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***Abstract*—Communication techniques for Internet of Things (IoT) have attracted research attention because of the increasing number and variety of connected devices. The IoT systems are able to provide a variety of applications by collecting information from various "things" using the network constructed by the things. The IoT systems are required to provide the applications in real-time. For example, the immediacy and the time restriction will be more important to the applications. Although there have been many applications of real-time IoT systems, a specific model for performance evaluation has not received adequate attention. Therefore, in this paper, we focus on the modeling aspect for evaluating the performance of real-time IoT system. Specifically, our proposed model is constructed by utilizing feedback control theory. In order to apply feedback control theory for our model, we introduce a method for representing the "things" as the controlled objects in the control theory. After that, the overall system model of the real-time IoT with the controlled objects is represented. Finally, our represented method is validated through the numerical analysis while varying the parameters.**

***Index Terms*—Internet of Things (IoT), Feedback control theory, modeling, real-time performance.**

I. Introduction

Due to the explosive increase of devices, which connect to the Internet (e.g., smart phones, vehicles, appliances and so forth), the research attention given to Internet of Things (IoT) is also increased [1]–[3]. Additionally, with the increase in popularity of devices with various form factors, such as wearable devices like smart-watches or smart-glasses, it is expected that these wearable devices will be equipped more frequently with wireless communication modules [4]. Moreover, with the development of Machine-to-Machine (M2M)/IoT such as small sensors, devices and Wireless Fidelity (Wi-Fi) using IEEE802.11ah that is optimized for M2M/IoT based Wireless Local Area Networks (WLANs), the importance of wireless communication technology increases [5], [6]. With these developments, many different devices can collect variety of information and send the information to the Internet [7]. An overall view of M2M/IoT applications are that they collect information from devices which are equipped with sensors and the collected information is used for a variety of applications (e.g., visualization, management, and control). Conventional IoT systems only periodically provide information such as the state of the system because usually no one tries to take control of things in real-time. However, in the future, the M2M/IoT will be required to be dynamic by applications with time variation and change in mobility.

In this work, we define the IoT that the state of the system changes in real-time as the real-time IoT. The real-time IoT is essential because there are applications with demands that change in real-time with changes in the surrounding environment. In the real-time IoT, the information collection, analyzing the information, and controlling the "things" according to the analysis are done at the same time repeatedly. This will allow to take action in real-time with the rapid change of the state of the things and their surrounding environment. Thus, the concept of the real-time IoT is important and the model to evaluate its performance is required.

However, the system model of the real-time IoT does not exist in the current literature. Therefore, in this paper, we construct the model to evaluate the performance of real-time IoT system. Especially, our proposed model is constructed by utilizing feedback control theory. In order to apply feedback control theory for our model, we introduce a method for representing the " things " as the controlled objects in the control theory. By introducing the feedback control theory to the model, the architecture that the information collection, analyzing, and controlling things are done at the same time is represented in the model in an appropriate manner. By constructing a system model of the real-time IoT, it makes it possible to contribute to the development of the future IoT, which leads to the creation of various new services in the future society.

The remainder of the paper is as follows. A summary of recent relevant works and future works are presented in Section II. Section III details the application model of the feedback control assumptions and definitions. Section IV presents the performance evaluation of our represented system model. Finally, this paper is concluded in Section V.

II. A real-time IoT for the Future

In this section, we introduce the current IoT system. Additionally, we define what is real-time in IoT applications. Moreover, we explain what is required for the real-time IoT as the future IoT with some examples of applications.

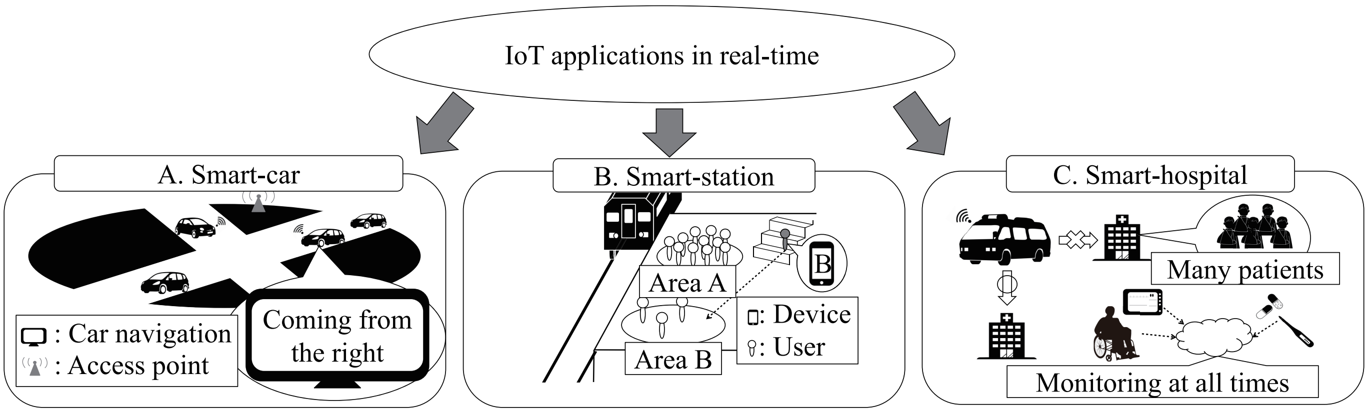

Fig. 1. Application examples of the real-time IoT

Currently, many IoT applications are widely prevalent, such as Home Energy Management System (HEMS) [8], and Building Energy Management System (BEMS) [9] in the smart system. HEMS provides the information of the used amount of electricity, gas, and so forth, and automatically controls the electric household appliances with constant monitoring. BEMS efficiently control equipment through data analysis, such as equipments located at a building. As the above examples illustrate, a variety of IoT systems begin to appear around us.

With the development of these IoT applications [10], [11], applications referred to as the real-time IoT have attracted particular attention over the year. Real-time IoT applications change the state of all related things in order to create the required environment (e.g., the resolution of congestion depends on the movement of the users, the moderation of traffic depends on vehicle derivation). We define real-time as the provision of the application as fast as possible and for specified periods of time.

In the future, IoT applications will be required to be real-time. We show three application examples of the real-time IoT in Fig.1. At first, "A. Smart-car" will enable communication with other vehicles through a vehicle-to-vehicle network or through an access point [12]. Smart-cars are able to avoid the traffic accidents by receiving information of other cars, coming from blind spot areas through a real-time IoT application. Secondly, the real-time IoT application of "B. Smart-station" makes suggestions to users in order to reduce the degree of congestion on a platform by transmitting a control message to the users [13]. Finally, it is possible for an ambulance to select the optimal hospital to take a patient to by receiving the state of the hospitals in the "C. Smart-hospital" system [14], [15]. Moreover, the smart-hospital will be able to always monitor the information of patients by connecting all of the medical devices in the hospital.

As shown above, real-time IoT applications will appear in a near future. However, a system for the real-time IoT applications does not exist in the current literature. Therefore, in this work, we show a method for representing a system model for the real-time IoT with focus of a feedback control theory.

III. Assumed Application and System Model

In this section, at first, we explain an overall view of the assumed application for the real-time IoT. Secondly, we explain the feedback control theory with the block diagram to represent the real-time IoT application model.

A. The assumed application

We explain the assumed application of the real-time IoT like "B. Smart-station" in Fig. 1. We assumed the bias of the users in the environment. The purpose of the application is to reduce the bias of the users by moving the users to the other places in real-time. The users in the assumed environment transmit the position information to the closest access point. Each access point is connecting to the server. Then, the server detects the degree of the congestion in the place where the users transmitting the information are, and calculates the difference of the number of users in each place. After that, the server makes a suggestion to the users to move to avoid the congestion by using the electronic bulletin board in real-time. In this way, the server feedback the information of the degree of the congestion to the users. After the users moved according to the feedback information, the IoT system repeats these flow in regular intervals. Here, we use the model of feedback control theory to represent these flow in the assumed environment. In the next subsection, we show the way to introduce the model to represent the real-time IoT application.

B. Introducing block diagram to represent the application model

At first, we introduce the block diagram to represent the real-time IoT application model with the feedback control theory. Secondly, we represent the movement of users as the controlled objects by utilizing the transfer function. At last, we show the method for representing the overall of the system model for the real-time IoT.

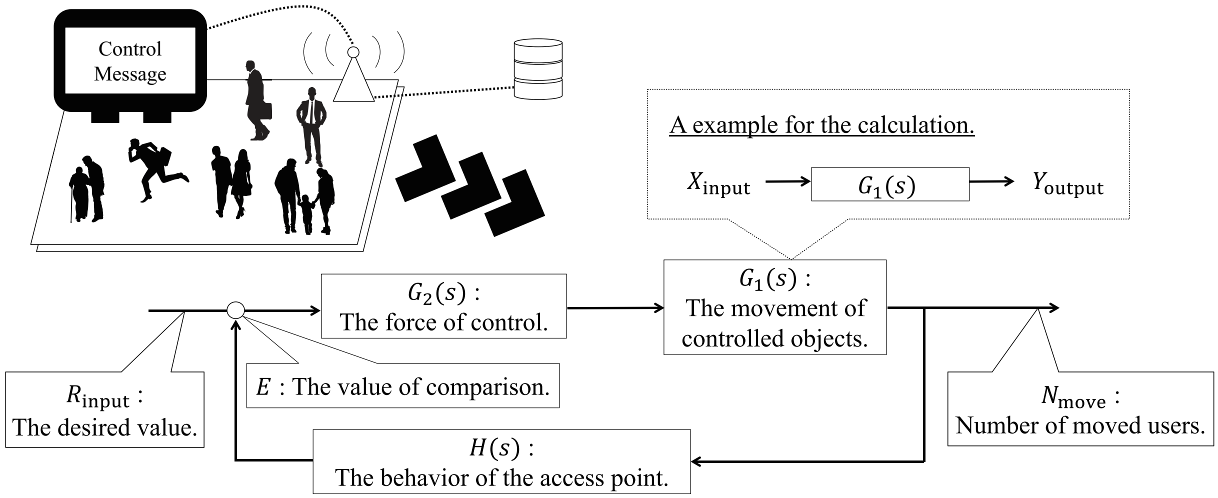

Fig. 2. An overview of the physical surroundings and the block diagram

1) The role and how to use the block diagram:

We introduce the block diagram to represent the assumed application as shown in Fig. 2. A block diagram shows each part of the feedback control theory in the assumed application and their relationships. In this work, the assumed control system consists of the four parts, that the server, the users as the controlled objects, the electronic bulletin board, and the feedback information. Here, the arrows in the block diagram show the flow of the signal and its direction. Additionally, in the feedback control theory, transfer function is used to represent the state of change of the objects. A transfer function is able to represent the relationship between the input (such as the suggested number of moved users) and the output (such as the number of moved users) in a certain block of the block diagram. Therefore, for any input, the output can be calculated if we use the transfer function. Here, we want to calculate the system model for the real-time IoT with the function of t which denotes time. It is because we have to represent the concept of the real-time in IoT applications. However, if we calculate the relationship between the input and the output by using the function of t, it will be the complex calculation. For the simplicity of the calculation, we introduce the function of s which denotes complex number. The calculation becomes simple by showing the information of time region at the complex number plane. By the method stated above, we show an example of the calculation with the block diagram of the controlled objects as shown in the dotted frame of Fig. 2. The relationship between the input and the output of the block diagram is expressed as follows:

$$Y_{\text{output}} = G_1(s) \cdot X_{\text{input}}, \tag{1}$$

where Y_{output} and X_{input} show the number of the moved users and the suggested number of moved users, respectively. Additionally, $G_1(s)$ represents the transfer function which defines the relationship between the input and the output.

2) The method for representing the controlled objects:

In this work, we assume the users as the controlled objects which have the devices. To construct the model for representing the controlled objects, at first, we explain the movement of the users. When the users watch the electronic bulletin board, they move according to the instructions on the board. Additionally, many users move according to the electronic bulletin board instruction for a while just after the instructions was displayed at first. After that, although the users continue moving while the instructions continue being displayed, trust for the instruction falls over time when the same instruction continues being displayed, and the number of the moving users slowly decreases. To represent those movement of the users, we use a transfer function, namely $G_1(s)$, which is expressed as follows:

$$G_1(s) = \frac{a}{s+a}, \tag{2}$$

where a and s show the sensitivity of the users when the users watch the electronic bulletin board and the complex number. The sensitivity of the users represents the degree of difficulty in order to move according to instructions(e.g., distance, flow of people and so on). If the value of a is high, it means that there are many users who start to move immediately after watching the electronic bulletin board. For example, the moving distance between areas in the movement to another place, hard-to-reach place in the congested area. Additionally, we can be easy to calculate the transfer function by utilizing the function of s. Thus, we construct the model of the feedback control theory by using its controlled objects model.

3) The overall of modeling with feedback control theory:

At last, we explain the method for representing the feedback control theory for the real-time IoT applications by using the block diagram as show in Fig. 2. When $R_{\text{input}}(s)$ is input of the feedback control theory, the server compares the value of the input and the feedback value. Here, we define the transfer function as $H(s)$ to represent the behavior of access point, such as the type and the function. Additionally, we define the difference of the input and the feedback value as E, which is expressed as follows:

$$E = R_{\mathrm{input}}(s) - H(s) \cdot N_{\mathrm{move}}(s), \tag{3}$$

where $H(s) \cdot N_{\mathrm{move}}(s)$ is the feedback information of users who moved according to the number of users the instructions. The server calculates the number of the moved users from the collected information including the users' position, which is transmitted from the users' devices. After the calculation of E, the server decides how many users should move in the next interval. Additionally, in this work, the value of $H(s)$ is set as follows:

$$H(s) = 1. \tag{4}$$

This is because that the collected information is directly transmitted to the server.

Next, when we set the E as the input and the N_{move} as the output, the relationship between the input and the output is expressed as follows:

$$N_{\mathrm{move}} = G_1(s) \cdot G_2(s) \cdot E, \tag{5}$$

where $G_2(s)$ denotes the force of control by utilizing the electronic bulletin board. The force of control represents the largeness of the impact, which the instructions of the electronic bulletin board give for the users. This means that the number of users who seek to watch the electronic bulletin board. The adjustment of the value of $G_2(s)$ is possible as a design of the IoT systems. Therefore, the large value of $G_2(s)$ means that many users are willing to move according to the instructions. Then, when we set the R_{input} as the input and the N_{move} as the output, the function that represent the overall of the feedback control theory is expressed by using Eq. 3, 4, and 5 as follows:

$$N_{\mathrm{move}}(t) = \mathcal{L}^{-1}[\frac{G_1(s) \cdot G_2(s)}{1 + G_1(s) \cdot G_2(s)} \cdot R_{\mathrm{input}}(s)], \tag{6}$$

where $\frac{G_1(s) \cdot G_2(s)}{1+G_1(s) \cdot G_2(s)}$ has the role of transfer function that represents the overall of the feedback control theory. Thus, the transfer function denotes the relationship between the input and the output when the suggested number of moved users, $R_{\mathrm{input}}(s)$ is input into the control system. Here, in this research, we set the force of control, $G_2(s)$, as follows to treat it as a constant value:

$$G_2(s) = K. \tag{7}$$

For the simplicity of the construction of the model, the above expressions are formulated by using s. However, the function of s has not the information of time. Additionally, it is required to transform those expressions to the functions using t which denotes time. It is because the system model for the real-time IoT have to represent the concept of time to confirm the real-time of the applications. Thus, using Eq. 6, the function of t can be calculated as follows:

$$N_{\mathrm{move}}(t) = \frac{K \cdot R_{\mathrm{input}}}{K+1}(1 - e^{-a(K+1)t}). \tag{8}$$

Eq. 8 denotes the overall feedback control theory, when the number of the moved users is represented as N_{move} with the function of t and the suggested number of moved users is represented as R_{input} as the input into the feedback control theory. Therefore, we can express the applications of real-time IoT by the system detecting the amount of change of the controlled objects as the feedback information in regular intervals.

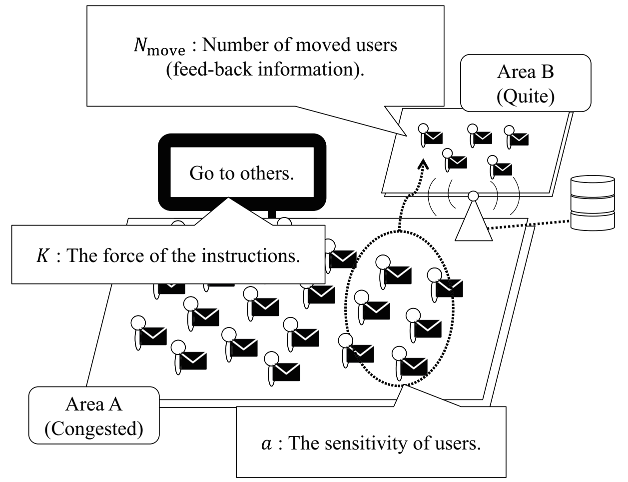

Fig. 3. An overall of the assumed scenario with real-time IoT application

IV. Numerical Analysis

In this section, we confirm that the proposed system model for the real-time IoT applications can be used via numerical analysis. It is supposed that the real-time IoT application which is shown in Fig. 3 is used, which have a bias of the users in a certain environment. The controlled objects is the users, which have the devices. The purpose of the application is to reduce the bias of the users by controlling the movement of the users. Then, we analyze the required time until the unbalance of users is resolved while varying the sensitivity of the users, a, and the force of the control, K.

A. Parameter Setting

In this numerical analysis, it is supposed that there are two fields that the number of the users is different. One is the congested area and another is the quiet area. The number of the users in the congested area is set to 100 and that of the quiet area is set to 0 initially. Thus, since the goal of the state is that the bias of the users is resolved, the suggested number of moved users, R_{input}, is set to 50. Here, we assume that the value of R_{input} is the constant value. Additionally, we set the power of the instructions, K, to 10, 20 or 30, and the sensitivity of the users, a, to 0.01, 0.03 or 0.05 to assess the model in the different environment.

B. Numerical Results

Fig. 4 and Fig. 5 show the required time until the unbalance number of the users is resolved while varying the sensitivity of the users and the force of the control, respectively by calculating the ratio of the number of users in area A and B. From the results, it is confirmed that the constructed model can

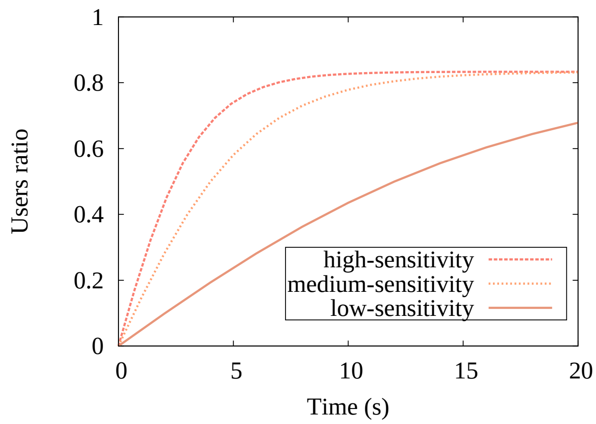

Fig. 4. The behavior until arrival at the desired value (when the movement of the users is changed)

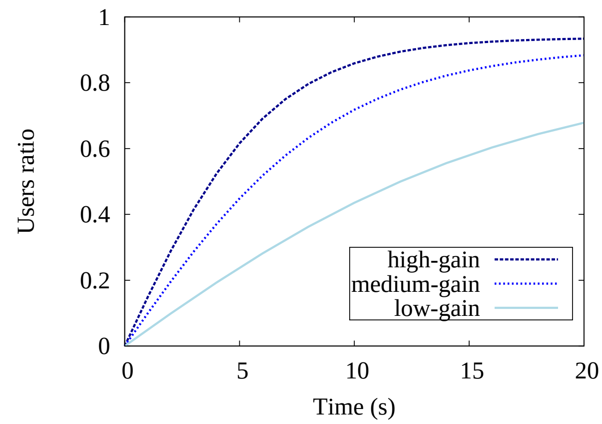

Fig. 5. The behavior until arrival at the desired value (when the power of instruction is changed)

represent the movement of the users in the assumed application which utilize the feedback control theory. Additionally, the model can represent the difference of the environment such as the sensitivity of the users and the power of the control. From Fig. 4, and Fig. 5, it is shown that high sensitivity and high power cause that the rapid initial rise and the superior mark, respectively.

V. Conclusion

In this paper, we represented the system model of the real-time IoT by utilizing the feedback control theory. It is essential for IoT systems to consider the concept of real-time because the future IoT systems are required to provide the applications in real-time. To represent the system model for the real-time IoT, we showed the method for representing the "things" as the controlled objects in the feedback control theory. After that, the way to construct the model for performance evaluation of real-time IoT systems is presented with the feedback control theory. Additionally, from the numerical results, it is confirmed that the constructed model can correctly represent the assumed real-time IoT application with utilizing the feedback control theory. It is considered that the proposed model contributes to the development of future IoT systems as an evaluation tools for real-time IoT.

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