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A Study of Timing Issues for Multimodal Human Machine Interface for Smart Home

By WU Chuyao

A thesis submitted to
School of Information Science,
Japan Advanced Institute of Science and Technology,
in partial fulfillment of the requirements
for the degree of
Master of Information Science
Graduate Program in Information Science

Written under the direction of
Professor Yasuo Tan

September, 2018

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Professor Yasuo Tan
Associate Professor Yuto Lim
Research Associate Professor Razvan Florin Beuran

August, 2018 (Submitted)

Abstract

Nowadays, vary with the development of Wireless Networks, rapid evolution of Internet of Things (IoT), smart home, smart city are very near to us. Smart Home is a home like environment that possesses ambient intelligence and automatic control, in which to responds to behavior of residents with various facilities. The main target of smart home is to support resident goals of life comfort, safety, security, energy-efficiency and enhance intelligent living. One important thing towards making a smart home is automation. The automation could be related to the individual appliances or equipment being intelligent enough to take local decisions. Traditional human machine interface (HMI) is good enough for the normal user, but not adaptive to ambient environment. Thus, multimodal HMI is proposed which process two or more combined user input models, such as original switch, remote controller, speech, pen, touch, manual gestures, gaze, and head and body movements in a coordinated manner with system output of home appliance. These kind of combinations always lead conflict problems, thus, the timing issues need to be analyzed before the implementation of MHMI.

In this research, I do a study of timing issues for multimodal human machine interface for smart home. In the first chapter, I introduced the background of MHMI for smart home environment, which is the trend of near future to any human in the world. The aim of this research is that before create the novel MHMI for smart home, the timing issues need to be discussed. Thus, the survey of home appliance and related interaction methods is necessary. Then, based on the survey, the real experiment of MHMI should be built to measure the real date for the analysis. Moreover, based on the results, the questionnaire survey with absolute category rating to evaluate the tolerable response time is important. The results of tolerable response time can be used for the optimization of MHMI.

Chapter 2 presents the introduction about smart home. By defining smart home, discussing the components of smart home. Then, a comprehensive judgment of my research background in human machine interface for smart home is introduced. In addition, the

traditional human machine interface has lots of limitations so we need to explain how to build a multimodal human machine interface to help user interact with machine in Smart Home.

Chapter 3 discusses the typical classification about the existing User Interface and proposes the basic four categories for MHMI. After the explanation of four user interfaces, the time issues of MHMI is described with the combination of these UI.

In Chapter 4, a real experiment environment is setup to do the response time measurements of TUI, AUI, MUI and GUI. Based on the typical response time of each UI, a additional delay range is designed to test the human feeling/tolerable timing of each UI. A questionnaires with absolute category rating is prepared for the tolerable experiments. Based on the results, the time issues of MHMI is discussed for smart home. Instead of real implementation of console, AUI and TUI are used to evaluate the importance and effectiveness of synchronization for MHMI. Instead of real implementation of console, AUI and TUI are used to evaluate the importance and effectiveness of synchronization for MHMI.

At last, we discussed the contribution of these research work, and show the future works.

Keywords: smart home, multimodal human machine interface.

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List of Abbreviations

ACR	Absolute Category Rating
AI	Artificial Intelligence
AUI	Acoustic User Interface
AWS	Amazon Web Services
BCI	Brain Computer Interface
CHI	Computer Human Interaction
CPU	Central Processing Unit
ECG	Electrocardiogram
EETCC	Energy Efficient Thermal Comfort Control
EKG	Electrocardiogram
EMG	Myoelectric Interaction
EOG	Electrooculography
GUI	Graphical User Interface
GPIO	General-Purpose Input/Output
GPU	Graphics Processing Unit
HCC	Human Computer Communication
HCI	Human Computer Interfaces

HMI	Human Machine Interface
HD	High Definition
IoT	Internet of Things
IR	InFrared
LAN	Local Area Network
MAN	Metropolitan Area Network
MHMI	Mulitmodal Human Machine Interfaces
MMI	Man Machine Interface
MUI	Motion User Interface
OI	Operator Interface
PAN	Personal Area Network
QoE	Quality of Experience
RF	Radio Frequency
RT	Response Time
SoC	System on a Chip
TUI	Tactile User Interface
UI	User Interface
USE	Users Using Questionnaires
USI	User System Interface
WAN	Wide Area Network

Chapter 1

Introduction

In this chapter, the background, aim, objectives of this research are introduced. The organization of this thesis is described at the end of this chapter.

1.1 Research Background

In recent years, with the rapid development of consumer electronics and the Internet of Things, the smart home has become a hot spot for research activity. The smart home technical base consists of a large variety of sensors, actuators and computational nodes that work together in harmony to provide adequate assistance and improve the quality of life of the occupants of a house. The base to support these sensors, actuators, and computational nodes is the network. Normally, the networks can be classified by their scale, i.e., personal area network (PAN), local area network (LAN), metropolitan area network (MAN), wide area network (WAN), etc. Basically, LAN is mostly used for the smart home environment. Also, there are lots of network protocols which are important for the smart home environment, e.g., TCP/IP, ECHONET, IEEE 802.11 groups (WiFi), Bluetooth, ZigBee, etc. The more detail of above information is introduced in Chapter 2.

Besides, interaction between human and home device (e.g., air-condition, TV, light, camera/monitor, etc.) takes an paramount importance in the smart home Environment. Although there are a lot of effort in Human Computer Interfaces (HCI) has been invested by the research community, this is the first time where timing issues of multimodal human machine interfaces have been deeply discussed before broadly deployed in the smart home. These multimodal interfaces have the potential to improve the interaction of the user with the home substantially, by providing the most appropriate to the user and/or combining various modalities to improve usability.

Multimodal interfaces are comprised by various components each providing a unique modality. The orchestration and synchronization of these components is necessary to provide useful multimodal human machine interfaces. Due to the heterogeneous nature of the various components and their connectivity options, time issues (e.g., synchronization) become a challenging task. The key to solving this problem is a mechanism that simplifies time issues to avoid synchronization problems while at the same time keeping delay to a bare minimum. Currently, to the best of my knowledge such a general synchronization mechanism does not exist.

1.2 Research Aim

Technological advances in consumer technology and network connectivity enable the creation of Mulitmodal Human Machine Interfaces (MHMI) in the context of the smart home. Compared to user interfaces that utilize single modality, these multimodal interfaces have the potential to be more user-friendly, customizable and intuitive in their use. However, failing to orchestrate the various components of a MHMI may lead to suboptimal user experience and thus reduce the users satisfaction regarding the smart home. This research proposes a synchronization mechanism for MHMI in the smart home that aims to reduce synchronization lag and simplify the orchestration of the various components of an MHMI. For evaluation purposes, various MHMIs will be implemented and compared to traditional single modality interfaces. The MHMIs will be evaluated by users using questionnaires such as USE [1].

1.3 Research Objectives and Methods

The objectives of this research are list as follows:

- Survey of home appliances and related interaction methods
  - Conduct a preliminary survey regarding the currently available smart home appliances and classify the interaction methods that they provide, similar to [2]. Along with [3], the results of the survey will help in better understanding interface modalities and provide inspiration for the experiments that will be conducted in this research.
  - To produce original classification of HMI for smart home, so that it can simplify the orchestration of the various components of MHMI.
- Experiments setup for measurement
  - For this objective, users will be asked to complete various commonly occurring tasks, such as turn on/off the lights, set the temperature of the air condition, operate the TV and others, with each kind of HMI. Each task will be attempted first by using a single modality HMI and then discussing the time issues. During the experiments various statistical data (such as task completion time) will be collected. Upon the completion of an experiment the user will be asked to fill in the questionnaires selected in next stage.
- To analyze Quality of Experience (QoE) with Absolute Category Rating (ACR) levels in order to clarify the allowable range of delay for each user interface (UI) of MHMI
  - Conduct preliminary research regarding questionnaire-based evaluation. ACR is a test method used in quality tests. In this step, preexisting questionnaires such as USE will be considered for evaluation purposes. However, should these questionnaires prove to be insufficient for our purposes, the design of a new questionnaire that covers the modalities that were discovered of first objective

shall be pursued. Different factors such as user satisfaction, task completion time will be considered. Previous evaluation work can be found in [4, 5, 6].

  - Define ACR levels that depend on ITU-T P.910 to define 5 levels which include Excellent, Good, Fair, Poor and Bad.

- Discuss synchronization model for multimodal HMI

  - Discuss the key synchronization mechanism responsible for orchestrating the various components of an MHMI. This mechanism should be designed to respond to application state change events, coordinate the logical input model provided by the MHMI as well as distribute updates to every connected component of the MHMI with minimal time delay which is results from the evaluation.

1.4 Research Significance

The significance of this research could be split in three parts:

- First, as a result of this research a general discussion on time issues will be developed that supports the creation of heterogeneous MHMIs. Using the results of time issues, the task of composing MHMIs from components will be vastly simplified.

- Secondly, the viability of MHMIs that use the above results will be evaluated. Usability and ease of use of MHMIs will be evaluated using standard questionnaires such as USE.

- Finally, this research has the potential to benefit society as a whole by making smart home technologies more accessible to the masses and simplifying everyday tasks for people who are in need of support and assist in their daily lives.

1.5 Organization of this Thesis

The remainder of this thesis is organized as follows:

- Chapter 2

  Presents the introduction about smart home. By defining smart home, discussing the components of smart home. Then, a comprehensive judgment of my research background in human machine interface for smart home is introduced. In addition, the traditional human machine interface has lots of limitations so we need to explain how to build a multimodal human machine interface to help user interact with machine in Smart Home.

- Chapter 3

  Discusses the typical classification about the existing User Interface and proposes the basic four categories for multimodal HMI. After the explanation of four user interfaces, the time issues of multimodal HMI is described with the combination of these UI.

- Chapter 4

  A real experiment environment is setup to do the response time measurements of classified four UI. Based on the typical response time of each UI, a delay range is designed to test the human feeling/tolerable of each UI. A questionnaires with absolute category rating is prepared for the evaluation. Based on the results, the time issues of multimodal HMI is discussed for smart home.

- Chapter 5

  Summarizes the work in this research, draws contributions and mentions the future work.

Chapter 2

Smart Home and Multimodal Human Machine Interface

In this chapter, I present the necessary background of smart home and other information of the multimodal human machine interface. The first section introduced the basic information of smart home. The second section is about the background of smart home, including the definition of smart home, and so on. The third section introduces the key components of smart home, such as smart devices, network protocols, and human machine interface. Based on these techniques, multimodal human machine interfaces is the inevitable trend of development.

2.1 Introduction

Smart Home is a home like environment that possesses ambient intelligence and automatic control, in which to responds to behavior of residents with various facilities [7]. The main target of smart home is to support resident goals of life comfort, safety, security, energy-efficiency and enhance intelligent living. The concept of smart home has been introduced more than a decades. Now, the smart home is include several components, such as the networking, all of the smart devices and equipment or Internet of Things (IoT) devices and equipment [8], the control system/platform, the interface between machine and human,

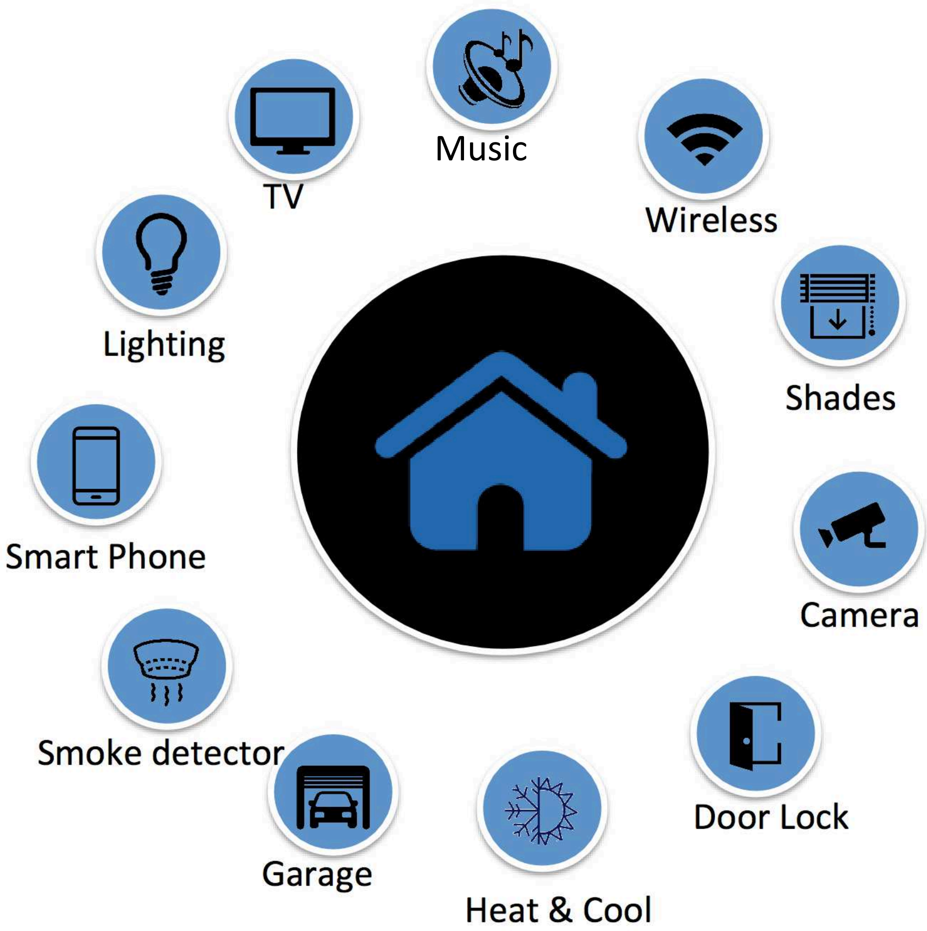


Figure 2.1: Typical Smart Home Appliances

etc.

As we know, the internet can provides access to different kinds of information even with a simple action, such as push of a button. The whole network is move to a novel paradigm, which is called IoT. IoT is defined as the network of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and connectivity which enables these things to connect and exchange date [9], creating opportunities for more direct integration of the physical world into computer-based systems, resulting in efficiency improvements, economic benefits, and reduced human exertions [10]. Thus, it makes the control of home appliance more easier, convenience and efficiency.

In Figure 2.1, the typical home appliances are shown. Almost all aspect of life in which technology is introduced (light bulbs, washers, water boiler, etc.) are proving alternative technologies for smart homes:

- Smart TV connects to the Internet to access/download through applications, such as video and music. For the smart TVs, by control with voice or gesture recognition is more "smart" than traditional remote controller.

- For smart light systems, rather than the original switch or "IR" based remote controller, use smart phone Apps or with the sensor detection to remotely and customized adjust the lighting, not only on/off, also include intensity and color adjustment with smart light bulbs.

- For smart thermostats, e.g., energy efficient thermal comfort control (EETCC) system [11], come with integrated ECHONET [12], to reduce energy consumption while satisfying the thermal comfort level of residents in timely manner by using air-conditioner, window, and curtain. The benefits of EETCC system is that it use the natural resources for thermal comfort by opening window and/or curtain.

- For smart home door/gates, smart locks and garage-door openers, resident users can allow or deny access to visitors. Smart locks can also detect that residents' location, if they are near and then the doors can unlock automatically.

- For smart home security, web cameras are necessary. Home situation can be remotely monitored when resident are away of home or on their vacation. Based on the technology of image identification and artificial intelligence (AI), residents, visitors, pets and burglars can be easily identified, if suspicious behavior is detected, resident also can received notify authorities.

- For smart kitchen system, all kinds of kitchen appliances can be controlled automatically. E.g., smart coffee makers can brew you a fresh cup after you woke up; smart refrigerators can records the expiration dates and track them, you can get notifications if some of them are expired; also, if some of your favorite food is not enough, like eggs, it can automatic shopping on the internet, or based on what's inside, it can provide resident food menu on how to cooking them. Similar for the washing machines and dryers.

- For household system, monitors are sense electric and water situations. If there is some failures or accidents, they can automatic turn off the electric or water for resident safety live.

2.2 Background of smart home

A smart home, then, may be defined as a residence or a building with equipment which can be remotely controlled and operated from any location in the world by means of smart devices, such as through a smart phone. Smart home comprises of devices that provide comfort, security, convenience, energy-efficiency and enhance intelligent living. The devices communicate and interact with each other and form a connected network system. Smart home is usually understood as automated home but the actual capabilities are beyond of automation. Smart home comprises of a set of connected gadgets with intelligence that help them in executing the task and take necessary decisions.

Smart Homes present some very exciting opportunities to change the way we live and work, and to reduce energy consumption at the same time. The owners of smart homes are empowered with conveniences like: being able to check messages, open windows, operate lights and curtains and monitor how much money the house has made or saved from the renewable energy system or smart energy management system, through their respective smart phones, from anywhere in the world.

One important thing towards making a smart home is automation. The automation could be related to the individual appliances or equipment being intelligent enough to take local decisions. A simple example could be a standalone porch light that turns on/off only when there is movement detected or wirelessly operated when curtains or blinds are turn down/up. Another example could be a camera that records the movements for a period of time after a gate is opened.

Further, smart home is a common and unifying gateway to the world for its occupants, various sensors and automating elements inside it. In fact it may be commented here that many other functions of connectivity may be considered as embedded within a Smart Home. As an example, remote patient monitoring, vehicle charging, solar rooftops, metering, home appliances, electric and air conditioning controls, entertainment, health and fitness equipment and a host of other connected devices are part of a home and a smart home system is expected to provide a unified view of all these services.

2.3 Components of Smart Home

For smart home, the components must be employed includes the following elements: intelligent control, home automation and internal network [13]. The intelligent control is provided by a control system, comprised of two types of elements, i.e., sensors and control agent. Sensors is used to monitor, report the status of the home situation and control the home appliance [14]. Control agent normally acts on the information which are provided by the sensors. Home automation functions are performed by electrical or electronic equipment; which are called actuators. Actuators interact and modify the environment by performing specialized tasks. These tasks are typically applied to more complex goals defined by the system user. The purpose of the home network is simply to ensure that all components can send and receive instructions to each other. More detail is introduced as follows (see Figure. 2.2):

- Control System is a critical part of smart home due to it determines reliability, usability and overall effectiveness of the solution provided. This system is written as a piece of software that is run on a computer or embedded in an electronic device. This system offer the ability to control a subset of the home appliances from a specified location. The basic idea of home automation is to employ sensors and control systems to monitor a dwelling, and accordingly adjust the various mechanisms that provide ventilation, heating and cooling, lighting, automated Appliances and Furniture, security and so on. These usecases are described in the following subsection.

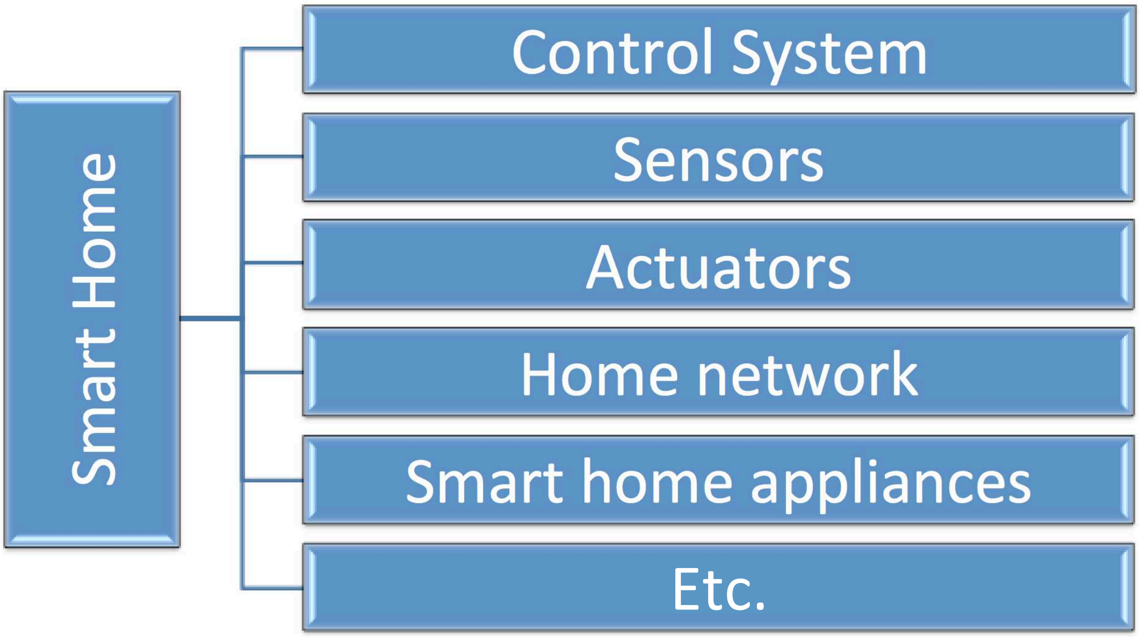


Figure 2.2: Typical Components of Smart Home

- Sensors are used to measure all of the data that can be used for the "smart" home, such as temperature sensors, wind sensors, etc. They sense all the information generated inside/outside the house. Based on the information, the control system can provide more intelligent actions for different type of life styles. The real-time measuring and monitoring of home appliances/environments is a key and integral part of smart home.

- Actuators are electrical or electronic devices taht can control a household appliance. When it is individual device, it need to be electrically coupled with the appliance and can be controlled when some simple commands is executing, such as switching on/off. When it is embedded within the appliance itself, they can be more sophisticated and provide more value added to the resident user.

- Home network can be subdivided into two main areas, depending on the communication media used:

  - Wired network is a system which plug in directly to the house electrical network (electrical mains) and do not require additional cabling, such as TV cable, Wireless LAN cable, etc. This technology can be simply configured with low cost. It's weakness may be the lack scalability and considered the least reliable due to its susceptibility to electrical interference.

  - Wireless network is a system which do not require any wires to operate. This technology can be further subdivided into Radio Frequency (RF), and Infrared (IR). They are commonly used due to the low cost per unit. The typical techniques are such as WiFi, ZigBee, Bluetooth, etc.

- Smart home appliances are already introduced in the previous section (see Figure 2.1). They are the core part of the components for smart home. They can provide comfort, entertainment, convenience, and efficiency to residents.

Although the way to use them "smartly" is important, the way to control them is also very important. Any software or devices that allows human to interact with a machine are collectively called Human Machine Interface (HMI) [15], which have great relationship with all above components.

2.4 Systems in Smart Home

Moreover, there are several typical systems in smart home. The detail are list as follows:

- Ventilation, Shading, heating and cooling Conditioning System
  A proper heating, ventilation, and cooling system is a key parts of every smart home. This system works much more than programmable thermostats and timer controls [16]. Smart home technologies on ventilation, shading, heating and cooling system is important to give residents no matter where you are on the earth (see Figure. 2.3). Resident can feel confortable and also cutting down their energy bills by using an automated system monitoring or programs which lead to keep the home well-insulated or ventilated, such as EETCC system [11].

  Moreover, you can free from small tasks, e.g., adjusting the insulation at home with these system. This might save your time and the energy as you have remote access

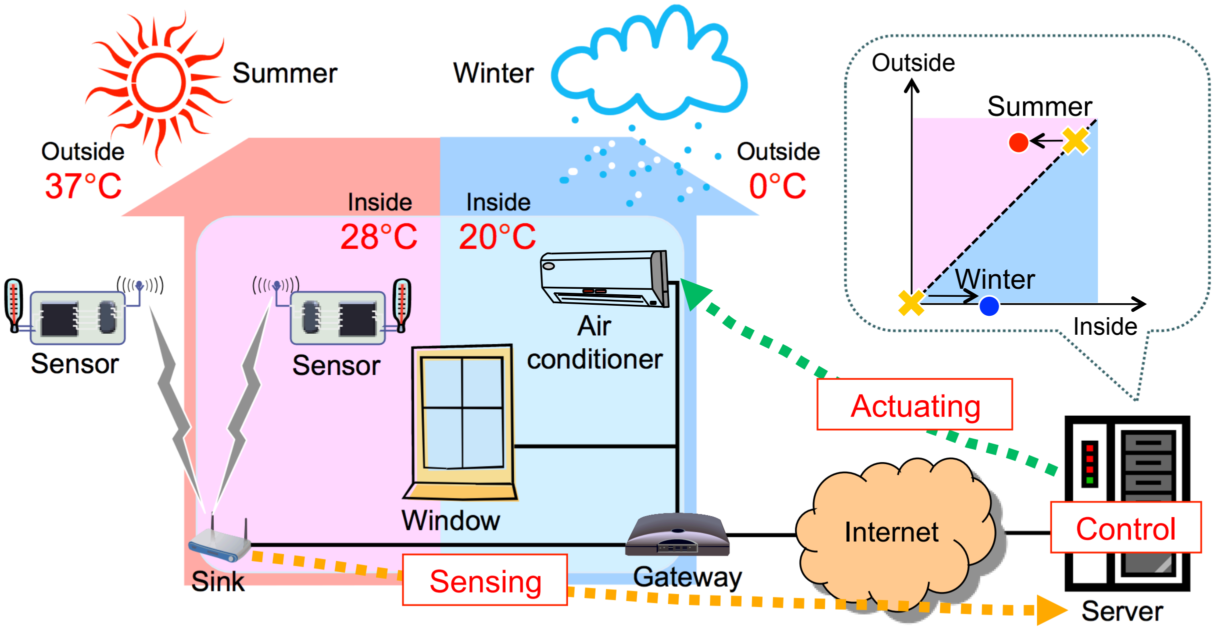


Figure 2.3: Ventialation, Shading, Heating and Air Conditioning System

outside your home, even as automatically control by itself depending on the changes on temperature of the current outside weather (see Figure. 2.3).

- Lighting System

  With a single click on a button, or a flip on a switch, it is already possible to turn on/off all the lights in any house. In smart home, the lighting system should automatically control all of the lights, not only turn on/off, also brighten or set a dim level in a selected room depending on resident user's situation. Other than having remote access to all the lights, it also should allow resident users to program desired brightness in every room of their home.

- Appliances and Furniture Automation System

  Smart home systems can offer voice-controlled appliances such as voice-controlled fun, TV, entertainment systems, AI voice system, and so on. Having these automated home appliances relieves you away the laborious tasks especially it is necessary for the elders, children and disable people. Voice recognition based software/products are made them available for smart home environment, such as easily program with simple commands to home appliances and so on.

- Home Security System
  Home security system is the top component for every smart home. Smart home requires full security since it is vital to keep residents and their property safe from harm. As violence increases, home security systems are important to every home resident. Having a home security system installed contain many concepts, such as installation of wired surveillance cameras, smoke detectors, motion sensors, fingerprint or eye scanners, and others. With installation of these concepts, the home can be definitely prevented burglary from occurring.

For this research, more focus are on the human machine interface rather than any other components. With the internet of things (IoT) became a dominant trend in the world,in order to operate the devices, HMI are becoming more complex. This research can simplify each HMI, and focus on the time issue for their combination in smart home. The light system is selected to do the evaluation of each type of human machine interface due to it is easy to implemented with low cost.

2.5 Human Machine Interface (HMI)

Human machine interface (HMI) is a component of certain devices that are capable of handling human machine interactions. The HMI consists both hardware and software that allow the translation of user inputs as signals for machines that, in turn, provide the required result back to the user. HMI technology has been used in many different industries, e.g., electronics, entertainment, medical, military, etc. HMI help in integrating humans into complex technological systems (for example, see Figure. 2.4). Human machine interface is also called Computer Human Interaction (CHI), Man Machine Interface (MMI), Human Computer Interaction (HCI), User Interface (UI), User System Interface (USI), Human Computer Communication (HCC) or Operator Interface (OI).

Vary with the development of IoT and wireless technologies, the HMI is not only for the industries, it is used anywhere, anytime in the world. In this research, the HMI is more

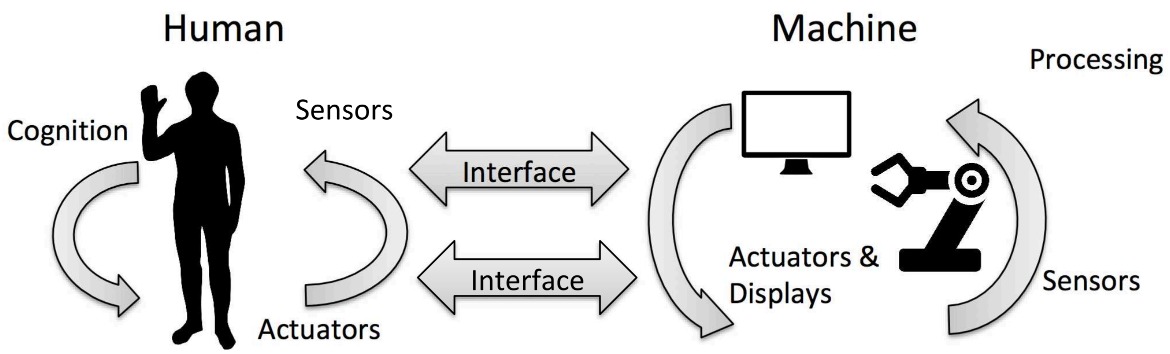


Figure 2.4: Human Machine Interface

focus on the smart home. In HMI, the interactions basically contain two types, in another word, both human to machine and machine to human. In home environment, resident usually interact with home appliance through an interface. Thus, in this research it can be assumed that HMI stands for human machine interaction as well as human machine interface, and call HMI as User Interface (UI) for simple. Since HMI technology is ubiquitous, information can be exchanged between human and machine through sight, sound, feeling and other physical modes or cognitive modes. Typical HMIs include switch button, remote controller, motion detection sensors, touch screen and other peripheral devices, speech-recognition devices and any other interaction devices in home environment.

In smart home, the basis design of HMI largely depends on the understanding of residents' physical, behavioral and mental capabilities. Or we can say, ergonomics constitutes are the basic principles of HMI. In order to enhance the experience and efficiency for resident/user, HMI also bring unique opportunities to home applications, recreation and learning, e.g., [17, 18]. In fact, HMI helps resident to master the way of using equipment rapidly. A good HMI can bring realistic and natural interactions between user and external home appliance/devices.

Typically, HMI provides the advantages include error detection and reduction, system and user efficiency enhancement, reliability and maintainability improvement, increased user acceptance and comfort, reduction in training and skill requirements, reduction in physical or mental stress, reduction in task saturation, increased economy of production and productivity, etc [19, 20]. HMI technology is also widely used in other field, such as displays on virtual and flat, pattern recognition, Internet access, personal computer interaction, data/program input for electronic devices, and information fusion. In smart home, the main goal of design HMI is easy interaction, low risk of injury, fatigue, error and discomfort, as well as improve the productivity and quality of interaction. Also, how to built the HMI to lead resident towards more natural interfaces that is more intuitive to use, and not carry out any restrictions on natural movements is getting more important.

2.6 Multimodal Human Machine Interface (MHMI)

Usually the traditional human machine interface in smart home is designed for the normal user, not adaptive to ambient environment. HMI like based on only one modality, can not provide a natural way of human interaction.

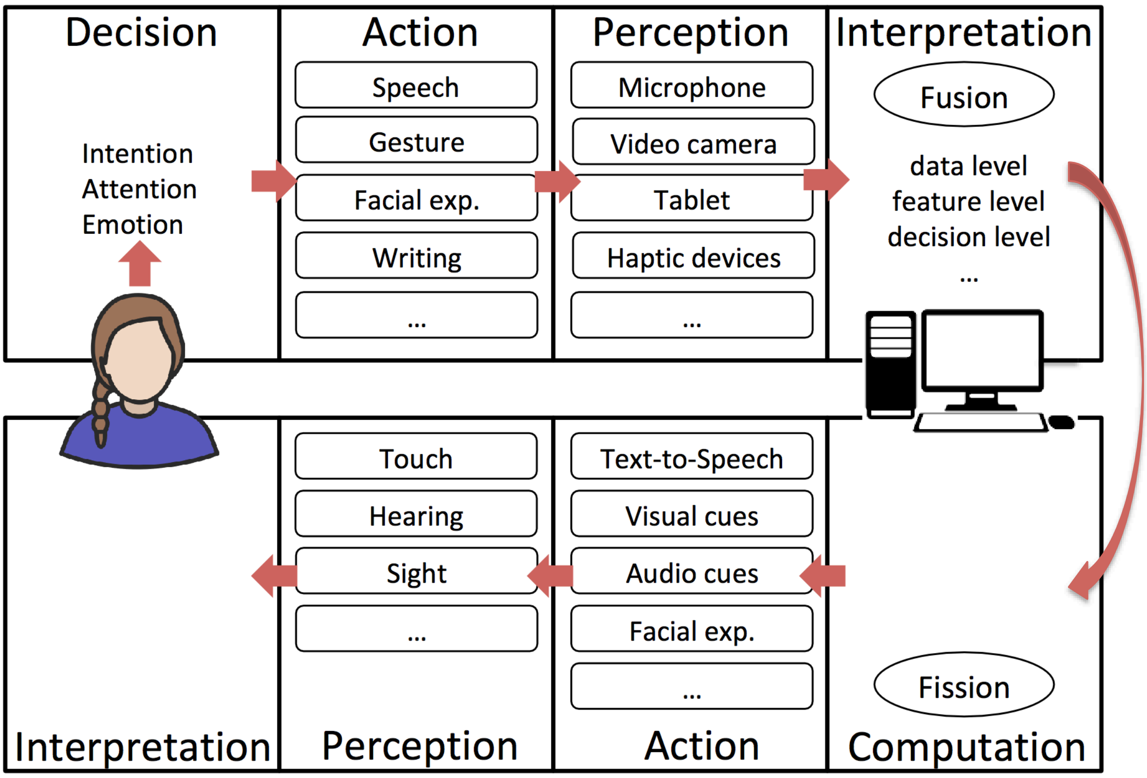


Figure 2.5: Multimodal Human Machine Interface

Thus, the multimodal HMI is proposed. For example, Figure. 2.5 is shown the multimodal human computer interface. Similar to multimodal human computer interface, MHMI has same concept. When we imagine communication human-human, human receivers information from many sources and not just using speech. For example, mimic, gesticulation and many others. Multimodal systems process two or more combined user input models, such as original switch, remote controller, speech, pen, touch, manual gestures, gaze, and head and body movements in a coordinated manner with system output of home appliance, similar as Figure. 2.5. This exchange of information is more natural than just using of one modality. This class of systems represents a new direction for computing, and a paradigm shift away from conventional human machine interfaces [21].

The growing interest in multimodal HMI design is inspired largely by the goal of supporting more transparent, flexible, efficient, and powerfully expressive means of human machine interaction. Multimodal HMI are expected to be easier to learn and use, and are preferred by users for many home appliance [22]. The future potential is significant when the system is considered for people with disabilities, elders, children, etc.

The advent of multimodal interfaces based on recognition of human speech, gaze, gesture, and other natural behavior represents only the beginning of a progression toward computational interfaces capable of relatively human-like sensory perception. Such interfaces eventually will interpret continuous input from a large number of different visual, auditory, and tactile input modes, which will be recognized as users engage in everyday activities. The same system will track and incorporate information from multiple sensors on the users interface and surrounding physical environment in order to support intelligent adaptation to the user, task and usage environment.

General requirements of MHMI are list as follows:

- Supplementary and complementary use of different modalities
- Seamless synchronization of modalities
- Multilingual support
- Easy to implement
- Accessibility

- Security and privacy
- Delivery and context
- Navigation specification

Multimodal HMI brings several advantages:

- Input overloading

  In the case of using only one modality, every command transmitted only through this modality and it can lead to the "overloading" [23]. For MHMI, these overloading normally not exist.

- Flexibility

  Since individual input modalities are well suited in some situations, and less ideal or even inappropriate in others, modality choice is an important design issue in a multimodal system. As systems become more complex and multifunctional, a single modality simply does not permit all users to interact effectively across all tasks and environments.

- Collection of information

  Another major advantage of MHMI is a collection of information. This advantage can be easily explained using the example of the authentication/security system. Imagine a home security system using biometric features. In the case of using only one biometric feature such as speech (speaker recognition) which we know that the percentage is more than 80%, we would have to rely on it. This can in many cases, lead to a false identification. This disadvantage can be removed by an additional modality, such as the identification by the face [24].

- Redundancy

  This advantage is similar to the collection of information from previous examples. Advantage can be explained on the same authentication system. Provided that the system is used to identify the speaker in an environment. Provided that the system is used to identify the speaker in an environment, where success rate around 95% can be achieved under ideal circumstances. But in the real environment conditions, the environment can be adversely affected by various factors, such as noise. In this case, use redundant information from a system of identification using face.

- Minimizing cognitive load

  As task complexity increases, there is evidence that users self manage their working memory limits by distributing information across multiple modalities, which in turn enhances their task performance during both perception and production [].

2.7 Summary

I would like to conclude this chapter with a remark intended to MHMI is very important to smart home. Smart home can lead the opportunities to change the way of resident lives and work, also reduce energy consumption and improve the security, especially very nice for child, elder, and disabled person. To easily control all of the home appliance, HMI is the best way which support resident to control appliance friendly, easily, more convenience and safety. However, traditional HMI is not adaptive to "smart" home environment. MHMI is proposed to solve the problems and brings several advantages. In the next chapter, all of the user interfaces is introduced, and the problem of MHMI is analyzed.

Chapter 3

Multimodal Human Machine Interfaces Classification and Timing Issues

In this chapter, several types of human machine interfaces are introduced. A novel classification of human machine interfaces is defined for smart home, which are Tactile User Interface (TUI), Acoustic User Interface (AUI), Motion User Interface (MUI), and Graphical User Interface (GUI). Moreover, an example is given to show the problem of timing issues when multimodal human machine interfaces is designed. To analyze the timing issues, for each type of UI, I select one typical UI for the measurement and evaluation in next chapter.

3.1 Introduction

Different with previous works, as [2], a novel classification of human machine interfaces is defined for smart home. This definition is a simple and easy way to classify all of the human machine interface into these four categories. Under the definition, the MHMI is more clear to understand and design.

3.2 Background

Here, HMIs are introduced into 5 kinds of broad categories, as shown in Figure. 3.1. Each has a unique HMI and will be discussed as follows:

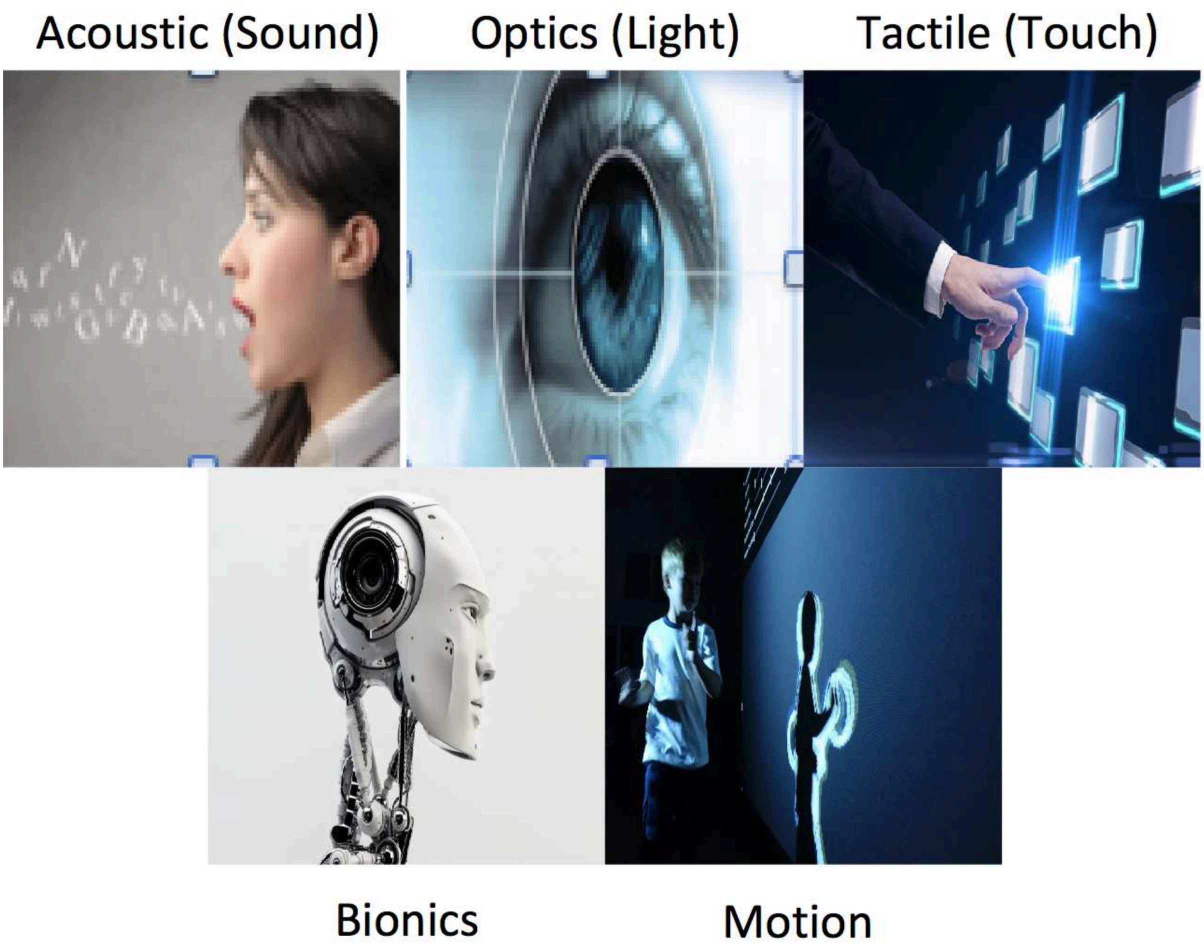


Figure 3.1: Types of Human Machine Interface

- Optic (Light) based technology

  In Optic based technology, normally camera is used as the primary hardware. HMI utilizes camera or similar equipment for computer vision. Lasers and LEDs also can be include into optic area, but normally are used in different way. The advantage of optic based HMI is that it does not require the user to touch anything physically. Movement, hand/face motions or gestures are commonly used to interact with the device/appliance. Thus, optic based technology can be recognized as an effective public interface.

- Camera - Computer Vision

  Base on this vision, hand gesture recognition and tracking, camera recognition and motion analysis are typical usecase. Due to the upwards of millions of pixels, these lead the recognition and tracking possible. These interface can easily be coupled with other technologies to make it more error resistant.

- Laser and LED's

  Laser and LED based technology is normally used for distance detection. Basiclly, they are implemented on robots as a backup, or collaborate with other technology, such as camera. The main future of laser or LED is support/-collaborate with other technologies potentially to enhance the human-machine interaction [25].

• Acoustic (sound) based technology

Acoustic based technologies focuses on speech recognition, which convert nature language to computer understood text or equipment understood orders, to control or communicate with devices [2]. The goal of speech recognition is not only transfer the nature language to machine language, also to recognize any human voice with minimal error. Speech recognition has great potential in many fields. Many smart phones or smart devices have already built with voice recognition technologies. Popular acoustic technologies are such as Apple Siri, Google Assistant, Amazon Alexa, etc.

• Bionic technology

Bionic is the most human-like area and provides a lot of cutting edge technology. Bionic technology has been around for a number of years but still not widely used for common daily life except some specific area. It combined with biology, robotics and computer science, in order to provide machine with functional parts, for example. bionic eyes, ears, legs, feet, arms, hands or other human-like parts.

Some of the cutting edge research are list as follows [25]:

  - Brain Computer Interface (BCI)
  - Myoelectric Interaction (EMG)
  - Electrocardiogram (ECG or EKG)
  - Electrooculography (EOG)

- Tactile (Touch) technology

  Tactile based technology is the only one that requires user to touch/push something physically. The most widely used touch technology is the switch button, such as switch of lighting system. Also, with more function, it provide more powerful skills, such as used on the remote controller, which can be considered as the most useful HMI to control devices. Computer keyboard is also a very useful HMI, is the basic components for any PC.

- Motion Technology

  Motion technology normally detect the motion (e.g., movement, hand motion, etc.) to control the machine/device with the already programmed functions to let the automatic operation. It normally is combined with sensors to provide the function services. Thus, the definition of motion technology is used to detect motion which requires user to physically move part of the hardware.

  Other interesting motion techiniques are:

  - Motion sensing gloves [26]
  - Hap-tic feedback device [27]
  - 3 dimensional (3D) mouse [28]

Other categories of HMI:

- Command language based interfaces
- Menu-based interfaces
- Direct manipulation interfaces

3.3 Classification of HMI for smart home

In my research, for smart home, I will classify all human machine interfaces into 4 main categories, which are tactile user interface, acoustic user interface, motion user interface, and graphical user interface. More detial are described in the following subsections.

3.3.1 Tactile User Interface (TUI)

The definition of TUI for smart home is that based upon the sense of touch (haptic), not relies upon the sense of sight (display technology is not belong to TUI). Typical TUI in smart home are such as switch buttons, remote controllers, keyboard, mouse, touch displays, combination lock, game controllers, and so on. The TUI normally based on the real physical devices, and the location and function of each button of TUI are fixed. TUI normally use the wire cables, or infrared, and so on. To measure the response time and evaluate the delay of TUI, button switch is used (see Figure. 3.2) in this research.

Figure 3.2: Typical TUI - Button Switch

3.3.2 Acoustic User Interface (AUI)

The definition of AUI for smart home is that focuses on speech recognition and speech synthesis, and mutual conversion of input voice and machine language. Famous AUI are such as Siri, Google Assistant, Amazon Alexa, etc. To measure the response time and evaluate the delay of AUI, Amazon echo plus is used in this research (see Figure. 3.3). Alexa is Amazons cloud-based voice service available on tens of millions of devices from Amazon and third-party device manufacturers. With Alexa, you can build natural voice experiences that offer customers a more intuitive way to interact with the technology they use every day.

Figure 3.3: Typical AUI - Amazon Echo Plus

The procedure of speech recognition are list as follows:

- User speak to microphone
- Machine record your voice
- Machine convert voice sound waves to electrical signal

- Signal improvement
  - Noise reduction and background separation
- Analyze voice
  - Pattern recognition
- Feedback to user

If speech recognition can work with high accurately, lot of applications can be controlled through AUI, such as controlling your home appliance, lighting system, machine automation, robotics control and others. Some of the applications are:

- voice controlled wheel chairs, voice controlled home appliances [29]
- voice enabled in-car entertainment system [30]

Acoustic based technology is one of the most potential HMI. Although speech recognition is not perfect but holds a lot of opportunity for the future, especially for smart home, smart building and smart city. With collaboration with AI technologies, AUI can be recognized as the best way to communicate with machine.

3.3.3 Motion User Interface (MUI)

The definition of MUI for smart home is that based upon resident users' physically move or rotate by detectors. To measure the response time and evaluate the delay of MUI, wearable MUI is easier than setting a group of different kinds of sensors for detection in this research. Wii controller is one of the most notable motion sensing appliance, which uses infra red sensors and accelerometer to detect motion. Similar with wii controller, the Kymera Magic Wand Remote Control is used (see Figure. 3.3). Other famous MUI for smart home such as Leap Motion, Myo Gesture Control Armband, G-speak, Maestro sensor, singelcue, and so on.

The Kymera Magic Wand Remote Control gives users the opportunity to perform magic in their own home. Kymera Wand is a Universal Remote Control is an advanced,

Figure 3.4: Typical MUI - Kymera Magic Wand Remote Control

gesture based universal remote control, designed to control almost all home entertainment equipment worldwide such as TVs, DVD players, Blue-ray players and iPod docks, using infrared codes learned from conventional remote controls by the means of gestures rather than by pressing buttons.

3.3.4 Graphical User Interface (GUI)

The definition of GUI for smart home is that uses icons, menus and other visual indicator (graphics), displays information and related user controls, manipulates with pointing device. GUI is a type of user interface that allows users to interact with electronic devices through graphical icons and visual indicators such as secondary notation, instead of text-based user interfaces, typed command labels or text navigation. Beyond computers and TV, GUIs are used in many handhold mobile devices such as MP3 players, portable media players, gaming devices (psp, Nintendo Switch, etc.), smartphones and smaller household, office and industrial controls.

Figure 3.5: Typical GUI - Display Screen Smart Phone

A GUI uses a combination of technologies and devices to provide a platform for users to interact with electronic devices, for the purpose of gathering and producing information. A series of elements conforming a visual language have evolved to represent information stored on the device. This makes it easier for people to use it. The most common combination of such elements in GUIs is the windows, icons, menus, pointer (WIMP) paradigm, especially in personal computers, smart phones, tablets and so on. To measure the response time and evaluate the delay of MUI, smart phone/tablet might be the easiest way in this research.

3.4 Timing Issues of MHMI for Smart Home

In previous section, 4 kinds of UI for smart home are introduced, they can be combine together to control the home appliance, which means multimodal HMI. When MHMI is designed for smart home, timing issues are very important. If the timing issues is not considered, synchronization problems might occur, including the delay caused by

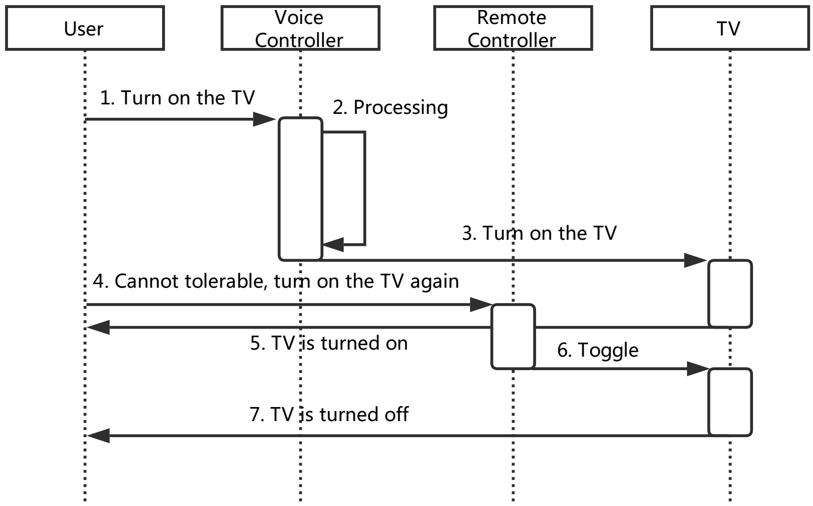


Figure 3.6: UML Sequence Diagram on Synchronization Problem of MHMI

the synchronization and the error or collision. Here, an example is given to show the synchronization problem of MHMI.

As we know, the response time of each UI is quite different. Here is an example, user want to turn on the TV. First, user asked Google Assistant/Amazon Echo to turn on the TV, due to the processing of AUI is a little bit long, user wait for a while, then use the remote controller to open the TV directly. However, the TV is turned on, and immediately turned off. To understand the problem more clearly, UML sequence diagram is used to describe the problem (see Figure. 3.6).

A simple way to solve this kind of synchronization problems/timing issues is set the no operation time period. As shown in Figure. 3.7, a middle layer which is called console is set. User want to use AUI to turn on the TV, and after 1 to 2 second, user cannot wait anymore, then use remote controller to do the toggle on the TV again. Console is set that not do the same operation within a fixed time period. Then the concurrency control problem can be solved. MHMI should be designed with these solutions of timing issues rather than ask resident to follow the rules/instructions to operate the home appliance.

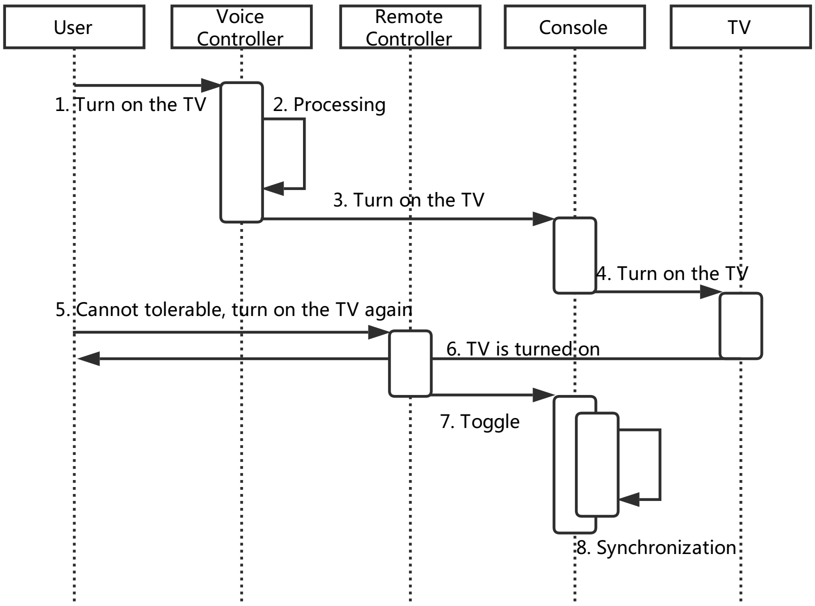


Figure 3.7: UML Sequence Diagram on Synchronization Problem Solution of MHMI

Then, the importance of timing issues on MHMI for smart home is clear. Two step of analysis are necessary before design the MHMI. Firstly, the response time of each UI should be clear. Secondly, the tolerable delay of each UI for most of users should be clear. These works will be explain and setup in the following chapter.

3.5 Discussions

To solve the synchronization with delay or error/collision, several ways are list as follows:

- All of the "toggle commands" should be canceled, which means single operation output only with one command with one single button. This can easily solve the upon problems. However, the problem is that it is impossible to change all of the remote controller with function of "toggle commands".

- Another way to solve upon problem is set an console for MHMI for smart home, as we shown in Figure. 3.7. However, all of the operational commands must directly come to the console instead of home appliances. It is difficult to implement.

- If the console is implemented, one more thing is necessary which is the command category. Thus, the objectives of commands from MHMI need to be clear, for example, multiple commands to single home appliance, multiple commands to multiple home appliances, etc.

Under the console with command category, synchronization problem can be discussed by analyzing the allowable range of delay of each UI. The allowable delay of each UI is discussed in the next chapter.

3.6 Summary

In this chapter, several types of human machine interfaces are introduced. A novel classification of human machine interfaces is defined for smart home, which include TUI, AUI, MUI, and GUI. Moreover, an example is given to show the problem of timing issues when MHMI is designed. To solve the timing issues on MHMI for smart home is not different. However, before design, two kind of time should be measured, which are the response time and tolerable delay of each UI. Based on these measurement, MHMI can provide better quality of experience (QoE) to resident users.

Chapter 4

Timing Issues on each User Interface

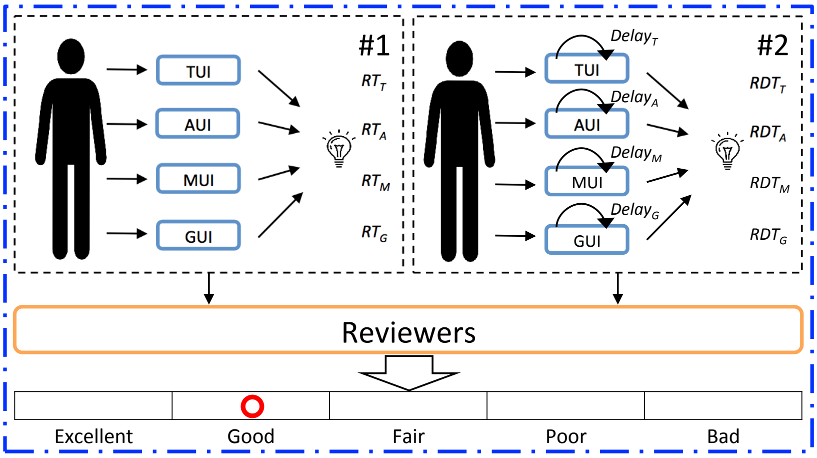
In this Chapter, the timing issues on each UI for smart home are described. As I mentioned in the previous chapter, this measurement and evaluation are important for the design of MHMI in smart home. In another word, it is necessary to analyze and solve the synchronization problem of MHMI and let MHMI more friendly, efficiency and effectiveness. The Raspiberry Pi 3 is used for the measurement and evaluation. Typical UI are selected for the measurement and evaluation in last chapter, which are switch button for TUI, Amazon echo plus for AUI, Kymera Magic Wand Remote Control for MUI, and normally Android smart phone for GUI. Depend on the necessary response time of each UI, I add a couple of extra delay for the evaluation of each UI. A questionnaires with absolute category rating is prepared for the evaluation. Based on the results, the time issues of MHMI is discussed.

4.1 Introduction

In Chapter 3, typical UI are introduced. For each UI, response time on the operation of home appliance are quite different. Thus, to understood the difference of response time is the first important thing. Here, the experiment target is set as lighting system due to it is basic necessary concept of any home. To design the MHMI for smart home, like [31], the time issues is not considered. Without the discussion of time issues, the implementation might face the synchronization problems as I discussed in previous chapter. Based on the response time I measured, I set a group of delay and use a questionnaires of ACR to evaluate the tolerable time of each UI. Moreover, based on the difference of tolerable time of each UI, the design of MHMI will be discussed.

4.2 Experiment Setting

To measure the typical response time of each defined UI for smart home, the methodology of the experiment setting is that only the UI parts is different, the rest part should use the same device/situation as possible as we can. In Figure. 4.1, the "RT" is stand for typical respond time, is the time cost between user's operation and light system's response action. The experiment environment and experiment devices are described in next section.



Typical delay of each UI (#1)			
TUI	RT_1	RT_h	...
AUI	RT_2	RT_i	...
MUI	RT_3	RT_j	...
GUI	RT_4	RT_k	...

ACR Database (#2)			
Excellent	$Delay_1$	$Delay_h$	...
Good	$Delay_2$	$Delay_i$	...
Fair	$Delay_3$	$Delay_j$	...
Poor	$Delay_4$	$Delay_k$	...
Bad	$Delay_5$	$Delay_l$	...

Figure 4.1: Measurement Methodology of Typical Response Time for each UI

#1 is the experiment for the typical RT. The results are saved into one table which named "Typical delay of each UI". In #2, extra delay is added to each UI, followed the with five ACR levels, more than 20 reviewers are do the evaluation for each UI. The delays of each UI are saved into the table named with "ACR database".

4.2.1 Experiment Environment

In this subsection, the experiment environment is introduced. In Figure. 4.2, number 8 is the lighting system, the real light bulb I used in the daily life is used for more accuracy to the real world. Here, number 7 is the relay. The distance between light bulb and reviewers is set as 1.5 meters, which is similar distance from the ceiling to the resident in normal apartment. Number 1 to 4 are the typical UIs which are described in previous chapter. Number 5 is the Raspberry Pi 3, which is the base to combine all of the UI together to control the light system. Number 6 is the WiFi router which provides wireless service to Amazon Echo Plus (number 2), Smart Phone (number 4) and Raspberry Pi 3 (number 5).

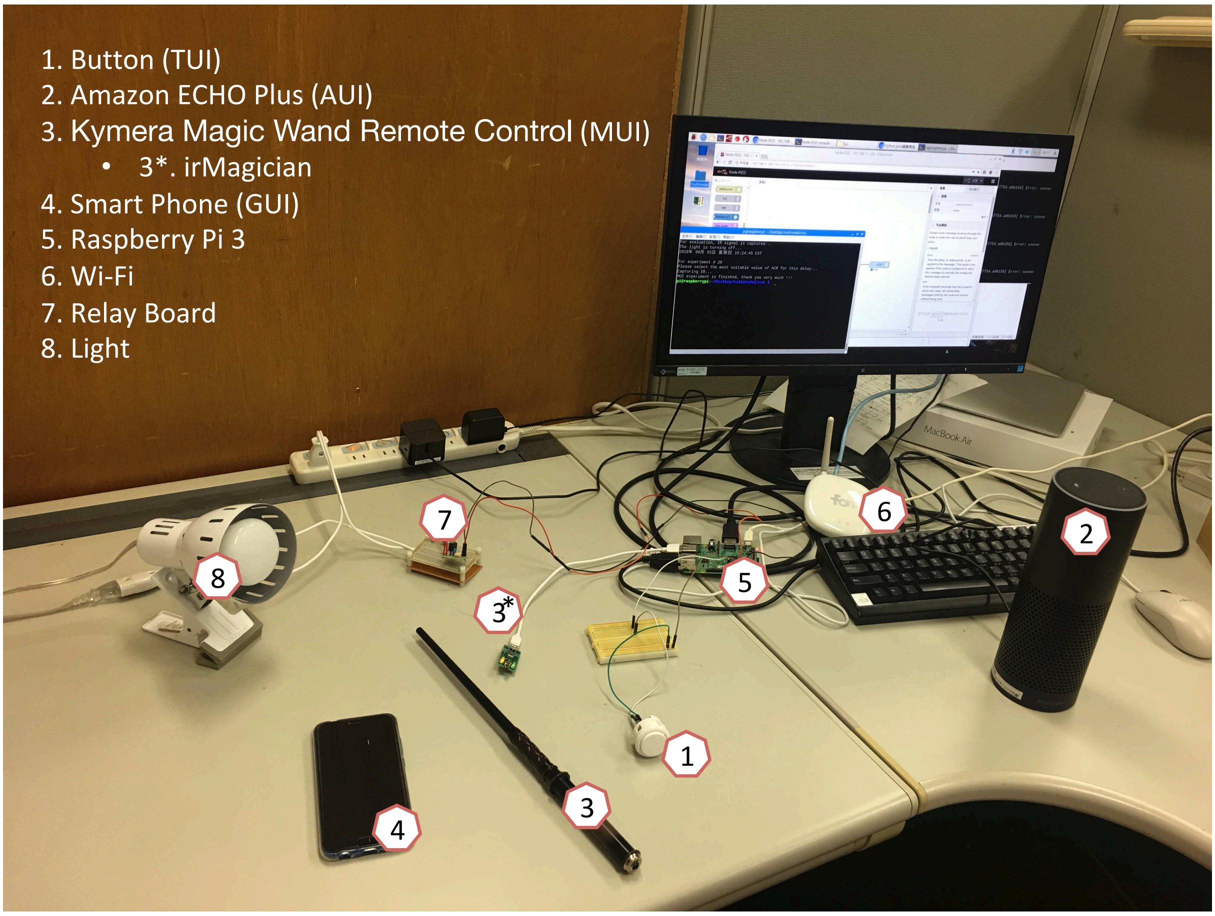


Figure 4.2: Experiment Environment

The Raspberry Pi (number 5) is a series of small single-board computers developed

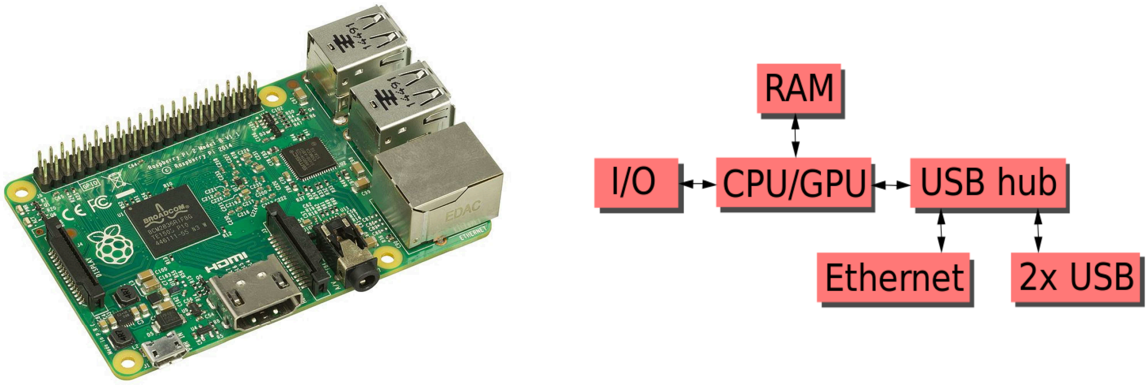
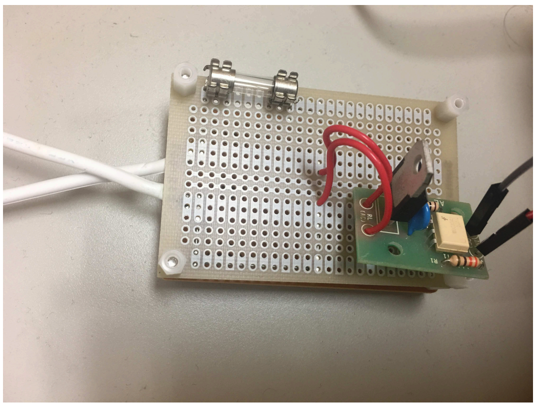
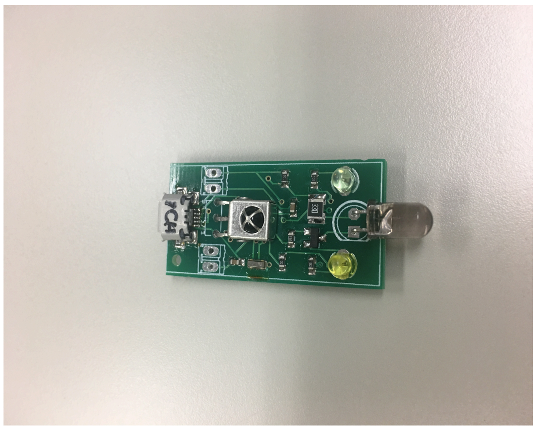


Figure 4.3: Image of Raspberry Pi and its Block Diagram

in the United Kingdom by the Raspberry Pi Foundation to promote the teaching of basic computer science in schools and in developing countries. All models feature a Broadcom system on a chip (SoC) with an integrated ARM compatible central processing unit (CPU) and on-chip graphics processing unit (GPU). Here, I use Raspberry Pi 3 for the experiment. In Figure. 4.3, the image of Raspberry Pi and its block diagram is shown. GPIO information can be found in Appendix A.



(a) Image of Relay



(b) Image of irMagician

Figure 4.4: Other Device for Experiment

A relay is an electrically operated switch (see Figure. 4.4(a)). Many relays use an electromagnet to mechanically operate a switch, but other operating principles are also used, such as solid-state relays. Relays are used where it is necessary to control a circuit by a separate low-power signal, or where several circuits must be controlled by one signal.

Figure. 4.4(b) shows irMagician which is USB controller type infra-red remote controller. PIC-18F2550 is main controller for using it. CDC-ACM is used for making connection to major OSs such as Windows, MacOSX and Linux.

4.2.2 Experiment Devices

In this subsection, I list all of the basic experiment devices for the experiment setting (see Table. 4.1). Also, Internet is necessary for the experiment. More detail of each UI settings are described in the following section.

Device Name	Number of Devices
Button	1
Amazon ECHO Plus	1
Kymera Magic Wand Remote Control	1
irMagician	1
Smart Phone	1
Raspberry Pi3	1
WiFi router	1
Relay	1
Light	1
Monitor	1
Keyboard	1
Mouse	1
Power Strip	several
Breadboard	1
Jumper Wires	several
AAA battery	2

Table 4.1: Experiment Devices used for Measurements and Evaluation

4.3 Measurements of typical response time

In this section, the measurements of typical response time are introduced. More detail about the settings, the definition of response time, the function code are described. The delay with red color in all of the figure in this section, is used for the next section for #2.

4.3.1 TUI Settings

In this subsection, the experiment setting of TUI is introduced. As shown in Figure. 4.5, the RT (response time) is defined as:

$$RT_T = t_T + t_r \tag{4.1}$$

where t_T is the time cost from the action of human to Raspberry Pi try to send the order to the light system, t_r is the time cost from the Raspberry Pi to the light system.

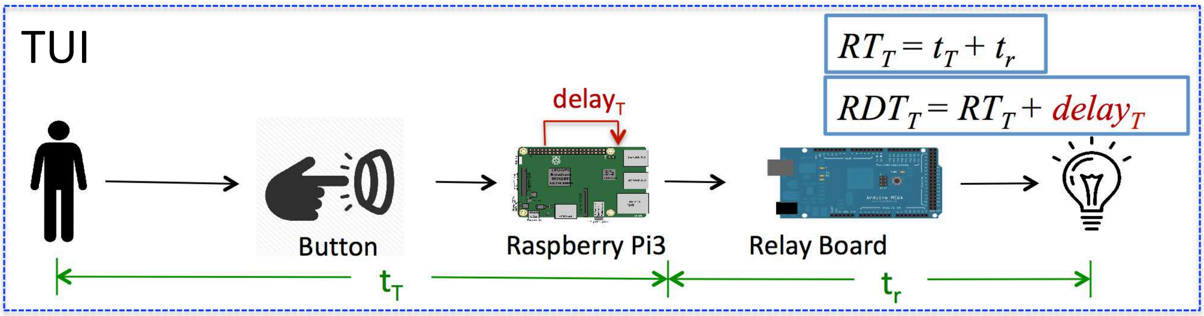


Figure 4.5: Experiment Setting of TUI

Figure. 4.5 is the most simple and common way to control the light system at home. In order to implement this function in Raspberry Pi, Python is used. The core part of code are list as follows:

- Definition Parts:

```
import os
from time import sleep
import RPi.GPIO as GPIO
GPIO.setmode(GPIO.BCM)
button=10 % No.10 GPIO is used.
Light=17 % No.17 GPIO header is used.
GPIO.setup(button,GPIO.IN,pull_up_down=GPIO.PUD_UP)
GPIO.setup(Light,GPIO.OUT)
Light_state=False
```

- Main Parts:

```
while(1):
    if GPIO.input(button)==0:
        print('Button was Pressed!')
        os.system('date')
        if Light_state==False:
#             sleep(3)
            GPIO.output(Light,True)
            Light_state=True
        else:
            os.system('clear')
#             sleep(3)
            GPIO.output(Light,False)
            Light_state=False
```

4.3.2 AUI Settings

In this subsection, the experiment setting of AUI is introduced. As shown in Figure. 4.6, the RT (response time) is defined as:

$$RT_A = t_A + t_r \tag{4.2}$$

where t_A is the time cost from the speech of human to Raspberry Pi try to send the order to the light system, t_r is the time cost from the Raspberry Pi to the light system.

In Figure. 4.6, the processing is a little bit complicate to control the light system at home. The procedure of AUI includes the speaking to ECHO Plus, transmitting speech to Amazon Alexa Skill through WiFi and Internet, recognizing the speeck through Lambda, and then from the Amazon Web Services (AWS) to send the operation command to registered Raspberry Pi, then Node-RED is used to translate the operation command to "0" or "1" to light system.

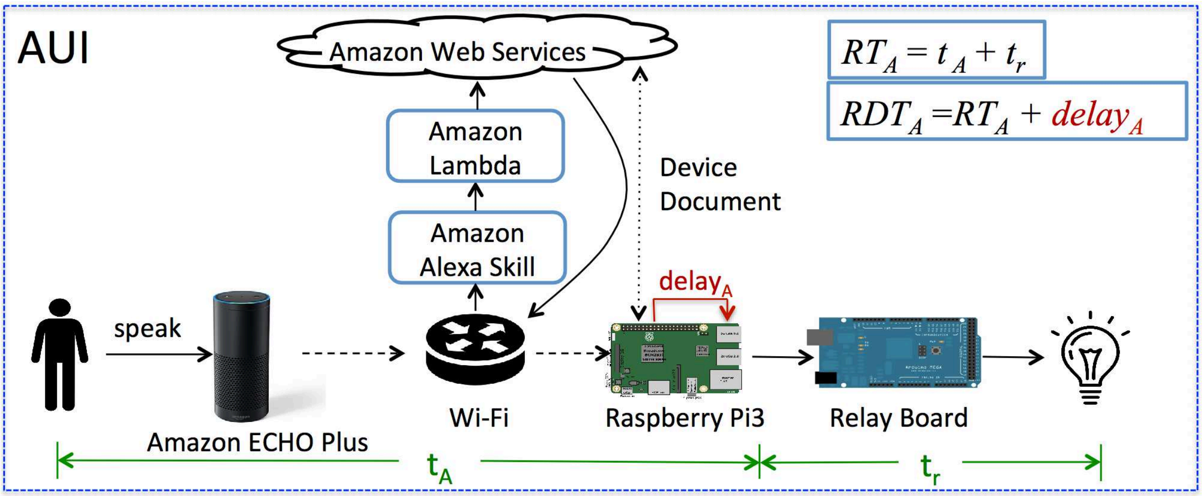


Figure 4.6: Experiment Setting of AUI

Thus, the first thing is register Raspberry Pi on the Amazon Web Service. Then Raspberry Pi can be recognized and easily controlled through "Alexa" applications. Still, when Raspberry Pi received the command, still need to translate the command to control the light system.

Figure. 4.7 shows the operation on the Node-RED programming tool. Node-RED is a programming tool for wiring together hardware devices, APIs and online services in new and interesting ways. It provides a browser-based editor that makes it easy to wire together flows using the wide range of nodes in the palette that can be deployed to its runtime in a single-click. More information can be found on *https://nodered.org/*. Under Node-RED, Raspberry received the command ("Turn On Request" or "Turn off Request") and change it to payload ("True" or "False"), then use the yellow box which named trunonoff to change the "True" or "False" to "1" or "0" to control the GPIO pins. Moreover, the purple box is used to add extra delay for the following ACR evaluation.

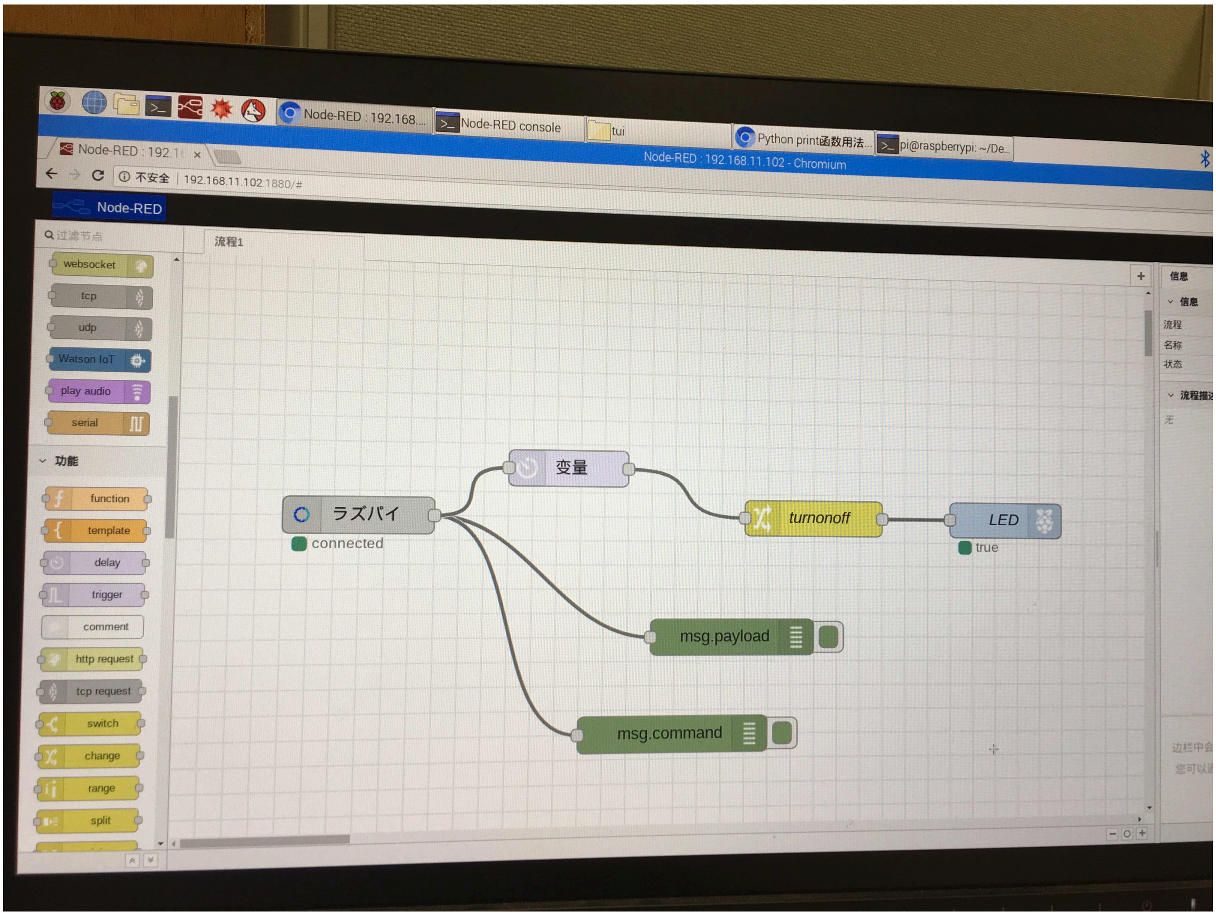


Figure 4.7: Operation setting on Node-RED

4.3.3 MUI Settings

In this subsection, the experiment setting of MUI is introduced. As shown in Figure. 4.8, the RT (response time) is defined as:

$$RT_M = t_M + t_r \tag{4.3}$$

where t_M is the time cost from the action of human to irMagician which connected to Raspberry Pi, till Raspberry Pi try to send the order to the light system, t_r is the time cost from the Raspberry Pi to the light system.

The procedure of MUI is that Kymera received resident's movement/gesture, then follow the registered orders to send the IR signal to irMagician. Figure. 4.8 is the very similar

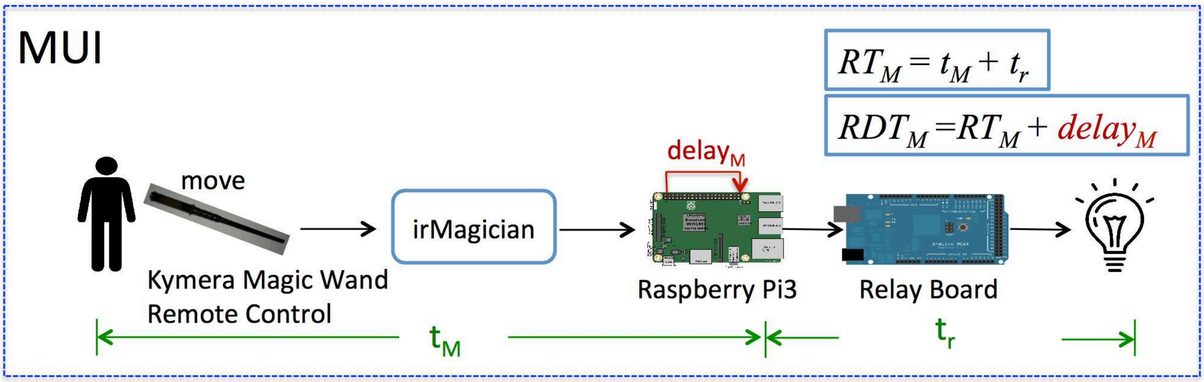


Figure 4.8: Experiment Setting of MUI

with TUI settings. In order to implement this function in Raspberry Pi, the core parts of code of Python are list as follows:

- Definition Parts:

```
import serial
import time
import os
import RPi.GPIO as GPIO
% setting the device, frequency, and time interval
ser = serial.Serial("/dev/ttyACM0", 9600, timeout=1)
GPIO.setmode(GPIO.BCM)
Light=17
GPIO.setup(Light, GPIO.OUT)
GPIO.output(Light, GPIO.LOW)
Light_state = False
```

- Main Parts:

```
print "Capturing IR..."
while True:
    ser.write("c\r\n")
    msg=ser.readline()
```

```
        if len(msg)==8 and Light_state==False:
            print"IR singnal is captured..."
            os.system('date')
            print"The Light is turning on..."
            GPIO.output(Light,GPIO.HIGH)
            Light_state=True
        elif len(msg)==8 and Light_state==True:
            print"IR signal is captured..."
            os.system('date')
            print"The Light is turning off..."
            GPIO.output(Light,GPIO.LOW)
            Light_state=False
#       else:
#           print"Cannot capture the IR singnal..."
#           print"Please try it again"

    ser.close()
```

4.3.4 GUI Settings

In this subsection, the experiment setting of GUI is introduced. As shown in Figure. 4.9, the RT (response time) is defined as:

$$RT_G = t_G + t_r \tag{4.4}$$

where t_G is the time cost from the action on smart phone to Raspberry Pi try to send the order to the light system, t_r is the time cost from the Raspberry Pi to the light system.

In Figure. 4.9, the processing is a similar to AUI. The procedure of GUI includes the operation with Alexa Apps (register and login are necessary) on smart phone through WiFi and Internet, and then from the Amazon Web Services (AWS) to send the operation

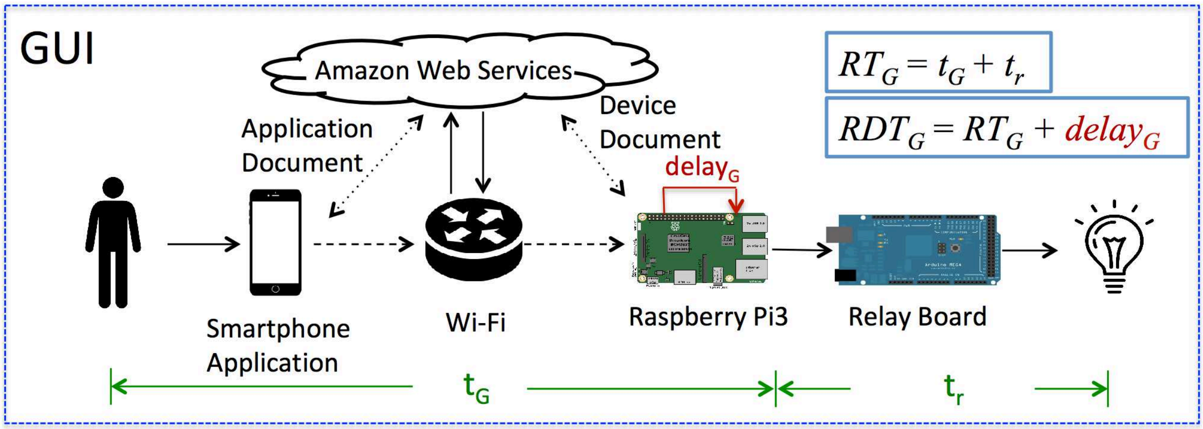


Figure 4.9: Experiment Setting of GUI

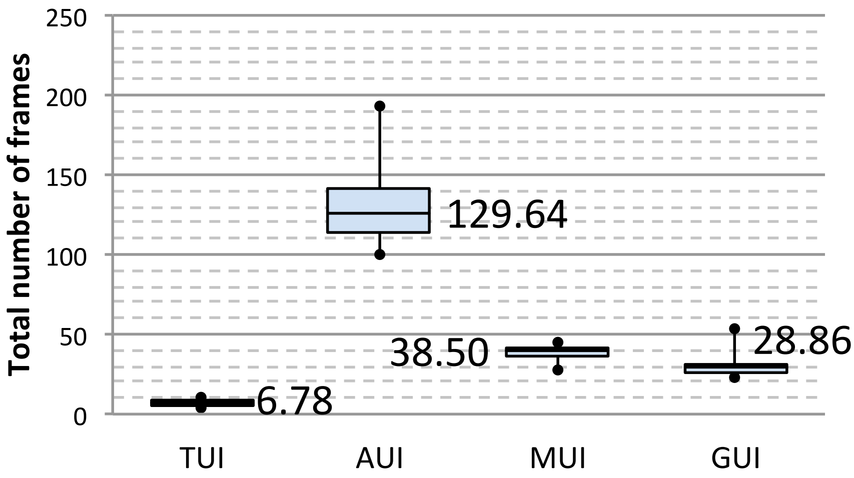
command to registered Raspberry Pi, then Node-RED is used to translate the operation command to “0” or “1” to light system.

4.3.5 Results of Necessary RT

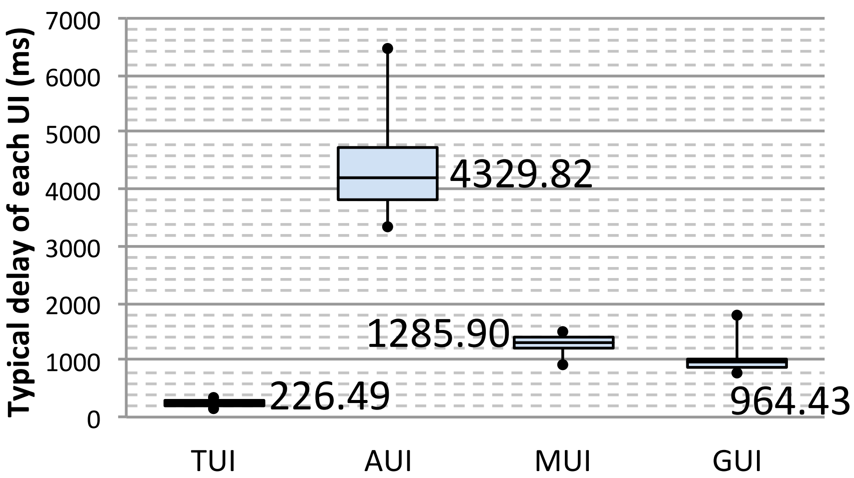
In order to minimize the influence of network communication quality, for each UI, I turn on and turn off the light system two times per hour for whole day long (24 hours). In another word, in total there are 96 times. Then use a HD camera which can provide 30 frames per second (fps) to record the entire experimental process. By counting up the number of frames in every experiment, the response time can be calculated. Through multiple operations of each UI, we can obtain more results to calculate the average value with high accuracy. The equation of typical response time is defined as

$$RT = \frac{1}{fps} \times No.frames \times 1000 \tag{4.5}$$

In Figure. 4.12, (a) and (b) are the boxplot on total number of frames of each UI and typical response time of each UI, respectively. More detail can be found in the Appendix B. According to the results, we can know that the average typical response time of each UI clearly. TUI needs only 226ms, which is the fastest in these UIs. The floating range is also the smallest one. AUI (4330ms) is the slowest in all of UIs. The time is approximately more than 18 times than TUI. The floating range is also the worst one. MUI (1286ms)



(a) Total number of Frames of each UI



(b) Typical Response Time of each UI

Figure 4.10: 24 Hours Experiments of Necessary Response Time Measurements

and GUI (964ms) are more than 5 times and 2 times than TUI respectively. The floating range of MUI is similar to TUI, due to the direct operation with light system. The floating range of GUI is similar to AUI, due to both of them are influenced with the quality of network conditions. To sum up, from Figure. 4.10(b) we can clearly see the period of scatter typical response time and the average typical response time of each UI which as a benchmark for the experiments.

4.4 Classification of ACR Levels

I used the Absolute Category Rating (ACR) in order to evaluate tolerable response time of each UI. Absolute Category Rating (ACR) is also called Single Stimulus Method, which is a test method used in quality test. Similar to [32], I also define 5 level of the scale, which are sorted by quality in decreasing order:

- **Excellent**
  - User cannot recognize the difference of delay
    - The same feeling with the actual situation (no delayed demo)
- **Good**
  - User can recognize the small difference of delay
    - A little bit different feeling with the actual situation (no delayed demo)
- **Fair**
  - User can recognize the difference of delay
    - A little bit delay can be felt compare with the actual situation
- **Poor**
  - User can recognize the difference of delay, and it is tolerable for user
    - Delay can be felt, but still OK
- **Bad**
  - User can recognize the difference of delay, and it is not tolerable for user
    - Long delay
    - Feeling to do it again
    - Feeling that there must be some problem

4.5 Experimental Design

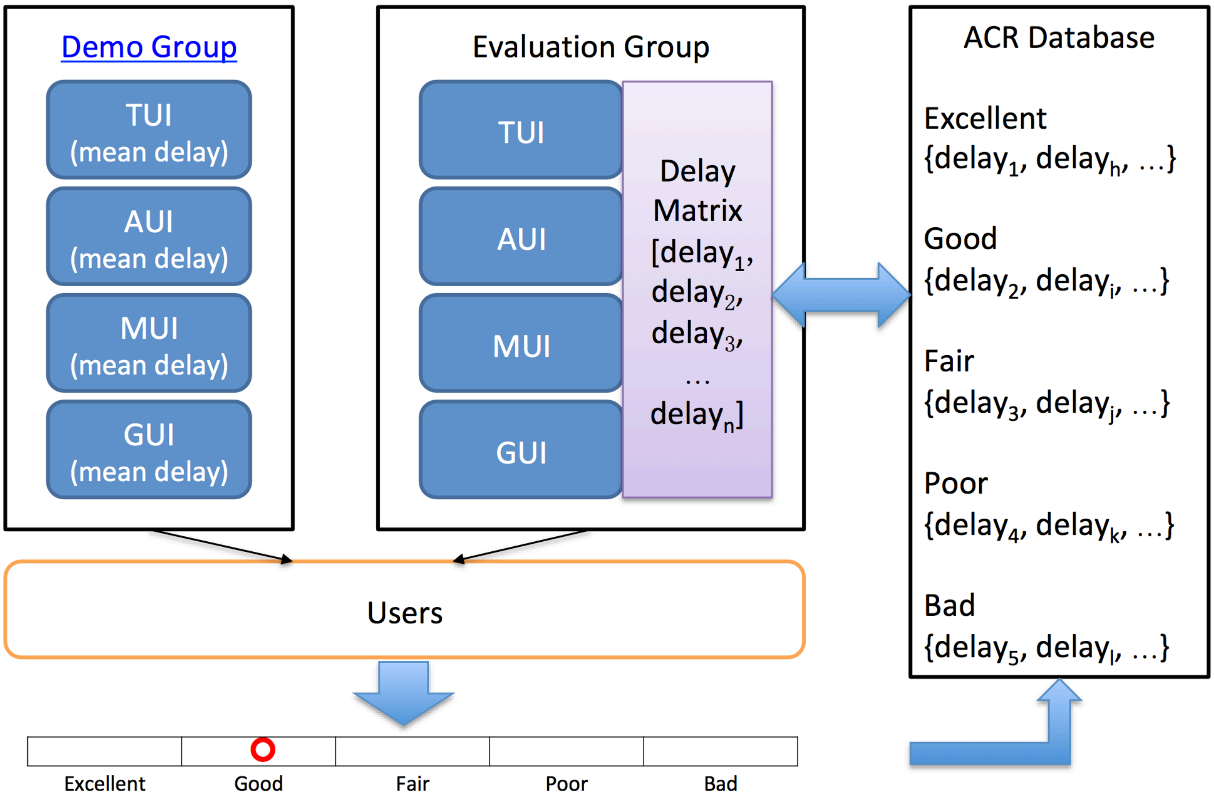


Figure 4.11: Experiment Design for ACR Evaluation

In this section, I will design the evaluation experiment of tolerable levels on each UI. Based on the results from Section 4.3.5, I insert the delay to each UI, and let reviewers to choose the ACR levels based on their own feeling. Then, the ACR levels on response time plus delay of each UI are analyzed.

In Figure. 4.11, the procedure is shown. There are two groups, which are demo and evaluation. Demo group means the light turns on with average response time, and evaluation group means add extra delay based on the average response time. For each reviewers, they need to feel the demo group first, and based on the feeling of demo group, operate the UI with evaluation group and choose the most suitable value of ACR levels on the questionnaires sheet. Then, repeat the demo group and evaluation group for several times with fixed delay interval. This methodology can increase the accuracy of the selections.

After one UI is finished, repeat the experiment for other UI with the same process. In order to make the reviewers have a clear feeling about excellent and bad; the excellent demo and bad demo are prepared.

The experiment parameters are list as follows:

Parameters	Explanation
Delay Start Point	0.0×
Delay Interval	0.2×
Delay End Point	4.0×
Total Intervals	20
Reviewer	20
Demo Response time (Excellent)	$\bar{RT}$
Demo Response Time (Bad)	5.0×

Table 4.2: Experiment Parameters for ACR Evaluation

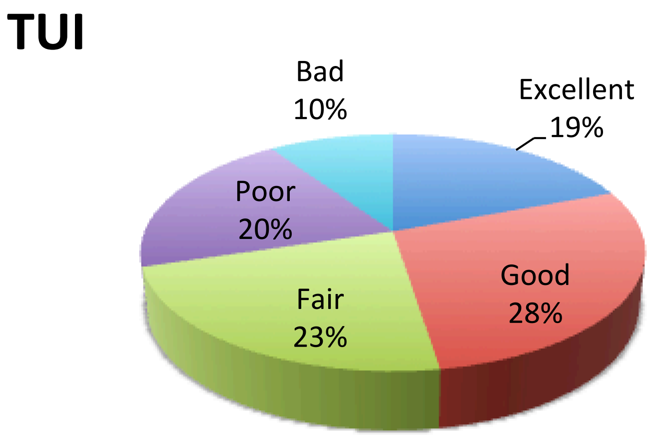
There are twenty reviewers assist in this experiment and need to do 20 groups of evaluation groups of each UI, total 80 groups of results per each reviewer.

4.6 Numerical Results

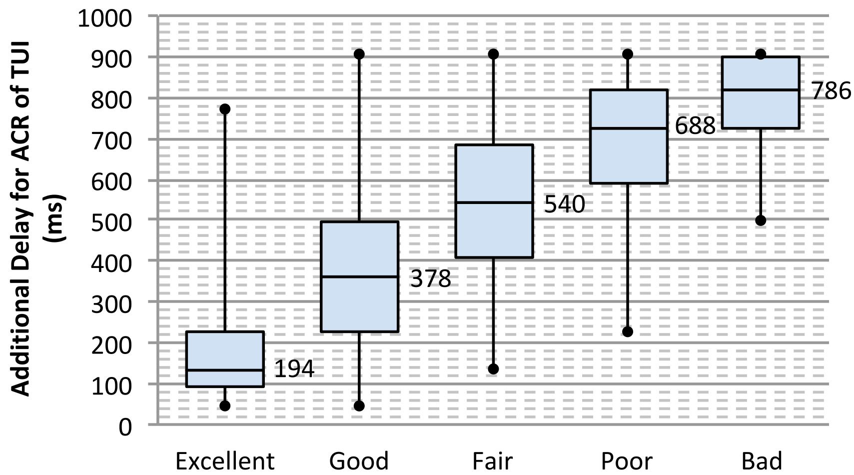
In this section, the results of experiment for ACR levels evaluation is analyzed (ACR databese in Figure. 4.11).

4.6.1 Pie and Boxplot Results of TUI

Figure. 4.12(a) illustrates the evaluation of reviewers control the light with difference extra delays by TUI. From the graph it can be obviously concluded that the reviewers choose Good (28.25%) account for the highest proportion of TUI. The second most common choice is Fair which takes 23%. Apart from Good and Fair, which consisted half of all election, Poor (20%) and Excellent (19%) in the third and fourth place more or less the same. And Bad which constitute approximately 10% is the smallest present of all. To sum up, for the experiment with extra delays, the reviewers showed the high tolerance and gave the positive feedback in TUI.



(a) Pie results of TUI



(b) Boxplot results of TUI

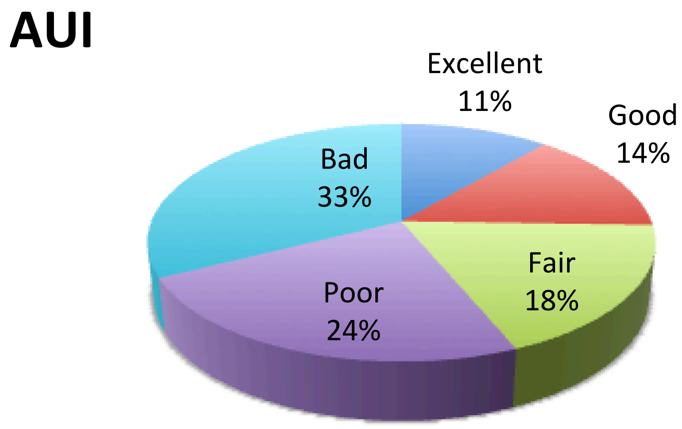
Figure 4.12: Results of ACR levels on TUI

Figure. 4.12(b) shows the detail of time distribution in all evaluation of TUI. According the results, we can know that additional delay distribution range and the average of all additional delay of each level in TUI. There are average of the additional delay in five levels of scale, which are 194ms (Excellent), 378ms (Good), 540ms (Fair), 688ms (Poor), and 786ms (Bad). As the additional delay goes on, the reviewers began to weary of the user experience. In these 5 levels of scale, Good is the biggest one of floating range and covers all the values of additional delay. And the floating range of the Bad is the smallest one in all 5 levels. And from the pie chart we can know, choose Excellent and Good covers approximately half of all election. In other words, the additional delay in this experiments in TUI, although the reviewers can recognize different feeling with the actual situation (demo without extra delay), the overall feeling is positive. To sum up, because the typical response time of TUI is the shortest of all UIs, with extra delay time, the reviewers are also show the high tolerance.

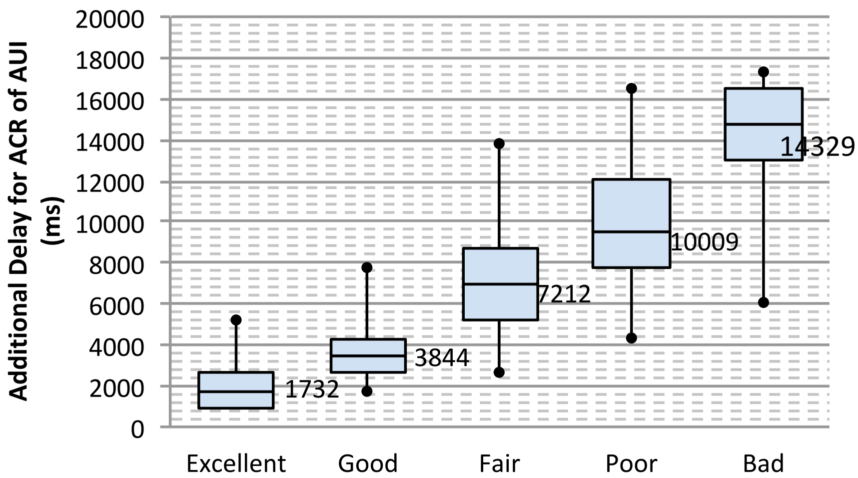
4.6.2 Pie and Boxplot Results of AUI

Figure. 4.13 illustrates the evaluation of user control the light with difference extra delays by AUI. From Figure. 4.13(b), it is explicit that the majority of reviewers choose bad (33%) and poor (24%) to the evaluation of AUI. Nearly a fifth of reviewers choose fair (19%). Only a small minority chooses excellent (11%) to evaluate the AUI. And the reviewers who choose bad and poor is more than two times than choose excellent and good (15%). Obviously, the reviewers show the low tolerance and negative feedback.

Figure. 4.13(b) shows the detail of time distribution in all evaluation of AUI. From this figure, we can know that additional delay distribution range and the average of all additional delay of each level in AUI. Average of the additional delay are in five levels, which are 1732ms (Excellent), 3884ms (Good), 7212ms (Fair), 10009ms (Poor), and 14329ms (Bad). As the additional delay goes on, the reviewers begin to weary of the user experience. And from Figure. 4.13(b), we can know nearly a third of reviewers recognize the difference of delay, and can not be tolerable, or want to do it again. Bad which the average of additional delay is 14329ms, is nearly 10 times of Excellent. we also can know that the floating rang about Excellent is the smallest one, and has approximately the same floating rang with Good. And because the AUI is influenced with the quality of network condition, and typical response time is the longest of all UIs, to users, it is difficult to show the high tolerance. That means only if the additional delay very small, the users can have perfect user experience.



(a) Pie results of AUI

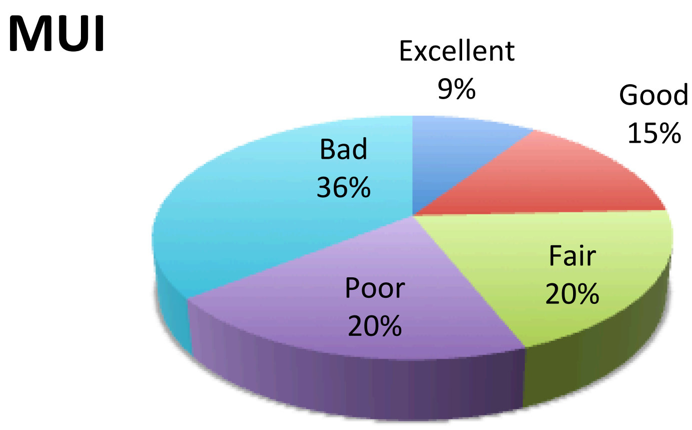


(b) Boxplot results of AUI

Figure 4.13: Results of ACR levels on AUI

4.6.3 Pie and Boxplot Results of MUI

Figure. 4.14(a) shows the evaluation of reviewers control the light with difference extra delays by MUI. From the diagram we can see the reviewers choose bad (36%) account for the highest proportion more than a third of MUI. To tie for second common choices are fair and poor, which are around 20%. These three parts which negative feedback account for over two third of whole. When we compare the election of excellent (9%) and good (15%) with bad, we see the summation of excellent and good is less than bad. And the



(a) Pie results of MUI

(b) Boxplot results of MUI

Figure 4.14: Results of ACR levels on MUI

number of reviewers who choose the Excellent is a quarter of Bad. Obviously, in MUI, the reviewers did not give a positive feedback, instead, reviewers showed the low tolerance.

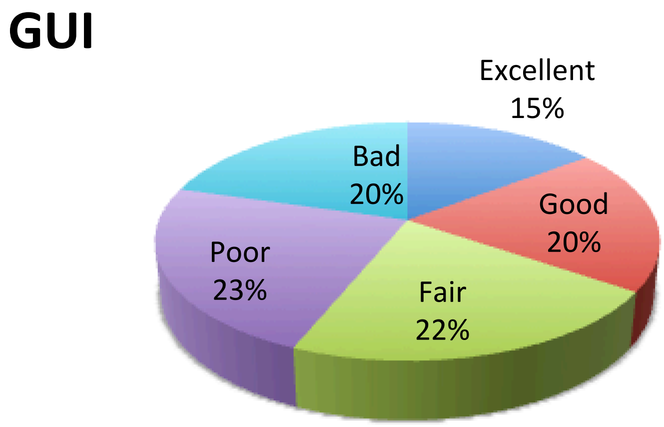
Figure. 4.14(b) shows the detail of time distribution in all evaluation of MUI. From this graph we can know that additional delay distribution range and the average of all additional delay of each level in MUI. There are average of the additional delay in five levels of scale, they are 612ms (Excellent), 1367ms (Good), 2119ms (Fair), 2877ms (Poor), and 4022ms (Bad). And the Excellent has the smallest average of the additional delay.

The Good average of the additional delay is 1367ms, which is approximately more than one time longer than Excellent. And when we compare the average of additional delay in Excellent and the average of additional delay in Fair , we see the Fair is around three times of Excellent. In this graph we can see that the floating range about Bad is not the biggest one, and Good, Fair and Poor are approximately the same floating range. And from Figure. 4.14(a) we can know, choose Poor and Bad covers approximately half of all election, in other words, the reviewers can obviously recognize different feeling with the actual situation (demo without extra delay), and sometimes want to operate MUI again.

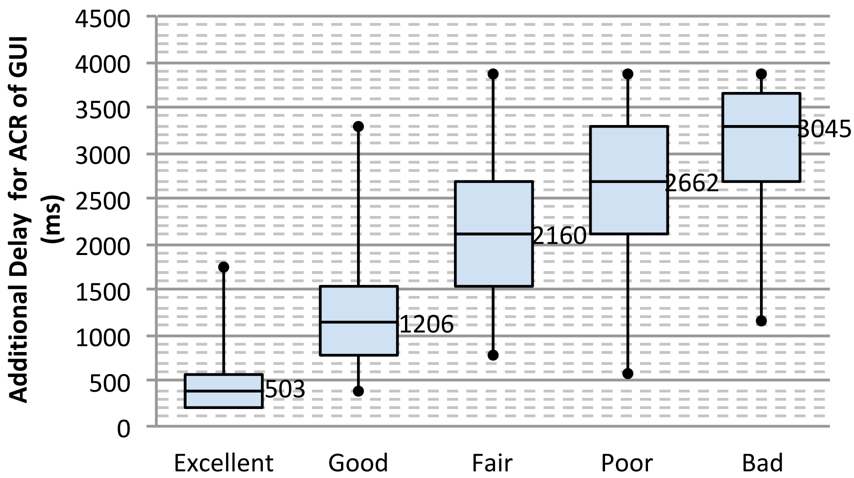
4.6.4 Pie and Boxplot Results of GUI

Figure. 4.15(a) explains the evaluation of reviewers control the light with difference extra delays by GUI. It can be seen from the graph that the proportion of bad, poor, fair and good are essentially the same. From high to low, they are the poor, which is 23%, the fair that is 22%, the bad and good which are 20%. And the excellent, which constitute approximately 15% is the smallest of all. When we compare all the proportion of election, we see in GUI there are not great differences that exist in these five levels. And a very noticeable characteristic was that the reviewers show remain stable throughout on tolerance.

Figure. 4.15(b) shows the detail of time distribution in all evaluation of GUI. According the results, we can know that additional delay distribution range and the average of all additional delay of each level in GUI. There are average of the additional delay in five levels of scale, which are 503ms (Excellent), 1206ms (Good), 2160ms (Fair), 2662ms (Poor), and 3045ms (Bad). As the additional delay goes on, the reviewers began to weary of the user experience. In these 5 levels of scale, Excellent is the smallest one of floating range. And Good, Fair, Poor and Bad approximately have the same floating rang. And from Figure. 4.15(a) we can know, the reviewers who chose Good, Fair, Poor and Bad also have an approximate proportion. The reason is because the GUI is influenced with the quality of network condition, the GUI probably not a perfect user experience, there are the smallest reviewers who choose Excellent. And when we compare the average of additional delay



(a) Pie results of GUI



(b) Boxplot results of GUI

Figure 4.15: Results of ACR levels on GUI

in Fair, Poor and Bad, we realize that the time is increase approximately 400ms in each level. In a word, although the reviewers do not feel the best user experience, they given a stable evaluation.

4.6.5 Discussion

Table. 4.3 shows the average response time of demo and each ACR level for each UI. Depend on which UI is used for MHMI in smart home, the tolerable response time is

	#1 $\overline{RT}$	#2 $\overline{RDT}$				
		Excellent	Good	Fair	Poor	Bad
TUI	226	420	604	766	914	1012
AUI	4330	6062	8174	11542	14339	18659
MUI	1286	1898	2653	3405	4163	5308
GUI	964	1467	2170	3124	3626	4009

Table 4.3: Average Response Time of each UI (ms)

quite different. For the response time which is less than 2 times of demo, user can not feel the difference, although AUI is much longer than TUI. For the response time which is more than 2 times and less than 3 times, reviewers can feel the little bit different. For Fair and Poor, there is not a clear boundary line, due to the tolerable level of reviewers. For the response time which is more than 4 times of demo, no matter which UI is used, all of the reviewers cannot accept the response time.

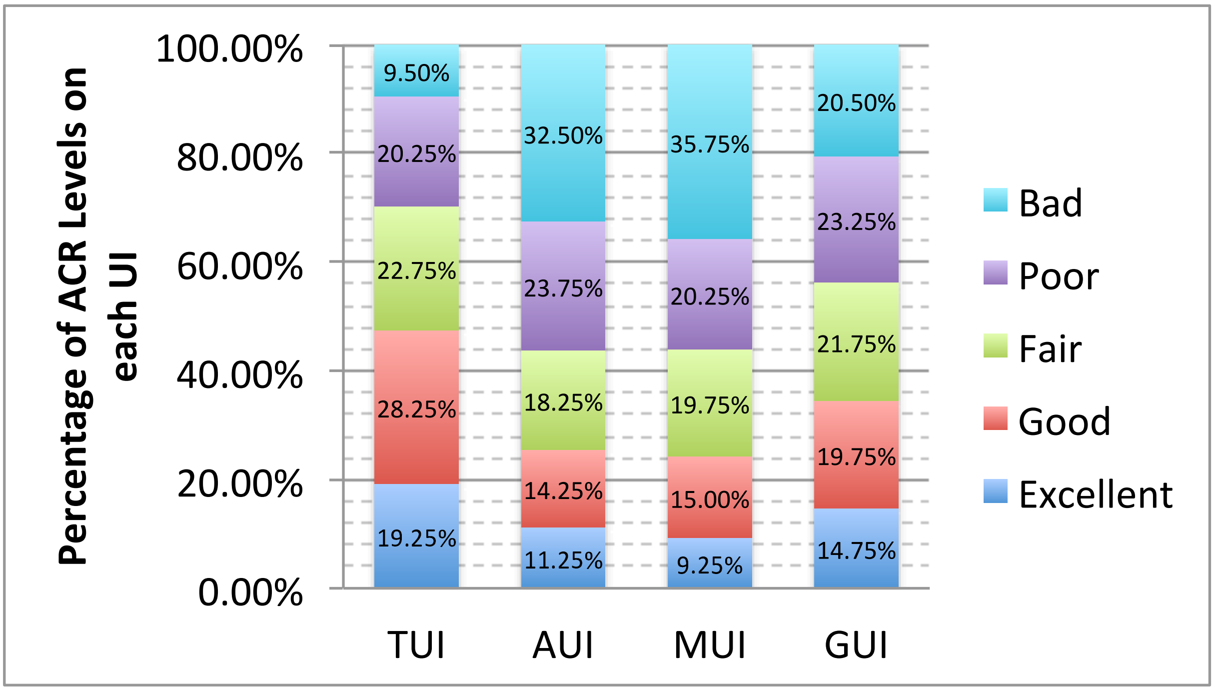


Figure 4.16: Percentage of ACR Levels on Each UI

Figure. 4.16 shows the percentage of ACR levels on each UI. It can be noticed that due to the reviewer used to TUI, they can easily clear the difference with random additional delay on typical response time. AUI is similar to TUI because the response time of AUI is the longest one. GUI and MUI are quite similar, even the additional delay is smaller than AUI, most of the cases, reviewers still cannot tolerate. We can conclude that for each UI, if the additional delay is under 2 time of its response time, reviewers won't feel unsatisfied.

For the timing issues of MHMIs, the design should pay more attention on MUI and GUI; and the synchronization problem can be easily fixed follow the average response time of each UI under the ACR of Good.

4.7 Evaluation of Synchronization with TUI and AUI

In this section, the synchronization is evaluated with TUI and AUI. The experiment design and numerical results are described in the follow subsections.

4.7.1 Experiment Design

In this subsection, the experiment design is described. Here, TUI and AUI are select to evaluate the synchronization due to the gap between them is huge. We set the same operation refer Figure. 3.6. Follow this operation, we design the experiment schedule as follows:

- Firstly, use AUI to turn on the light
- Secondly, wait for around two second without any other operation (depend on the reviewers, the two second might be quite different)
- Thirdly, use TUI to turn on the light
- Finally, get the response from the light and monitor.

With synchronization, all of the experiment schedule are same. The only difference is that the average RT of AUI is set on TUI as a delay. Three kinds of series would happen, which are:

- Light is on, “Light is turned on by TUI!” is shown on the monitor.

  This series is numbered with 1. Series1 means the light is turned on by the TUI first. Then the light is turned on again by AUI. In MHMI, this can be treated as an error, due to the light is turned on by the TUI not the AUI, which means AUI is influenced by the TUI. TUI has the function called toggle, which is one button can toggle the home appliance opposite (ON/OFF).

- Light is on for a while and then off. “Light is turned off by TUI!!” is shown on the monitor.

  This series is numbered with 2. Series2 means the light is turned on by the AUI and then turned off by TUI. In MHMI, this is the error/collision that should be avoid.

- Light is on, nothing is shown on the monitor.

  This series is numbered with 3. Series3 means the light is turned on by the AUI. There is no operation by TUI. In MHMI, this is the correct operation. However, due to the RT of AUI is the longest, either influenced by recognition/processing time or network delay.

The experiment is evaluated by 10 reviewers. Each reviewer repeat the experiment schedule for 30 times without synchronization, and repeat the experiment schedule for 30 times with synchronization. Thus, there are 300 results for each group and in total 600 results.

4.7.2 Numerical Results

In this subsection, through the numerical results to evaluation the importance and effectiveness of synchronization for MHMI.

Figure. 4.17 shows the percentage of three series with and without synchronization. Without synchronization (left side), we found that the percentage of series3 is quite small. Due to the RT of TUI is quite smaller than AUI. Although we let the reviewer do not

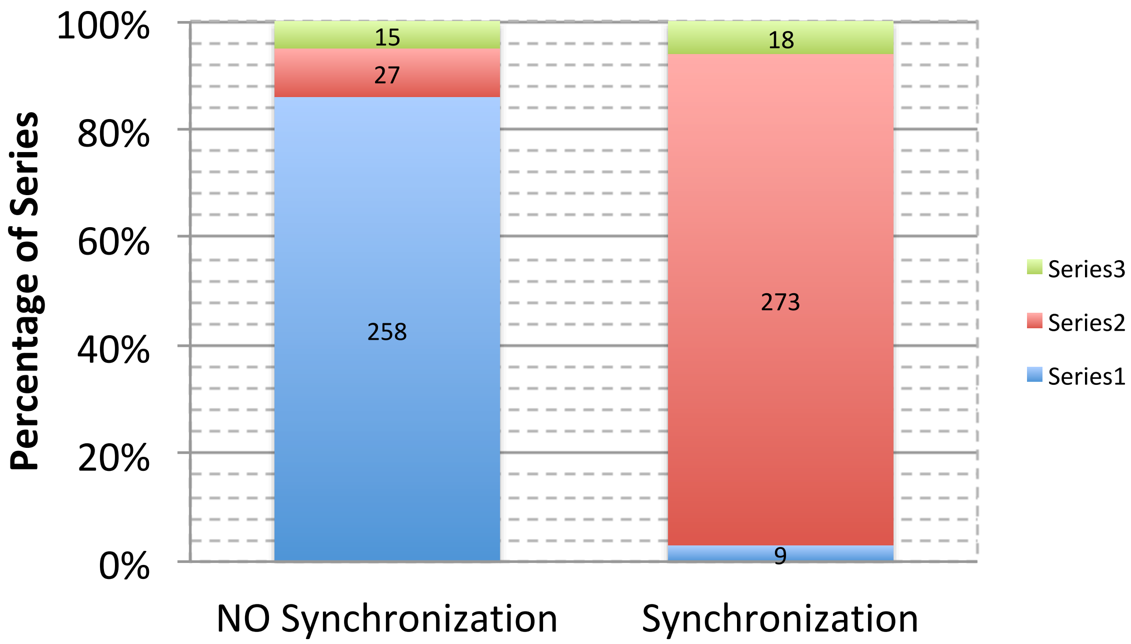


Figure 4.17: Percentage of three series with and without synchronization

use the TUI within two seconds, still reviewer touch the TUI to turn on the light. Thus, only 5% of the operation is that the reviewer not use the TUI until the light is turned on by AUI. Series2 is the problem we mentioned on Figure. 3.6. Although light is turned on by the AUI correctly, then for a short while, the light is turned off by the TUI. This is the error/collision, even it is only 9%. For series1, as we described in previous subsection, it can be treated as an error. Around than 86% indicates that without synchronization, error (caused by residents) is increased even the error is not caused by the MHMI. To avoid this kind of error in MHMI, we add the synchronization into the console. As we see in the right side, it has great effect. Here, the series2 increase sharply means good, because the implementation of console is not done yet. Thus, we add the average RT (4.33s) on TUI, then if the TUI not turn on the light immediately, then it means the synchronization can prevent the collision.

4.8 Summary

In this Chapter, the timing issues on each UI for smart home are described. This measurement and evaluation are very important for the design of MHMI. Based on the results of response time measurement, the experiment with ACR level is designed. To let MHMI more friendly, efficiency and effectiveness, the analysis of tolerable response time is necessary. Results revel that from the point of timing issue, the TUI and GUI is more efficiency than AUI and MUI. Also, the synchronization problem between TUI and GUI is not terrible, rather than with AUI and MUI. Follow the results and discussion from this chapter, the timing issues can be clear for the MHMI design for smart home.

Chapter 5

Conclusions and Recommendations

In this chapter, I conclude my research done in this thesis and the contribution make clear concept of timing issues of MHMI for smart home. It will also let other researchers to further design the efficiency and effectiveness MHMI based on the results we got.

5.1 Concluding Remarks

In this thesis, I do a study of timing issues for multimodal human machine interface for smart home. In the first chapter, I introduced the background of MHMI for smart home environment, which is the trend of near future to any human in the world. The aim of this research is that before create the novel MHMI for smart home, the timing issues need to be discussed. Thus, the survey of home appliance and related interaction methods is necessary. Then, based on the survey, the real experiment of MHMI should be built to measure the real date for the analysis. Moreover, based on the results, the questionnaire survey with absolute category rating to evaluate the tolerable response time is important. The results of tolerable response time can be used for the optimization of MHMI.

Chapter 2 presents the introduction about smart home. By defining smart home, discussing the components of smart home. Then, a comprehensive judgment of my research background in human machine interface for smart home is introduced. In addition, the traditional human machine interface has lots of limitations so we need to explain how to build a multimodal human machine interface to help user interact with machine in Smart Home.

Chapter 3 discusses the typical classification about the existing User Interface and proposes the basic four categories for MHMI. After the explanation of four user interfaces, the time issues of MHMI is described with the combination of these UI.

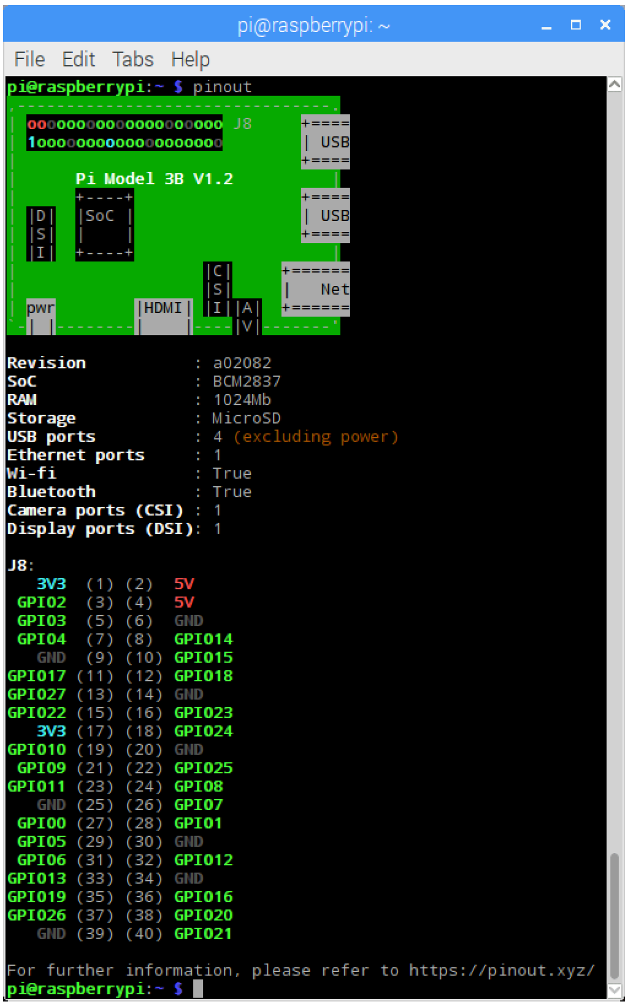
In Chapter 4, a real experiment environment is setup to do the response time measurements of TUI, AUI, MUI and GUI. Based on the typical response time of each UI, a additional delay range is designed to test the human feeling/tolerable timing of each UI. A questionnaires with absolute category rating is prepared for the tolerable experiments. Based on the results, the time issues of MHMI is discussed for smart home. Instead of real implementation of console, we use the AUI and TUI to evaluate the importance and effectiveness of synchronization for MHMI.

5.2 Future Works

- Based on the results and discussion of this research, the smart MHMI with less errors can be designed. The other parts of MHMI can be recognize as a kind of future work.
- The modalities manager can be built based on the discussed timing issues, which also can be treated as a kind of future work.
- How to create the feedback system with discussed timing issues is also very interesting for MHMI.

Appendix A

GPIO pins of Raspberry Pi



Appendix B

Typical Response Time of each User Interface (ms)

Time	Execution	TUI	AUI	MUI	GUI
0:00	Turn on (1)	233.8	4809.6	1402.8	1035.4
	Turn off (1)	200.4	3674.0	1336.0	901.8
	Turn on (2)	233.8	3507	1336.0	1068.8
	Turn off (2)	200.4	3440.2	1202.4	901.8
1:00	Turn on (1)	267.2	4342.0	1436.2	1035.4
	Turn off (1)	233.8	3607.2	1235.8	835.0
	Turn on (2)	267.2	4542.4	1169.0	1002.0
	Turn off (2)	200.4	4676.0	1235.8	801.6
2:00	Turn on (1)	267.2	3774.2	1402.8	1035.4
	Turn off (1)	233.8	4542.4	1369.4	935.2
	Turn on (2)	233.8	5678.0	1336.0	1002.0
	Turn off (2)	300.6	4943.2	1002.0	1068.8
3:00	Turn on (1)	267.2	4943.2	1402.8	1035.4
	Turn off (1)	167.0	4375.4	1269.2	835.0
	Turn on (2)	267.2	4108.2	1436.2	968.6

	Turn off (2)	167.0	4542.4	1269.2	868.4
4:00	Turn on (1)	267.2	4976.6	1402.8	1169.0
	Turn off (1)	167.0	4843.0	1369.4	1002.0
	Turn on (2)	300.6	5477.6	1369.4	1002.0
	Turn off (2)	300.6	5410.8	1235.8	835.0
5:00	Turn on (1)	267.2	5577.8	1369.4	1002.0
	Turn off (1)	267.2	4976.6	1269.2	868.4
	Turn on (2)	300.6	4776.2	1369.4	935.2
	Turn off (2)	167.0	4542.4	901.8	835.0
6:00	Turn on (1)	267.2	5477.6	1469.6	1002.0
	Turn off (1)	267.2	4074.8	1503.0	835.0
	Turn on (2)	267.2	3807.6	1402.8	968.6
	Turn off (2)	233.8	3740.8	1302.6	801.6
7:00	Turn on (1)	233.8	4308.6	1402.8	1002.0
	Turn off (1)	133.6	4041.4	1269.2	801.6
	Turn on (2)	233.8	4275.2	1068.8	868.4
	Turn off (2)	167	4308.6	1336.0	768.2
8:00	Turn on (1)	267.2	6012.0	1302.6	1002.0
	Turn off (1)	233.8	5277.2	1135.6	868.4
	Turn on (2)	334.0	6446.2	1402.8	968.6
	Turn off (2)	334.0	5410.8	1369.4	868.4
9:00	Turn on (1)	233.8	3841.0	1336.0	1002.0
	Turn off (1)	167.0	4008.0	1236.8	835.0
	Turn on (2)	233.8	4208.4	1336.0	1035.4
	Turn off (2)	133.6	4108.2	1302.6	868.4
10:00	Turn on (1)	233.8	3774.2	1302.6	968.6
	Turn off (1)	334.0	3941.2	1235.8	801.6
	Turn on (2)	233.8	3907.8	1436.2	1035.4

	Turn off (2)	200.4	3707.4	1302.6	901.8
11:00	Turn on (1)	233.8	4141.6	1369.4	1035.4
	Turn off (1)	300.6	4041.4	901.8	868.4
	Turn on (2)	267.2	4208.4	1436.2	1068.8
	Turn off (2)	200.4	3707.4	1402.8	868.4
12:00	Turn on (1)	233.8	5076.8	1402.8	1002.0
	Turn off (1)	200.4	3473.6	1235.8	901.8
	Turn on (2)	300.6	4208.4	1503.0	1035.4
	Turn off (2)	133.6	4676.0	1336.0	1002.0
13:00	Turn on (1)	233.8	4241.8	1469.6	1002.0
	Turn off (1)	133.6	3907.8	1402.8	868.4
	Turn on (2)	233.8	4141.6	1336.0	935.2
	Turn off (2)	200.4	3674.0	1369.4	1503.0
14:00	Turn on (1)	233.8	4876.4	1402.8	1102.2
	Turn off (1)	167.0	4108.2	1235.8	901.8
	Turn on (2)	267.2	5577.8	1135.6	1770.2
	Turn off (2)	167.0	4342.0	901.8	801.6
15:00	Turn on (1)	233.8	4609.2	1102.2	1002.0
	Turn off (1)	133.6	4375.4	1269.2	968.6
	Turn on (2)	233.8	4575.8	1135.6	968.6
	Turn off (2)	167.0	4241.8	1102.2	935.2
16:00	Turn on (1)	167.0	3874.4	1402.8	968.6
	Turn off (1)	167.0	4909.8	1302.6	801.6
	Turn on (2)	233.8	4909.8	1469.6	935.2
	Turn off (2)	233.8	3807.6	1002.0	868.4
17:00	Turn on (1)	233.8	4442.2	1503.0	901.8
	Turn off (1)	133.6	5811.6	1102.2	901.8
	Turn on (2)	233.8	5444.2	1436.2	1002.0

	Turn off (2)	267.2	4642.6	1169.0	868.4
18:00	Turn on (1)	267.2	3841.0	1102.2	968.6
	Turn off (1)	233.8	4709.4	1102.2	935.2
	Turn on (2)	233.8	4574.8	1102.2	1035.4
	Turn off (2)	200.4	3507.0	968.6	768.2
19:00	Turn on (1)	267.2	4408.8	1135.6	1035.4
	Turn off (1)	133.6	5711.4	1068.8	935.2
	Turn on (2)	267.2	4375.4	1035.4	1035.4
	Turn off (2)	167.0	3941.2	1269.2	968.6
20:00	Turn on (1)	267.2	3841.0	1369.4	1068.8
	Turn off (1)	233.8	3807.6	1302.6	901.8
	Turn on (2)	267.2	3507.0	1469.6	968.6
	Turn off (2)	133.6	3740.8	1002.0	1002.0
21:00	Turn on (1)	233.8	3373.4	1102.2	1035.4
	Turn off (1)	133.6	3340.0	1336.0	901.8
	Turn on (2)	233.8	4041.4	1436.2	1235.8
	Turn off (2)	167.0	4008.0	1302.6	935.2
22:00	Turn on (1)	233.8	3406.8	1302.6	968.6
	Turn off (1)	267.2	3607.2	1302.6	868.4
	Turn on (2)	233.8	3507.0	1436.2	968.6
	Turn off (2)	267.2	3674.0	1336.0	868.4
23:00	Turn on (1)	233.8	3440.2	1469.6	1202.4
	Turn off (1)	200.4	3406.8	1302.6	1035.4
	Turn on (2)	233.8	3540.4	1436.2	1002.0
	Turn off (2)	167.0	3540.4	1336.0	968.6

Appendix C

Code of Experiment

C.1 TUI

```
# coding: utf-8

import os
from time import sleep
from numpy import *
import random
import RPi.GPIO as GPIO

GPIO.setmode(GPIO.BCM)
button = 10
LED = 17

GPIO.setup(button,GPIO.IN,pull_up_down=GPIO.PUD_UP)
GPIO.setup(LED,GPIO.OUT)

LED_state = False
```

```
z = array([5, 1.4, 2.4, 1.0, 3.4, 1.6, 0.4, 3.6, 4.0, 2.8, 0.6, 1.2,
3.2, 0.8, 3.8, 2.6, 2.2, 2.0, 3.0, 1.8, 0.2])
tui_demo = 0.227
tui_delay = tui_demo*z
# print(tui_delay)

condition = 0
i = 0
while 1:
#    print(condition)
    print('Please press the button')
    if condition>=126:
        print('TUI experiment is finished, thank you very much!!!')
        break
    elif (condition % 2) == 0:
        if GPIO.input(button) == 0:
            os.system('clear')
            print('For DEMO, button was pressed...')
            print('Turning on the light...')
            os.system('date')
            if LED_state == False:
                GPIO.output(LED, True)
                LED_state = True
                condition += 2
                sleep(2)
            else:
                os.system('clear')
                print('For DEMO, button was pressed...')
                print('Turning off the light...')
```

```
                os.system('date')
                GPIO.output(LED, False)
                LED_state = False
                condition += 1
                sleep(2)

    else:
        delay = round(tui_delay[i],3)
        if GPIO.input(button) == 0:
            os.system('clear')
            print('For evaluation, button was pressed...')
            print('Turning on the light...')
            os.system('date')
#               print(delay)
            if LED_state == False:
                sleep(delay)
                GPIO.output(LED, True)
                LED_state = True
                condition += 2
                sleep(2)
            else:
                os.system('clear')
                print('For evaluation, button was pressed...')
                print('Turning off the light...')
                os.system('date')
                sleep(delay)
                GPIO.output(LED, False)
                LED_state = False
                print('')
```

```
        print("For experiment # %d") % i
        i += 1
        condition += 1
        print('Please select the most suitable value of ACR
        for this delay...')
        sleep(10)
```

C.2 AUI

Settings are following the Node-RED programming tool instructions. More information can be found on *https://nodered.org/*

C.3 MUI

```
# coding: utf-8

import serial
import time
from time import sleep
from numpy import *
import os
import RPi.GPIO as GPIO

ser = serial.Serial("/dev/ttyACM0", 9600, timeout=1)

GPIO.setmode(GPIO.BCM)
LED = 17
GPIO.setup(LED, GPIO.OUT)
GPIO.output(LED, GPIO.LOW)
```

```
LED_state = False

z = array([5, 1.4, 2.4, 1.0, 3.4, 1.6, 0.4, 3.6, 4.0, 2.8, 0.6, 1.2,
3.2, 0.8, 3.8, 2.6, 2.2, 2.0, 3.0, 1.8, 0.2])
tui_demo = 1.286
tui_delay = tui_demo*z

condition = 0
i = 0
while True:
    ser.write("c\r\n")
    msg=ser.readline()
#     print(condition)
    print('Capturing IR...')
#     print msg
#     print len(msg)
    if condition >=126:
        print('MUI experiment is finished, thank you very much !!!')
        break
    elif (condition % 2) == 0:
        if len(msg) == 8 and LED_state == False:
            os.system('clear')
            print('For DEMO, IR singnal is captured...')
            print('The light is turning on...')
            os.system('date')
            GPIO.output(LED,GPIO.HIGH)
            LED_state = True
            condition += 2
            sleep(2)
```

```
        elif len(msg) == 8 and LED_state == True:
            os.system('clear')
            print('For DEMO, IR signal is captured...')
            print('The light is turning off...')
            os.system('date')
            GPIO.output(LED,GPIO.LOW)
            LED_state = False
            condition += 1
            sleep(2)
    else:
        delay = round(tui_delay[i],3)
        if len(msg) == 8 and LED_state == False:
            os.system('clear')
            print('For evaluation, IR singnal is captured...')
            print('The light is turning on...')
            os.system('date')
#           print(delay)
            sleep(delay)
            GPIO.output(LED,GPIO.HIGH)
            LED_state = True
            condition += 2
            sleep(2)
        elif len(msg) == 8 and LED_state == True:
            os.system('clear')
            print('For evaluation, IR signal is captured...')
            print('The light is turning off...')
            os.system('date')
            sleep(delay)
            GPIO.output(LED,GPIO.LOW)
```

```
        LED_state = False
        print('')
        print("For experiment # %d") % i
        i += 1
        condition += 1
        print('Please select the most suitable value of ACR
        for this delay...')
        sleep(10)

ser.close()
```

C.4 GUI

Settings are following the Node-RED programming tool instructions. More information can be found on *https://nodered.org/*

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