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Blockchain Framework for Occupant-centered Indoor Environment Control Using IoT Sensors

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Abstract: As energy-saving techniques based on human behavior patterns have recently become an issue, the occupant-centered control system is adopted for estimating personal preference of indoor environment and optimizing environmental comfort and energy consumption. Accordingly, IoT devices have been used to collect indoor environmental quality (IEQ) data and personal data. However, the need to safely collect and manage data has been emerged due to cybersecurity issues. Therefore, this paper aims to present a framework that can safely transmit occupant-centered data collected from IoT to a private blockchain server using Hyperledger fabric. In the case study, the minimum value product of the mobile application and smartwatch application was developed to evaluate the usability of the proposed blockchain-based occupant-centered data collection framework. The results showed that the proposed framework could collect data safely and hassle-free in the daily life of occupants. In addition, the performance of the blockchain server was evaluated in terms of latency and throughput when ten people in a single office participated in the proposed data collection framework. Future works will further apply the proposed data collection framework to the building management system to automatically collect occupant data and be used in the HVAC system to reduce building energy consumption without security issues.

Keywords: blockchain, data management, IoT sensors, occupant-centered control, usability test

1. INTRODUCTION

Building sectors account for 36 percent of global energy consumption [1]. Moreover, carbon emissions from buildings are expected to increase due to building stock expected to more than double by 2050 [2]. Therefore, energy reduction has emerged as an important issue in building management systems. With this necessity, the occupant-centered control, the control strategy for indoor environments focusing on the needs of the occupant, has shown its potential to reduce excessive energy consumption by adjusting scheduling the HVAC system and lighting system. Dong et al. (2018) predicted the occupancy of 70% accuracy and presented 20% energy saving based on the prediction results [3]. Capozzoli et al. (2017) implemented the HVAC system schedule based on the occupancy patterns and reduced the energy consumption by 10% [4]. Kong et al. (2022) conducted the experiment in a commercial building to quantify the occupancy-based control and showed energy saving between 17 and 24% [5]. Overall, occupant-centered control could reduce energy consumption by focusing on the occupancy and occupant count.

Recently, occupant-centered control has been narrowed down to personal preferences. The personal preferences such as occupant behavior and thermal comfort range among the person helped reduce energy by adjusting a granular schedule of the HVAC system. Moreover, the occupant expected decreased energy consumption and increased thermal comfort based on personalized indoor temperature control. Therefore, several studies have collected personal data in various indoor environments to estimate different thermal preferences and thermal comfort ranges. Jung et al. (2022) conducted a climate chamber experiment and developed a personalized indoor temperature control model based on physiological data using a smart wrist band when occupant behavior changes [6]. Katic et al. (2018) collected data from the climate chamber and developed the personalized heating system using an artificial neural network to automate control of the heating chair [7]. Rissetoo et al. (2021) varied the ceiling fans and thermal conditions in the climate chamber to collect the personal preference in terms of air velocity and thermal comfort using a questionnaire [8]. However, data including personal preference collected from climate chamber experiments were conducted in a designed space and did not fully reflect the real world. To reflect the complexity of the real world, it is essential to collect data in daily life. In addition, it was required to collect a lot of data without interfering with the life of the occupant as much as possible. Particularly, it was required to safely collect sensitive data without security and privacy issues since occupant-centered control was based on physiological data collected from smart devices and sensitive personal data such as identification (ID) and location.

Therefore, in this study, a blockchain-based occupant data collection framework that can be applied to daily life without security and privacy issues was presented. Toward this end, a blockchain-based collection process was presented, and a smartphone application that can collect sensitive occupant data such as ID, clothes, and location was developed.

2. METHODOLOGY

2.1. Blockchain

Blockchain is the innovative distributed database technology in which encrypted blocks containing transaction history are assembled in a chain form. The recorded transaction history cannot be altered since the transaction history of all previous blocks is reflected in the newly recorded block in a chain form. Even if data in one node is tampered with, distributed ledger technology can verify that the data is correct or incorrect by referring to other nodes. Therefore, it is difficult to maliciously tamper with data in a blockchain since the malicious attackers must attack multiple nodes. In addition, blockchain participants can transparently check the transaction history to ensure transparency. Therefore, by collecting sensitive occupant-centered data in daily life, blockchain can reduce the possibility of security issues. In addition, the transparency of blockchain is suitable for an occupant-centered data collection framework that requires a significant level of reliability. In this study, private blockchain such as Hyperledger fabric was used to design the occupant-centered data collection framework [9]. It is noted that a private blockchain is different from a public blockchain that can be used by everyone anonymously. In the private blockchain, viewing transactions and deploying the smart contract to write and read the data are authorized only to participants with authorization. Therefore, a private blockchain is more suitable than a public blockchain for an occupant-centered data collection framework to avoid security issues.

2.2. Blockchain-based occupant-centered data collection process

Blockchain-based occupant-centered data collection framework consisted of four stages as shown in Figure 1: (i) registration of the participants to a private blockchain network; (ii) collecting and integrating occupant-centered data in the local server; (iii) uploading data to the blockchain server through the local server; and (iv) reading data and querying transaction history from the blockchain server.

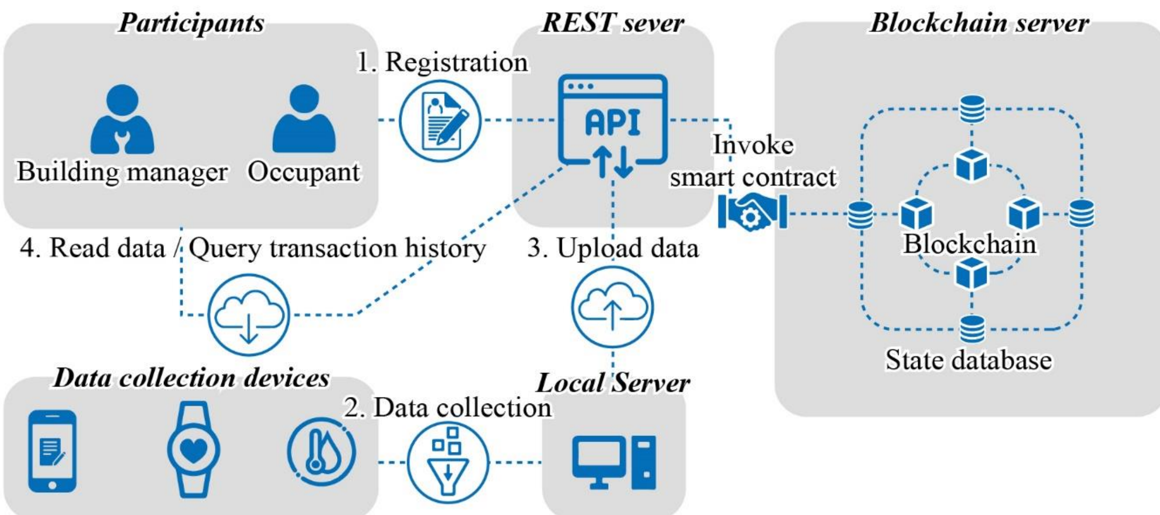

Figure 1. Blockchain-based occupant-centered data collection framework

First, building managers and occupants were registered to private blockchain in advance to collect occupant-centered data to the blockchain network. Not only building managers and occupants but also users who wanted to manage the occupant-centered data, such as data scientists and security managers, could participate in a private blockchain. When users requested to be registered in the blockchain network to the Representational State Transfer (REST) server, the REST server requested the blockchain to invoke the smart contracts using Application Programming Interface (API) to generate the public key and private key. It is noted that every smart contract was invoked using API to access the blockchain server. The REST server received the token (i.e., private key) to register the building manager and occupants, as shown in Figure 2. The token was used to get access to the private blockchain and get the smart contract approved. As a result, privacy is protected by guaranteeing anonymity in the blockchain server, which stores the hash value of public keys instead of occupants' names in the blockchain server.

Second, occupant-centered data were collected from the data collection devices such as smartphones, smartwatches, and IAQ sensors. Since the period and type of data collected from each data collection device are different, various data is consolidated on the local server every 1 second. Data with a collection period longer than 1 second was treated as blank. To upload atypical data to the blockchain server, the local server maps the collected data in JavaScript Object Notation format with the token since a smart contract was approved using a token to write data. It is noted that a local server is considered completely trustworthy since every participant in the private blockchain verified and agreed with it.

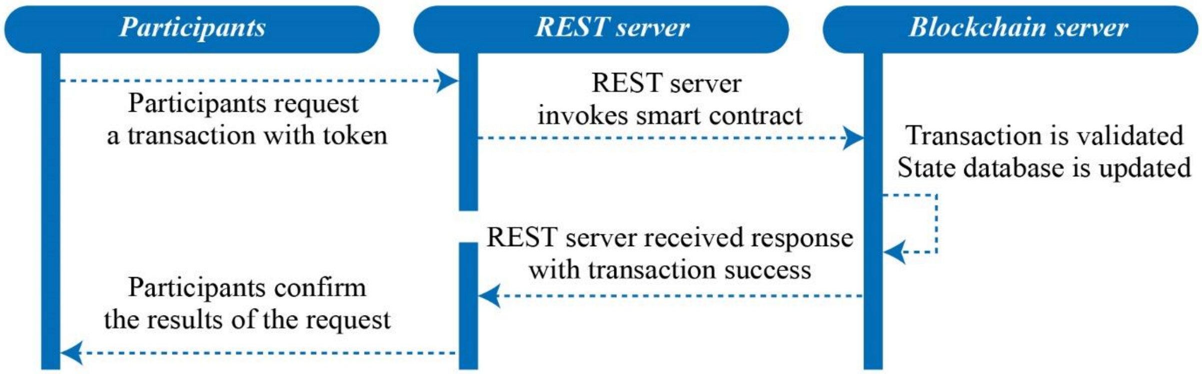

Figure 2. Transaction flow through the REST server

Third, mapped data was uploaded to the blockchain server. When the local server posts a request with mapped data and tokens to the REST server, the REST server requests the blockchain server to invoke the smart contracts to write the configured data to the state database. It is noted that each distributed nodes in the blockchain server have a state database (i.e., off-chain database) which saves the occupant-centered data, and a blockchain that records a transaction log. Since access to the state database is only possible through requesting from participants who have been approved, an unauthorized person could not falsify or inquire about data.

Last, the occupant-centered data was read through the participants who have been approved. Since the record of when and who read data remains in the blockchain, an occupant can query how and when its data was used from the transaction history. Moreover, the building manager could request occupant-centered data to analyze the occupancy using GPS information. Based on this, the schedule of the HVAC system could be adjusted using the analyzed occupant schedule. Moreover, the building manager could reduce system operation time by monitoring the real-time occupant-centered data uploaded to the blockchain.

2.3. Design of data collection application

For applying the blockchain-based occupant-centered data collection process, simple mobile and smartwatch applications were developed to collect the thermal sensation and location. Moreover, they were aimed to collect personal preference and physiological data as much as possible without interfering with the lives of occupants. It is noted that applications were developed with the concept of a minimum value product.

Unlike the traditional survey in the forms of web or paper, a mobile survey application enables continuously transmitting collected occupant-centered data to the server anytime, anywhere. The goal of the developed mobile application is to collect personal preference data related to thermal comfort (i.e., clothes and thermal sensation) in daily life. Therefore, four functions for each page were implemented in the developed mobile application. First, the login page was designed to identify who the occupant is. User information could be a name or a unique token received from the blockchain registration process. Based on the user information, the collected occupant-centered data could be classified by individual. Second, The cloth page was designed to select clothes according to the ASHRAE 55 standard [10]. Clothes information was collected to calculate the insulation of clothes, which affects the thermal comfort of the occupant. Third, the survey page was designed to collect the current thermal sensation of the occupant. The ASHRAE seven-point scale (i.e., -3,-2,-1,0,1,2, and 3 correspond to cold, cool, slightly cool, neutral, slightly warm, warm, and hot) was used for assessing thermal comfort [10]. Last, the time remaining until the next survey was displayed. The time interval between surveys was set to 30 minutes, the minimum unit of working hours determined by the Korean Ministry of Employment and Labor [11]. When the next survey time came, an alarm was given with a vibration to induce continuous surveys.

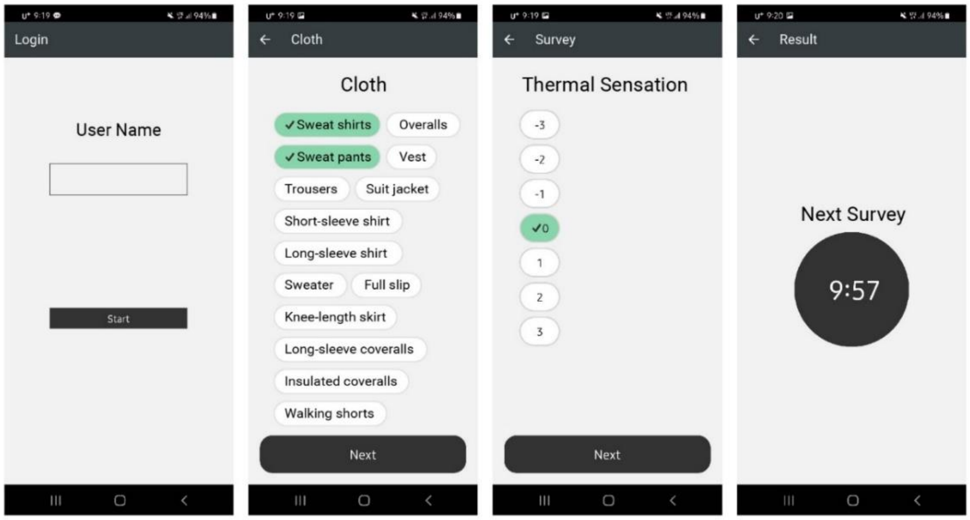

Figure 3. Screen design of the mobile application

A smartwatch is an IoT device that is widely used with smartphones. The smartwatch helps to continuously collect occupant-centered data. For example, various sensors in one smartwatch can collect physiological data such as heart rate, skin temperature, and EDA, as well as physical information such as acceleration, gyroscope, barometer, and GPS. Fitbit sense, which could fetch the raw data to the server using API, was used to develop a simple smartwatch application using JavaScript language [12]. A smartwatch application was designed to collect data related to occupant behavior (i.e., heart rate, accelerometer, and gyroscope) and data related to location (i.e., barometer, latitude, and longitude). It is noted that a barometer was used to determine the altitude at which occupants are located and predict the floor of a building. The developed applications are available online at https://github.com/JJaewon7210.

3. RESULTS AND DISCUSSIONS

In this section, a usability test was conducted to evaluate the developed mobile application. In addition, a blockchain server was proposed using Hyperledger fabric to assess the proposed data collection process in terms of scalability. It is noted that the Intel Core i7-12700 CPU @3.61 GHz processor and 32GB memory were used to operate the blockchain server.

3.1. Usability assessment

To evaluate the proposed mobile application in terms of collecting occupant-centered data in real life, a usability assessment was conducted. Ten subjects who were accustomed to using smartphones and had previously performed thermal sensation surveys were recruited. They were requested to use and evaluate the proposed mobile application for 30 minutes to receive an alarm after conducting a survey using the application. Particularly, they were asked to input a unique token received from the blockchain registration process on the login page. The age of subjects ranges from 21 to 53 years old. The proposed mobile application was evaluated in three ways according to ISO 9241-11: effectiveness, efficiency, and satisfaction [13]. Effectiveness is the completion rate of the data collection survey and is measured by calculating the successfully completed tasks over the entire tasks during the experiment. Efficiency is evaluated as the time taken to complete a task. Satisfaction was measured through System Usability Scale (SUS) test [14]. The SUS test is a globally reliable tool for measuring usability, which consists of 10 simple item questionnaires with five options on the Likert scale (i.e., from 1 (strongly disagree) to 5 (strongly agree)). SUS test shows high accuracy even with a small sample, and a score of 68 or higher is considered acceptable.

The results of the usability test are shown in Table 1. First, in terms of effectiveness, the results showed that all subjects successfully used the mobile application without errors. Therefore, the probability of erroneous data is low when survey data is collected using a mobile application. It is noted that error is the number of case where the subject entered an incorrect value in the designed mobile application and failed to move on to the next screen. Second, in terms of efficiency, the time on task was measured from opening the application to completing the survey. The results showed that the average time to complete the survey using the mobile application was 18.89 seconds. Particularly, there was no significant difference in the measured time according to age in performing the functions of the designed mobile application. The survey time is expected to be further reduced since the clothes worn by subjects did not change significantly, and if the token value entered on the login page is fixed. Last, in terms of satisfaction, the subjects conducted the SUS test after 30 minutes of using the mobile application. The results showed that the average SUS score was 71.0, which corresponds to 'B-'in the top 31 to 35% according to Sauro et al. (2012) [15]. Particularly, the average score of question number 8, "I found the system very cumbersome to use," was 1.9, which indicates that the data collection using mobile applications did not interfere with the daily life of the occupant.

Table 1. The result of the usability test

No.	**Error**	**Age**	**Time spent**	**SUS score**	**SUS question # 8**
U1	0	31	23.60 sec	70	1
U2	0	27	17.58 sec	77.5	1
U3	0	29	24.92 sec	82.5	1
U4	0	29	8.73 sec	65	3
U5	0	32	11.32 sec	92.5	1
U6	0	26	14.04 sec	72.5	2
U7	0	29	18.82 sec	52.5	4
U8	0	24	24.72 sec	67.5	2
U9	0	53	25.05 sec	60	1
U10	0	21	22.77 sec	70	3
Average	0	30.1	18.89 sec	71.0	1.9

3.2. Blockchain server performance

The blockchain server performance was evaluated when the number of clients was fixed at ten since it is expected to have ten employees in a single office room that micro-enterprises have at most ten employees according to OECD [16]. Blockchain server performance was evaluated in terms of latency and throughput, as in the case of evaluating the other network performance. Latency is the time it takes to send data from the local server to the blockchain. The lower the latency, the faster the occupant data has reflected the server in real-time. Throughput is the transaction per second (tps) when data is transmitted from the local server to the blockchain. The larger the throughput, the more transactions could be processed at once, and the more occupants could participate in the occupant-centered data collection process. In particular, the performance of 1 TPS or less means the degraded network performance since the local server collects and sends data every second. The data size for each request was 671 bytes, which corresponds to the data size survey from the mobile application and occupant data from the smartwatch application. The results showed that the average latency was 2,221 ms and the minimum and maximum latency was 2,204 ms and 2,268 ms, while the average throughput was 4.49 tps. As a result, the building managers and users can utilize the real-time occupant-centered data within three second after the request which is enough to control the indoor environment. In addition, it is expected to transfer data about 4.49 times more, which means that the blockchain-based occupant collection process presented in an office space with more than ten people could be performed without overloading the blockchain network.

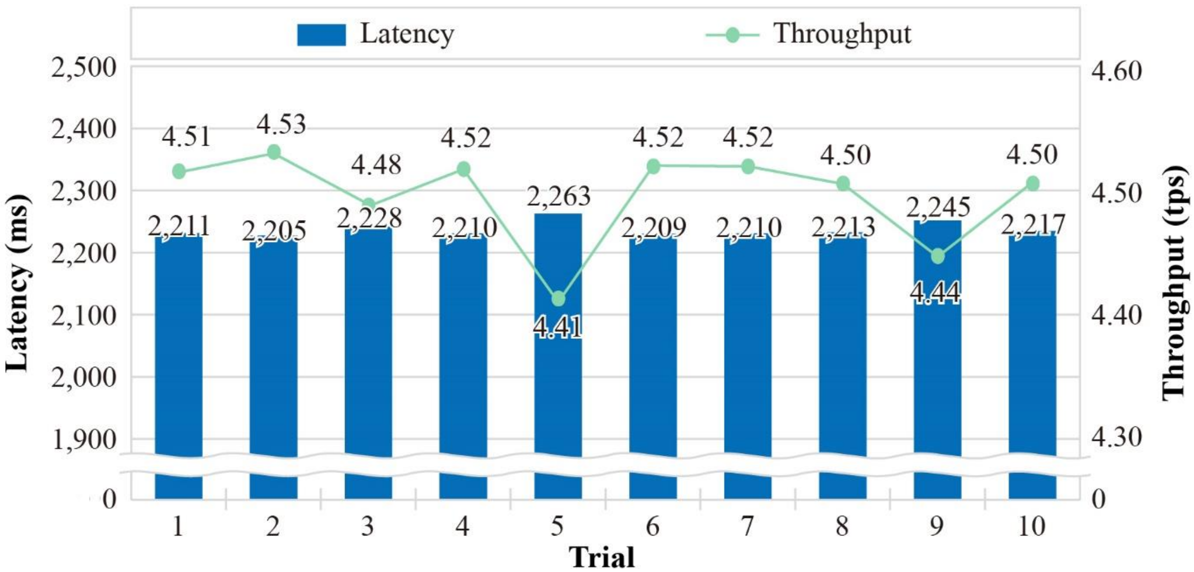

Figure 4. Performance of the blockchain server

4. CONCLUSIONS AND FUTURE WORKS

In this study, the blockchain-based occupant-centered data collection process was proposed with four stages, registering the participants to a private blockchain, collecting and integrating occupant-centered data, uploading data to the blockchain server, and reading data from the blockchain server. The case study was conducted to evaluate the usability of the developed minimum value product for a mobile application and to measure the performance of the blockchain server. The results showed that the survey using a mobile application took an average of 18.89 seconds, and it did not interfere with the daily life of the occupant. In a single office room with ten people, the blockchain-based occupant-centered data collection process was performed with a latency of 2,204 ms and throughput of 4.49 tps. The outcomes of this research could be helpful for researchers or building managers who want to collect occupant data safely and continuously in daily life, and occupants who want to measure and monitor personal information. Future research will apply the blockchain-based occupant-centered data collection process to the building management system for automated collection process and managing the HVAC system. In addition, considering when the number of occupants increases or when data needs to be recorded in real-time, future research should evaluate the performance according to the data size or the number of occupants with the improved and increased number of computers.

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