evacuation route. The system consists of road flooder, road information management DB, and route calculation server.

When the evacuee agents search for an evacuation route, the route calculation server excludes impassable roads calculated by the road flooder and computes them according to the current location of the agent and of the nearest shelter. By inputting the location of the evacuee agents and the destination node ID, the route calculation server determines a route by weighted Dijkstra method in consideration of distance and cost, and it returns a list of nodes on the route. In the evacuation simulation, the location of the evacuee agents and the ID of the destination node are transmitted by MQTT via the federation bus. Upon receiving the data, the smartphone emulator receives a list of nodes from the route calculation server using the REST API and transmits the list to the evacuation simulator using MQTT.

The route calculation server generates a weighted undirected graph $G_N = (\mathbb{N}, \mathbb{N}_{next})$ with the distance between nodes as the weight. Simultaneously, a set node $\mathbb{N}_{next}$ is selected from a table of links connecting to the set of nodes $\mathbb{N}$. The initial value of the cost of the graph G_N is configured to the distance between the nodes; however the ID of the nodes and links that have become impassable due to the flood expansion can be updated to the graph G_N via the road information management DB. After the river floods, if the grid on a agents' route becomes impassable, the node ID and link ID included in the grid are transmitted to the road management DB, and the cost of the corresponding nodes and links of the graph G_N is updated. After the cost is updated, when the agent inquires of the evacuation route via their smartphone, the route calculation server returns the detour route.

The evacuation routes information system receives MQTT messages for timing control from the federation bus. Upon receiving this MQTT message, the evacuation routes are calculated based on the flood values received from the flood analysis simulator. It also receives MQTT messages from the evacuation simulator about the current location and destination of each evacuee agent, calculates the safety evacuation routes based on this data, and then publishes the evacuation routes for each evacuee agent.

4.7 Communication Failure Emulator

Our communication failure emulator is an emulator that simulates communication failures related to smartphones in floods. The emulator consists of a mobile base station, a mobile relay station, a wired communication line between the mobile base station and the relay station, and a power supply to the mobile base station and the relay station. The mobile base station transmits radio waves within a defined range and is used for information access by evacuee agents within the range. If the flood water level rises in the flood analysis simulator and the mobile base station itself or the power supply function of the mobile base station is flooded, the mobile base station loses its communication function. The wired communication lines between the mobile base station and the relay stations are connected by the shortest path. When there is damage to the communication line due to flood flow, the mobile base station to which it is connected loses its communication function. The mobile base stations and the relay stations are supplied with electric power, and when a power outage occurs due to flood, the power supply is stopped and the communication function is disconnected at the same time. Channels and alternative means of power supply to the mobile base station are not considered in this paper.

The communication failure emulator sends the availability status of the mobile base station via MQTT over the federation bus. Depending on the location of the evacuee agent, it determines which base station to use and transmits the availability status of that base station back to the evacuation simulator. If the mobile base station is active, evacuee agents in the evacuee simulator will have access to routes to the shelter and alerts. If the base station is not available, the evacuee agents will not be able to access information. With the above steps, the communication failure emulator simulates information access in the event of a flood.

The communication failure emulator receives MQTT messages for timing control from the Federation bus. Upon receiving this MQTT message, it calculates the communication status and power supply status of base stations, fiber, and relay stations based on the flood values received from the flood analysis simulator. According to the calculation results, it publishes MQTT messages for the location, communication range and status of each base station.

5 PERFORMANCE STUDY

5.1 Overview

The previous section describes a system that uses a federation strategy to simulate and analyze human impacts from disaster phenomena simultaneously with information service technology. We use this system to generate scenarios of communication failures during floods. The flood analysis simulator uses data of the Kuma River flooding that occurred on July 4, 2020 in Hitoyoshi City, Kumamoto Prefecture, Japan. In this flood, the water level exceeded the flood hazard level at six water level observation stations, and overflows from the river occurred at 34 locations along the main Kuma River. Regarding telecommunications, 88, 70, and 111 mobile base stations were out of service in Kumamoto Prefecture by NTTdocomo, KDDI, and Softbank, respectively. We create scenarios in this system by changing alerts timing as trigger the start of evacuation and the time of the simulation. Using the scenarios, we analyze the possibility of creating multiple scenarios and the effects of communication failures from the viewpoint of disaster victims.

5.2 Setup

To set up the flood analysis simulator, the API selects one of the breakpoints as the point where the levee broke in a past flood event, and uses the flooding time series data from the largest assumed flood disaster. The evacuation simulator generates evacuee agents according to the population distribution in Hitoyoshi City and sets them to move to the nearest evacuation center. For the communication failure emulator, we visually survey the actual mobile base station locations within Hitoyoshi City and set them up in the emulator in the same arrangement as the actual base and relay stations. The setting values are the location information of a total of 31 antennas installed on top of buildings, telephone poles, and steel towers, the communication coverage areas of the base stations are set to radiuses of 1,000 meters, 200 meters, and 1,500 meters, respectively. Note that we have not set a distinction between telecommunications carriers. When the mobile base stations in the communication failure emulator are in operation, our evacuation routes information system presents the shortest route to the shelter, excluding flooded roads, in response to access by the evacuee agent in the evacuation simulator. Each simulator runs on a virtual machine placed in the same network and exchanges data via MQTT.

For performance study, we experimented and discussed two assessment points. The first study creates a scenario that includes the impact of communication failures. This study aims to investigate the feasibility of developing a system that creates scenarios to reflect the impact of a communication failure during a flood event, using a federation strategy that is integrated with a communication failure emulator. The second study is to confirm that it is possible to create multiple scenarios of communication failures, and then to discuss the impact of the communication failures from the viewpoint of the victims in each scenario. For the performance study, we prepared three scenarios, Scenario A)-C).

5.3 Damage Scenario

Scenario A) Scenario A) assumes that evacuation information is published before 60 minutes of the flood, and evacuee agents in the evacuation simulator start moving to the nearest shelter. The evacuee agent obtains the information every 10 minutes with a probability of one-half. This assumes that information is updated every 10 minutes. Since the frequency of information access is expected to depend on each evacuee, this scenario is set to a probability of one-half. to obtain the information. When the evacuee agent arrives at the evacuation shelter, the system counts the completed evacuation. For the performance study of the communication failure emulator, the evacuee agent is set to start evacuating as soon as the information is published. If a road is flooded to a depth that prevents passage, the evacuee agent searches for another evacuation route using their smartphone. The base station of the communication failure emulator stops working when it is flooded more than 1 meter depth, and the evacuee agents within its communication area cannot connect their smartphone to the station. We assume this setting because power supply facilities installed at base stations are often located at the similar heights. Under the above conditions, the purpose of Scenario A) is to investigate the differences between this system with and without the communication failure emulator under conditions where there is a relatively long time remaining before the flooding starts.

Scenario B) In Scenario B), we set the evacuation information to be published as soon as the flooding starts, and the evacuee agents in the evacuation simulator start moving to the nearest evacuation shelter. The information access rate of the evacuation agents, the time to evacuation, and the communication failure settings are the same as in Scenario A). The purpose of Scenario B) is to investigate the difference between this system with and without the communication failure emulator in a condition where communication failure is more likely to occur.

Scenario C) Then, in Scenario C), approximately 60 minutes after the flood, evacuation information is published and the evacuee agents in the evacuation simulator begin evacuating to the nearest shelter. The information access rate of the evacuation agents, the time to evacuation, and the communication failure settings are the same as in Scenario A). In an actual flood situation, it is unlikely that evacuation information would be published 60 minutes after the flood. However, we will investigate the impact of the communication failure in the setting of Scenario C) to find out how large the impact of the communication failure would appear, if the evacuation behavior occurred after the communication failure.

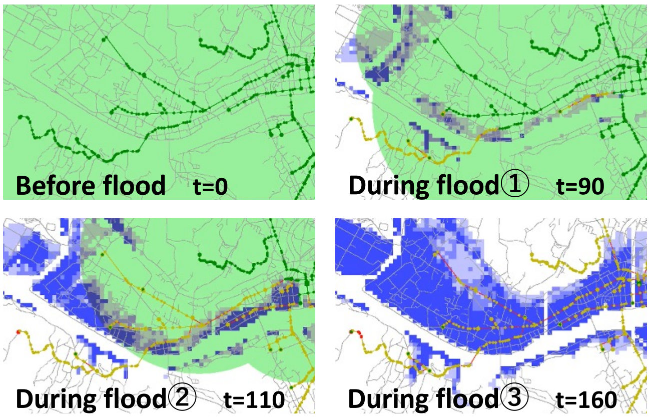

Figure 3: Communication failure

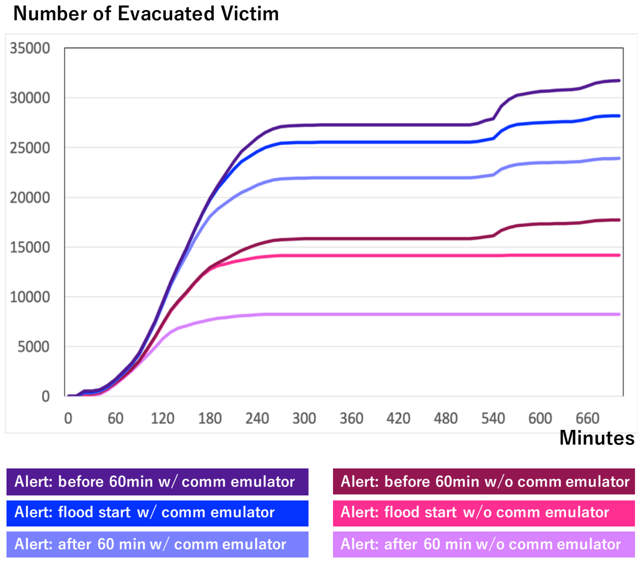

Figure 4: Performance study results

5.4 Result and Discussion

Scenario A) Figure 3 shows the communication failure when we operated a system that uses the federation strategy. The green areas indicate communication available areas. Green dots and lines indicate active base stations and fibers, yellow indicates fibers with downstream base stations that have stopped function, and red dots and lines indicate base stations and fibers that have stopped their function. As the floodwaters spread, the power supply facilities of the base stations are flooded and stop working as well as the area where communication is not possible is expanding.

The 31 base stations became inoperable as the flooding expanded, and the area where communication was not possible gradually expanded. The time series change in the number of evacuee agents that have completed evacuation is shown in Fig. 4. When there is no communication failure emulator, many agents are able to complete the evacuation. Without the communication failure emulator, evacuee agents can obtain evacuation information at any time. Also, their behavior is not affected by the information availability necessary for their movement, such as the evacuation route. On the other hand, with a communication failure emulator, the number of agents who have completed evacuation is reduced by half. The availability of evacuee agents to obtain evacuation information is affected by whether they are in a communication-enabled area, and the probability of obtaining such information decreases after the flood expansion. In addition, if roads on the evacuation route are flooded, alternative route information is not accessible.

In the scenarios with and without the communication failure emulator, shown in Fig. 4, we confirmed that our system would have different numbers of evacuation completed. Since there are many settings that differ from the actual situation, such as flooding phenomena, population distribution at the time of flooding, and communication fiber paths, it seems unlikely that the system was able to reproduce the actual situation of communication failure during a flood, but at least by operating the system including the communication failure emulator, a scenario was created considering the effects of communication failure.

Scenario B) Figure 4 shows the results of the scenario when the evacuation information was published at the same time as the flooding started. Without the communication failure emulator, many agents completed the evacuation. The number of agents who completed the evacuation with the communication failure emulator was lower than that without the emulator, as in Scenario A). The number of agents who completed the evacuation with and without the communication failure emulator was lower than in Scenario A), which changed the announce timing of the evacuation information. We confirmed that different scenarios can be created by changing the setting values in Scenario A) and Scenario B).

In Scenario B) situation, many agents will not be able to receive the evacuation information because communication failures have already occurred when the evacuation information is published. Furthermore, the probability that moving agents will encounter flooding will be higher than in Scenario A). There is also a higher probability that there will be no passable roads left due to flooding at the time of rerouting. Therefore, it is likely that fewer agents in Scenario B) will be able to complete the evacuation than in Scenario A). The above effects could be considered as the impact of communication failure on the victims.

Scenario C) The results of Scenario C), assuming that the evacuation information was published 60 minutes after the flood, are shown in Fig. 4. Without the communication failure emulator, the number of agents who were able to move, among those who received the evacuation information, was the lowest in Scenario C). However, more agents still completed the evacuation than in the case without the communication failure emulator in Scenario A). With the communication failure emulator, in this scenario, a flood spread throughout the city at evacuation information announcements, and communication failures occurred in various locations. As a result, few agents were able to obtain information after the evacuation information was published, and many agents faced difficulties in moving relatively early in the process. This is indicated in the other scenarios, where the number of agents completing the evacuation is constant between 180 and 240 minutes, but in this scenario, it becomes constant at about 120 minutes, with almost no increase in the number of those who complete the evacuation. It would seem that after this time, even if the information was accessible, it would not have led to the evacuation completed because they would not have been able to continue to move. In reality, it is unlikely that evacuation information would be published this late. However, when evacuation information access is delayed for some reason, as in the case of disaster victims' access to information, and they are unable to move, the impact of communication failures will be greater. This suggests that the more the water damage proceeds, the greater the impact of communication failure will be on the victims.

Discussion We investigated two assessment points in this performance study. The first one is to examine whether this system can create scenarios that consider the impact of communication failures. The second is to investigate whether the system can create multiple scenarios, and in each scenario, what impact the communication failure has on the victims. For the first assessment point, through scenario A)-C), we examined the case with and without the communication failure emulator and found a clear difference in the number of agents who completed evacuation in all scenarios. This difference can be considered to result from the accessibility of information and the behaviors based on this information access with and without the communication failure emulator. Information access affects the triggers for behaviors such as starting an evacuation, as well as the choice of behaviors based on the situation, such as rerouting. We think that the federation strategy allowed us to reproduce such information situations in our system. Although this performance study uses a number of assumptions in its setup, which may differ from the actual number of victims who can complete the evacuation, we believe that we were able to show some differences in the impact of the system with and without communication failures.

Regarding the second assessment point, the three scenarios with different timing of information announcements resulted in different numbers of agents who completed the evacuation. We suppose that this can be described as several different scenarios with different settings. This means that we were able to develop a system that could create multiple scenarios, which we had aimed to achieve. Obviously, in this study, we modified just one setting value and created relatively simple scenario.

In addition, examining the specific behaviors of agents' information access in scenarios A)-C), there were several aspects of information access that were important. The first issue is the access to evacuation information. Communication environments are required if they rely only on smartphones for evacuation information. While information can be accessible while the floodwaters are not expanding, this is not possible in the case a communication failure occurs. If victims search for information by themselves before the floodwaters spread, they can access information, whereas if they are familiar with providing information, this will have a significant impact. As a matter of course, in reality, smartphones are not the only means of accessing information. There are a variety of other means available, such as television, radio, and emergency broadcast system. However, each of these has its own disadvantages, such as the need for a power supply for television and the difficulty of hearing the emergency broadcast system during heavy rain. We consider it necessary to improve our system so that the federation strategy can reproduce the actual information access environment in the future. The second issue is information access for rerouting. In our setting, when flooding occurs, the agents use their smartphones to search for a passable route. If the search fails, the agent stops moving. But realistically, as residents, they already know of other routes (except if the road is flooded or not.). Therefore, they do not need to have a communications environment in order to continue moving. On the other hand, it is considered that other routes could be flooded and that non-resident victims may not have knowledge of the routes. This setup is not exactly realistic, but there are victims for whom this setup is applicable. The system would be able to simulate the likely effects of real-world access to information by changing the setting values in addition to the information announcements.

Finally, our system uses a federation strategy to simultaneously operate a flood analysis simulator, an evacuation simulator, a communication failure emulator, and an information service. This enables us to consider factors that have not been previously incorporated into the simulation, such as communication failures. Meanwhile, we concern that there are difficulties due to the increase in the number of factors. All simulators and emulators require configuration settings, although it is difficult to reproduce flood flows, the population distribution during a disaster, the communication environment, and information systems in a precise manner. While some accuracy is necessary, we believe that a perfect setup and reproduction of reality is difficult to achieve. Therefore, we would like to use this system not to perfectly reproduce the real disaster situation, but to output the likely impact on victims and infrastructure, and to derive countermeasures to address the situation. This performance study does not reproduce past disasters, using the data available as setting values. However, the impacts on victims' information access identified in this study could well occur in the real situation. We believe that our next challenge is to improve our system in order to simulate these potential impacts.

6 CONCLUSION

This paper proposed a system that uses the federation strategy to create scenarios that include the impact of communication failures during floods. Communication failures caused by power outages and physical damage to communication systems occur frequently during floods. Physical failures are considered to have a significant impact on the disaster victims because their recovery requires physical system relocation. Particularly in disasters such as floods, where damage spreads gradually, it is relevant to the accessibility of information to the disaster victims before and during the disaster. Therefore, it is important to consider strategies including communication failures in providing and obtaining information.

This paper focused how the occurrence of such communication failures affects the access to information for disaster victims during a disaster. We develop a system to create scenarios that simulate communication failures by using our federation strategy, which allows multiple simulators to be implemented in a cooperative manner. Using this system, we confirmed that it is possible to generate multiple scenarios (optimistic scenarios and worse scenarios) related to communication failures.

Our system can simulate and analyze human impacts from disaster phenomena simultaneously with information service technology. It consists of multiple simulators operating in a cooperative manner. Four simulators / systems (flood analysis simulator, evacuation simulator, evacuation route service system, and communication failure emulator) exchange data with each other considering their operation timing, and progressively compute their own simulations using data from other simulators. The incorporation of multiple factors into a simulation model requires complex and massive development efforts, although our federation strategy allows for the cooperative implementation of these multiple simulations. It can also be expected to be used as a mechanism for evaluating the accuracy and usefulness of the information service in a disaster situation.

After we developed four simulators / systems, we generate scenarios of communication failures during floods. Creating scenarios, we used data of the Kuma River flooding that occurred on July 4, 2020 in Hitoyoshi City, Kumamoto Prefecture, Japan. We set actual mobile base station locations within Hitoyoshi City up in our communication failure emulator. Four simulators/systems were simultaneously operated to simulate flood water value by the flood analysis simulator and to simulate the accessibility of information by the evacuee agents generated by the evacuation simulator. Using the scenarios, we confirmed the possibility of creating multiple scenarios and analyzed the effects of communication failures from the viewpoint of disaster victims.

This paper confirms that our system is capable of creating multiple scenarios. Our goal in the future will be to analyze in more detail the relationship between communication and behavior of disaster victims. Especially key to this analysis will be the extraction of worse cases that have occurred in previous disasters, as well as cases that have not occurred so far but could occur. We plan to develop a method for extracting these cases, and to develop more practical means of access to information for evacuees so that their behavior can be simulated more closely to actual situations.

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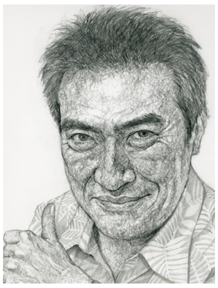

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