

博士論文

Indoor Mobility Enhancement of Smart Building

(スマートビルディングにおける屋内モビリティの強化)

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ABSTRACT

This research conducted into indoor mobility enhancement for smart building, in which a number of proposals comprised of fine-grained spatial modeling, accessibility semantics measurement, and dynamic facility control have been developed.

Firstly, from the perspective of overall mobility in smart building, a lack of the spatial, physical, semantic reference makes the smart building incapable of recognizing the dynamics of the indoor environment, including the location of the moving objects' as well as the status of its surrounding environment, which causes difficulty in further delivering the mobility-supportive information and the ambient environment intelligence to the moving objects for assisting them in moving efficiently, smoothly and dependently.

In view of the problems as mentioned above, we proposed a spatial model for fine-grained referencing the spatial, semantic and dynamic environment to improve the overall indoor mobility. Based on this model, we also proposed a routing mechanism that bridges the association between use cases with accessibility semantics for context-aware routing. To validate the above proposal objectively, we performed a visually impaired oriented user study. We implemented an effective user interface for delivering the mobility-supportive information to the participants. As a result, the path description extracted from our proposed model made a substantial contribution to enhancing the efficiency and smoothness of movement for those visually impaired participants.

Furthermore, elevator functions as an essential facility as well as a significant intersection node to connect horizontal and vertical dimension within indoor mobility platform. It remains stand-alone from the communication platform of the building, that restricted the flexibility and intelligence for the indoor vertical mobility significantly. In particular, during the peak-time, the limited elevator physical capacity and the momentary traffic increment give rise to the persistent problem

of vertical traffic bottleneck. Whereas, the internal mathematical optimization on the controller makes the insufficient efficiency improvement. In the research, we proposed the elevator-centric control optimization to improve the indoor vertical mobility. Upon the development of IoT-enabling hardware as a first step, an agent server architecture was proposed to empower elevator computation capability. Based on this fundamental architecture, we developed two implementations to deliver the indoor vertical mobility enhancement to the end-users.

One implementation is PrecaElevator, which enables passengers to reduce their waiting time through pre-registering elevator calls. We conducted an experiment in the practical smart building environment by integrating with the indoor localization platform. The effectiveness has been evaluated by the simulations based on learning of waiting time from the historical data over five months, demonstrated the great potentials of reducing passengers' waiting time. Differentiating with the previous works, this proposal attempted to enable pre-registration of elevator call by utilizing the context-aware platform on the agent server without any additional off-line sensors. Hence, the minimum cost of hardware development, flexibility was achieved.

Another implementation is Intellevator, premised on a designed user interface for the provision of mobility-assistive information, simplicity in operation, and intelligence for passengers. Meanwhile, to seek the time-efficiency, Intellevator system has the capability to real-time predict the upcoming fine-grained traffic flow, then to enforce proactive management of the traffic distribution based on self-adaption on the designed user interface. We experimented the Intellevator by integrating with a conventional elevator system and performed both a user study and simulation to validate the effectiveness of our proposal. As a result, both the user acceptance of the novel usage and system improvement were validated quantitatively, which demonstrated the effectiveness of our proposal.

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Contents

Chapter 1	Introduction	1
1.1	Background	2
1.1.1	Indoor Mobility	2
1.1.2	Accessibility Measurement: Perspective on Overall Mobility	4
1.1.3	Facility Control on Elevator : Perspective on Vertical Mobility	10
1.1.4	New Trends in Smart Building	12
1.2	Research Goals	13
1.3	Research Issue Definition	14
1.3.1	How to structure the indoor spatial environment	14
1.3.2	How to develop routing mechanism correlating use case to accessibility computing	15
1.3.3	How to optimize control of the facility - elevator	15
1.3.4	How to develop end-user-oriented services	16
1.4	Contribution and Novelty	17
1.5	Outline	18
Chapter 2	Related Work	21

2.1	Indoor Spatial Reference	21
2.1.1	Indoor Maps	21
2.1.2	Indoor Localization Technology	22
2.1.3	Indoor Spatial Model	23
2.1.4	Indoor Accessibility Measurement	28
2.2	Facility Control: Elevator-centric Mobility	29
2.2.1	Algorithm-based Stand-alone Optimization	29
2.2.2	Data Collection to Minimize Uncertainty	30
2.3	Summary	33
2.3.1	Summary of Indoor Spatial Reference	33
2.3.2	Summary of Elevator-centric Vertical Mobility	34
Chapter 3 Spatial Model-based Proposal : Overall Mobility		36
3.1	Introduction	36
3.2	Proposal	37
3.2.1	Fine-grained Indoor Spatial Model	38
3.2.2	Routing Mechanism	44
3.3	Experiment	46
3.4	Evaluation	47
3.4.1	Participants and Setup	48
3.4.2	User Interface	50

3.4.3	Procedure	51
3.4.4	Results	51
3.5	Summary	54
Chapter 4 Elevator Control Optimization : Vertical Mobility		56
4.1	Introduction	56
4.2	Problem Definition	58
4.3	Proposed Overall Architecture	61
4.3.1	IoT-Enabling Development on Elevator	62
4.3.2	Agent-based Architecture	66
4.3.3	Novel Elevator System Design	70
4.4	Summary	70
Chapter 5 Proposed System: PrecaElevator		71
5.1	Introduction	71
5.2	Proposal	73
5.2.1	System Architecture	73
5.2.2	BLE-based Indoor Localization Platform	73
5.2.3	End-user Centric System Design	77
5.3	Evaluation	79
5.3.1	BLE-based Localization Estimation	79

5.3.2	Historical Waiting Time Calculation	83
5.4	Summary	87
Chapter 6	Proposed System: Intellevator	88
6.1	Introduction	88
6.2	Proposal	91
6.2.1	System Architecture	91
6.2.2	Peak-Pattern Detector	94
6.2.3	Markov Decision Process	94
6.2.4	User Interface	96
6.3	User study	97
6.3.1	Participants and Procedure	100
6.3.2	Results	103
6.3.3	Feedback and Findings	110
6.3.4	Summary of the User Study	113
6.4	Simulation	114
6.4.1	Notation for the Dynamics	114
6.4.2	Simulator	114
6.4.3	Simulation Setting	116
6.4.4	Results	120
6.5	Limitations	129

6.6	Summary	131
Chapter 7	Discussion	132
7.0.1	Who is the ICT Service Provider?	132
7.0.2	Increased Physical Demand is NOT a Pain	134
7.0.3	Mobility as a Service (MaaS) Concept	135
7.0.4	Optimizing the Planning of Elevator Deployment	135
Chapter 8	Conclusion	138
8.1	Conclusion	138
8.2	Future Work	141
References		143

List of Figures

1.1	Context-aware mobility enhancement in smart building	3
1.2	Illustration of accessibility measurement	4
1.3	Smart city strategy index, reprinted from [1]	7
1.4	Segway examples with one-wheel, two-wheels, with-handle, without-handle	8
1.5	Conceptual representation of building, reprinted from [2]	11
2.1	The cartesian coordinate system	24
2.2	A simple example of graph-based hierarchy model of building . . .	26
2.3	Traffic patterns occurring throughout the day in a typical office building, reprinted from [3]	29
2.4	Figure shows the usage of remotely call on elevator, reprint from [4]	31
2.5	Figure shows the prototype to collect sensor data for generating elevator calls, reprint from [5]	32
2.6	The elevator-cabin for riding is optimized by passengers' id, reprint from [6]	32
3.1	The proposed model for fine-grained routing	37
3.2	Graph-based hierarchical structure of a building	39

3.3	Entities and relationships in the hierarchical graph	39
3.4	An example illustrates the accessibility semantics modeling on stairs	41
3.5	The example shows the computation of orientation and authorization while passing the door	43
3.6	Parameter indexing example for accessibility computing	45
3.7	A real example of evaluation	48
3.8	Participant profiles	50
3.9	Comparison of the time-consuming on moving	52
3.10	Result of evaluation on the designed interface	53
4.1	The state transition on the elevator using	57
4.2	Illustration of negative user experience of using the elevator	59
4.3	The overall architecture for the elevator-centric vertical mobility optimization	62
4.4	Figure shows how to IoT-enabling on elevator	63
4.5	Hardware development for IoT-enabling	65
4.6	Real-time monitoring on elevator moving after IoT-enabling	66
5.1	The system structure of PrecaElevator	72
5.2	The flow chart of the PrecaElevator system	73
5.3	Illustration of 3D BLE-beacon based localization method	74
5.4	Matrix mapping for coordinating the BLE beacons	75

5.5	The example shows computation flow of a BLE beacon based localization for P1 place	77
5.6	Example of real time computing for pre-call	78
5.7	The deployment of BLE beacon inside the building	80
5.8	The real BLE RSSI values of 18 scanned places in the building . . .	81
5.9	A visualization example shows the RSSI mapping of spot "p1" . . .	82
5.10	A visualization example shows the RSSI mapping of spot "p11" . .	82
5.11	A visualization example shows the RSSI mapping of spot "p14" . .	83
5.12	The FSM model for presenting the state transition of elevator . . .	84
5.13	The state transitions of both the elevator and passenger	85
5.14	Simulation based on the real records of elevator	86
6.1	System architecture of the proposal	90
6.2	The agent server-based system architecture	93
6.3	Targeting floor based on traffic prediction	95
6.4	An example shows the real-time managed user interface	98
6.5	The system usage of Intellevator	99
6.6	The experiment setting of the user study.	101
6.7	Results of the user experience questionnaire	103
6.8	The usefulness of various contexts.	105
6.9	User preferences for advice-providing (N=22)	106

6.10	The rating averages of NASA-TLX	109
6.11	Illustration of compared methods: PT, FR, DT	117
6.12	The figure shows the traffic flow with fluctuation on peak-time . . .	121
6.13	An example shows traffic managed under FR method	122
6.14	An example shows traffic managed under DT method	123
6.15	Comparison of cumulative time and transported traffic flow of the three methods	124
6.16	The results of average waiting time	124
6.17	The results of average journey time	126
6.18	The results of total labor effort loss	127
6.19	Average journey (travel) time based on setting of floor number vs Δf	128
6.20	Average waiting time based on setting of floor number vs Δf	129
7.1	Cost of inadequate interoperability by stakeholders, reprint from [7]	133
7.2	Elevator deployment planning	136
8.1	A simplified diagram shows proposals for enhancing indoor mobility	139

List of Tables

2.1	Comparison on geometric model and symbolic model	27
4.1	Parameters of the elevator	64
4.2	Input and output of signals on IoT-enabling development	65
4.3	Real-time elevator-related context provided by the agent server . .	67
5.1	Parameters of the FSM model	84
6.1	Subjective weightings and ratings on NASA-TLX.	109
6.2	Parameters for dynamics representation	116
6.3	Elevator environment settings	119
6.4	Performance of different methods on the evaluation (in seconds) . .	125

Chapter 1

Introduction

Over the most recent few decades, there are multiple dominant directions in respect of indoor mobility enhancement. For instance, indoor location-based service (LBS), way-finding for robotic device, context-aware indoor navigation, indoor human activity recognition, and so on. These prior studies have made contribution to evaluating the potential of indoor mobility.

In this research, from a more comprehensive and deeper perspective, additional contributions are made to the existing work. This research gives consideration to the dynamics and semantics within the smart building, which should be fine-grained and spatially modeled. Based on the fine-grained model with the sensing data from the physical world, the smart building is capable to recognize the spatial, semantic and dynamic relationships among the indoor objects. It also has the capability to make further adaption in real-time and achieve automation of the indoor facilities by leveraging internet of things and artificial intelligence, which finally contributes to the indoor mobility could be enhanced considerably.

1.1 Background

1.1.1 Indoor Mobility

The ability to travel safely, comfortably, gracefully, and independently was defined in [8], referred to hereafter as the single term "mobility". Similarly, mobility was interpreted in [9]: assessing the ability to move from one place to another.

Concerning the outdoor environment, GNSS (Global Navigation Satellite System) -based localization research prototype and sustained perfection of the outdoor spatial information-sharing, such as the digital map resource provided by either commercial giant like Google Maps [10] or communities like the OpenStreetMap [11], finally the prevalence of mobile phones, have made collective contribution to navigating a person or a car smoothly in outdoor environment. Outdoor environment like roads or railways can be commonly modeled by one-dimensional elements within a clearly defined network. The relevant research has been thoroughly conducted and the solution are relatively well developed.

While nearly 90% of people spend most of their time indoors [12], the accumulation of geographic data, especially concentrated on indoor structure, can achieve significant growth and bring convenience when indoor mobility service is offered. However, the challenges have persisted for decades with the issues left unresolved. The technical factors and corresponding reasons are indicated as follows:

- Firstly, the building is constructed by architectural components, such as floors, elevators, stairs, rooms, doors, etc. [13, 14], which are multi-dimensional (multi-floors) and more complicated than outdoor environment.
- GNSS-based localization is unavailable under an indoor setting. The three-dimensional structured environment leads to the typical geographic coordinate system which represents the location by latitude and longitude becoming

inadequately accurate even useless [15]. As a result, indoor location information can only be explained at logical or topological levels. There is neither unique nor straightforward representation to describe a precise location or relation [16].

- Existing indoor maps, i.e., indoor floorplans [17] is static, semantic-less, low-readability, thus closely associated with human cognition [18]. Moreover, it is impossible for a majority of accessibility semantics to be diversified solely by map figure. For example, it is difficult to identify on the map whether there are steps around the door, or how to operate the door to make it open. Last but not least, the typical map is lacking in interoperability, which makes itself insufficient for indoor mobility computation.

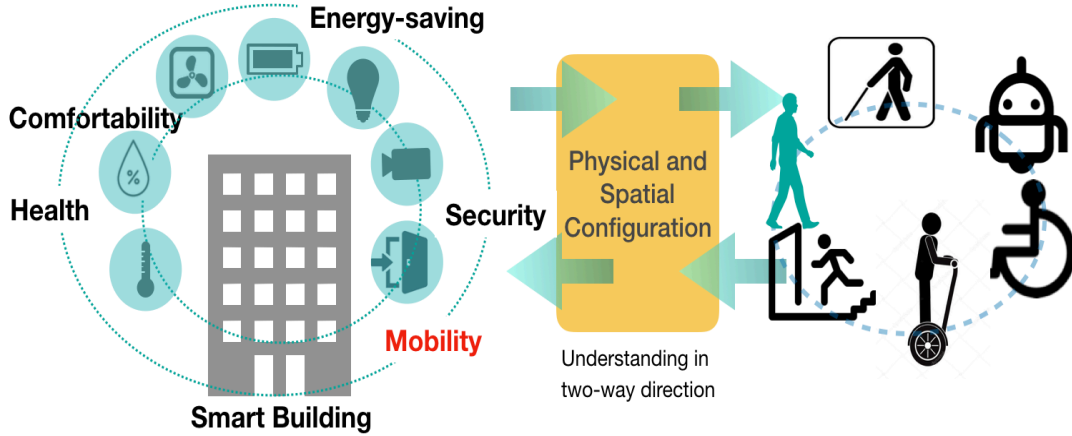


Figure 1.1: Context-aware mobility enhancement in smart building

In essence, mobility impairment would result from physical, cognitive or sensory disability, or a combination of them. As Figure 1.1 illustrates, the moving objects including disabled people, robotic devices, and even ordinary people, would be faced with practical restrictions on mobility owing to the dynamical change in environment and the insufficient provision of information.

Meanwhile, the necessary contextual and semantic information differs with

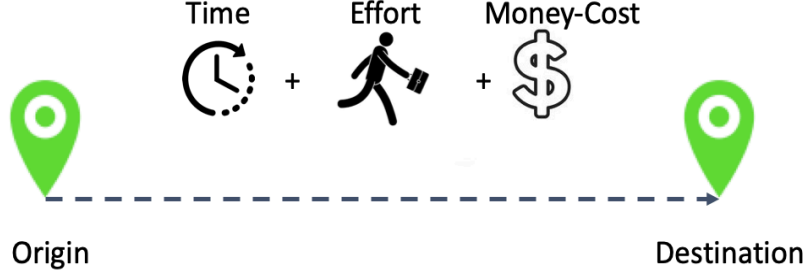


Figure 1.2: Illustration of accessibility measurement

their different desires, preferences or surrounding contexts. For instance, the object is prevented from waiting for authorization, the node in emergency evacuation path is obstructed for occupied, people require the fine-grained reference of orientation, and so on. Moreover, while indoors, rather than distance, spatial accessibility assessment [16, 19, 2] and dynamic facility control planning are considered to be more significant.

On the basis of these previous points, the notion of context-aware presents a crucial element for the development of mobile system to improve indoor mobility. As explained by Dey [20] : "Context is typically the location, identity, and state of people, groups, and computational and physical objects". The context of user involves: user profile, preference, physical/cognitive capability and the transportation they used for interacting with the mobility platform, etc.

1.1.2 Accessibility Measurement: Perspective on Overall Mobility

In the mobility dimension, the notion of "accessibility" also has been referred to in the transportation planning field for 40 years [21]. The accessibility promises to provide a useful tool for assessing the transportation system as well. Enhancing accessibility is regarded as a common factor in the goals section for almost all sorts of transportation plans [9]. The notion of "Accessibility" originates from the word

"access" and "ability", indicating the capability to gain access [21] to something. It also refers as a way of measuring the ease of reaching (and interacting with) destinations activities distributed in space [21]. Similarly, as revealed in Figure 1.2, Koeing et al. described "accessibility" as: **an origin and a destination (OD) combining with potential activities during reaching the destination and the travel time/effort/money-cost, are the main parts of any accessibility measures**[22]. Apparently, the cases with "Low accessibility" suggest that it is relatively more difficult or costly for reaching the destinations. This is because a given amount of **time/effort/cost** is necessitated.

Moreover, as for the smart building, the problem of how to model these types of indoor accessibility semantic information (including static and dynamic) need to be addressed in advance. Here, a summary is made of the accessibility semantics into two aspects, which are static accessibility and dynamic accessibility:

- Static accessibility

Static accessibility semantics are **impenetrable, tangible, and usually visible**. For example, the obstacle (e.g, steps, slope, etc.) around an entrance, the open mode of a door, the width of the passageway, and so on. Depending on the movement ability of the moving object, the accessibility semantics would be completely different to be defined.

- Dynamic accessibility

On the contrary, dynamic accessibility semantics is **sometimes invisible and constant-changing from time to time**. With the real-time changes in indoor environment, dynamic accessibility semantics are possible to occur or disappear dynamically. For example, from the perspective of time-efficiency, if people get stuck around an entrance, the level of accessibility on the spot is reduced. In particular, once an emergency arises, elevator would be prohibited for use also shows the case of dynamic accessibility.

At present, there remains the lack of an effective spatial model integrated with fine-grained accessibility semantics. This progress imposes restrictions on further mobility application developments, such as barrier-free navigation, evacuation routing for emergency, way-finding for robotic device.

Barrier-free navigation In the navigation system, the notion of "barrier" was also applied for representation of accessibility. There are plenty of obstacles inside a building, for example, steps around a door, limited width of corridor, complex operations of a door, etc. These factors in indoor environment will make a significant impact on indoor mobility. Thus, these factors need to be incorporated as accessibility semantics into indoor spatial model to provide mobility reference for assisting the objects moving smoothly and independently. Meanwhile, based on users' with special preference or needs, the mobility system should provide the barrier-free assistance, such as audio-guidance or remotely control, automation, etc, for delivering the ambient intelligence in an accessible way.

Way-finding for robotic device Emerging technology of Internet of Things (IoT) further enhances the connectivity between physical objects and virtual data. There are several key fields for applying IoT solutions, for example: smart city, smart buildings, smart transport, and so on [23]. Mobility as a Service (MaaS) represents an integrative concept that consolidates different transport modalities into joint, seamless service offerings for providing tailored mobility solutions that suit users' travel needs [24].

As illustrated in Figure 1.3, an assessment framework suggested by Roland Berger [1] revealed that the dimension of building (including facility management, home applications, construction) and the dimension of mobility (traffic management, multi-modality, logistics) are regarded as equally significant to the development of smart city. Recently, new transporters like Segway with examples given in Figure 1.4, have been widely accepted as powerful personal transportation vehicles. It was also recognized as having a huge potential to become prevalent and meet

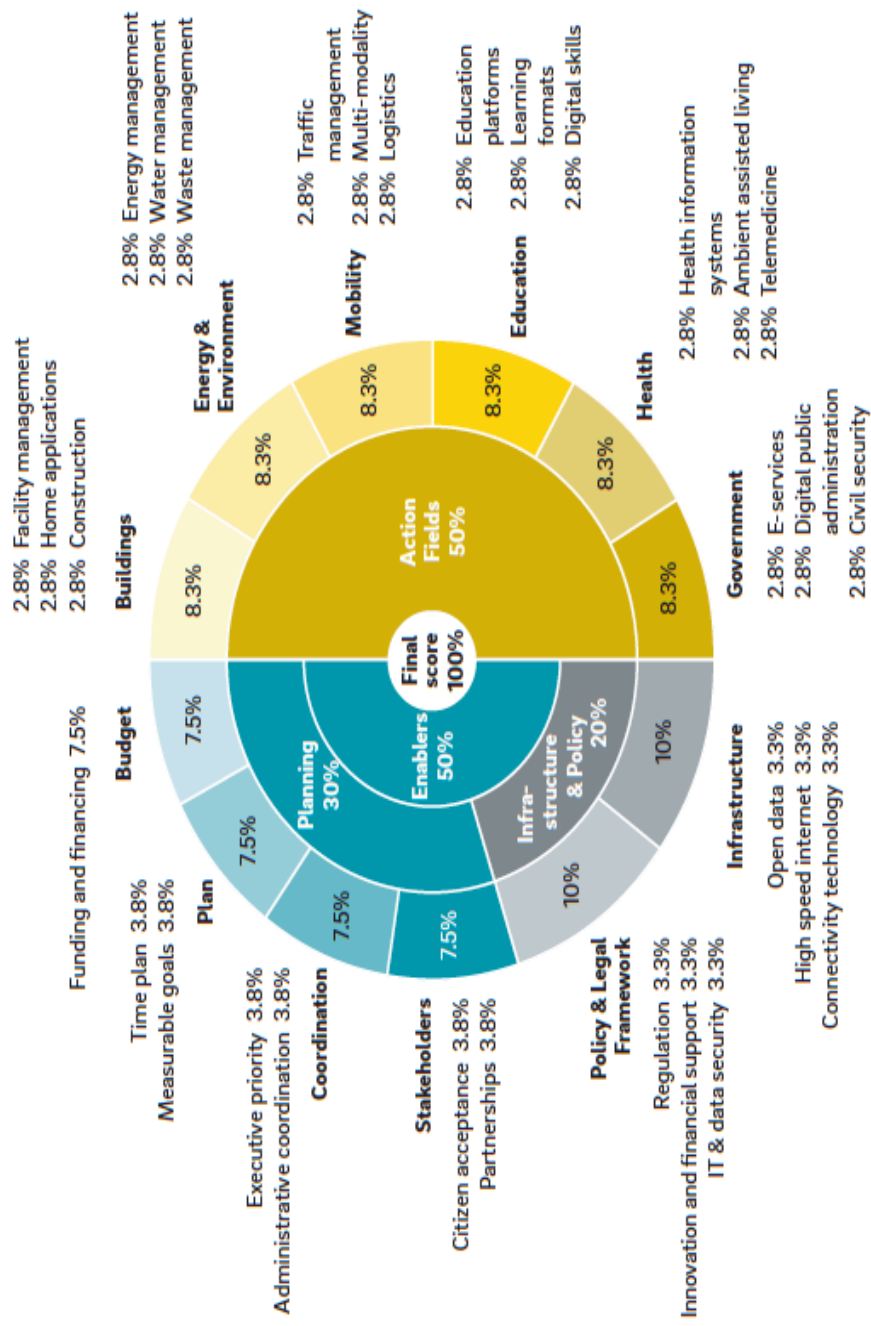


Figure 1.3: Smart city strategy index, reprinted from [1]

human needs for transport [25] as they are made increasingly lighter and more portable.

Apparently, it can be viewed as a phenomenon (occurring with the emergence of new technologies and constructions) or as a new solution to transport (which combines the different available transport modes and mobility services) offered to the public [26].



Figure 1.4: Segway examples with one-wheel, two-wheels, with-handle, without-handle

In order to improve the indoor mobility of such personal transportation (e.g., segway, scooter), there were requirements for smart building to provide the supportive barrier-free information of physical environment. Besides, the smart building also was anticipated to dynamically interact with autonomous robotic device based on the computation of both the static and dynamic accessibility semantics.

Accordingly, it would be an essential mission to track the constant change of situation in real-time when objects being moved with their surrounding environment mapped. Subsequently, smart building makes use of proactive and automatic control over multiple facilities (i.g., doors or elevator in the mobility dimension) to make adaption to the personal transportation optimally to assist them in ensuring

a smooth move.

Dynamic evacuation routing Dynamic evacuation routing is regarded as most crucial to a building's mobility, which providing the possibility of safe escape in the event of emergency [27]. As revealed by the National Fire Protection Association (NFPA) in 2012, 480,500 structure fires were reported in the United States leaving 2470 civilian dead, 14,700 citizens and 69,400 firefighter injured, which resulted in a total loss of \$9.8 billion in property damage [28].

Likewise, as shown by the white paper of analysis and statistics of death in fire published by the Ministry of Internal Affairs and Communications Fire Department of Japan demonstrated, the delay for evacuation accounts for 46.7% of the overall death from fire. Among the sub-classifications, "the ones who are taking escape action but seem to be unable to exit" makes up 16.9%, is the highest number of the whole. Following behind, the reason that "the notice or being aware of the emergency is delayed, turning out that there is no way to escape", constitutes 14.7% of the total [29].

On the other hand, there are a high proportion of commercial buildings equipped with plenty of instruments such as smoke detector and fire alarm. Nevertheless, the alarm system always was triggered by a stand-alone device. Warning and surveillance systems have been widely applied in buildings themselves to help the public be aware of such emergency and dangerous situations [29]. Despite this, the current warning systems have yet to be integrated with the evacuation system. Due to this limitation, there remains no integrated solution for transiting building systems data to emergency responders [30].

Consequently, the dynamics of the emergency or disaster under the indoor context is unstructured and non-integrated, resulting in the lack of an efficient evacuation system. Moreover, the behaviors people performed in case of such emergency situations are rather unstructured [31]. The evacuated people with extreme anxiety or panic tend to look for their nearest exit. However, instead of

the partial nearest perspective, the fast and secure evacuation is deemed necessary. At present, it remains difficult for them to achieve the goal in an easy way.

In order to protect the indoor occupants upon the recognition of warning notification, the spatial model ought to firstly structure the whole perspective and dynamics, inclusive of both real-time emergency status and the behaviors performed by people inside. Secondly, the model computes and determines the most effective evacuation path. Finally, the path information should be delivered effectively on the specific interface design.

1.1.3 Facility Control on Elevator : Perspective on Vertical Mobility

Internet of Things (IoT) technologies have enabled a plenty of devices, such as light, HVAC (heating, ventilation and air conditioning) system to be accessible through wireless network. This facilitates the integration of heterogeneous devices and real-time context aware control for automation and intelligence in smart building.

As a result, the smart building has the capability to play the roles as a planner, decision-maker and administrator to optimize the efficiency and comfortability on indoor mobility. The concept of indoor "access system" has been proposed by Jean-claude, et al [2]. As indicated in Figure 1.5, it consists of staircases, elevators and doors allowing movement between floors or between indoor and outdoor spaces.

Among these facilities, door and elevator are considered as two key elements for the computation of dynamic mobility. The facility control for accessibility optimization on the door is primarily about authorization or security that takes into account the context of individual user profile and preference.

At present, the research problems of access control on door have already been addressed to a certain degree. As the control on the door comprised of "Open" and

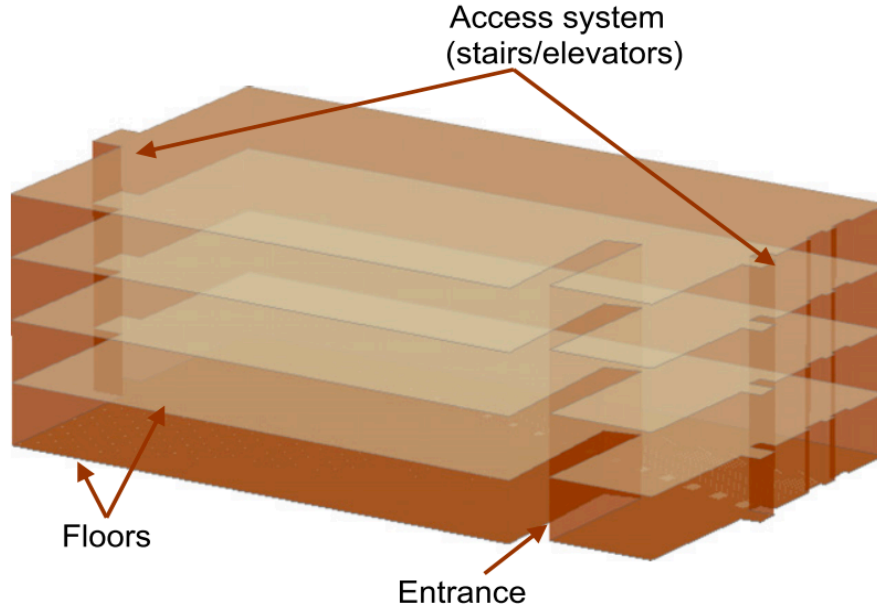


Figure 1.5: Conceptual representation of building, reprinted from [2]

"Close", is comparatively simple to be resolved. It comes up with the solution that is relatively mature and commercial, such as the Yale smart locker manufactured by Apple HomeKit [32].

While Elevator system, functioning as a vertical transportation indoors, is significant to the mobility platform, but with higher complexity. As revealed by IBM's survey of Smarter Buildings Study [33], the result obtained from investigation and calculation on the 6,486 office workers in 16 U.S. cities indicated that the total amount of over 92 years was wasted on the wait for the elevators in 2009. The elevator-related investigation in Future Design [34] demonstrated that nearly 80 percentage of subjects (totally 1030) indicated that the waiting time on the elevator is excessively long and need to be reduced.

Obviously, these investigations evidenced the low efficiency of elevator system, resulting in plenty of time-effort requirement while people are in vertical movement.

Moreover, the issue of elevator-centric vertical mobility is constantly evolving and the challenges to encounter are increasing with the ever-growing height of buildings [35]. Crucially, the root cause of the elevator-centric vertical mobility problem lies in the elevator system that is isolated from the communication infrastructure in the building, for which a greater accessibility is necessary [3].

As the vertical mobility enhancement is more complicated and yet to be addressed for enhancing the time-efficiency, in this research, multiple proposals are made to optimize the elevator-centric facility control for the enhancement on vertical mobility.

1.1.4 New Trends in Smart Building

The notion of the Internet of Things (IoT) [36] concerns the varieties of devices in the physical world are connected to the Internet. Especially, as one of the most significant technology trends, the popularity of smart buildings has been on the rise over the last 25 years [37]. It is also expected that the value of IoT in the building construction industry, will grow by nearly quadrupled from \$23 billion in 2014 to more than \$85 billion by 2020 [37]. This estimation projected the growth in related IoT data services in smart building [37].

Smart buildings where the Internet of Things (IoT) and Artificial Intelligence (AI) [38] technologies are leveraged, have the capability to create an ambient intelligent environment. Plenty of pervasive and powerful indoor smart objects (including sensors and IoT-enabled devices) were available for being integrated. Meanwhile, a variety of different control styles premised on artificial intelligence, i.e., automatic, adaptive control could be applied to launching the services that make contribution to the pursuit of energy-saving, comfortability and health improving, security management, mobility enhancement, and so on.

So far, we have made introduction of the background and the issues regarding

indoor mobility. The indoor mobility in particular, the safe, independent, efficient indoor mobility remains a difficult issue to address. **Fundamentally, the spatial model which fine-grained structuring the indoor dynamics, including the internal relations, semantics, and the facilities' status remains lacking.** Therefore, the spatial model which makes direct contribution to the goal of enhancing the indoor mobility should be proposed at first. **Subsequently, according to the context-aware mobility computation, as well as pro-active decision-making and facilities automation, the smart building needs to ensure the indoor objects to move in an efficient, smooth, independent way.**

In brief, this research consists of indoor spatial modeling, indoor accessibility semantics computation and finally optimization on the elevator control for enhancing the indoor mobility, will be elaborated in the following parts, respectively.

1.2 Research Goals

Thus, the ultimate goal of our research is to enhance the indoor mobility of smart building, which could be achieved in two ways listed as follows:

- To make the smart building capable to identify the spatial and semantic relationships between the indoor environment and users' preference, and finally, to provide mobility-assistive information as well as efficient moving plan for assisting indoor mobility via proactive and adaptive control on the indoor facilities.
- To assist the indoor moving object to (1) move smoothly and independently by providing them the mobility-supportive path information which references made to both the physical and semantic environment; (2) in addition, to assist them to move in a time-efficient way by executing proactive and adaptive control on the facilities inside the building.

1.3 Research Issue Definition

To achieve the research goals referred to above, it is considered that when the smart building functions as a complex system for mobility optimization, a spatial model represents a fundamental necessity to realize the physical, spatial and semantic configuration for indoor environment. Besides, the research issues in this dissertation are summarized as follows:

1. Fundamentally, how to establish an effective spatial model for structuring the fine-grained accessibility semantics;
2. Meanwhile, how to construct the routing mechanism based on the correlation between the spatial model and use-cases;
3. Based on the spatial model, how to optimize control over the mobility-related facility (i.g., elevator) for enhance the mobility;
4. How to design human-oriented mobility service, such as the development of a better user interface on elevator for mobility improvement.

1.3.1 How to structure the indoor spatial environment

As explained in Section 1.1.1, the multi-dimensional and complicated indoor environment caused ambiguity in the representation of indoor location. The ambiguous representation of indoor location results in various indoor spatial models that have been proposed at research level, but lacking in a united definition nor an one-fit-all solution.

Particularly, with consideration given to the fine-grained accessibility semantics, the prior studies are found to be insufficient for the computation of the efficient mobility. To address this problem, firstly, we need to clarify the definition of what

kind of property on the indoor object or relationship ought to be considered as accessibility semantics. After these properties are classified, the modeling method should be taken that structures both the indoor mobility-related objects and fine-grained accessibility semantics.

1.3.2 How to develop routing mechanism correlating use case to accessibility computing

The factor of distance is possible to be unsuitable or even meaningless in indoor routing considering accessibility semantics. In order to design an effective routing solution covering cross, the correlation between the use case and accessibility semantics needs to be made clear in the first place.

Therefore, the routing mechanism needs to be developed as support for the high-granularity accessibility semantics computation, which gives consideration to the user preference as input at first, then extracts the feasible path information for the target users. Besides, to amplify the utility value of human-centered service, the model design needs to consider the reasonableness of structuring for generating path description with good readability.

1.3.3 How to optimize control of the facility - elevator

In respect of the control optimization on the elevator, the mobility problem located at the elevator in the vertical dimension should be clarified at first. As briefly described in Section 1.1.3, while using the elevator for vertical moving, a large amount of time-effort requirement makes the end-users dissatisfied and frustrated.

It is believed that the emerging technology trends, such as the internet of things and artificial intelligence applied in the smart building could be effective ap-

proaches for enhancing the elevator-related mobility problem. Nevertheless, the existing elevator system remains stand-alone from the mobility platform, that makes the methods for optimizing the mobility on the elevator can be divided into several sub-challenges are listed as follows:

- How to empower the elevator to communicate and coordinate with the mobility framework in the building;
- How to design the architecture that could insure the flexibility and applicability of the proposal;
- How to develop an optimal control method that effectively enhances the time-efficiency on vertical mobility.

1.3.4 How to develop end-user-oriented services

Finally, in order to deliver mobility assistant service for end-user, this research also focuses on the issue of how to achieve effective interaction between users and system. Especially, based on the context-aware concept, the challenge of how to customize user interface depending on user's profile and environmental context needs be considered for this research point.

For instance, in this research, an effective user interface for the visually impaired users is suggested. The user interface combining the swipe-based gestural input and text-to-speech (TTS) output, has been designed for those specific users. This designed user interface assists the visually-impaired users to receive step-by-step path description in an effective way.

1.4 Contribution and Novelty

In this research, the proposals for indoor mobility enhancement of smart building is made, which is conducive to developing novel applications in this field. The contributions made by this dissertation are manifested in the following points:

1. **A proposal of the spatial model with fine-grained accessibility semantics** for overall spatial, relational, semantic reference. The suggested model comprised of a base hierarchy graph where all the edges is muti-directional defined and structured with various accessibility semantics. Besides, the spatial model also enables the indoor dynamics to be structured to perform mobility computation in real-time. For example, the status of normal or emergency, the usage status of free or crowd on each indoor relation could be made as a reference.
2. **A designed mechanism for context-aware routing** based on the proposed model. The routing algorithm is capable to calculate value pair made up of path and the corresponding accessibility index, where the accessibility index is factored for the assessment of the accessibility level of the path.
3. **An implementation of the proposed model: the visually impaired oriented application** was developed and positively evaluated based on the feedback from the participants. In our research, the experimental data was processed with the analysis was conducted, which could refer to potential improvement for further development of this research.
4. **A proposal of hardware architecture for the integration with the stand-alone elevator and smart building.** The hardware architecture to integrate conventional elevator with IoT-enabling technologies was proposed. The IoT-enabling development on elevator is practical and have been experimented in a real smart building environment. After the IoT-enabling devel-

opment, the stand-alone elevator gained the capability of context-awaring in the external environment.

5. **A proposal of the agent server-based architecture for transferring and improving the computational ability** of the elevator, such as utilizing the BLE-based localization platform for location-aware on the passenger side, markov decision process for self-adaption, and so on.
6. **Two novel elevator system implementations: One is PrecaElevator** proposed for pre-registering elevator call to achieve the goal of zero-waiting time. This proposal marks the very first attempt made to apply the context aware platform of the smart building without any additional off-line sensors, which improved the flexibility while maintaining the computational capability.
7. **Another implementation is Intellevator**, which enables the passive functionality of elevator to be proactive and intelligent. To the best of our knowledge, this comprehensive work is the first for elevator system to execute proactive and adaptive control on the traffic flow and deliver the intelligence to end-users for enhancing passengers' vertical mobility by managing the presented contents on user interface in real-time. The novelty is also lying on: for end-users, a blended but more efficient vertical moving plan (combining elevator, stairs, etc.) could be provided according to the real-time optimization on the vertical mobility. This novel usage also received positive acceptance.

1.5 Outline

This dissertation consists of 7 Chapters and the remainders are structured as follows:

Chapter 2 presents a summary of the reviewed related work, including indoor spatial model and accessibility semantic measurement as well as the elevator control optimization. A survey is conducted to summarize each of these three significant parts of prior works, individually.

Chapter 3 makes an introduction of a spatial model for mobility enhancement in the overall perspective. Our proposal for assessing model design and accessibility is elaborated in detail. The routing mechanism based on various use cases will be described in this chapter. Finally, the implementation and evaluation of the proposed model are presented as a conclusion of this part.

Chapter 4 presents the proposals of elevator-centric control optimization for mobility enhancement from the perspective of vertical mobility. In this chapter, the overall architecture with IoT-enabling development and agent server for context awareness the external environment will be introduced. Finally, a brief introduction of the upper-layer implemented system : PrecaElevator and Intellevator is presented at the end.

In Chapter 5, the proposed implementation of PrecaElevator will be presented in specific. After the introduction, the proposal encompasses system architecture, the method integrated with the indoor localization platform will be elaborated. Finally, the evaluation including user study and simulation will be explained in detail.

Chapter 6 makes proposal of Intellevator. The agent server consisting of traffic paek-pattern detector, markov decision process as well as the novel user interface design will be described in detail. Then, the user study, simulation and their results will be presented in detail for demonstrating the evaluation.

Chapter 7 presents the discussion of the research conducted from the perspective of multiple disciplines.

Finally, Chapter 8 will draw the conclusions from this research and the future

work will be outlined.

Chapter 2

Related Work

In this Chapter, the relevant work on indoor mobility will be elaborated. Our survey was divided into two parts: One is indoor spatial reference, including indoor maps, indoor localization technologies and indoor spatial model. The other one is a survey in relation to the research conducted into elevator-centric vertical mobility. We investigated these related researches and summarized the remaining problems arising from these two fields at the end of this chapter.

2.1 Indoor Spatial Reference

2.1.1 Indoor Maps

The current indoor maps are primarily manually created by CAD (Computer-aided Architectural Design)¹ or with other drawing tools. The created indoor maps will be printed, stamped somewhere inside building or on the Internet for indoor reference. However, indoor map is human-understandable present of the indoor environment [14]. How much information the user could gain access to is largely dependent on the map readability of the humans. That is to say, the function performed by indoor maps will be restricted for the users with either

¹http://en.wikipedia.org/wiki/Computer-aided_architectural_design

visual impairment or poor sense of direction, or for robots if without learning.

What makes it worse is that the existing indoor maps show no interoperable digital form [39], which make them not directly applicable for machine understanding and computation. Thus the maps with existing style will be rendered completely unfit for use in mobility computation if there is no support from other digital and interoperable indoor spatial reference.

Furthermore, the part of accessibility semantics in indoor environment is more difficult to be incorporated into indoor plan. Therefore, digital indoor map (indoor plan) is possibly one reference for support indoor mobility, however, how to associate the accessibility semantics with high granularity context aware-based reference also remains as a major problem needing to be considered.

So far, we have gained understanding that the application of existing indoor map alone is unaffordable for indoor mobility computation. Noticeably, it is incapable to sustain high granularity context aware accessibility computation. Digitally modeling of indoor environment will constitute a basic part of indoor mobility computation, which also ought to be processed in advance as well.

2.1.2 Indoor Localization Technology

In brief, localization transforming from "here" in the real indoor environment to "there" on the indoor map is quite challenging if in the absence of the assistance provided by indoor locationing technology. Back in the previous decades, beacon-based wireless communication technologies were applied and leveraged to fulfill the potentials for acquiring the physical environment information, including RFID, NFC, BLE or WiFi and so on, with difference in the communication distance, algorithmic complexity cost, etc [40, 41].

Using these short distance communication technology is beneficial, supplemen-

tary and necessary for the positioning of indoor objects. The beacon also can be made use of the recognition of the semantics on landmarks inside building (e.g., store, entrance, elevator, etc) by the typical emission of wireless signals with unique identifier in association with environmental knowledge [41].

2.1.3 Indoor Spatial Model

Indoor spatial models constructed for research fields encompass mobile robot mapping and ubiquitous computing, to indoor location-based services (LBS), and most recently to context aware navigation services applied to indoor environments [16]. These models are categorized into symbolic, geometric, and hybrid model [16][42][40].

Geometric model Geometric model with coordinates utilized to define every location on Earth. A commonly-seen example is GPS coordinates with latitude, longitude and altitude, which have already been extensively applied to outdoor localization. A similar example is Cartesian coordinates, which is comprised of an ordered triplet of lines (the axes) with X, Y, Z axis to define locations in three-dimensional space (the example shown in Figure. 2.1).

Geometric model makes location-dependent queries (for example, the users intend to search for a target store at a specific location), range queries (for example, the users expect to find target stores within a radius of 100m) also can be supported well. They also can be applied to perform calculation of the distance between two geometrically defined locations, by making reference to such as Euclidean distance [43].

Moreover, by means of geometric operations, it can also be ascertained whether or not two areas overlap, touch each other, or one area covers the other, i.e., topological relations represented by spatial relationships, such as “overlap” , “inside” , “intersect” and “disjoint” can be inferred based on the geometry of objects.

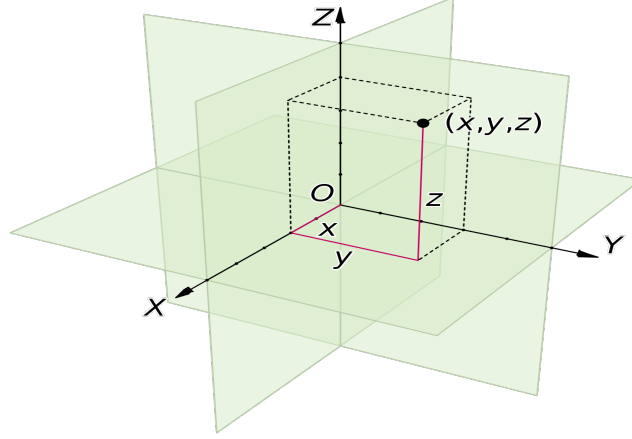


Figure 2.1: The cartesian coordinate system

Therefore, by making location query and distance calculation, range query made geometric coordinates develop the capability of simple spatial reasoning, for instance, the nearest person and the target object which is 100 meters away from here.

Nevertheless, the geometric model where the object is simply identified by numerical coordinates, adds to the difficulty in extension for powerful location reasoning of objects. Therefore, regarding the practical use of location service, there is another kind of model which is integrated with geometric model to make a better reference know as Symbolic model. It will be described as follows:

Symbolic model In comparison to geometric information, symbolic information makes qualitative human-readable descriptions of moving objects according to structural entities or points of interest (e.g., room or floor identifier, building name) [16]. Therefore, instead of coordinates, positions or relationship between objects in the symbolic model are frequently defined in the form of abstract symbols, e.g., names of the room or building, the identifiers of a sensor, etc.

Similar to geometric model, symbolic descriptions enable topological relations (e.g., containment, or connectivity) that exist between entities in the environment

which need to be explicitly modeled. Symbolic descriptions perform spatial and semantic reasoning on an abstract level, thus assisting interaction taking place between spatial entities and within the indoor space [42]. Nevertheless, the distance between two symbolic descriptions is not vaguely specified. The symbolic models are divided into multiple categories: e.g., set-based model, hierarchical model, graph-based model. The detail definition will be presented as follows:

- Set-based model

Set-based model is capable to identify places or entity within an indoor space, before gathering these symbolic identifiers into sets or subsets. The set of symbolic identifier provides the basis for the set-based approach with “contain” structure.

For example, assuming a building with multiple floors and multiple rooms, the set B of building can be modeled as Building: $B = \{\text{Floor1}, \text{Floor2}, \text{Floor3}, \dots, \text{etc.}\}$, and the set F of floor can be modeled as Floor: $F = \{\text{Room1}, \text{Room2}, \text{Room3}, \dots \text{etc.}\}$.

- Graph-based model

Graph-based approaches regard an indoor space as a graph in which nodes model predefined locations (e.g., place, gate, point of interest), and edges denote the connections that enable move in among these locations.

In the graph-based approach, symbolic coordinates determine the vertices V of a graph $G = (V, E)$. An edge is added between two vertices in case that a direct connection between them exists. Considering how the graph is constructed, it is already clear that a graph-based model supports the definition of the topological relation “connected to” between symbolic coordinates. For example, in brief, a floor plan can be organized as room indicated as nodes and doorways as edges.

In the graph-based model, indoor objectives are inter-connected by edges if a link between these locations exists in reality. For example, two rooms will

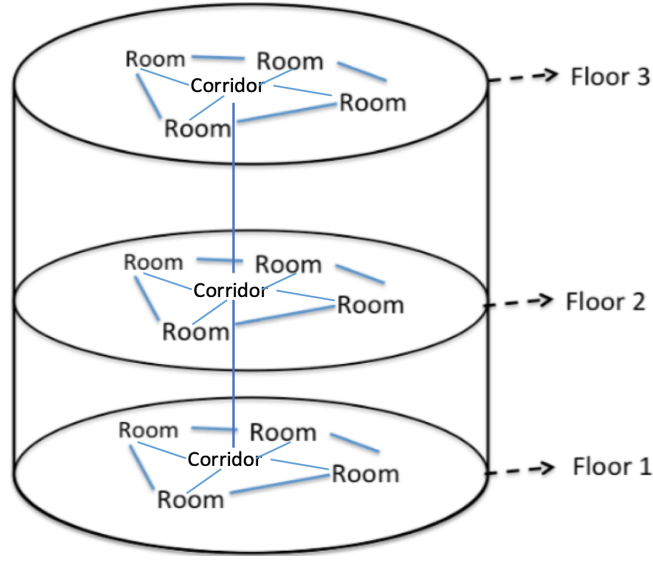


Figure 2.2: A simple example of graph-based hierarchy model of building

be connected in the graph if there is a door between them; two floors will be connected if stairs lead from one floor to the other, etc.

- **Hierarchical model**

Hierarchical model using graph-based model to achieve further hierarchical organization of the environment [42]. Hierarchical model is suitable to represent the multiple layer structure of a building [14]. Figure 2.2 below illustrates a simple example of a graph-based hierarchy model for building. The building is shown to consist of floors, in which rooms are connected.

Hybrid model Each model has both merits and drawbacks as indicated in Table 2.1. In a relative term, hybrid model is employed to overcome some limitations of these models by consolidating the different types of models. In the hybrid model, not only can the object be identified by coordinates for distance calculation, it is also modeled with the qualitative human-readable descriptions for the sake of better spatial semantics reasoning.

Graph-based representations have a long attempt to model indoor environ-

Table 2.1: Comparison on geometric model and symbolic model

		Geometric model	Symbolic model
Location computing	Distance calculation	○	△
	Range query	○	△
Topological relationship	Overlap	○	○
	Containment	○	○
	Connection	△	○
	Intersection	△	○
	Disjoint	△	○
Semantic reasoning		Low level	High level

ment as proposed by [44, 14, 13, 45]. A significant advantage displayed by these approaches is that a structural representation is conducive to performing the studies of functional properties or semantic attachment, as well as the human cognition of the environment.

As an example introduced by Lorenz, et al.[14], where rooms or corridors are mapped to nodes, and pathways are mapped to links in the designed graph. Likewise, the model proposed by Stoffel, et al [13], where each element corresponds to a certain domain concept (‘room’ , ‘door’ , ‘floor’ , etc.), and can be annotated with meta information.

Hu, et al. [46] proposed a semantic location model that preserves topology and distance semantics for exit-hierarchy routing. Similarly, ucR-based spatial information framework [47, 48] was proposed to make distinguish between the places by a unique number known as “ucode” [49] and describe attributes or information of these places with a semi-structured data model known as “ucR model” .

Nevertheless, theses prior defined models are similar to structure the indoor environment at coarse-grained. There yet to be further investigation conducted

into what sort of dynamic semantics needs to be considered as accessibility for context aware computation.

2.1.4 Indoor Accessibility Measurement

The American with Disabilities Act (ADA) standards [50] is regarded as the most inclusive handbook in the United States to solve the problem of "what element as well as the properties of itself on the route can make it more difficult or even impossible for the disabled to pass". However, the ADA standard concentrates on the architecture design or construction view. Moreover, in addition to aiming for the disabled users, where the dynamic properties are lacking an effective reference.

Hassan, et al. [51] offered interpretation for indoor routing for special needs and reference. According to their proposal, three types of use cases, e.g., unfamiliarity with buildings; people with special needs and emergency evaluation have been examined. Mahdi, et al. proposed the methodology of emergency evacuation for the disabled by applying the ADA standards [19]. Likewise, McIntyre, et al. [52] explored way-finding experiences by 10 visually impaired participants attended. This work identified a number of accessibility issues related to doors, hazards posed by the building.

These prior works revealed a handful of evidences for defining what kind of characteristics as accessibility semantics. In addition, the works also presented some theoretical basis and investigation for summarizing and classifying collected some corpus of indoor static accessibility semantics, for the objective of assisting the disabled in mobility. Despite this, the dimension of dynamic accessibility semantics has barely been made mention of.

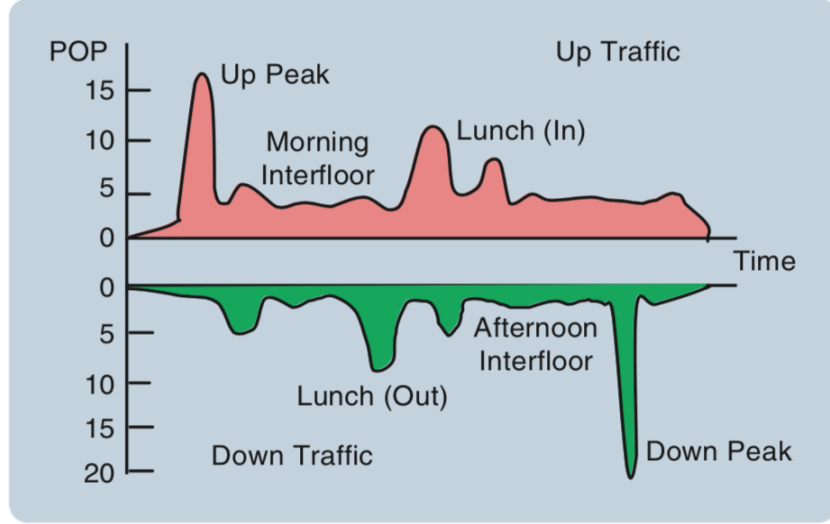


Figure 2.3: Traffic patterns occurring throughout the day in a typical office building, reprinted from [3]

2.2 Facility Control: Elevator-centric Mobility

A variety of prior studies have been conducted to enhance elevator scheduling efficiency, by optimizing multiple relevant criteria, for instance, the average time a passenger waits (AWT), the average time passenger takes ride on the cabin (AJT), the long waiting time percentage of calls (LWT%), energy consumption, and so on.

The related work pursuing the perspective of time-efficiency to improve mobility, could be primarily divided into two aspects, algorithm-based optimization on elevator's controller [53, 54], data collection to minimize uncertainty [55, 5, 56].

2.2.1 Algorithm-based Stand-alone Optimization

In most elevator environments, traffic patterns show periodical changes within a day, there are up-peak traffic, down-peak traffic, or lunch-peak traffic and so on

[3, 57]. The Figure 2.3 demonstrates the movement of population (pop) over time to reveal the traffic patterns [3]. Brand et al. suggested an optimized parking policy of elevator according to the analysis of the traffic patterns of up-peak and down-peak. The proposed parking strategies could reduce passengers' waiting time by locating a free car at a designated floor [54]. A genetic algorithm based controller have been proposed and evaluated by simulation [58]. The simulation showed the proposal is effective in reducing waiting time during peak traffic at lunch time.

For artificial intelligence approaches, elevator control and management has become a major area of application [35]. Plenty of studies have been performed to enhance time efficiency for elevator by taking mathematical approaches, such as fuzzy logic [59], genetic algorithm [60, 58, 61], reinforcement learning [62], neural networks [63, 64], and hybrid methods [65, 66, 67]. For example, Dai, et al. proposed a hybrid genetic algorithm for scheduling group elevator based on the condition that the information on destination floor could be registered in advance [68].

2.2.2 Data Collection to Minimize Uncertainty

Meanwhile, some studies have been carried out to gather more data from the users by applying sensor technologies. In these works, for example, camera [69], floor sensor, and additional buttons, etc, were adopted [55, 5, 70, 6].

A patent work intended for generating registration call also has been proposed in [4]. As Figure 2.4 shows, a trigger sensor ought to be locally equipped at the floor. At the same time, the passengers are required to carry a portable transmitting device. When a passenger passes by the trigger sensor, he/ she could send a signal to the remote beacon, and then through the elevator beacon, a elevator call is triggered. The proposal requires a dedicated device to be carried and manual operation on the passenger side.

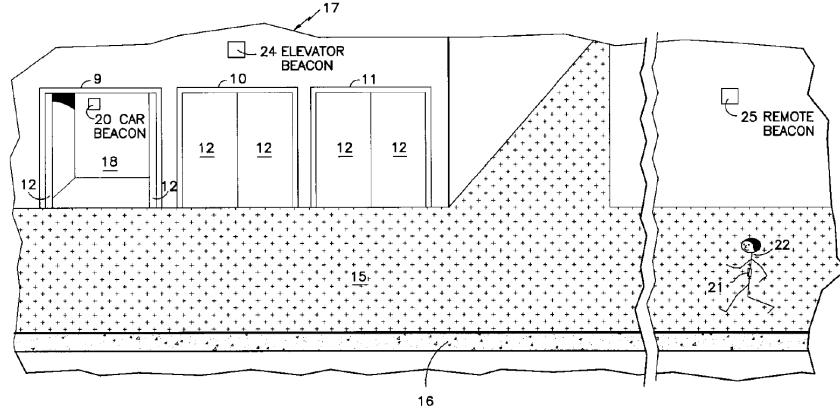


Figure 2.4: Figure shows the usage of remotely call on elevator, reprint from [4]

Likewise, Kwon et al [55, 5] utilized sensor technologies to initiate reservation calls on the elevator to reduce the passengers' waiting time. They employed a single-type sensor : floor sensor in their first proposal [55]. Then, as illustrated in the Figure 2.5, they made improvement to their proposal by applying three types of sensors, RFID, as well as camera and floor sensors [5]. In this proposal, when passengers at specific places are detected, a reservation call on the elevator will be initiated. The shortcoming of the proposal lies in low accuracy. Moreover, the high cost of both the computational and local hardware equipment is another issue.

On the other hand, RFID sensor technology are applied as well for associating passengers' profile information [71]. By querying the database of passengers' profile, their destinations could be informed before their entry into the elevator car. A RFID tags and camera-based elevator control system is developed by Mitsubishi Electric Corporation. With RFID sensor technology and image processing combined, the system distinguishes whether a person intends to use an elevator or just passes by [72]. Nevertheless, the RFID-tag-based approach for pre-input of destinations is disadvantageous in the accuracy of predicting the user's intention. If the passenger intends to go to a floor which is not the one associated with the identifier, this approach would be not suitable.

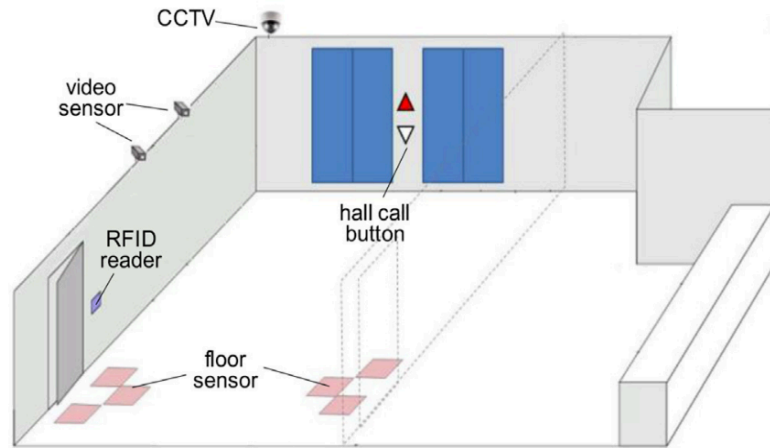


Figure 2.5: Figure shows the prototype to collect sensor data for generating elevator calls, reprint from [5]

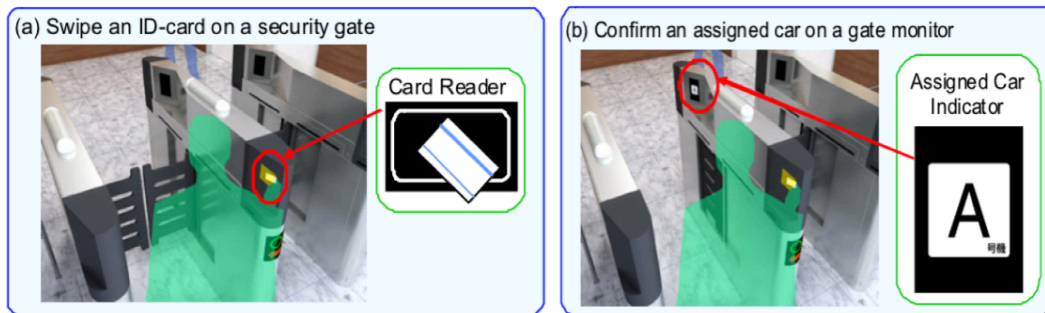


Figure 2.6: The elevator-cabin for riding is optimized by passengers' id, reprint from [6]

The most recent work [6] demonstrated a more intelligent method to achieve elevator-centric mobility enhancement. The proposal optimizing the car allocation based on the cabin capacity and categorization of passenger groups. As revealed in Figure 2.6, when the passenger taps the ID-card for passing through security-protected gate, the optimally assigned car number could be presented at the gate. This work leverages ID-card authorization at the gate of lobby floor and the contribution was restricted by the necessary identification-related information.

Elevator systems where the destination floor could be pre-registered were proposed by [73, 66]. In these proposals, an additional button panel was equipped outside the elevator. By using hardware equipment, the function of the destination floor being a pre-input is achieved. However, in case of an update lacked on the elevator controller, the viability would be limited. Definitely, the cost of updating both the hardware at each floor and computation capability in controller would be increased significantly as the number of floors rises.

2.3 Summary

2.3.1 Summary of Indoor Spatial Reference

Related works on indoor spatial reference could be summarized as follows:

- The related works of indoor spatial model were often designed by a prescribed objective, few research solution covered cross. In the whole perspective, a majority of studies have been focused on the argument on the level of summary and discussion, without further work of development of model's use, resulting in uncertainty applicability and efficiency for the model.
- Structural approaches reliant on graph-based symbolic representation have made attempt to construct indoor environment model. The major advantage

shown by these approaches lies in a structural representation that facilitates the studies performed of functional properties or semantic attachment, in addition to the human cognition in the environment.

- With regard to indoor accessibility semantics, it was discovered that a lack of model with accessibility semantics made routing premised on comprehensive accessibility semantic references impossible, inclusive of the static, dynamic dimension. Especially, few work has given consideration to structuring the dynamic accessibility semantics, for instance, the emergency status on the indoor facilities, the status of crowd, etc. Thus the application development to increase the overall indoor mobility inside smart building, covering barrier-free navigation, robot way-finding or emergency evacuation has been constrained.

2.3.2 Summary of Elevator-centric Vertical Mobility

To summarize the elevator-centric vertical mobility:

- Plenty of related works have been undertaken for the time-efficiency optimization for elevator. However, nearly all of the previous works concentrated on the stand-alone elevator, for which only limited works have taken into account the integration with the mobility platform of building. The deployments of sensing technologies, hardware update, complex algorithms, advanced decision rules for taking control of the stand-alone elevator are lacking in flexibility to enhance the global intelligence and efficiency inside the smart building.
- Being real-time monitored and context-aware controlled from the whole smart building for mobility optimization is expectedly desirable. However, hardware-embedded development to enable the elevator as a smart-object with the assistance of IoT-enabling lacks. Besides, the architecture that integrates with

the context aware framework to achieve the computing capability from the entire external environment was lacking as well.

- Finally, as a crucial transport system, the passengers' user experience, not only the long-waiting time, but also the uncertainty of provided information need to be undertook for enabling them to move vertically in an efficient, comfortable and smooth way. However, the development of end-user oriented interface which would improve passengers' user experience on vertical moving has been restricted for a long time due to the lack of research conducted from this perspective.

Chapter 3

Spatial Model-based Proposal : Overall Mobility

In this chapter, the spatial modeling-based proposal to improve the indoor accessibility and overall mobility for passengers is introduced. Firstly, an indoor spatial model fine-grained designed with accessibility semantics is suggested in detail. Subsequently, the routing mechanism with the accessibility index considered will be elaborated. Finally, the conducted experiment and evaluation will be elaborated.

3.1 Introduction

For the sake of improving the overall indoor mobility, a spatial model composed of a graph-based hierarchy model that involves accessibility semantic measurement is proposed. With regard to the accessibility semantics, our proposed model could provide a reference including real-time environmental status, barrier-free information, operation and authorization of passing the door, and so on.

Further with the proposed model, we put forward a routing mechanism for the computation of the context-aware based accessibility while indoor routing. For evaluation, we developed a systemic approach to generate indoor path descriptions for implementation. The visually impaired oriented case study was performed

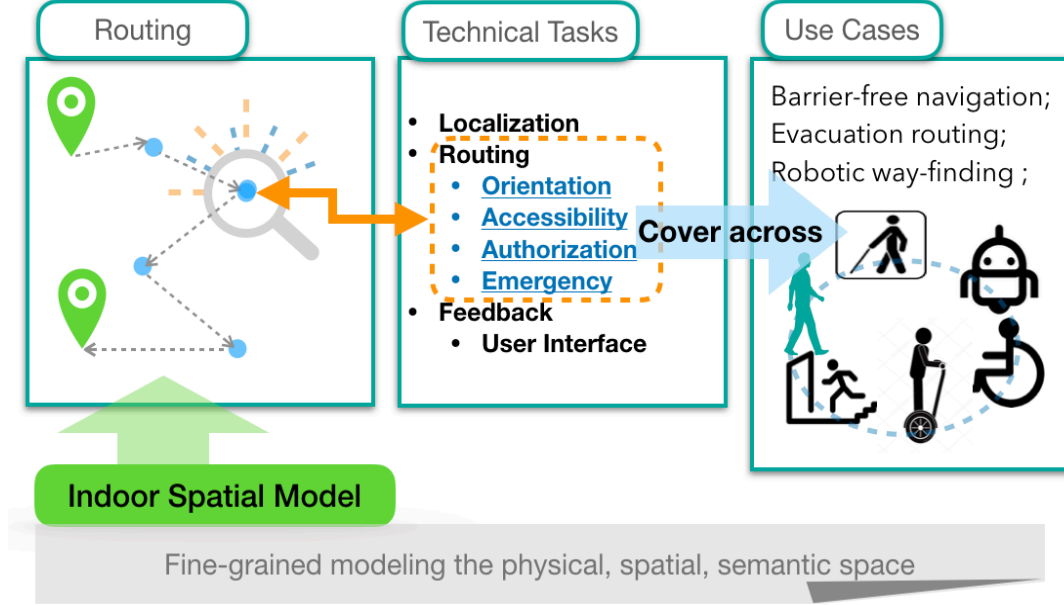


Figure 3.1: The proposed model for fine-grained routing

for subjectively evaluating our proposed method. The promising result will be presented at last.

3.2 Proposal

As demonstrated in Figure 3.1, we proposed a fine-grained spatial model with diverse accessibility semantics could be taken as a fundamental component for making physical, spatial, semantic reference. For applications, they are capable of accomplishing multiple technical tasks in fine-grained routing, for instance, the orientation, accessibility, authorization, emergency computation.

Our proposed spatial model consists of:

1. A base spatial model with hierarchical structure of graphs, in which the graph of building is structured into the graph of floors and stairs, elevators, etc., in

weighted indoor routing graph applied to user-adaptive routing computation.

2. Classified characteristics have been encapsulated as properties of the node and edges within the graph, which could be referred as both the static and dynamic accessibility semantics.

3.2.1 Fine-grained Indoor Spatial Model

Base Spatial Model

From the perspective of functionality reasoning or human cognition, our model was designed as a hierarchical graph-based structure. Graph-based approaches represent an indoor space as a graph where nodes are predefined as locations (e.g., place, gate, point of interest), with edges signifying the connections.

The proposed model illustrated in Figure 3.2 fits building structure and navigation strategy, made our proposal available for almost floor-structured building. It is believed that commonalities between the model of a building and its physical structure in the real phenomenon makes it easy for ordinary people to understand and model the indoor environment, leads to bottom-up indoor spatial data without much professional skills or knowledge.

Similarly, as shown in Figure 3.3, the hierarchical graph structure and containment relationships have been illustrated in Figure 3.3. The root graph presents the building, which is comprised of floor nodes, as well as edges called "relationship_between_floors" representing stairs, elevator, etc. Meanwhile, the upper hierarchy of floor is a graph of vertices representing room, corridor, indoor POI (indoor place of interest), edges called "relationship_in_floor" connecting these vertices, which denotes door or passageway. Indoor POI is used for labeling some special spots, such as the entrance of stairs or elevator, from where navigate pedestrian vertically move to another floor.

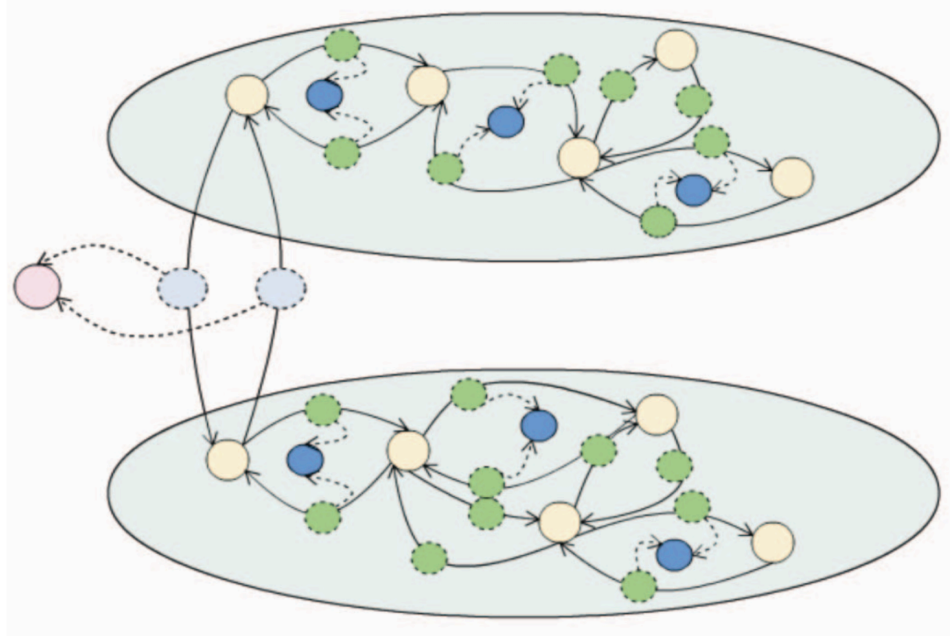


Figure 3.2: Graph-based hierarchical structure of a building







Graph	Vertice	Edge	Entity of Edge
building	floor	relationship_betwe en_floors	stairs, elevator, escalator, etc.
			
floor	room, corridor, indoor, POI	relationship_in_flo or	door, passageway
			

Figure 3.3: Entities and relationships in the hierarchical graph

Therefore, in our proposal, room->hallway is indicated as a pair of combination; In contrast, hallway-> room presents another different independent pair of combination. They are defined as abstract relationships defined as “relationship_in_floor”, and the detail entity of a door is interpreted as a property “entity” of this abstract objects.

Identifier

A global unique and formal identifier system played a significant role on spatial modeling as well as spatial information collection. However, unlike the outdoor environment where we can easily identify the objects with longitude and latitude, there is no formal definition of identities in indoor environment. Therefore, Identifier issue is the one of the most fundamental components of making model practical for application development.

In our proposal, we used 'ucode' to identify indoor entities and indoor relationships in this implementation. Because ucode [74] is a 128-bit fixed length identification number which could be uniquely assigned to individual objects, spaces, and other abstract concept or content information for ubiquitous computing.

Accessibility Semantic Modeling

It is noteworthy to mention that there is a noticeable difference from the prior designs, which is that we defined abstract edges between indoor entities for structuring some prerequisite properties. In the proposed model, directed edge caused the two opposite directions, which enable the model to structure completely different accessibility semantics between nodes. A majority of the accessibility semantics was on the intersection, could be structured in the edges for computing efficiency. Aiming for the fast-speed of routing, it is efficient to assign accessibility indexes to edges.

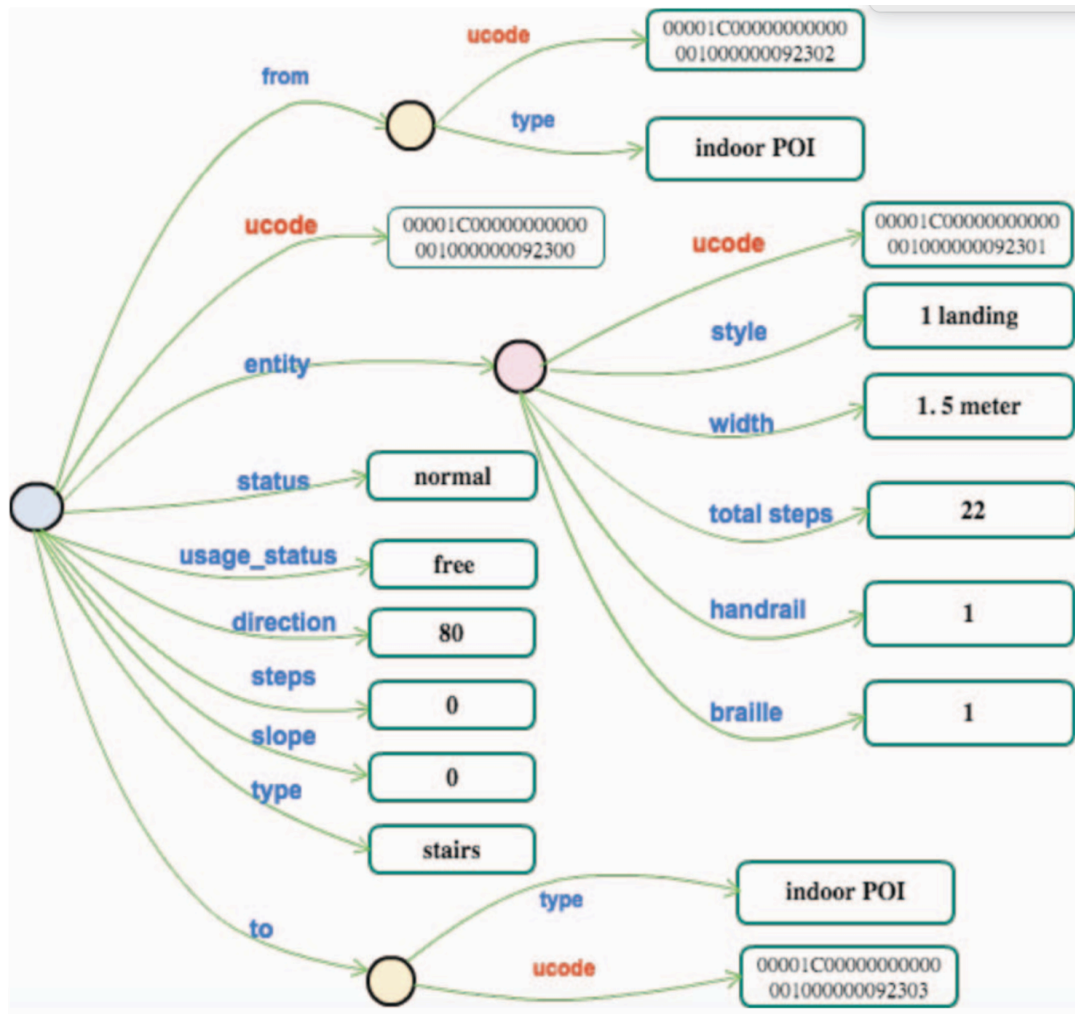


Figure 3.4: An example illustrates the accessibility semantics modeling on stairs

In respect of indoor accessibility semantics, it is categorized into two types as described in Chapter 1 as follows. Figure 3.4 presents the example.

- One is static accessibility semantics, which is impenetrable, tangible, and visible. The static accessibility semantics are classified as follows:

Barrier information: involving steps or slope around an entrance, the width of hallway, the open mode of door, etc.

Direction: direction is regarded as an essential character for the mobility of the visually impaired or robot, which have restricted ability of spatial awareness. In addition, information of direction promotes creation of turn-by-turn path description based on the previously specified direction and next direction along the way.

- Another one is dynamic accessibility semantics, which processes invisible nature that only creatures can perceive. Indoor environmental status ought to be dynamically monitored and recorded in real-time by the model, and reflected into navigation services to guide pedestrian inside in an intelligent and effective way. Based on this consideration, two properties named as ‘status’ and ‘usage status’ assigned to the edge for real-time monitoring accessibility semantics for representing the values of normal or emergency as well as crowd or free.

As exemplified in Figure 3.5, it is representative for the explanation of orientation computation premised on physically structured azimuth-based abstraction. It is assumed that the moving objects colored by blue faces 270° degrees to west direction in the hallway, prior to entry into the room from hallway, the moving objects are required to turn a certain degrees (from θ_{min} to θ_{max}) to the right, with authorization being granted for entry. The individual inside the room which colored by orange need to turn a certain degrees (depend on azimuth-based computation in the physical environment) to the right to leave room for hallway and

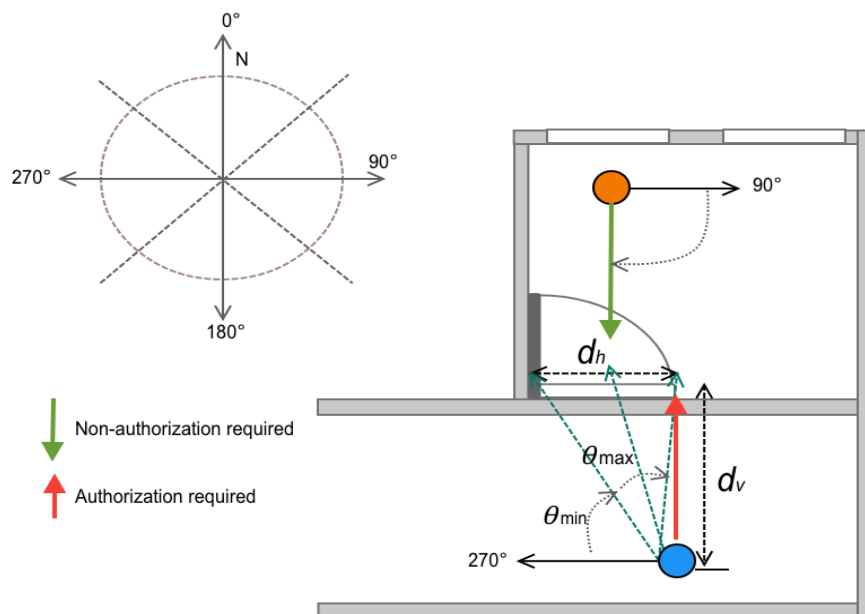


Figure 3.5: The example shows the computation of orientation and authorization while passing the door

no authorization is required. These sorts of characteristics exactly are not belong to door itself, but could be modeled into two mutual relationships.

In recent years, the development of SLAM technology [75] enables the robot to detect semantics during moving. However, the problems on computational complexity and accuracy still remain. It is considered that our proposal of fine-grained spatial modeling is possible to reduce the computational burden on the robot side by modeling the physical environment in advance.

3.2.2 Routing Mechanism

The problems with algorithm design which gives context awareness to make routing strategies with high intelligence are required to be addressed as well. We constructed routing mechanism in which use cases are correlated to path extraction. As the factor of distance is possibly unfit or even meaningless while taking into account accessibility semantics indoors, we suggest the algorithm for routing all the current accessible paths with the accessibility index. The following algorithm 1 describes the details on the routing mechanism.

As algorithm 1 describes, finally multiple pairs of routing and the corresponding accessibility index would be calculated. The accessibility index should be pre-assigned in advance and routing computed in the edges is presented in the example listed in Figure 3.6.

Indexing for significant parameters of AS

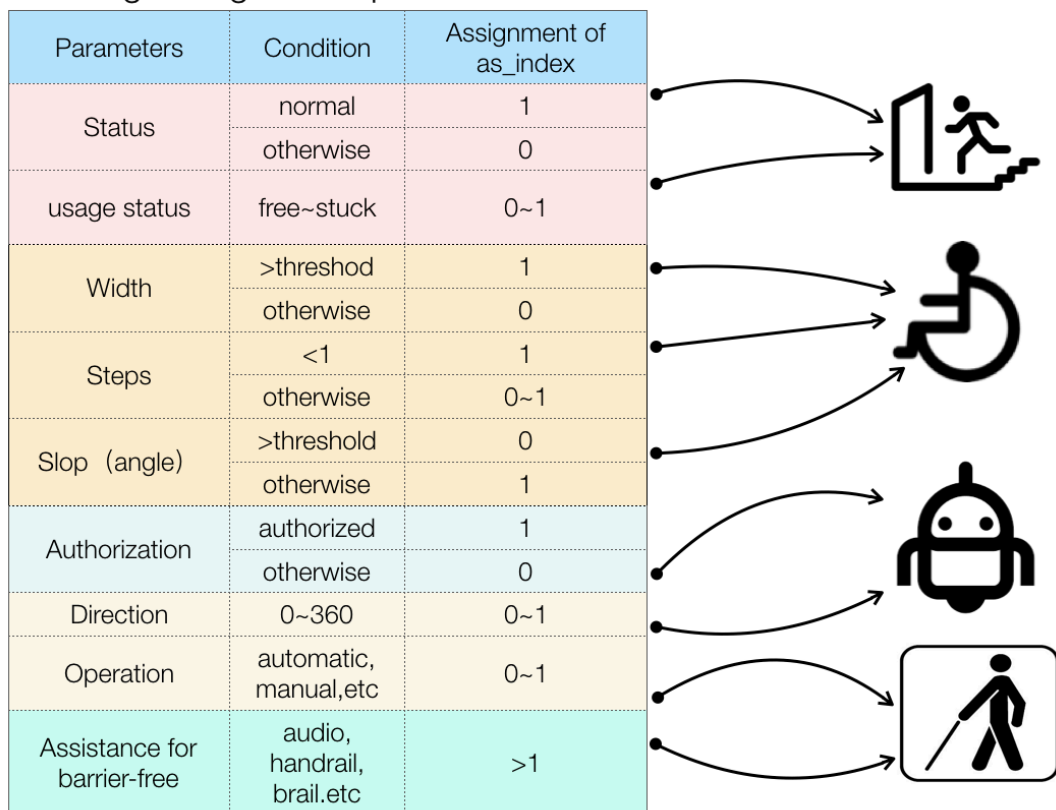


Figure 3.6: Parameter indexing example for accessibility computing

Algorithm 1: Algorithms for Routing with Accessibility

```
1  $G = (N, E)$ 
2  $N = (n_o, n1, n2, \dots n_d)$ 
3  $E = ((n_o, n1), (n1, n2), \dots (n_d - 1, n_d))$ 
4 Initialization :
5  $AS\_index = 1$ 
6  $N' = n_o$ 
7  $P = [(N', AS\_index)]$ 
8 for each  $(N', AS\_index)$  in  $P$  do
9   while  $v$  adjacent to  $n_o$  and  $v$  not in  $N'$  do
10     delete  $N', AS\_index$  in  $P$ 
11      $AS\_index = AS\_index * as\_index'$ 
12     if  $AS\_index > 0$  then
13       add  $v$  into  $N'$ 
14        $n_o = v$ 
15       add  $(N', AS\_index)$  into  $P$ 
16     end
17   end
18 end
19 Return  $P$ 
```

3.3 Experiment

We implemented a systemic approach of path generation in which multiple path patterns can be extracted from our proposed model with different granularity indicated as follows:

1. Moving out from the room, then enter the hallway;
2. Moving out from room by passing through the door, then enter the hallway;

3. Turning to 180° direction, after automatically authorized, and pulling the door to open, then you can get out from room to hallway;
4. Turning to 180° direction, after automatically authorized, and pulling the door to open, then you can get out from room to hallway. The current status around the entrance is normal, the usage status around there is not crowd;
5. Turning to 180° direction, after automatically authorized, and pulling the door to open, then you can exit room for hallway. The current status around the entrance is normal, the usage status is not crowded, and there is braille in front of entrance, and without any steps or slop around there.

Pattern 1 and pattern 2 serve as examples of conventional descriptions that can be created by the current coarsely designed models. Nevertheless, users having special needs or preferences or unfamiliarity with the environment require paths description with much more fine-grained accessibility semantics. Take pattern 3 as an example, which is premised on pattern 2, but with the extension of body rotation and operation of doors, that could be beneficial to people with only limited knowledge of the indoor environment.

Pattern 3 and pattern 4 offer people the certainty of usage through real-time monitoring of status, which also could be essential to intelligent select the effective path for the scenarios like emergency evacuation. Pattern 5 which based on pattern 4, is extended by barrier information, which is essential to the disabled people' s mobility, as well for fine-grained mobility information required robotic device in particular.

3.4 Evaluation

To subjectively verify the quality of path description generated by our proposal, we conducted a case study with 6 visually impaired participants attended

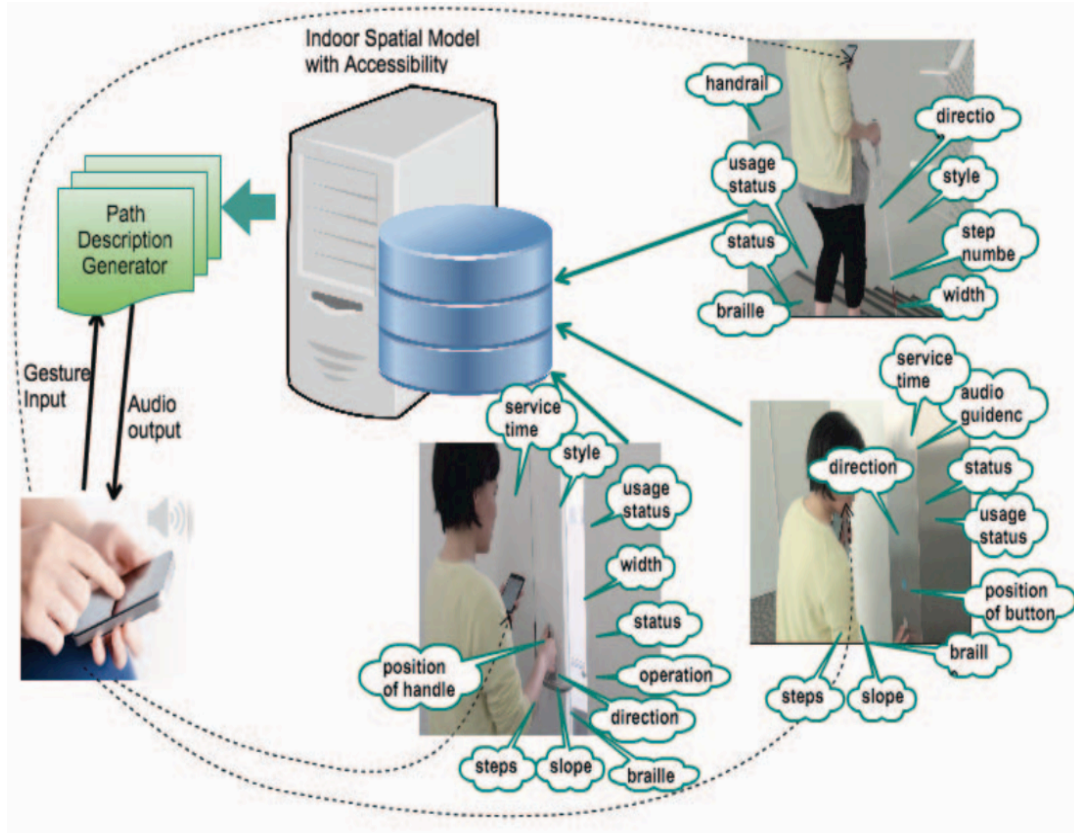


Figure 3.7: A real example of evaluation

for evaluation. The case study was conducted in the place of Daiwa Ubiquitous Computing Research Building of the University of Tokyo.

3.4.1 Participants and Setup

Information redundancy could obstruct participants in moving. Especially for the visually impaired, retrieving requisite accessibility semantics for reference in an efficient way is required. Therefore, we conducted a prior hearing for clarifying the significance of these accessibility semantics by a rating system. The participants were asked to score these characteristics of accessibility semantics based on the scoring criteria scaling from 5 to 1 as follow:

5. Necessary (Unable to move if without it)
4. Desirable to exist for reference
3. Neither necessary nor not (No big difference)
2. Desirable not to exist (Excessive service)
1. Unnecessary (They are obstacles for moving)

The subjective result uncovered distinct evidences that 28 characteristics are really needed for the visually impaired marked as shown in Figure 3.7. The result of rating system revealed the characteristics could be considerable for reference if the threshold value was set as 3.

After pre-selecting accessibility semantics for the participants, the detail version (description pattern 5 shown in section 3.3) and simplified version without accessibility semantics (description pattern 1 shown in section 3.3) of path description were selected for comparatively evaluating the usefulness of the accessibility semantics.

Participants' memory of spatial awareness after an exploration could greatly affect the result of subsequent explorations. In order to avoid this case, we designed two paths with totally different situations. Path 1 and path 2 include all the types of indoor entities, making them covered overall accessibility semantics scored as considerable for reference. Both path 1 and path 2 spanned multiple floors. Path 1 is started from a room at floor 3 and ended in main hallway at floor 1, including two doors and elevator, four direction-changings. Path2 is started from 1st floor and ended in the exhibition room at B1-th floor, including one door, stairs and three direction-changings.

6 participants (P1-P6), including 3 males and 3 females, joined our case study. They are not familiar with the experimental site till they start the experiment. The average age of them is 22.6. All of them use white cane for aids and go outside almost every day. They also need guidance from others when entered a building at

Id	Age/ Gender	Experience of getting lost	Vision Impairment	Group No
P1	36/Female	occasionally	Blind	A
P2	19/Male	always	Blind	B
P3	22/Female	always	Blind	A
P4	20/Male	occasionally	Low vision	B
P5	19/Female	always	Low vision	A
P6	20/Male	occasionally	Blind	B

Figure 3.8: Participant profiles

the first time.

On the experiment, the participants were divided into two groups. The summarization of their profile, division and experience of getting lost while indoors was list in Figure 3.8. we assigned two tasks to each team. Group A was given the task of walking by following the detail version of path 1 and the simplified version of path 2. Contrarily, Group B is to walk by following the detail description version of path 2 and the simplified description version of path 1.

3.4.2 User Interface

Compared to sighted people, the visually impaired has the limited ability of unilateral auditory receiving information from devices. For this reason, we developed a prototype by using smartphone with a touch screen. The participant are enabled to access the application by the interaction based on gestural input and Text-to-Speech (TTS) output. The architecture also is shown in Figure 3.7. The details of TTS control is designed with a set of touch gestures as follows:

1. Swiping to left for retrieving the next content;
2. Swiping to right for retrieving the previous content;

3. Swiping to bottom for retrieving the detail description of accessibility semantics;
4. Double tapping for retrieving speech of the current content repeatedly;

3.4.3 Procedure

Participants were told that the purpose of the study was to verify the usefulness of path description with accessibility semantics, and their task was go to the target spot by referencing path description which voice transferred by the demo application on the smartphone. There is no time limitation or frequency limitation of retrieving path information from the demo application. The whole experiment process was recorded by a video camera for later analysis.

Each participant is followed by an observer while they walked along the path. The observer takes the responsibility of re-navigating the participant to correct trajectory if participant deviated from the path about 10 meters. Excepting the information provided by our proposal, participants also can query other accessibility semantics from the observer if needed.

3.4.4 Results

The results was promising and gave insight on the potential of our work. All participants finally reached at the target spots by referencing the path description. However, as Figure 3.9 shows, the mean time of following the path description of simplified version was longer than following the detail one, since the uncertainty of the door or entrance of a stair or elevator caused by lacking references on accessibility leads to a hard groping along the path, and taking more time.

It becomes an evidence that detail version with various accessibility semantics generated by our proposal could greatly enhance the mobility of the visually impaired. The higher mean scores of “easy to learn” and “usefulness” of path

Table 3. Result comparison of detail and simplified version
(Mean, SD)

Items	Path1		Path2	
	Detail Version	Simplified Version	Detail Version	Simplified Version
Easy-to-learn	4.6(0.5)	3.33(1.52)	4.00(0)	2.00(0)
Usefulness	4.6(0.5)	4.00(1.00)	4.3(0.58)	3.00(0)
Walking time (second)	130.3 s (44.4 s)	222.7 s (148.4 s)	103.7 s (15.0 s)	125.7 s (50.0 s)

Figure 3.9: Comparison of the time-consuming on moving

description’ s detail version in the Figure 3.9 indicates that participants felt easier to learn the situation of paths, and considered the detail version was more useful and reliable for their walking.

Besides, the usefulness of some specific features also has been investigated. The result is shown in Figure 3.10. The much lower mean score of usage status shows that participants were relatively careless about the dynamically monitored usage status of crowd or free. 2 participants stated they would keep moving on even if usage status is crowd thus it could little influence on the perspective of the barrier-free mobility. However, the information of direction was considered as a significantly helpful reference for their moving.

During the experiments, 3 participants have queried the detail information related to direction. As P2 asked “I was told that I can pass the door by heading east, please tell me now which direction I am heading” , P3 asked “Heading west direction that I can enter the elevator, so which side should I need to turn for heading west direction” , P6 asked “Please tell me which side is west direction” after he informed that turning west direction to enter stairs.

In addition, the designed user interactions of swiping left or right to control,

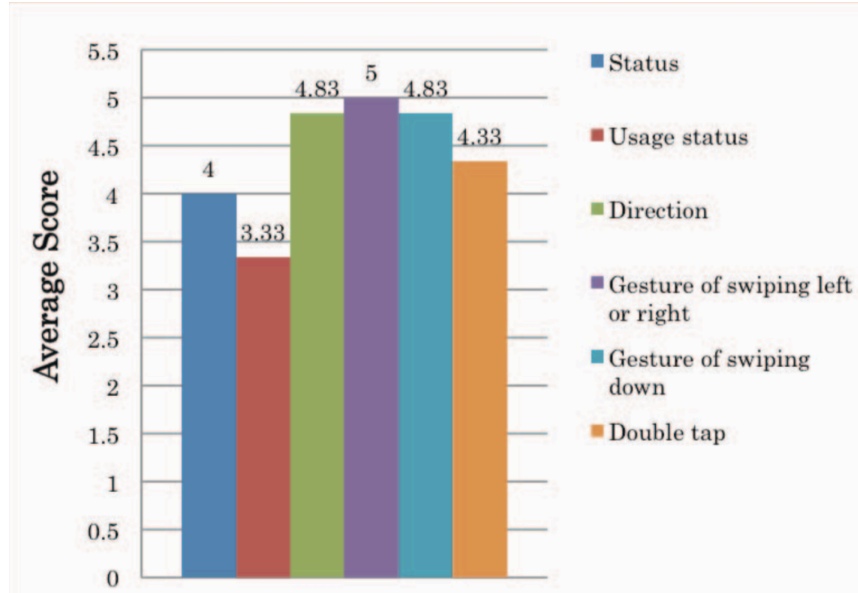


Figure 3.10: Result of evaluation on the designed interface

swiping down to retrieve details, double tap for repeat speech transmission have also been evaluated. The result was promising as overall participants rated the swiping left or right to control as 5, which indicates that participants have fully satisfied with this gesture control.

However, P2 who rated another design of swiping down as 4, recommended that it could be better that if there is a general instruction of accessibility semantics, such as the total number of items and the current number. P5 rated double tap as 3, said “For my own opinion, there is few problem about retrieving current information, however, searching for the previous one could be demanded a lot.”, which give us a insight of needs of information transmission control. Overall, we can infer that the deigned user interaction received a high acceptance.

All the participants positively commented the generated path description, stated that they intend to use our system for indoor exploring. P1 commented that depending on cases, it could be extremely useful to attend some events in of-ficial building. She thought it also could be helpful for visually impaired students

to reach at the target classroom smoothly. Especially, P3 recommended that our proposal not only notified the path information of reaching the target place, but also helped him build three dimensional space cognition of the building. It could be considered as an extra benefit for the visually impaired which was beyond our expectation.

From participants' free feedback, 3 participants considered that it brought more satisfaction if the application could automatically sense the heading direction, and give hint of body rotation. This gave us a motivation to develop fine-grained navigation fusing environmental information with real-time localization and mobility of participants.

3.5 Summary

We have proposed an accessibility semantic model-based design to enhance overall indoor mobility. According to the proposed model, we constructed the routing mechanism and devised systematic approach to automatically generating path description on various granularity levels. The visually impaired oriented case study was carried out for evaluating our proposal.

As revealed by the outcome of user study, path description filled with accessibility semantics could be effective in improving the visually impaired mobility significantly, also the simply designed user interaction for gaining access to path information have received a good acceptability. These results demonstrated the potential of application in fine-grained indoor navigation.

This work also indicated the significance of various accessibility semantics for the visually impaired with a subjective rating system, which is capable to provide valuable reference for the design of mobile service for the visually impaired as well as sharing semantics of our physical surrounding to provide assistance for their

mobility.

With the limited visual cognition, the visually impaired encounter massive challenge while indoor exploring and thus require greater accessibility semantics for reference. This motivates us to set our experiment as being visually impaired oriented. However, it is noteworthy that in addition to the visually impaired, as it necessitated reference information on the real physical environment about obstacle, barrier-free assistance, etc, which could largely effect on the path selection for robotic device as well. Our proposal is also capable to bring benefits to such as robotic device.

At present, the accessibility semantics involved in the model of our work is restored manually. The process resulted in low efficiencies for a large amount of time and labor inefficient. On the other hand, in view of the new trends represented by Crowdsourcing [76] and Volunteered Geographic Information (VGI) [77], collaborative efforts are possible to provide a considerable means to collect and share these sorts of location-based information.

Last but not least, sighted people intent on assisting the visually impaired navigation are often couple with a lack of knowledge and understanding as how to navigate blind people. This proposed model and evaluation result also can be taken as a reference of data structuring for nowadays emerging social computation of crowdsourcing to collaboratively share our surrounding.

Chapter 4

Elevator Control Optimization : Vertical Mobility

In this chapter, elevator-centric vertical mobility improvement is elaborated. Firstly, the mobility issue with the elevator will be analyzed in detail. Then, the overall optimization based on hardware development, system architecture will be suggested. Finally, two recommended system implementations: PrecaElevator and Intellevator will be explained in brief. The specifics of the suggested systems will be elaborated in the following chapters.

4.1 Introduction

In the indoor mobility platform, elevator plays an essential role in the overall mobility platform, and functions an intersection node to connect the horizontal and vertical dimension. It acts as a means of transport with the following characteristics.

- The status is subject to dynamical changes;
 - Distinct from escalator, user interfaces are equipped for passengers to operate.
- The particulars on input and output of the system will be introduced in the

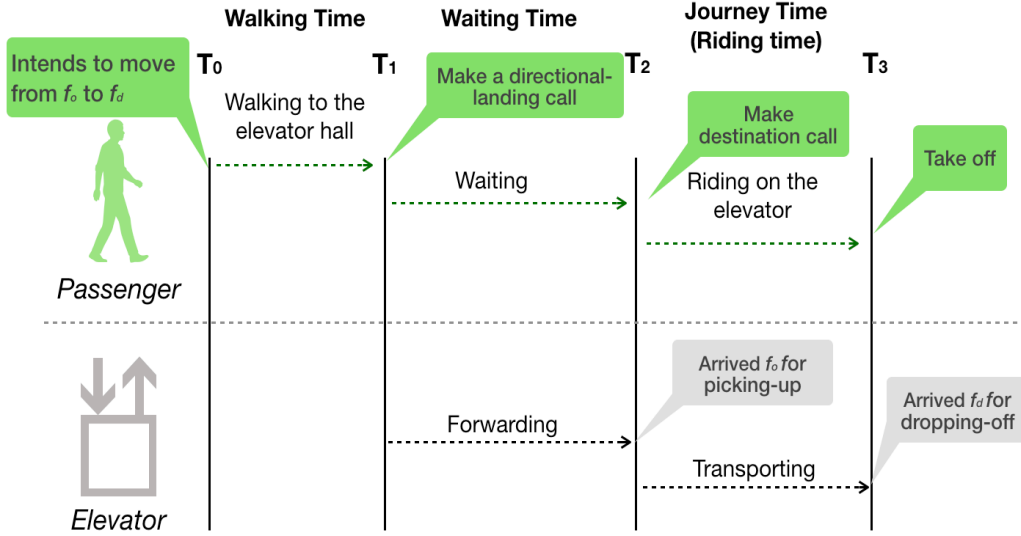


Figure 4.1: The state transition on the elevator using

following section.

A conventional elevator control system consists of hall call buttons that are situated on each floor, destination call buttons fixed inside cabin, and a controller [3]. In a generic usage scenario, as illustrated in Figure 4.1, when passengers intend to travel from one floor (f_o) to another (f_d) by taking elevator, he/she firstly should walk to approach the elevator hall, then press directional button (upward or downward) to make a landing call. Afterwards, elevator controller identifies the landing call and forwards to pick up, finally terminates at the requested floor if the current direction matched the requested one.

After passengers get into the elevator cabin and pressed the destination floor button, the elevator would start to transport the passenger and stop at the destination floor if current direction is the same as the one of landing call for pick off.

Accroding to the above-described usage procedure, several time concepts could be defined as foolows:

- $T_{walking}$: The elapsed time ($T_0 \sim T_1$) for passenger getting to the elevator hall;
- $T_{waiting}$: The elapsed time ($T_1 \sim T_2$) for passenger waiting for elevator to arrive, which is equivalent to elevator's forwarding time;
- T_{riding} : The elapsed time ($T_2 \sim T_3$) for passenger riding on the elevator cabin, which is equivalent to elevator's transporting time;

As described in Chapter 2, a plenty of previous works have been undertaken attempts to enhance elevators scheduling performance by optimizing several relevant criteria of time, for instance, AWT (the average waiting time), AJT (the average journey time), AST (the sum of AWT and AJT), the LWT% (the long waiting time percentage of calls), etc [57]. As revealed by psychology research, passengers tend to attach more importance to the waiting time for elevator to arrive than the time spent inside the cabin. Therefore, the AWT is treated as the most commonly used criteria for optimizing the scheduling of elevator [57, 78].

4.2 Problem Definition

The current situation of elevator usage gives rise to an issue that elevator is incapable to know about the passengers' destination floor information while passengers wait for its arrival. The uncertainty regarding the precise destinations of passengers in wait have substantially constrained scheduling efficiency for the elevator [3]. Moreover, the existing interface design also causes a adverse effect on user experience as passengers are required to press the destination button additionally after entry into the elevator.

Elevator, functioning as a vertical transport facility, remains stand-alone from the communication infrastructure in the building and thus needs to be made more

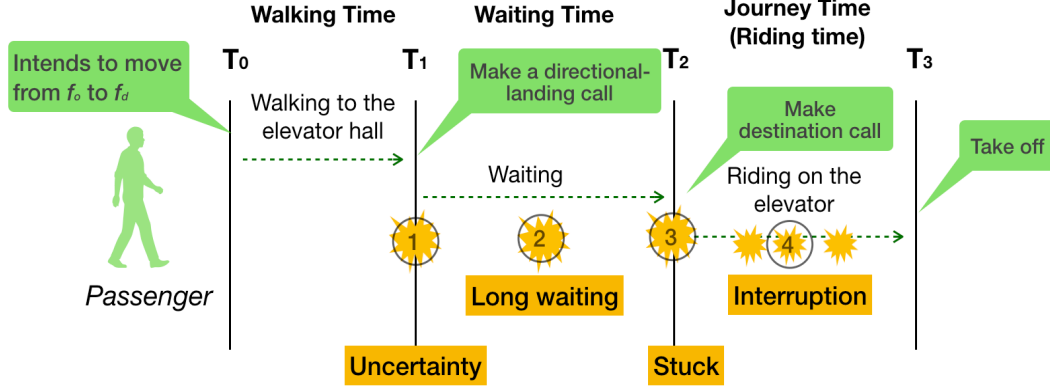


Figure 4.2: Illustration of negative user experience of using the elevator

easily accessible. As indicated by Figure 4.1, prior to the elevator system being initiated by the directional button, it is incapable to be context aware in the external environment, which would restrict the scheduling flexibility and intelligence significantly, thus leading to the long waiting and the further frustration for passengers. The problem remains unresolved qualitatively for decades.

As shown by IBM's survey of Smarter Buildings Study [33], the result obtained from investigation and calculation on the 6,486 office workers in 16 U.S. cities, an aggregate amount of as long as over 92 years was spent on waiting for the elevators in 2009. According to the elevator-related investigation in Future Design [34] as high as almost 80 percents of subjects (totally 1030) admitted that the waiting time on the elevator is long and need to be reduced, indicating the inefficiency of elevator system. Moreover, the problem is constantly evolving and the challenges to be faced are growing as the height of buildings is on the rise [35].

Besides, as a device designed to offer user-oriented service, little of the previous work paid attention to the user experiences, which is primarily attributed to the user interface (UI) design. Apart from the basic functionalities, the elevator system is faced with the challenges arising from the new emotional and psychological requirements. In this research, we have summarized a number of factors

contributing to negative user experiences for passengers as follows:

1. **Uncertainty for elevator to arrive.** marked with ① in Figure 4.2. A lack of information supports, such as the real-time waiting time, elevator position, situation inside of the cabin, or even any other moving plan could be taken into account;
2. **Long waiting time,** marked with ② in Figure 4.2. Particularly, while in the high-rise office building, the commercial passengers may expect an efficient vertical journey to save their valuable time.
3. **People being stuck,** marked with ③ in Figure 4.2. Such as the case of crowded cabin with no space for riding-on;
4. **Interruption,** marked with ④ in Figure 4.2. While taking ride on the elevator cabin and heading to the destination, the movement would be subject to interruption by the external request without notice; Especially, when the cabin is overly crowded for passengers to take, the constant disrupted request from the outside will exacerbate the situation.

Both the low time efficiency and negative passenger experience were closely associated with the architecture of elevator system. Passenger experience represents a realistic human-machine-interface problem that necessitates not only advanced in the machine technology but an understanding of human behavior along with the interaction between the two. In order to achieving the goal of optimizing the vertical mobility on elevator system, the local optimization on a standalone elevator is inadequate.

Passenger experience is not a single specific technology or component can figure out, yet the combination of multiple system fields affecting the overall experience of individuals and group. The elevator, building ecosystem and approaching traffic

distribution ought to be integrated and adaptively computed depending on the actual situations.

With regard to smart building, the capability of the elevator system incorporated into context aware platform of the entire building framework could be enhanced by making use of the high-performance computation clusters. Thus, elevator would be capable of accomplishing the tasks, for instance, detecting the crowd waiting outside the elevator, with consideration given to the events being held at the specific floor, or making prediction of moving objects' intention for riding, such as automatic generation call for an authorized robotic device, and the likes, thus enabling context aware scheduling for efficiency and intelligence of the vertical mobility.

4.3 Proposed Overall Architecture

In this section, the overall architecture will be introduced in detail. As indicated in Figure 4.3, **the overall architecture is premised on a combination of IoT-enabling development, agent server-based architecture and novel user interface design.** The detail of each single part will be introduced in the following sections.

- Hardware embedded architecture for enabling IoT technology on a traditional elevator.
- Agent server design to improve computational capability through integration with the external environment. The agent server enables the elevator to integrate with context aware platform, for example, the localization platform or IoT sensory platform for pro-actively automation inside the building, mobility computation and planning infrastructure for robotic devices, etc.
- Novel elevator system design.

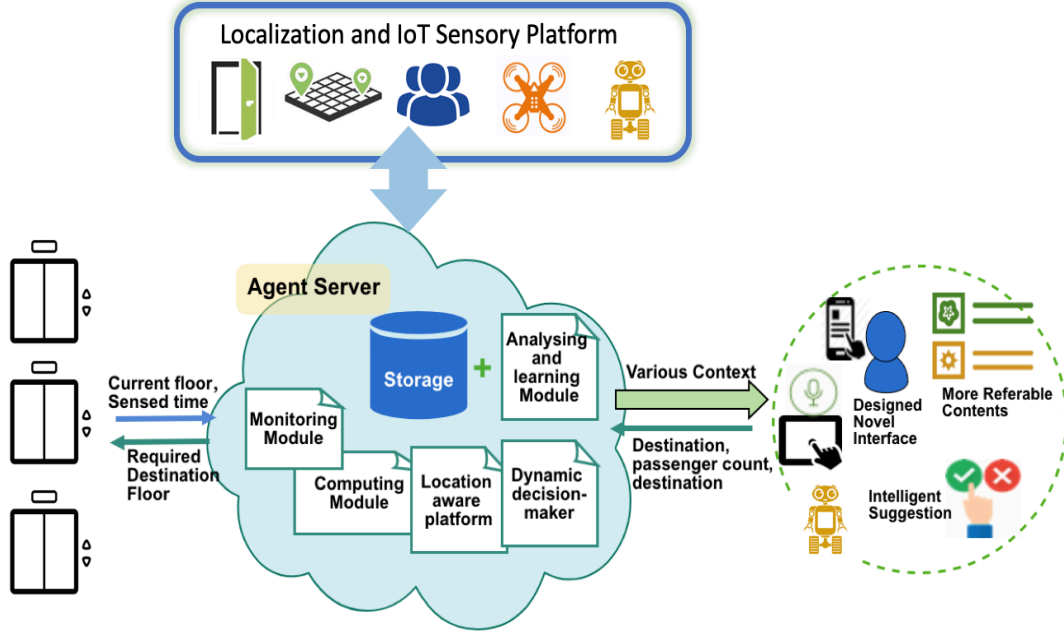


Figure 4.3: The overall architecture for the elevator-centric vertical mobility optimization

4.3.1 IoT-Enabling Development on Elevator

Figure 4.4 shows the overall development to IoT-enable a conventional elevator. As illustrated in Figure 4.4 (A), the basic components of a conventional elevator consist of a control unit with inputs from the landing call buttons (directional buttons of upward or downward which equipped at each floor) and destination call buttons (floor buttons inside the elevator cabin); further, the output device of the current position monitor shows the current elevator position.

While focusing on the I/O design on the control unit, the output signal could be considered as the one that real-time output from a single sensor with the data structure of current position and sensed time; the input from both landing call buttons and destination call buttons could be integrated as the stop requested floors. Based on this consideration, We embedded I/O device and central process

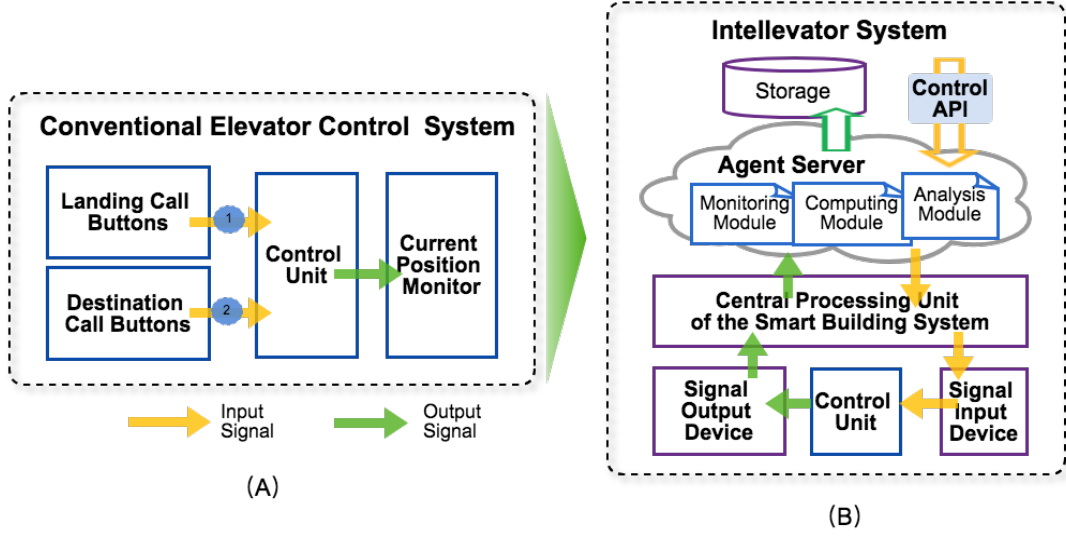


Figure 4.4: Figure shows how to IoT-enabling on elevator

unit to develop the IoT technology for the elevator as illustrated in Figure 4.4 (B).

We utilized a signal input device to replace both the landing call buttons and destination call buttons; a signal output device to capture the current floor information. The input and output signals were processed by the central processing unit that computes other contexts from heterogeneous devices or sensors of the whole building, such as the status of light, temperature, and humidity.

We experimented IoT-enabling technology on a real elevator in the Daiwa Ubiquitous Research Building in the University of Tokyo, which has 5 floors, including B2F, B1F, 1F, 2F, 3F. This research building is designed as a smart building that multiple devices such as light, air conditioner, smart meter, have been enabled to be accessed by the designed web API.

The elevator system inside the building is a normal and conventional one, with one shaft and a single car, produced by HITACHI Co., Ltd. The parameters of the elevators are shown in Table 4.1. As the height of floors is 5m and the elevator moves by the uniform speed of 60 (m/min), thus the moving time (T_m) between

Parameter	Value
Series Number	P-11-CO60
Capacity of Passengers(persons)	11
Capacity of Loaded(kg)	750
Cabin Size(cm)	140×135
Uniform Speed(m/min)	60
Width of the Door (cm)	80
Motor Power(Kw/h)	4.6

Table 4.1: Parameters of the elevator

two floors assigned as 5s.

Figure 4.5 shows the hardware development for IoT enabling of the elevator. The platform operates on the U00B0021-02-CPU board, i.e., the T-Engine Reference Board¹. The SN-4008-STT input terminal block and SN-4016-RT output terminal block are used for receiving the output signals from and submitting the input signals to the elevator controller, respectively.²

The output and input signals to the terminal blocks are listed in Table 4.2. It is worthy to note that the signal input of destination buttons inside cabin are not necessary to be API-enabled. Because the signal input of landing calls at each floor, composed by the information both of the requested floor and requested direction is enough for scheduling computing.

The control API in this work was designed based on RESTful API, that has been applied for a plenty of previous works [79, 80, 81]. Elevator’s current position is real-time sensed, and is structured and stored by the data vector of the (floor,

¹U00B0021-02-CPU was a T-Engine Reference Board certified by by T-engine Forum as Target Board for T-Kernel 2.0 (<http://www.t-engine4u.com/en/>), with ARM 11 Core 500MHz.

²SN-4008-STT is an 8 point NPN input terminal block, SN-4016-RT is a 16 point NPN output terminal block, provided by ONTEC CO., LTD (<https://www.ontec.co.jp/>)

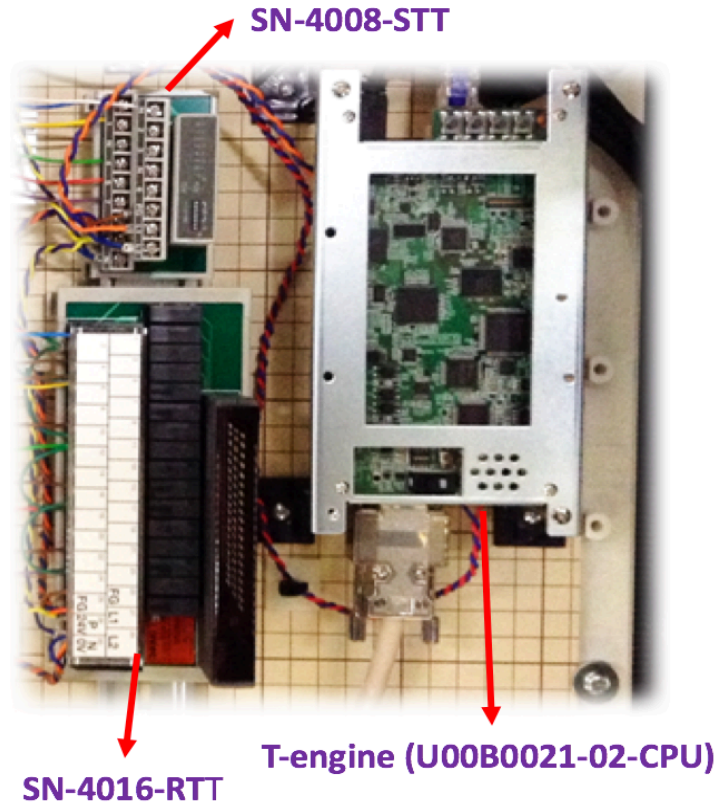


Figure 4.5: Hardware development for IoT-enabling

Hardware	Connected signal
SN-4008-STT	B2F, B1F, 1F, 2F, 3F
SN-4016-RT	3F_down, 2F_up, 2F_down,1F_up, 1F_down,B1F_up, B1F_down, B2F_up

Table 4.2: Input and output of signals on IoT-enabling development

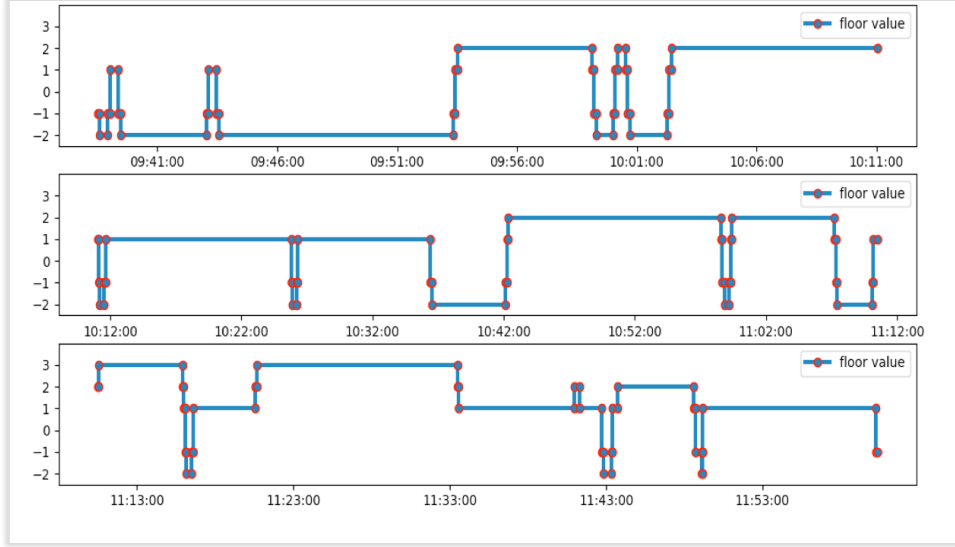


Figure 4.6: Real-time monitoring on elevator moving after IoT-enabling

sensed time), for a real example (3, 2017-1-30 09:37:03). Thus, the elevator's real-time moving could be monitored and visualized. Figure 4.6 shows the visualization of elevator-moving during 2 hours. The control command on the elevator was structured by two endpoints: `id` and `value`, for the example of `elevator_id` and `destination_floor`.

This embedded hardware architecture design of IoT-enabling is applicable and feasible for a conventional elevator since only control unit centered development required with no extra off-line hardware equipment needed at each floor, thus achieving the goal of minimum cost and effort on hardware update and also maintain the potentials of increasing computational capability by the agent server design.

4.3.2 Agent-based Architecture

An agent server was designed for enhancing the computational capability on the elevator by integrating with other context aware platform. Context awareness is a core feature for ubiquitous computing systems [82]. After IoT-enabling devel-

Context	Value Examples
Upward Requests	[2, +1], [3,-1]
Downward Requests	[1, -5]
Inside People Count	4
Current Floor	2
Current Moving Direction	up
Sensed Time	2018-03-07 14:57:51
Previous Floor	1
Previous_Sensed Time	2018-03-07 14:57:46
Current Status	Moving Upward
e.g., the departure floor	1
Waiting time	35s

Table 4.3: Real-time elevator-related context provided by the agent server

opment, fine-grained context on the elevator could be detected. Table 4.3 shows an example of the fine-grained structured context in real-time.

The status is iteratively calculated by the previous floor, current floor as well as the sensed time. If the time duration was beyond a certain time value, the value of current status is set as "Waiting", otherwise, the value is "Moving Upward" or "Moving Downward", in which the direction is calculated by the previous place and current place.

"Upward Requests" and "Downward Requests" show the floor requested to be terminated at the upward or downward direction. The respond value was structured as data vector of floor id and people count. As table 4.3 shows, the data example [2, +1] in Upward request states there is a terminate request at 2nd floor with 1 passenger riding on. Similarly, the data example [1, -5] in Downward request shows there is a terminate request at 1st floor with 5 passenger taking off. The "Inside people count" indicates the current people count inside the elevator cabin.

Real-time Waiting Time Calculation

The waiting time for arrival at the departure floor f_β also could be real-time calculated. The below Equation 4.1 shows the detail of real time waiting time calculation.

$TW(x) =$

$$\begin{cases} TS(f_c, f_x), & \text{if } MD_c = MD(f_c \rightarrow f_x) \\ TS(f_c, f_\mu) + TS(f_\mu, f_\nu) + TS(f_\nu, f_x), & \text{if } MD_c \text{ is } DOWN \text{ and } MD(f_c \rightarrow f_x) \text{ is } UP \\ TS(f_c, f_\nu) + TS(f_\nu, f_\mu) + TS(f_\mu, f_x), & \text{if } MD_c \text{ is } UP \text{ and } MD(f_c \rightarrow f_x) \text{ is } DOWN \end{cases} \quad (4.1)$$

$TW(x)$ denotes the real waiting time at x -th floor. f_c denotes the elevator currently located floor. $\mathcal{F}_n = \{f_1, \dots, f_{n-1}\}$ issues the list of n floors inside building, sorted by low to high with the data type is Integer.

As the Equation 4.1 states, the $TW(x)$ is computed based on the elevator's current Moving Direction (MD_c) and the absolute Moving Direction of elevator came from current floor to x -th floor, showed by $MD(f_c \rightarrow f_x)$. If MD_c opposites to $MD(f_c \rightarrow f_x)$, $TW(x)$ was separated to three sub time duration, since elevator would keep the current moving direction till to arriving f_μ or f_ν to firstly relieve the tasks which based on current move direction. f_ν means the highest floor in the Upward request, and f_μ means the lowest floor in the Down request.

The Algorithm 2 shows the details of calculation of the sub time duration $TS(f_\alpha, f_\beta)$ based on the Moving Direction from α -th floor to β -th floor, and the real-time context of UpwardRequest or DownRequest between the moving. where

$$requestedList = \begin{cases} UpwardRequests & Index_m > 0 \\ DownwardRequests & \text{otherwise} \end{cases} \quad (4.2)$$

Algorithm 2: Calculation of sub moving Time (TS) from $\alpha - th$ floor to $\beta - th$ floor

Input: f_α, f_β

Output: The sub moving time(TS) gets assigned

- 1 Calculate FN_t (number of terminated floors), and FN_m (number of moved floor)
 - 2 Initialization: $FN_t = 0$;
 - 3 Compute index of moving $Index_m$,
 $Index_m = \beta - \alpha$
 - 4 Assign the *requestedList* based on $Index_m$, as Equation 4.2 shows
 - 5 for each floor node i in *requestList*
 if $i > \alpha$ and $i < \beta$, then $FN_t ++$
 - 6 Calculate sub time duration as Equation 4.4 shows
-

$$T_t = FN_t \times T_boarding \quad (4.3)$$

T_t denotes the terminating time between $\alpha - th$ floor to $\beta - th$ floor. Here, we abstracted the terminating time as the multiplication of terminating floor numbers which calculated in 5 of Algorithm 2 and $T_boarding$ represented as the average boarding time to board elevator.

$$TS = T_t + T_m \quad (4.4)$$

In addition, as Equation 4.4 shows, the sub waiting time TS is the sum of the time of elevator moving and the time of elevator terminating. The value of TS will be assigned to equation 4.1 to predict the waiting time for elevator's arrival based on the current elevator position, and requested floors.

4.3.3 Novel Elevator System Design

Subsequent to IoT-enabling development and real-time context aware on the agent server, the elevator has the capability of integration with the external environment. Thus, novel elevator system could be designed for complying with the requirements as follows:

(1) firstly, to perform the basic function of receiving the transportation needs from passengers; (2) secondly, to enhance the efficiency and intelligence on elevator system to provide assistance with indoor vertical mobility. The proposed system provides more supportive information about elevator usage, as well as intelligent vertical moving advice taken into account for improvement made to time-efficiency or user experience.

In this research, two novel elevator systems were proposed: PrecaElevator and Intellevator to meet the above goals. The details on each proposed system will be explained in the following chapters, respectively.

4.4 Summary

In this chapter, analysis of the vertical mobility issues with the use of elevator has been conducted. In order to achieve context-awaring in the external environment for vertical mobility optimization, an overall architecture was proposed to promote IoT-enabling development on a traditional elevator and further to enhance the computation capability for elevator system. On the agent server, the elevator-related context including the real-time waiting time at each floor could be extracted for end users to visualize it. In accordance with this overall architecture, we will introduce two proposed end-user oriented elevator systems: PrecaElevator and Intellevator, that will be presented in the following chapters, respectively.

Chapter 5

Proposed System: PrecaElevator

In this chapter, one of our proposed elevator systems named PrecaElevator will be introduced in detail. Firstly, an overall introduction of this proposal will be made. Then, the system structure premised on the location awareness via integration with BLE-localization platform will be suggested. Next, the novel end-user-centric system design will be proposed. Afterwards, how the proposal is assessed will be explained in detail. Finally, a summary will be made at the end of the chapter.

5.1 Introduction

Elevator system faces a serious of challenges arising from reducing waiting time for passengers due to the constraints on computation by the stand-alone elevator system. We present our proposal – PrecaElevator, a novel elevator system applied to smart building that enables passengers to reduce their waiting time by means of pre-registration of elevator calls.

As explained in chapter 4, after a traditional elevator is upgraded to be Internet of Things (IoT)-enabled and the real-time computational capability is transferred to the agent server, the elevator is upgraded to be a smart object capable of computation on context awareness in both elevator and passengers.

With BLE-based localization of the passenger leveraged, PrecalElevator allows passengers to make pre-registration with elevator call if his/her location can be identified within the callable range for elevator control. Based on the context awareness on both the elevator and passengers, a user-centric application is designed, facilitating the intelligence that passengers' remote controllable range is dynamically scoped and visualized in real-time.

An experiment of the proposed system was conducted in the real smart building environment. The effectiveness has been validated by performing simulations based on the learning of waiting time from the historical data over five months, exhibiting the substantial potentials for reduction in waiting time for passengers.

Differentiate with the previous works, in this proposal, attempt was made to realize pre-registration of elevator call through the utilization of the context aware platform on the agent server with no addition of off-line sensors. Therefore, the lowest cost of hardware development and enhanced flexibility were made possible.

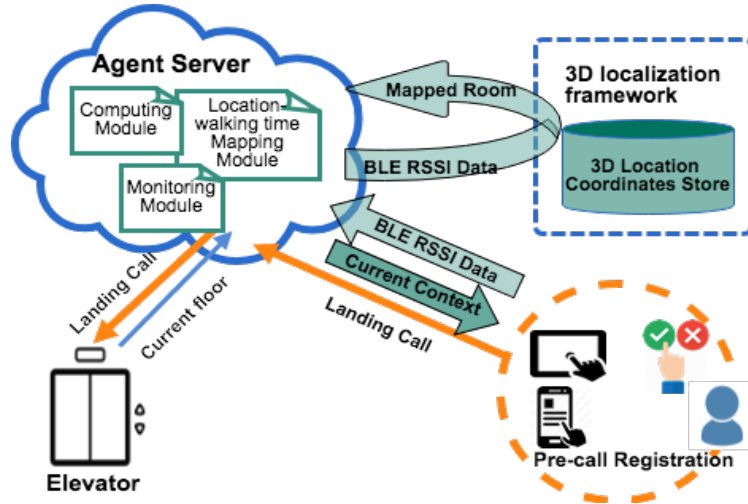


Figure 5.1: The system structure of PrecalElevator

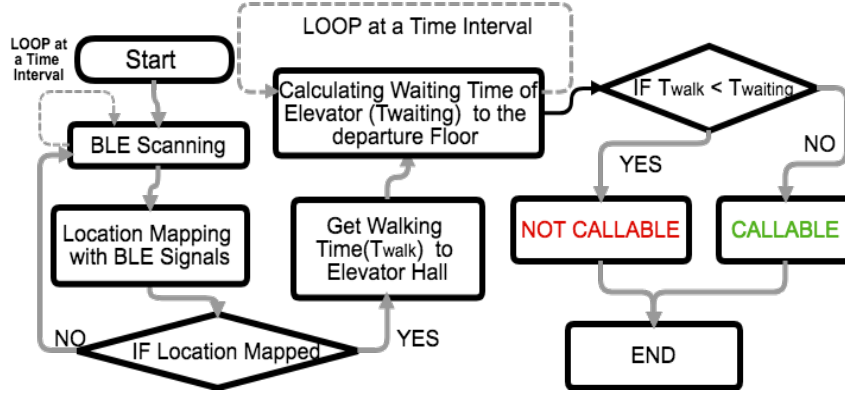


Figure 5.2: The flow chart of the PrecaElevator system

5.2 Proposal

5.2.1 System Architecture

The system architecture of PrecaElevator is presented in Figure 5.1. According to this approach, the Bluetooth Low Energy (BLE) beacon-based localization framework is leveraged to identify passengers' location at room-level. Thus, the agent server is made capable of real-time monitoring for the positions of the passengers and elevator and mapping both the corresponding time of arrival at the elevator hall. Finally, the callable range of elevator is adaptively adjusted and the intelligence on the map-based interface is delivered. The details of individual components will be presented in the following subsections.

5.2.2 BLE-based Indoor Localization Platform

With regard to the trade-off between robustness, coverage, proximity and computation overhead, the Bluetooth Low Energy (BLE)-based beacon technology was chosen for identifying location, with the last emerging localization method that being currently available on the modern mobile devices [83].

To undertake the challenge of location awareness of passengers, an unsupervised method of BLE beacon-based 3D localization framework was adopted. Thus, mobile devices are capable to recognize the locations of elevator hall accurately with low computation complexity. As the system flow showed in Figure 5.2, BLE fingerprints, i.e. RSSI (Received Signal Strength Indication) signals are utilized for the location computing and thus the walking time (T_{walk}) to arrive at the elevator hall were mapped as well. The Figure 5.3 shows the detail of localization. The unsupervised location awareness framework, therefore, has three key steps listed as follow:

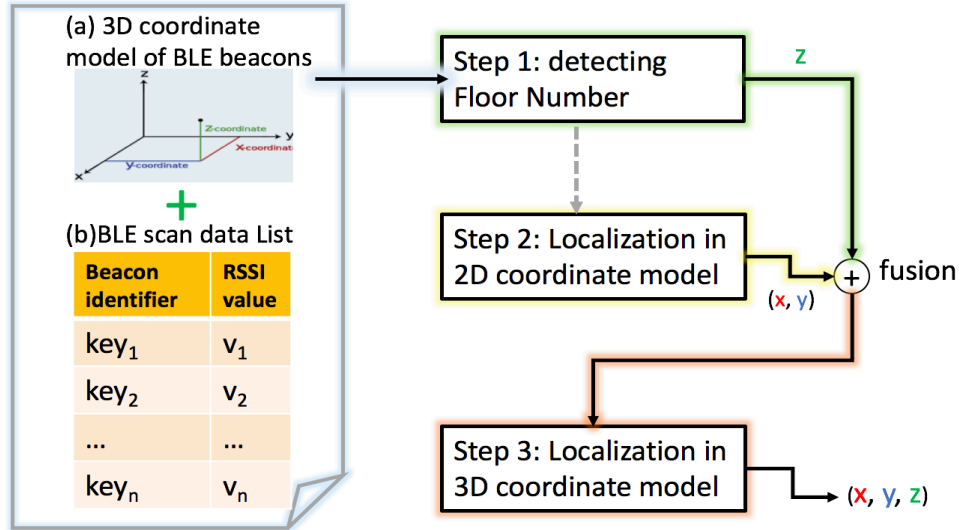


Figure 5.3: Illustration of 3D BLE-beacon based localization method

The Spatial Coordinate Model of 3D-deployed BLE Beacons

A 3D spatial model was used for structuring beacons that formatted by a 3d matrix. The 3D spatial model is shaped by (x, y, z) with z representing the floor number; x, y representing the matrix mapping structure of the 2D floor plan. As the example shown in Figure 5.4, the 2D floor plan was structured by the grid model, represented as: Coordinates = $[C_1, C_2, \dots, C_z]$, where:

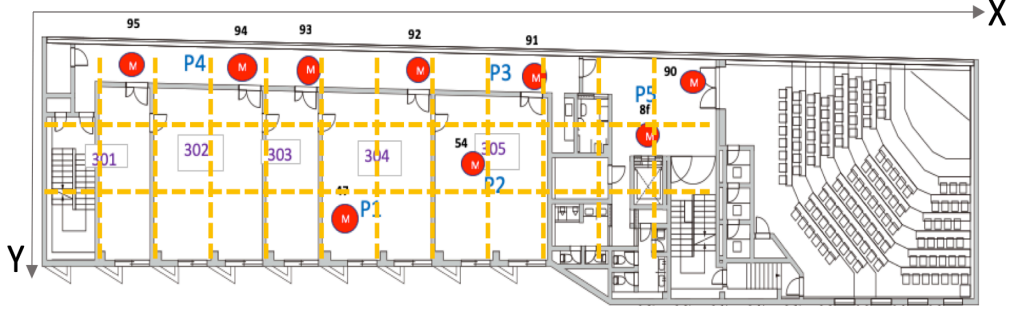


Figure 5.4: Matrix mapping for coordinating the BLE beacons

$$C_z = \begin{bmatrix} c_{1,1} & c_{1,2} & \dots & c_{1,y} \\ c_{2,1} & c_{2,2} & \dots & c_{2,y} \\ \vdots & \vdots & \ddots & \vdots \\ c_{x,1} & c_{x,2} & \dots & c_{x,y} \end{bmatrix} \quad (5.1)$$

RSSI measurements for Localization

Based on bluetooth beacon signal propagation, the distance between the device and the BLE beacon can be derived using a path loss model in [84], which can be expressed as:

$$R_k^i = R^0 - 10\gamma \log(d_k^i/d^0) \quad (5.2)$$

where R_k^i is the RSSI value of the i-th BLE beacon, R^0 is the reference RSSI value at 1m distance, γ is the path loss exponent, d_k^i is the distance between the device and the i-th BLE beacon, d^0 equals to 1m. Thus, based on the above path loss model, then the distance d_k^i can be derived as:

$$d_k^i = 10^{(R^0 - R_k^i)/10\gamma} \quad (5.3)$$

Based on the above RSSI matrix model as well as the distance computation equation, the corresponding distance matrix: $Distance_{x,y}$ spatially mapping to the

beacons in a single floor could be modeled as:

$$Distance_{x,y} = \begin{bmatrix} d_{1,1} & d_{1,2} & & d_{1,y} \\ d_{2,1} & d_{2,2} & & d_{2,y} \\ d_{x,1} & d_{x,2} & & d_{x,y} \end{bmatrix} \quad (5.4)$$

where the $d_{x,y}$ would be assigned if the RSSI from the corresponding beacon was received.

Position estimations in 3D environment

The unknown coordinates of the target position located in the 2d coordinate model is denoted as $C_{x_t, y_t} \in C^{x \times y}$, and the Euclidean distance $d_{x,y}$ between the beacon and the target position in the real phenomenon is subjected to the below equation 5.5, where the $\hat{\phi}$ represents the attenuation depending on the real floorplan information includes the doors, walls, and corridors. Thus based on the equation 5.4 and 5.5, for each $d_{x,y}$, there is a corresponding weighting 3d matrix constructed based on 2d matrix, listed as: Weightings = $[w_1, w_2, \dots, w_z]$, where w_z showed as Equation 5.6 with the weighting value was assigned from 0 to 1.

$$\sqrt{(x_t - x_b)^2 + (y_t - y_b)^2} = \hat{\phi} d_{x_b, y_b} \quad (5.5)$$

$$W_z = \begin{bmatrix} w_{1,1} & w_{1,2} & & w_{1,y} \\ w_{2,1} & w_{2,2} & & w_{2,y} \\ w_{x,1} & w_{x,2} & & w_{x,y} \end{bmatrix} \quad (5.6)$$

The below equation 5.7 was used for determining the 2d coordinate (x, y) of the target position. Meanwhile, based on the equation 5.8 used for determining the vertical coordinate z, the 3d coordinate of the target position will be output. Figure 5.5 illustrates the computation flow on a location detection based the proposed method.

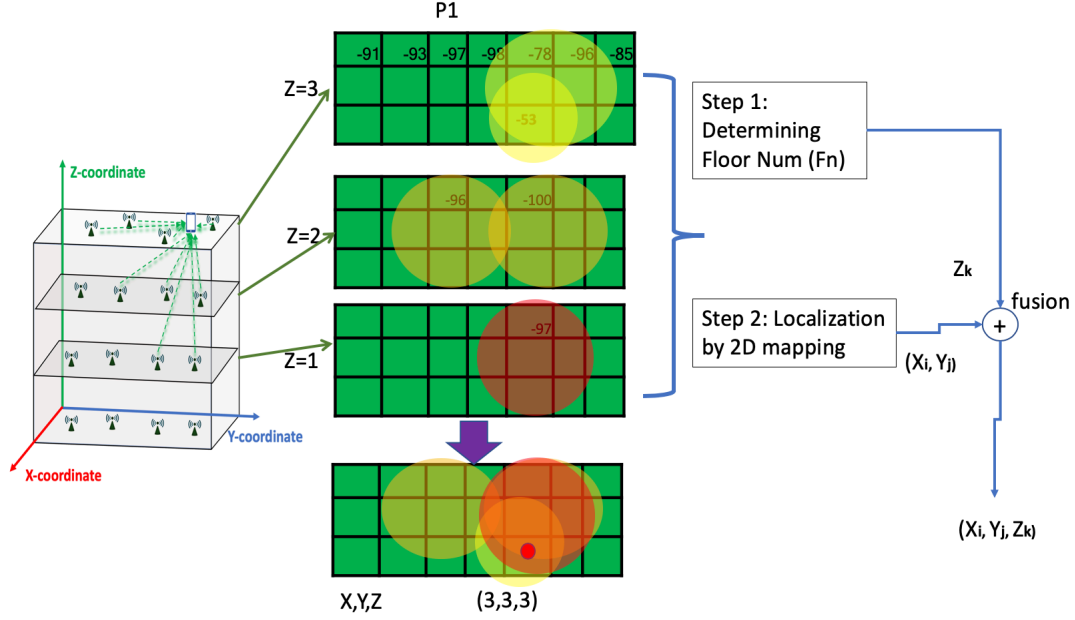


Figure 5.5: The example shows computation flow of a BLE beacon based localization for P1 place

$$c(\hat{x}_t, \hat{y}_t) = \arg \max_{C^{x \times y}} \sum_{i=1, j=1, k=1}^{x, y, z} w_{x, y} \quad (5.7)$$

$$f_z = \arg \max_{z \in Z} \sum_{i=1, j=1}^{x, y} Distance_{x, y} \quad (5.8)$$

5.2.3 End-user Centric System Design

Further with the BLE beacon-based room-level localization, an end-user centric system was developed. Figure 5.6 reveals the interface comparison performed of the status regarding whether it is callable or not for the passengers locating in different rooms in 3F floor. The designed novel interface promotes the intelligence of dynamic computation for the accessible range of the elevator control. The current place of elevator is presented in real-time, and the statuses of callable or not

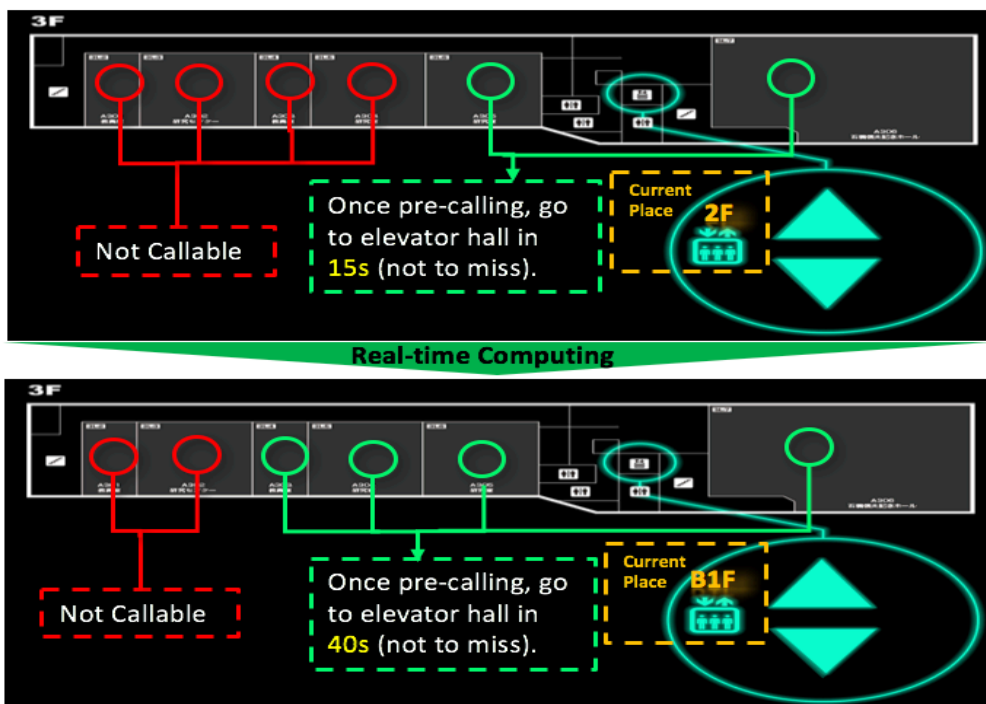



Figure 5.6: Example of real time computing for pre-call

for the room-level locations are dynamically visualized on the floor map.

The red circle signifies that the passengers located in these rooms currently are banned from pre-registration of elevator call, as the elevator is considered as arriving ahead of the passenger, and excess calls with no ride by anyone will cause the scheduling efficiency of elevator to decline. In contrast, passengers located in the rooms with green circle are allowed to register call on the elevator as they are regarded as arriving before the elevator does. Besides, call pre-registration will reduce their waiting time.

5.3 Evaluation

5.3.1 BLE-based Localization Estimation

We deployed totally 41 BLE beacons in the building. As presented in Figure 5.7, we deployed BLE beacons at each floor, respectively. The real place of BLE beacon equipped was marked as  with red color. The BLE location marker is called kokosil marker¹ with the frequency of 5Hz.

The proposed approach of room-level BLE beacon-based localization has been verified. We scanned 18 spots (marked as P1-P18 in Figure 5.7) in the building with the RSSI real scan data have been listed in the Figure 5.8. Three spots "P1", "P11", "P14" also have been visualized in the 3D environment for a better investigation. The circle mark represents the beacon in the 3D environment with the color shows the strength of RSSI: the darker color shows the stronger RSSI. The star mark shows the placed being predicted by localization method described above.

¹kokosil marker is a BLE-based location identifying marker (<http://kokosil.net/index.en.html>), provided by Ubiquitous Computing Technology Corporation (<https://www.uctec.com/en/>)



Figure 5.7: The deployment of BLE beacon inside the building

Id	Coord			B2F										B1F					1F					2F					3F																						
	X	Y	Z	6F	70	71	72	73	74	75	76	77	78	79	7A	7B	7C	7D	7E	7F	80	81	82	83	84	85	86	87	88	89	8A	8b	8c	8d	8e	8f	90	91	92	93	94	95	47	54							
P1	6	3	3																																																
P2	8	2	3																																																
P3	9	1	3																																																
P4	5	1	3																																																
P5	11	1	3																																																
P6	11	1	2																																																
P7	9	1	2																																																
P8	7	1	2																																																
P9	3	1	2																																																
P10	1	3	2.5																																																
P11	1	1	1										-91																																						
P12	4	1	1																																																
P13	8	1	1																																																
P14	11	1	1																																																
P15	11	1	-1																																																
P16	10	1	-1																																																
P17	11	1	-2																																																
P18	10	1	-2																																																

Figure 5.8: The real BLE RSSI values of 18 scanned places in the building

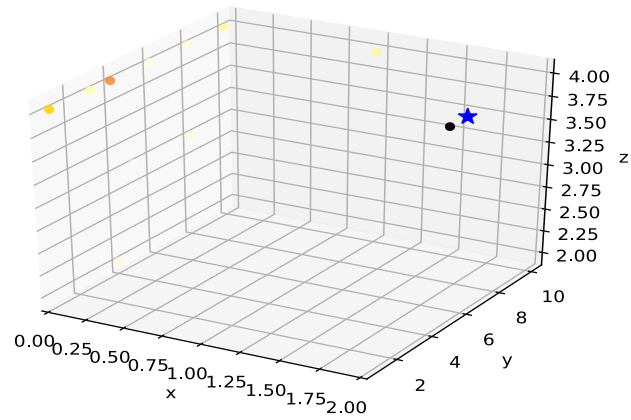


Figure 5.9: A visualization example shows the RSSI mapping of spot "p1"

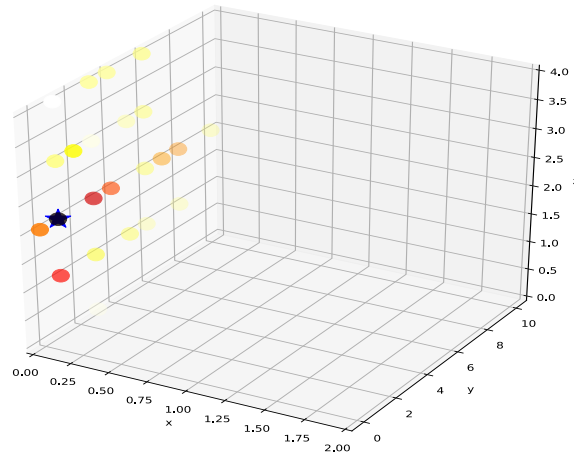


Figure 5.10: A visualization example shows the RSSI mapping of spot "p11"

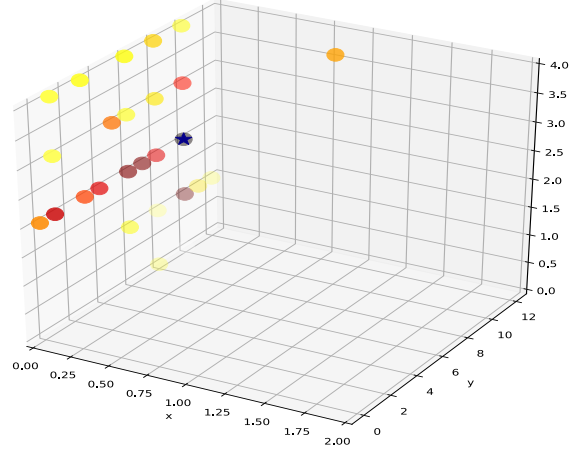


Figure 5.11: A visualization example shows the RSSI mapping of spot "p14"

5.3.2 Historical Waiting Time Calculation

Based on the real-time sensed position of the elevator, the states have been classified based on the time duration between the pre_sensed position and current position. After that, the continuous moving patterns, such as "waiting \rightarrow forwarding \rightarrow picking up", "transporting \rightarrow picking off \rightarrow waiting" on elevator have been abstracted by performing with finite state machine (FSMs) based on the states and conditions.

As shown in Figure 5.12, a graphical model of FSMs was used to implement the state transition recognition, with the parameters listed in table 5.1. We classified that the elevator has five different states, namely, the waiting (empty without any request), forwarding (moving to the landing call requested floor), picking up (picking up passengers), transporting (moving to destination floor), picking off (picking off passenger).

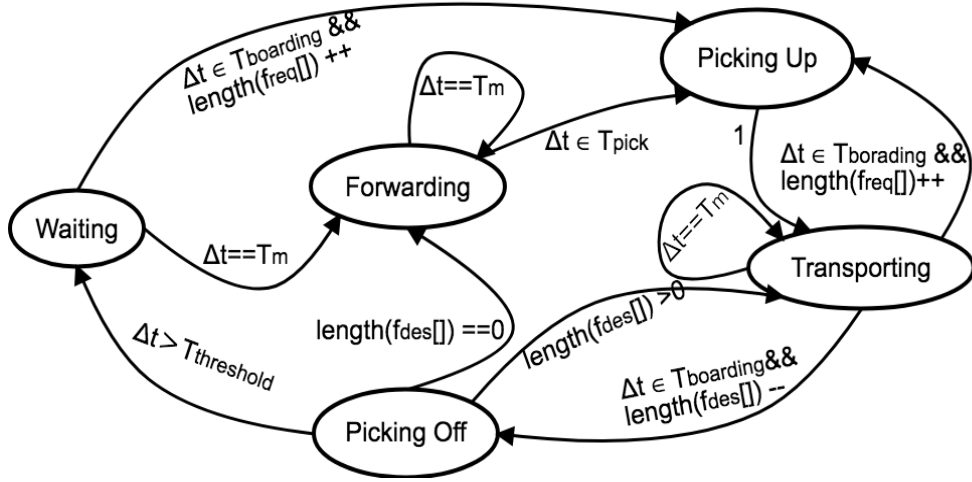


Figure 5.12: The FSM model for presenting the state transition of elevator

Table 5.1: Parameters of the FSM model

No.	Symbol	Feature description
1	$f_{req}[]$	the list of floor numbers requested to be stop for picking up
2	$f_{des}[]$	the list of destination floor numbers
3	Δt	the time duration after the last position detected
4	T_m	the constant time of moving between two floors
5	$T_{boarding}$	the boarding time for picking up or off passengers

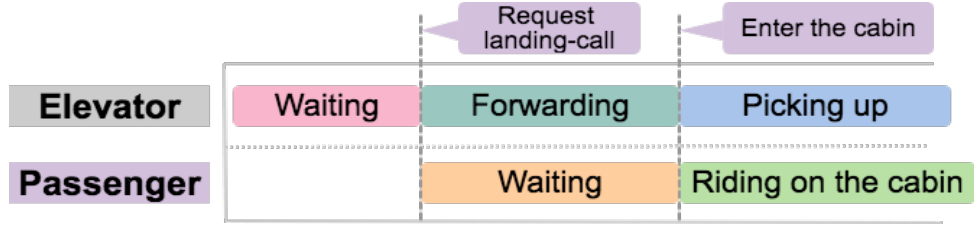


Figure 5.13: The state transitions of both the elevator and passenger

According to the predefined in-situation rules for the state transition of both the elevator and passenger, the time of elevator forwarding could be considered as the accurate reflection of passengers' waiting time. As Figure 5.13 shows, since the state change triggered by passengers' action of landing call request, while the elevator forwarding to pick up, the passengers remained at the state of waiting. Based on the above considerations, the state transition pattern on elevator of "waiting \rightarrow forwarding \rightarrow picking up" was selected to reflect the waiting time of passengers.

Result

We evaluated the effectiveness of this proposal based on the waiting time detection calculated from totally 23699 data vector records, spanning 121-days (from 2017.12.1 to 2018.3.31). Figure 5.14 shows the result of historical waiting time, the total amount waiting time is 58175 seconds with the average waiting time per passenger is 11.01 seconds (SD=0.28 s). PrecaElevator provides the possibility of zero-waiting time of calling an elevator on the basis that if the passenger pre-register the call for the elevator and arrived at the elevator hall at the same time that elevator reached.

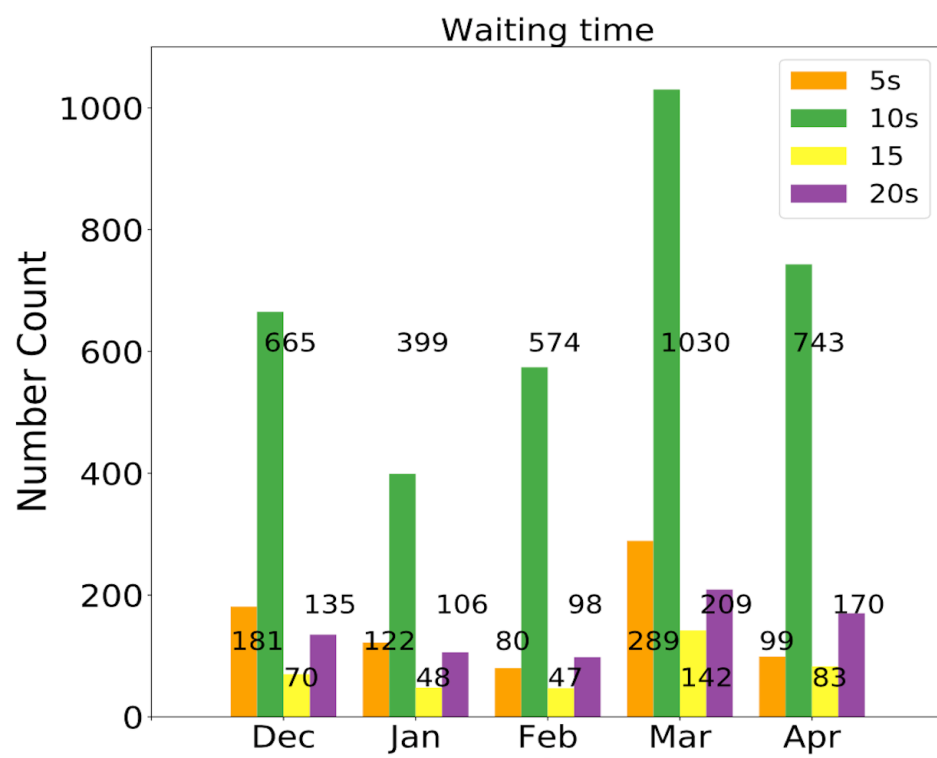


Figure 5.14: Simulation based on the real records of elevator

5.4 Summary

In this chapter, PrecaElevator : an elevator call pre-registration system to reduce passengers' waiting time is explained. The proposed system enables the elevator system to receive the passengers' intent in advance of the whole journey thus facilitating not only optimization of the performance of the machine but also improvement made to the passenger's experience.

To achieve the location awareness on the passenger side, BLE-based localization framework was proposed. In the experimentation, 41 beacons were deployed inside the research building, and the room-level localization was verified by our proposed BLE beacon-based localization method. The evaluation based on the pattern abstraction for the calculation of waiting time from elevator historical records demonstrated the effectiveness in reducing waiting time.

Chapter 6

Proposed System: Intellevator

In this chapter, another proposal called Intellevator : a context aware-based intelligent elevator system in smart building is elaborated. Firstly, an overall introduction of this proposal will be presented. Then, the method premised on traffic prediction and adaptive control will be explained in detail. The novel end-user interface design will be introduced as well. Afterwards, the evaluation comprised of user study and simulation will be elaborated in detail. Finally, the limitations and summary will be presented at the end of the chapter.

6.1 Introduction

Elevator system facilitates the building to be constructed into high-rise, and further promotes the process of urbanization development. Elevator system undertakes almost all vertical mobility tasks. Nevertheless, while in the high rise building and during peak-time, due to the following main factors: 1) the restricted elevator physical capacity; 2) Momentary increment that leads to the vertical traffic overload; 3) Internal mathematical optimization on the controller which achieves the limited performance improvement, the efficiency bottleneck issue always manifests itself.

Though, multi-car elevator (MCE) system has been deployed in the large-scale buildings, the problem of inefficient transport is constantly evolving and the challenges to be faced are increasing as the ever growing height of buildings [35], especially during the peak time, the current scheduling policies are faced with a significant bottlenecks that remain difficult to address.

Nevertheless, the trend of IoT and artificial intelligence techniques have given rise to a promising paradigm, and a more reasonable and intelligent elevator control system could be applied to improve the vertical mobility. Besides constant enhancements made to the controller of a stand-alone elevator, enhanced user experience is deemed necessary to enable passengers in a comfortable and Efficient way.

In this research, the Intellevator is proposed to improve the traffic time-efficiency premised on proactive traffic management. As shown in Figure 6.1, after calculating and predicting the fine-grained traffic distribution in real-time, the elevator system is optimized by proactive and adaptive traffic management. For passengers, time-efficient plans are possibly a mixed style transportation, involving elevator, escalator and stairs, which would be provided. Meanwhile, for elevator, intelligence on proactive management on traffic distribution based on dynamic control for efficiency improvement could be realized.

Besides, Intellevator is also proposed to improve end-user experience by presenting a more advanced means of information visualization, which features simplicity in operation, and intelligence for the end users. A novel user interface to call the elevator has been designed that the destination floor can be pre-entered and no further operation is required after entry into the elevator cabin. Moreover, suggestions to reduce both the passengers' waiting time and the total trip time are also provided and will bring benefits to both the passengers and elevator system by improving the vertical mobility.

The Intellevator was experimented through integration with a real conven-

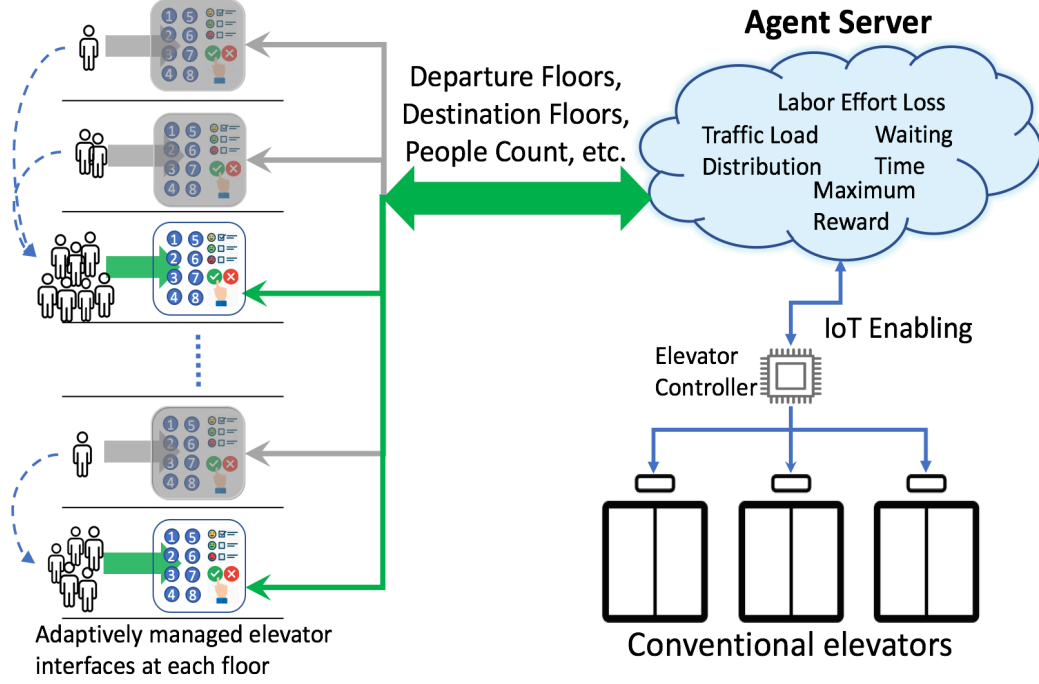


Figure 6.1: System architecture of the proposal

tional elevator and a 22-participants attended user study was conducted for evaluation. As revealed by the results, the system usability and user experience of the Intellevator is superior to that of the existing conventional elevator. Moreover, valuable feedbacks for advice making and context visualization have been collected, which will serve as an informed reference for the development of the future elevator system.

Additionally, the system performance was evaluated by a further simulation. The efficiency enhancement of Intellevator has been quantitatively validated. Moreover, the specific correlation between elevator environment setting and the optimization result has been determined as well. For instance, the overall floor numbers, elevator capacity, elevator cabin number and the optimization criteria, e.g., the average waiting time, the journey time as well as the labor effort which related to the physical health have been revealed quantitatively.

The key novelty of this research lies on the novel user interface enables the elevator system to be proactive in computation of the fine-grained traffic distribution at each single floor. While encountered with the congestion bottleneck, the system would be capable to proactive merge the traffic load with dynamical management of the user interface and provision of intelligent advice as guidance for the passengers to take a ride for pursuing time efficiency. Thus, for passengers, the recommended mixed efficient vertical transportation including stairs, elevator or escalator, could be considered reasonable for the goodness of both time-saving and physical health.

6.2 Proposal

In this proposal, there are several difficulties in improving the vertical mobility on the elevator system owing to two crucial challenges: (1). how to perceive the context of the external environment. The uncertainty of the number of passengers approaching or waiting and their precise destinations have limited the elevator scheduling efficiency substantially; (2) how to bridge the association between the dynamical environment and decisions; (3) how to feedback the decision to end-users in a practical and acceptable way.

6.2.1 System Architecture

Considering the above constraints on the elevator efficiency improvement, this paper provides a proposal that involves proactive and adaptive control of the traffic flow for enhancing the efficiency.

Figure 6.1 illustrates our basic idea of the system architecture. IoT-enabled elevator was developed to be accessible for remotely monitoring and control through the intranet of the building. An agent server was developed for dynamically per-

ceiving and computing with the external elevator environment, for instance, the waiting people count, their departures and destinations, etc.

Based on the real-time computation of the traffic flow, the agent server would take the decision on the target floor if the server detected superior vertical moving plan existed in the following phase. For passengers, the provided decision guides them to take a ride from other neighbor floor, thus reducing their waiting time, in addition to enhancing elevator efficiency.

We have already described the IoT-enabling development in Chapter 4. Based on IoT-enabled development, the proposed system -Intellevator is constructed by complying with the following requirements:

- Agent server design for improving computational capability that: (1) first, allows elevator system to make prediction of the approaching traffic flow comprised of passengers' origins and destinations (OD) on each floor, etc. (2) proactive and adaptive control on the traffic distribution to improve efficiency.
- A dynamic and intelligent user interface design. The interface was designed: (1) firstly, to satisfy the basic function needs of receiving the transportation requirement from passengers; (2) secondly, to retrieve the fine-grained traffic information (origin and destination of each passenger) for efficiency optimization (3) finally, to offer the real-time intelligent advice to end-users based on the proactive computation of the traffic flow by the agent server.

The agent server computes all the above dynamics for optimization. The agent server monitors and computes the fine-grained traffic load from all the floors in real-time. It consists of a peak-pattern detector and the Markov Decision Processor (MDP) for dynamically decision-making and a traffic load information store for dynamically and proactively computing.

Figure 6.2 describes the details of knowledge-driven adaptive computing mech-

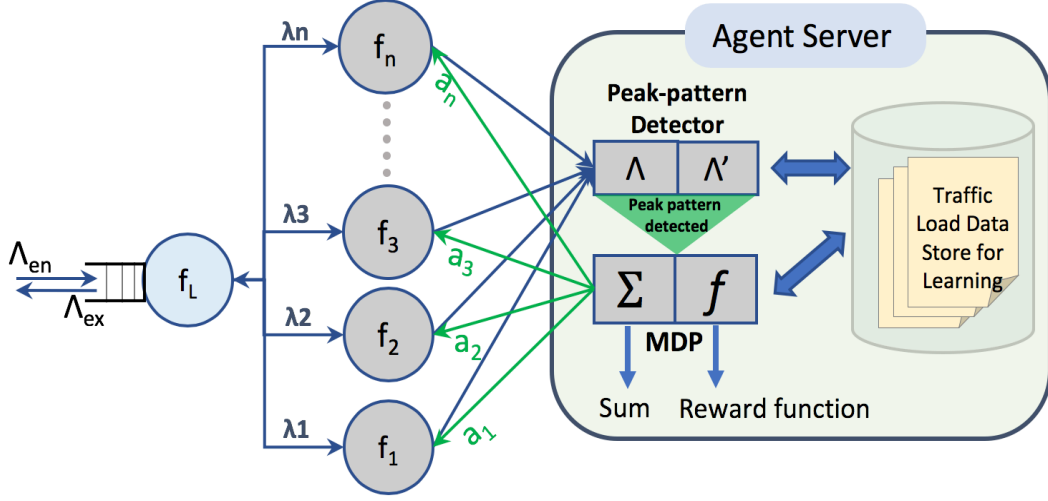


Figure 6.2: The agent server-based system architecture

anism on the agent server. The dynamic traffic flow was structured into fine-grained by the vector: $\vec{\lambda}_i = (\lambda_{ex}, \lambda_{en})$, where i was identified as the number of the floor; λ_{en} was noted as the traffic arrival rate for entering the floor; λ_{ex} was noted as the traffic arrival rate for existing from the floor.

The peak-pattern detector detects the real-time traffic pattern by the monitored overall arrival rate (Λ) of the lobby floor. If peak-pattern was detected, the system adaptively switches to proactive mode for dynamically managing the traffic load distribution based on the designed markov decision process (MDP). It computes the optimal reward globally by taking into account both the benefit on waiting-saving and loss on the physical effort of passengers based on the traffic arrival predication; Finally, it feedbacks the decision for the users at the i -th target floor (f_i) and takes the action (a_i) on the interface for managing the user interaction at the target floor for efficiency improvement.

6.2.2 Peak-Pattern Detector

As described in Chapter 2, there are four traffic patterns during a typical day in buildings [57]. These patterns depend on whether the main flow significantly ascends from the lobby floor (up peak), descends toward the lobby floor (down peak), both or none (interfloor).

Based on the definition, the traffic pattern detection method was proposed: known the threshold value of arrival rate (Λ'), comparing the real-time monitored overall arrival rate Λ at the lobby floor, to determine the peak pattern. The traffic pattern definition details could be formulated as the equation 6.1 shows:

$$TP = \begin{cases} UpPeak & \Lambda_{en} > \Lambda' \\ DownPeak & \Lambda_{ex} > \Lambda' \\ Inter_floor & \text{both } \Lambda_{en} < \Lambda' \text{ and } \Lambda_{ex} < \Lambda' \\ None_peak & \text{otherwise} \end{cases} \quad (6.1)$$

As illustrated in the Figure 6.2, the peak-pattern detector detects the real-time traffic pattern by the monitored arrival rate. If the peak-time was detected, the system switches to proactive mode to dynamically manage the traffic load distribution for time efficiency.

6.2.3 Markov Decision Process

MDP is suitable for modeling decision making in situations where an agent needs to make decisions computing on the dynamical input and executing actions sequentially [85]. In our proposal, the MDP consists of the 3-tuple (S, A, R_a) .

State. The state $s = 0 \cup 1$, describes the status of the user interface at the floor, where they were noted as: 1 means the user interface is open for passengers to make request of going up or down. 0 means the user interface is closed in a time

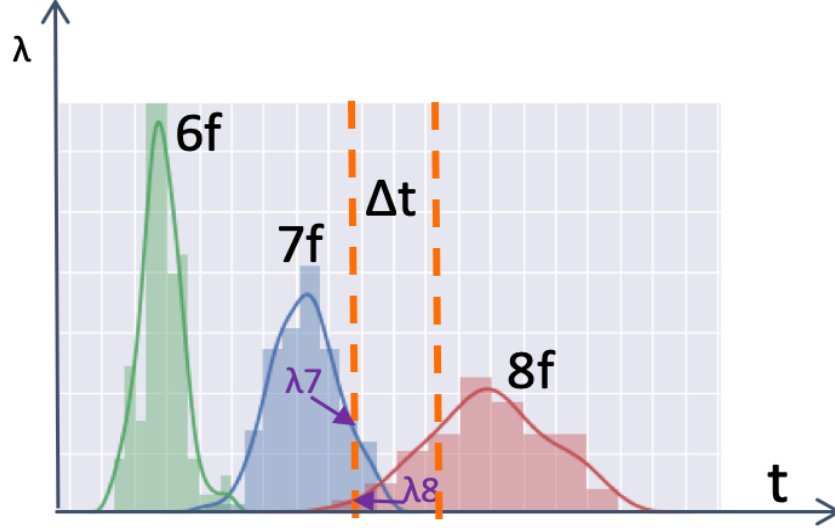


Figure 6.3: Targeting floor based on traffic prediction

phase for optimizing on the flow control, the intelligent guidance will be provided to the passengers.

Action The action $a \in 0 \cup 1$ were defined as 1 : switch the current state to the other state; 0: keep the current state.

Reward and Formulation The reward function of $reward(s')$ determines the reward value after executing action a_0 to switch the state on the interface at the n-th floor. The function represents the multi-criteria joint optimization with the reduced time-cost combined with the labor effort loss of passengers. To make the traffic flow control optimal, the reward function gives consideration to trade-off of the benefit of reduced waiting time and the labor effort loss according to the prediction of people count in a time phase (Δt).

$$a_i = \begin{cases} 0 & \text{if } f_i = f_{target} \\ 1 & \text{otherwise} \end{cases} \quad (6.2)$$

To simplify the policy for decision-making, two parameters are used as constraint: Δt : each decision corresponds to a time interval (Δt), thus each decision interval is $((k-1)\Delta t, k\Delta t]$; Δf : the floor numbers for grouping. Thus, the floors of building was split into : $(0, \Delta f], (\Delta f, 2\Delta f], \dots]$ for managing the traffic flow within the sub floor-groups.

Therefore, the core process for optimization in performing state-action-reward calculation is determining the i -th floor (f_{target}) 's to be targeted that maximizes the the E reward function within the window of Δf . Instead of the instant traffic arrival rate, the accumulative traffic amount based on Δt and Δf is crucial to making prediction.

As shown in Figure 6.3, instead of 7-th floor (where with a higher instant λ), the 8-th floor (where predicted to be more traffic flow coming) ought to be targeted. Thus, the crucial problem is to detect the PC_i with the maximum value within the following Δt window time, thus optimization could be simplified as follows:

$$\begin{aligned} \arg \max \int_{f_i}^{f_i+\Delta f} R_i &= \arg \max \int_{f_i}^{f_i+\Delta f} PC_i \\ &= \arg \max \int_{t_0}^{t_0+\Delta t} \int_{f_i}^{f_i+\Delta f} F(\lambda_i) d\Delta t \end{aligned}$$

6.2.4 User Interface

A dynamic and intelligent user interface also have been designed. The interface was designed: (1) first, to meet the basic function needs of receiving the transportation requirement from passengers; (2) second, to provide the dynamic feedback the real-time intelligent advice computed by the agent server.

The novel end user interface was deployed on the Android-based tablet-Nexus 7, with a display size of 7 inches, operating on the Android 6.0. The details of the

designed user interface was showed in Figure 6.4 with the advantages as follows:

More referable information. The user interface offers a single screen dynamically visualizing overall contents effectively without extra operations from the user. The dynamical contents includes the real-time waiting time for elevator arrival (marked with ①), the current state of the elevator (marked with ②), the real-time visualization of the moving elevator (marked with ⑤), passenger count of riding on, taking off at each floor as well as inside the elevator (marked with ⑤ and ⑥), and so on;

Simplicity of operation. The destination floor can be pre-input prior to riding on cabin and no further operation was required from passengers after he/she entering the elevator (marked as ④).

Intelligence. Based on fine-grained context awareness on the traffic load distribution, finally, the system could proactively compute a better option of riding for the perspective of efficiency and health management. The intelligent advice (marked as ③) would be an useful feedback on the user interface. As illustrated in Figure 6.4, an advice of riding at neighbour floor for time efficiency has been presented.

Figure 6.5 shows the usage example of the proposed system based on the designed user interface. Based on the above hardware development shown in Figure 6.5 (a), the agent server can real-time capture the position as showed in Figure 6.5 (b). In addition, through the designed REST-ful API on intranet of the building, the elevator could be controlled to move to the designated floor.

6.3 User study

We firstly conducted a user study to evaluate Intellevator, by providing end-to-end experience on the the real usage of elevator. This user study was designed

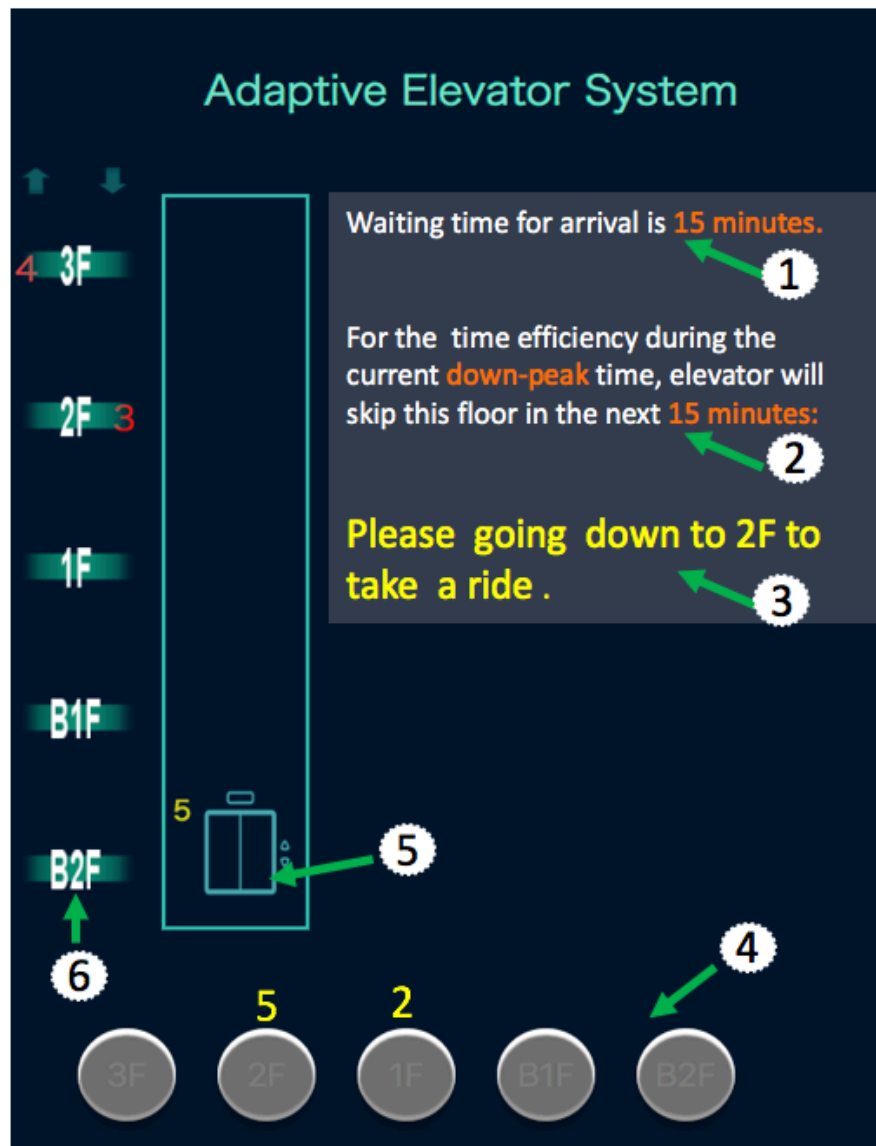


Figure 6.4: An example shows the real-time managed user interface

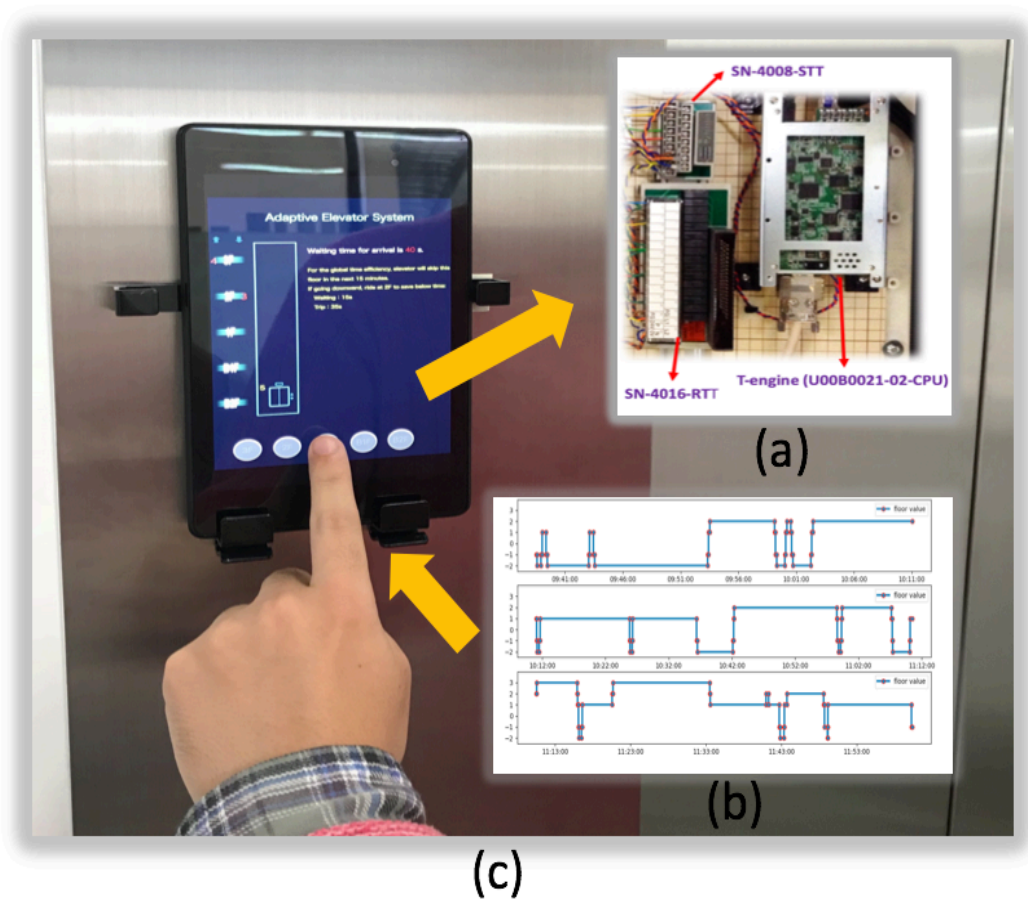


Figure 6.5: The system usage of Intellevator

to realize several goals, as listed below :

- Evaluation of the overall system usability and user experience of Intellevator;
- Evaluation of the usefulness and acceptance of provided various elevator-related context, especially, the advice for reducing time;
- Uncovering passengers' preferences for drawing a baseline of policies on advice-making;
- Gathering insights and recommendations from subjects for further improvement on user-oriented elevator system design;

6.3.1 Participants and Procedure

Totally 22 participants(P1-P22) were recruited in person (no advertisement involved), including 5 females and 18 males, average aged at 25. 64.55% of them usually use a elevator(above 5 times weekly), 27% use a elevator 3-4 times a week, and the rest use a elevator about 1-2 times weekly. The average duration of the whole experiment per participant was about 80 minutes, including introduction, tasks, questionnaires and the semi-conducted interview. The setting for user study is showed in Figure 6.6.

At the beginning of the user study, participants were introduced about the usage of Intellevator as well as the displayed context. After that, to help participants to develop a clear impression of the instruction on Intellevator, participants were asked to perform a training task. Training task is moving from 3F floor to any other floor which they desired by using Intellevator system. The position where elevator come from is random without any pre-set. Multiple trials of training task were allowed until they have no doubts on the usage of our proposed system. The successfully completion indicates participants have a well understanding about the instruction of our proposed system.

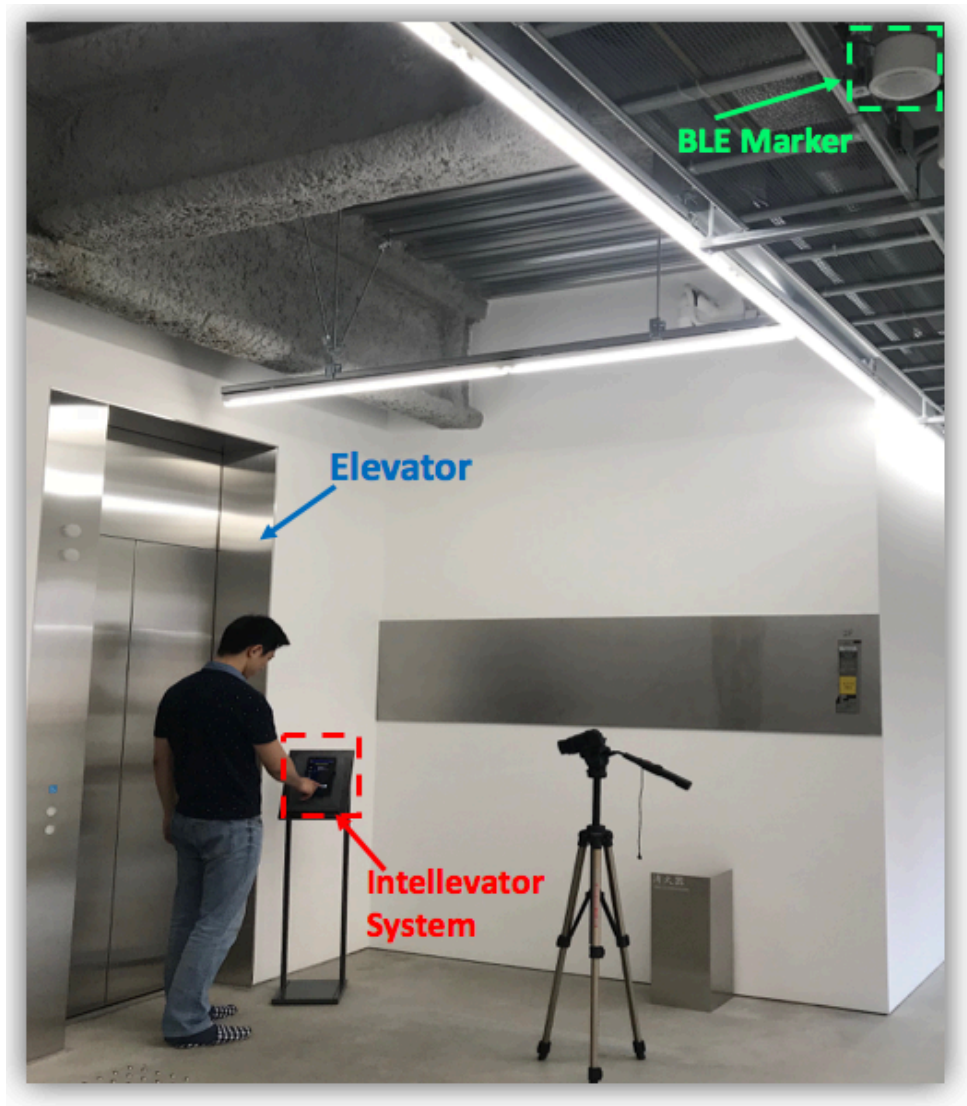


Figure 6.6: The experiment setting of the user study.

When the training task was finished, the comparative tasks were performed. The comparative tasks were divided into two versions: using existing elevator system and using Intellevator. Two patterns of moving were required, one is moving upward from B2F to 3F floor, the other is move downward from 3F to B2F floor. In order to ensure equal experiences for every participant, the initial floor of elevator at the start of the task was set at 3f floor and B2 floor, respectively.

While using the proposed system, the participants were asked to follow the provided advices, that is walking to other floor to take a ride that could reduce the waiting time and trip time. Since the elevator is publicly open as well as the building, other person rather a participant of the user study, who made a additional call would intervene the task. If that case occurred, the task would be restarted to avoid any experience bias. For the privacy concerns on unrelated persons, we did not use the surveillance camera for overall observation. The moving of elevator was checked by an observer who was real time monitoring the place of the elevator to confirm it moved as predicted without any interference.

Next to the comparative tasks, the participants were required to answer a questionnaire which was designed to subjectively evaluating this proposal. The questionnaire consists of NASA-Task Load Index [86], System Usability Scale (SUS) [87], User Experience Questionnaire (UEQ) [88]. The usefulness of various context items also was rated on Likert-scale from 1 to 5. The preference of following the advice to ride also was observed by the filling problems.

Finally, a semi-conducted interview was conducted for collecting feedback and insights from participants about the usage of elevator. The interview was structured to collect feedbacks of participants' overall experiences of daily usage both of existing elevator system and the proposal-Intellevator. The interview was semi-structured by two below questions and with video recorded for later analysis.

- *"How do you feel with the daily usage of elevator"*

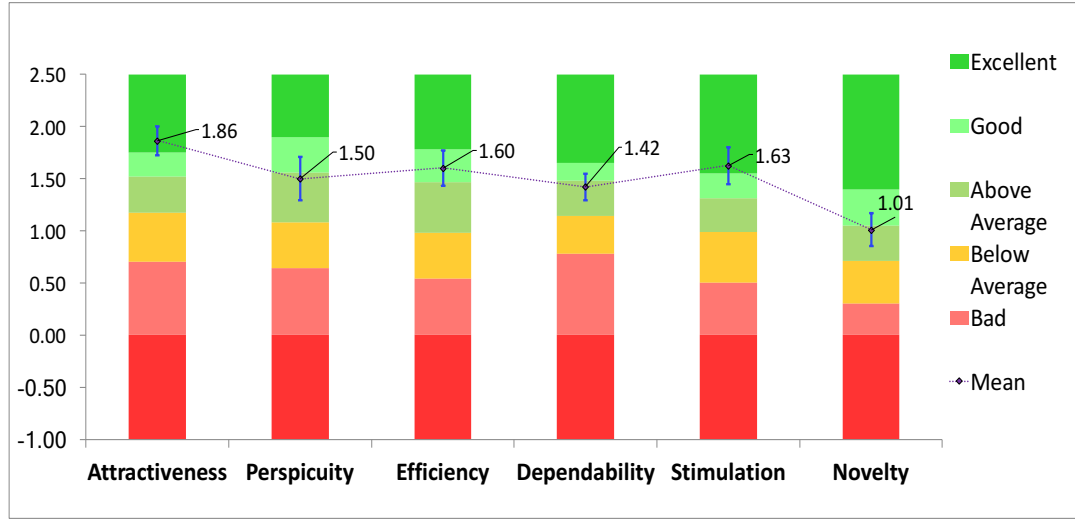


Figure 6.7: Results of the user experience questionnaire

- "How do you feel with the Intellevator after experienced in the user study".

6.3.2 Results

Task Completion

In spite of reminded that twice or more trials were allowed if any doubts remained, all the participants successfully completed the training task by only one trial. It verified that the ease to learn and ease to use of Intellevator at a certainty. While during the comparative tasks, totally 22×2 trials on the Intellevator have been performed.

Two participants individually made a mistake that they still pressed the destination floor button of B2F at floor 3 while they were enforced to follow the advice that walk to floor 2 to take a ride without operation at floor 3. However, after the first time experience of Intellevator, all participants successfully completed the second trial of going upward by using the Intellevator. The total error rate of task completion is 4.5%.

System Usability The System Usability Scale (SUS) have been measured for evaluating the attitudes towards the usability of Intellevator, covering the effectiveness (the ability of users to complete tasks using the system and the quality of the output of those tasks), efficiency (the level of resource consumed in performing tasks) and satisfaction (users' subjective reactions to using the system) [87].

The overall SUS score of Intellevator was on average 75.45 (SD=11.5). A basis for positioning SUS scores within the grade rankings has been provided [89, 90]: a System Usability Scale (SUS) above 68 could be considered above average, the acceptability is HIGH. Based on this reference, the rated overall SUS score of 74.45 above the average a few shows Intellevator matches users satisfaction by a effective and efficiency way. The system were designed easy to lean, useful to help them smoothly completed the tasks.

User Experience We also chose the user experience questionnaire (UEQ) [88] to measure their experience on Intellevator in a simple and immediate way. 6 factors Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, Novelty are analyzed with 26 items rated by 7-point Likert scale. Overall, the user experience was rated at 1.5 (SD=0.28) on the scale between -3 to 3.

The result details are interpreted as the Figure 6.7 shows. The User Experience Questionnaire (UEQ) with Attractive was rated as 1.86 (SD=0.66), ranked in the range of the 10% best results as Excellent. Perspicuity, Efficiency, Dependability, Stimulation, Novelty were ranked into Above Average (25% of results better, 50% of results worse), Good (10% of results better, 75% of results worse), Above Average, Excellent, Above Average as rated by 1.50 (SD=0.99), 1.60 (SD=0.79), 1.42 (SD=0.60), 1.63 (SD=0.84), 1.01 (SD=0.73), respectively.

Obviously, all scales show an extremely positive evaluation. We used the benchmark of UEQ data analysis tool which provided the data set collected from 9905 persons from 246 studies concerning different products [91]. The comparison of the results for Intellevator with the data in the benchmark shows Intellevator

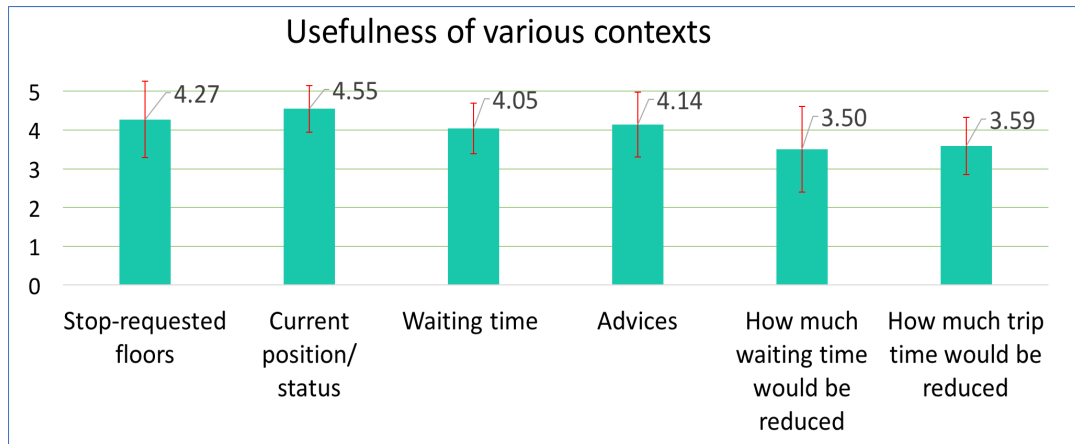


Figure 6.8: The usefulness of various contexts.

have the relatively high user experience quality.

According to subjectively rating results of System Usability Scale (SUS) and User Experience Questionnaire (UEQ), we can state that, Intellevator provided relative high quality of the overall system usability and user experience, that consequently could contribute to a high acceptance.

Usefulness of the Provided Contexts

In addition, the usefulness of presented various context were rated on a Likert-scale from 1 to 5. The results are showed in Figure 6.8. We can learn that visualization of existing necessary context is the most demand. Rather than waiting time provided, passengers prefer the advices being provided, but less care about the detail merit of the advices.

Figure 6.8 shows the usefulness of various contexts. Current Position/Status ($M=4.55$, $SD=0.6$) is most useful context for passengers, and the second highest rated context is Request Floor list ($M=4.27$, $SD=0.98$). Advice for Reducing Waiting time ($M=4.14$, $SD=0.83$) is rated a little higher than Waiting Time for Arrival ($M=4.05$, $SD=0.65$). However, the details of How Much Waiting Time ($M=3.50$,

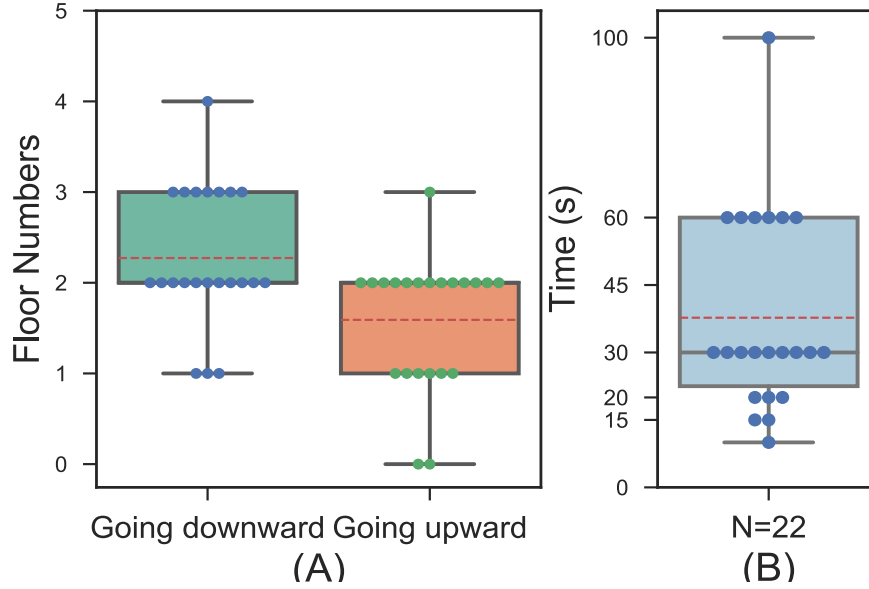


Figure 6.9: User preferences for advice-providing (N=22)

SD=1.1) Could Be Reduce and How Much Trip Time Could Be Reduce (M=3.59, SD=0.9) if following the advice was relatively rated lower.

User preference for Advice-providing Besides, participants were asked by three questions and give the answer to the filling part of the questionnaire, which was designed to quantitatively evaluate participants' preference, incentives of following the advice to take a ride.

- If advice presented that going to upper floor to take a ride for saving waiting time, what is the maximum floor numbers that could be considered.
- If advice presented that going to lower floor to take a ride for saving waiting time, what is the maximum floor numbers that could be considered.
- How much time reduced could be a incentive for following the advice.

Figure 6.9 (A) shows the answer of almost all the participants (21/22) of going

upward to take a ride is within 2 floors (overlapping in 1 and 2 floors) with the most of the answers (13/22) are 2 floors and mean is 1.59 floors. Meanwhile, The vast majority (21/22) answer of going down is within 3 floors (overlapping in 1, 2, and 3 floors) with quite a few (8/22) of below 3 floors and mean is 2.27 floors. As (B) shows, the most answers (21/22) of the minimum time could be incentive is 60 seconds with the majority (16/22) overlap above 30 seconds and the mean is 37.72.

Regarding to passengers preferences of following advices, we can clearly see that there is a offset on the overlaps of maximum floors of going downward (3 floors) and going upward (2 floors). The details quantitatively revealed the participants would rather to going downward than upward. Besides, in Figure 6.9 (B) shows if the waiting time could be reduced more than 60 seconds, most participants would like to follow the advices. Based on this results, we can conclude that the advice showed going upward or downward within 2 floors to take a ride thus the waiting time would be reduced more than 60 seconds would be considerable for the most participants.

Additionally, Figure 6.9 (B) shows that if the waiting time could be reduced by more than 60 s, most participants would like to follow the advices. Based on this result, we conclude that the advice showed going upward or downward within 2 floors to take a ride thus the waiting time would be reduced by more than 60 s would be considerable for most participants.

NASA-Task Load Index for Evaluating Demands

The NASA-Task Load Index consists of 6 dimensions: Mental Demands, Physical Demands, Temporal Demands, Effort, Performance and Frustration were required individually to reflect to the given tasks. Participants were firstly asked to evaluate the contribution of each dimension (its weight) to the given tasks, afterwards, to rate these dimensions within a 100-points range which divided into 20 equal intervals anchored with 5-point increments. We calculated the overall workload score (WWL) based on these weighted and rated dimensions[86]. Before the

evaluations, we made several hypothesis (H), uncertainty (U) in advance regarding on results of the NASA-Task load Index, as listed as below:

- (H1) Comparing the conventional elevator system, Mental Demands of Intellevator might be increased since Intellevator provided more information to retrieve and refer. Physical Demands also might be increased since participants were required to walk to other floor to get a ride if followed the advice. Consequently, the Effort mainly including Mental Demands and Physical Demands might be increased simultaneously.
- (U1) Temporal Demands and Performance leaves uncertainty need to be clarified. The mental cognition should be clarified via the realistic experience on Intellevator.
- (H2) Frustration could be decreased for the reason that the proposed system provided more referable content to help passengers obtain comprehensive knowledges of the elevator using. Moreover, the supportive advices for both reducing their waiting time and trip time are considered to be beneficial.

The results of NASA-Task Load Index are showed in Figure 6.10 and Table 6.1. Figure 6.10 shows the overall of average ratings of 6 dimensions. Based on these result, the H1, H2 have been verified subjectively. Temporal Demand decreased by 36%, and the Performance increased by a quarter, solved the U1. However, Besides, regarding to the Overall Work Load, there were no significant differences between using existing system and using Intellevator, which was 47.9 and 49.1 separately. The overall result of NASA-TLX could be summarized as that, comparing with the existing elevator system, Intellevator relief passengers temporal demand and frustration, while requires more passengers' physical demand and effort, the overall work load remains almost the same. Concerning for the goal of reducing their waiting time, this result was totally in line with expectations.

Table 6.1: Subjective weightings and ratings on NASA-TLX.

			Mental Demand	Physical Demand	Temporal Demand	Effort	Perfor- mance	Frust- ration
Weighting	Avg.		2.5	2.3	3.25	1.95	2.7	2.3
Rating	Exis-	Avg.	35.5	27.7	58.2	29.1	60.7	49.6
	ting	SD	28.78	22.24	31.26	26.62	34.51	18.87
	Intell-	Avg.	43.2	44.1	37.7	42.7	76.1	30.2
	evator	SD	21.19	27.80	24.96	26.71	21.82	18.87

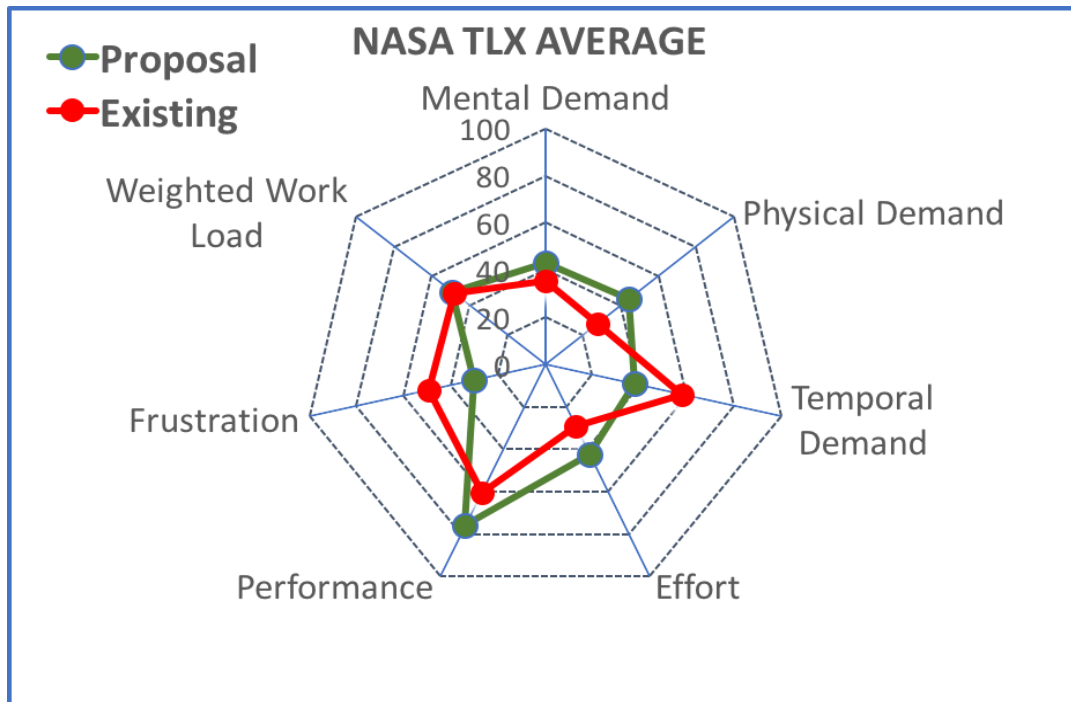


Figure 6.10: The rating averages of NASA-TLX

Based on NASA-TLX rating results and the semi-conducted interview, we can conclude that by comparing with the conventional elevator system :

- The mental demand of the Intellevator has been increased slightly because the Intellevator provided more information to retrieve and refer. The physical demand also has been increased because the participants were required to walk to other floors to obtain a ride if they followed the advice. Consequently, the effort primarily includes the mental demand and physical demand have been increased simultaneously.
- The temporal demand decreased by 36% showed that Intellevator helped passengers to relief the temporal demand for the real-time presented advices designed for assisting passengers' time efficiency. Performance increased by a quarter, means that the participants felt their own performance became better by using Intellevator.
- The frustration have been greatly decreased because the proposed system provided more referable context to help passengers obtain the comprehensive knowledge of the elevator use. Moreover, the assistive advices for both reducing their waiting time and trip time are considered to be beneficial as well.

6.3.3 Feedback and Findings

Quite a few of valuable and noteworthy feedbacks from the semi-conduct interviews have been collected.

Overall Positive Acceptance with a Few Drawbacks

Almost all the participants highlighted positively the usefulness, innovative idea of our proposal-Intellevator, stated that they would like use the Intellevator system. Though, the intuitive interface also have been commented as generally easy

to learn and easy to use, we still received some suggestions. P14 commented that, it is better to vertically arrange the destination floor buttons for quickly matching the vertical floor arrangement inside building.

Moreover, we found that if for the real usage, device with bigger screen size rather than tablet might be more applicable since three participants pointed that the buttons as well text of advices on the tablet screen are too small to have a clear see that badly effected on their experience on obtaining information.

Almost all the participants liked the function that destination floor button could be pressed outside the elevator, stated the design that only pressing the destination button required is convenient. However, on the other hand, some participants P1, P5, P10, who rated a little higher frustration point in NASA-LTX revealed that, by using the existing elevator system they can confirm the terminating floors from the inside button panel, while using Intellevator, they met the new uncertainty of the information of which floors would be terminated. They considered if the context also could be real-time visualized inside the cabin, that could relieve the discontent.

On the other hand, P19, P20, P5 mentioned that they worried about whether would miss the elevator at another floor after followed the advices. *"I hope the system run on my smart phone that i can real-time check the status of elevator during heading to other floor to take a ride. That kind of smart phone based application would be more appeal to me"* said P5.

Polarized Attitudes towards Waiting Time Depends on the Daily Used Elevator System

The fact of long waiting time has been revealed by almost each participant. Meanwhile, We found that the sensitivity of waiting time quite differs between the participants: a part of them have great dissatisfaction and complaints on the long waiting time.

Meanwhile, a part of them revealed the long waiting time, yet have no thinking on it. As a participant who use elevator 1-2 times weekly mentioned *"Though sometimes it takes a little long time for elevator arrival, i just wait without any thinking, not so much frustration"*. On the contrary, the participants who use elevator in a taller building with definite peak patterns are usually suffered with longer waiting time and have stronger complaint and criticism on the usage of elevator system.

A participant (P9) who has the work experience at a office building over 40 floors, revealed that *"Even though the usage of the elevators have been separated according to the floor numbers, there are quite difficulties for riding on elevator in my office building. During morning time and lunch time, it is common to take above 5,6 minutes to have a ride. The lunch time is more worse, even if the inside is too crowd to ride, elevator still terminates when outside call made. This makes people both outside and inside frustrated"*. The similar situation also has been mentioned by P22 *"During the rush for lessons in the building, it always takes about 3,4 minutes to wait for elevator arrival.... the building is 13 floors built.."*.

Regarding to the feedback of long waiting time of participants, since the passengers' attitudes for elevator system has strongly relevant to height of the building and the frequency of usage on the inside elevator. Attitudes towards the waiting time have been polarized.

This also make sense for relatively significant stand deviation in the rating results of NASA-TLX. The strong complaints further verified the serious problems in tall building with momentarily large traffic flow in terms of scheduling efficiency.

An Information Gap between Passenger Needed and the System Provided

From the analysis on the feedbacks, we also found that besides the factor of long waiting time, another factor that too much uncertainty leads to the negative user experience as well. Via this user-centered pilot test, quite a few of participants

stated that little information presentation of what time the elevator would come when they waited outside as well as while during riding inside which floors would be terminated for the call from outside is equally (more) made them dissatisfied and frustrated.

It indicated that there is a information gap between users demanded and system provided, which is challenging and have been ignored for solving. As such, we can conclude that for providing participants better user experience, besides enhancing the scheduling efficiency, yet solving the uncertainty and keeping the provided information both inside and outside consistent need to be undertook as well.

6.3.4 Summary of the User Study

By drawing comparison with the existing elevator system, Intellevator was evaluated that it owned better system usability, user experience. Moreover, this user study is possibly marked as the first attempt to expose some factors in negative user experiences such as frustration, dissatisfaction.

An agent server design brought possibilities of high-level application development, including utilizing artificial intelligence to further improve efficiency of elevator. Whereas, deciding whether user needed the content, how to design the interface and whether the decision provided is reliable and assistive, then following an user-centered improvement process are quite crucial for ensuring the better user experience on the elevator using.

It is hoped that the prototype experiment conducted in the real smart building and the user-centered pilot test would help gather users preferences and feedback via a realistic experience could bring innovative thinking and informed insight into the futuristic elevator system design.

6.4 Simulation

To further test the performance improvement made by our proposal, an evaluation was conducted based on the simulation performed of peak-time traffic optimization. The simulation and the results are presented in this section in detail.

6.4.1 Notation for the Dynamics

Various dynamics from elevator environment was approximated for decision-making as defined by the following parameters in Table 6.2. The elevator environment is composed of the static elevator parameters and the real-time conditions in relation to the traffic pattern and the external traffic load distribution.

The dynamic traffic flow was structured into fine-grained by the vector: $\vec{\lambda}_i = (\lambda_{ex}, \lambda_{en})$, where i was referred as the floor number; λ_{en} was denoted as the entering traffic arrival rate at each floor; λ_{ex} was denoted as the traffic arrival rate for existing from the floor.

6.4.2 Simulator

In addition, we tested the performance improvement made by our proposal by a simulator. The simulator consisted of several components: traffic flow generator, traffic flow manager and transporter. In the simulation, the traffic flow was generated, managed and transported in iteration. For each round, the simulator computes the sum of waiting time, journey time, passenger count in order to determine the average or maximum value for evaluation. The amount of current generated traffic flow was affected by the round time of the previous traffic flow. The algorithm of the simulator is presented as follows:

Algorithm 3: Elevator Transport Simulator

Data: overall floor number N , floor numbers for grouping Δf , overall arrival rate in lobby floor $\bar{\lambda}$, moving time between two floors t_m , boarding time for transporting passengers t_b , elevator cabin CN , arrival rates of all the floors λ^N , transported passenger count PC , the sum of waiting time WT , the sum of journey time JT

1 **while** *True* **do**

2 $tf, pc, wt, max_wt \leftarrow \text{GenerateTrafficFlow}(preRT, \bar{\lambda})$

3 $td \leftarrow \text{TrafficDistribution}(tf, \lambda^N, N)$

4 $new_td \leftarrow \text{ManageTrafficDistribution}(td, \lambda^N, \Delta f)$

5 $jt \leftarrow \text{TransportTD}(new_td, CN, t_m, t_b)$

6 $preRT \leftarrow maxWt + maxJt/CN$

7 $WT \leftarrow WT + wt$

8 $PC \leftarrow PC + pc$

9 $JT \leftarrow JT + jt$

10 **return** PC, WT, JT

Parameter	Description
N	Number of floors
E	Number of Elevator Cabin
C	Cabin capacity
CN	Cabin numbers
t_b	Boarding time at one floor
t_m	Moving time between two floors
$\Lambda \in \{\Lambda_{ex}, \Lambda_{en}\}$	The overall traffic arrival rate of existing or entering the lobby floor
$\lambda \in \mathbb{R}^{N \times 2}$	Individual traffic arrival rate of each floor, with two dimensions: entering and existing
TP	Traffic pattern
$S \in \{0, 1\}$	The status of the user interface: 1 (open) or 0 (closed)
$PC \in \mathbb{R}^{N \times 1}$	Overall people distribution composed by all the floors
$A \in \{0, 1\}$	Switches interface state (1) or not (0)
Δt	Time Interval for decision-making
Δf	Floor numbers for floor grouping

Table 6.2: Parameters for dynamics representation

6.4.3 Simulation Setting

Compared Methods

To evaluate the effectiveness of our proposed method, a comparison was drawn between our approach and the following baseline methods, with the parameter tuned for all methods.

- **Passive transport method (PT)** is widely applied in the conventional elevator control method, where the elevator system is passive in reaction to

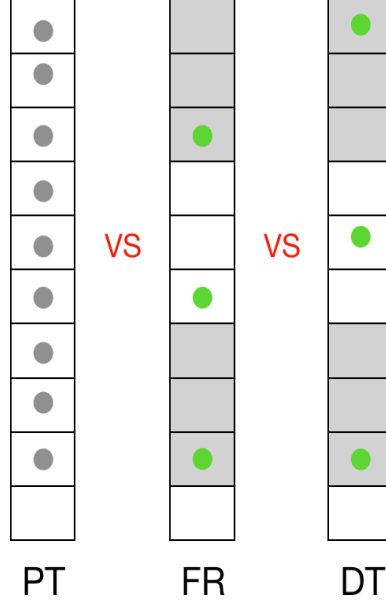


Figure 6.11: Illustration of compared methods: PT, FR, DT

all the requirement (origin to destination).

- **Fixed rule for traffic flow management method (FR)** represents a deterministic method for the management of the traffic flow. In the evaluation, the lowest floor was taken as the target floor to merge the traffic load within the floor window. This rule is capable to maximize the efficiency of elevator system. Nevertheless, the fixed target floor would give rise to additional labour effort loss.
- **Dynamically targeting for traffic flow optimization method (DT)** is a hybrid method based on our proposal that real-time predicts the traffic load and dynamically targeting the floor of which the traffic load would reach the maximum within the deterministic periodic time and floor group.

Figure 6.11 presents the three methods in comparison. Apart from the above base line methods, we also consider the peak-time fluctuation with arrival rates (*+

λ) varying among all the floors for simulating the realistic scenario for evaluation.

Control Strategies

Control Strategy 1 (CS 1) Known the current up-peak pattern in which the origin is centralized while the destination is distributed, to merge the going-up traffic flow by managing the user interaction on the destination floor;

Control Strategy 2 (CS 2) Known the current down-peak pattern in which the origin is decentralized, the destination is centralized, to merge the going-down traffic flow by managing the user interaction on the departure floor.

The decision-making was constrained by two parameters: periodic time and floor numbers for grouping;

Parameter Setting

The parameter setting of the elevator environment for evaluating our proposal is shown in Table 6.3. The floor window (Δf) has been restricted by the real result obtained from the user study. The boarding time for accomplishing the transport task is dynamically valued based on the passenger count on the floor, which has been signed as α . To get more insight, the value of λ_i was dynamically assigned with normal distribution $\lambda_i \sim (\bar{\lambda}_i, (0.1\bar{\lambda}_i)^2)$, in which $\bar{\lambda}_i$ presents the average value, $0.1\bar{\lambda}_i$ was taken as the standard deviation.

Evaluation Metric

The performances of the above methods were assessed using the following metrics:

Table 6.3: Elevator environment settings

Parameter	Value
Time interval for making decision Δt	300 seconds
Floor window for grouping Δf	1, 2, 3;
Floor Numbers (N)	15, 20, 25, 30;
Average Floor Population (pc_i)	200
Building Population (PC)	200*(N-1)
Cabin capacity (C)	15
Cabin numbers (CN)	N / 5
Elevator moving time between two floors (T_m)	5 s
Elevator boarding time (T_b)	5 s + 0.2* α
Overall average arrival rate in lobby floor ($\bar{\Lambda}$)	PC / 2 hours
Average arrival rate in a floor ($\bar{\lambda}_i$)	pc_i / 1 hour

- AWT: average waiting time passengers spent on waiting for elevator arrival. AWT is calculated as the total amount of waiting time to be divided by the total sum of transported passenger number.
- ATT: average journey time passengers spent on taking ride on the elevator. ATT is calculated as the total amount of travel time to be divided by the total sum of transported passenger number.
- Duration: the overall elapsed time for transporting the total passengers.
- LL Sum: the overall amount of the labor effort caused by traffic managing, which is calculated as the product of the affected passenger count and their corresponding floor numbers for walking. The unit was defined as the labor effort that one person walking one floor.
- Max Waiting time: the maximum waiting time during the simulation.
- Max journey time: the maximum journey time during the simulation.

6.4.4 Results

The simulation was real-time visualized. Figure 6.12 shows traffic flow generated with fluctuation on peak-time, where the average arrival rate $\bar{\lambda}$ is $200 \div 3600 = 0.055$. The offset on the peak value of the λ of each floor is randomly set.

Simulation Visualization

Both Figure 6.13 and Figure 6.14 show the real-time visualization of the traffic being generated, managed, transported under the same peak-time fluctuation which has been shown in Figure 6.12. As shown in Figure 6.13, FR method targeting floor by fixed rule, that always merged the traffic flow in lower floors within the Δf . On the contrary, as shown in Figure 6.14, DT method targeting floor by proactive traffic prediction that dynamically targeting the floor. Meanwhile, the caused related labor effort on passenger side was recorded as well.

To make a quantitative evaluation of the efficiency improvement, we started by fixing the parameter setting to floor number: $N=20$; $\Delta f = 2$ for testing. We ran 20 times on each scenario and took the average. The simulation results are presented in Table 6.4, consisting of values : the average waiting time (AWT), average journey time (ATT), total duration, max waiting time and max journey time in the duration under different traffic patterns.

To compare the transport efficiency variation on real-time, dynamical monitoring of the cumulative waiting time and journey time of both methods was conducted. The performance of the evaluated methods are also exemplified in Figure 6.15. While under the same increase in transported traffic flow, by comparing the traditional method (PT) which is passive to accomplish the transportation task and fixed rule method (FR) to target the floor fixed, the efficiency improvement by using Intellevator (DT) have been figured out with intuition.

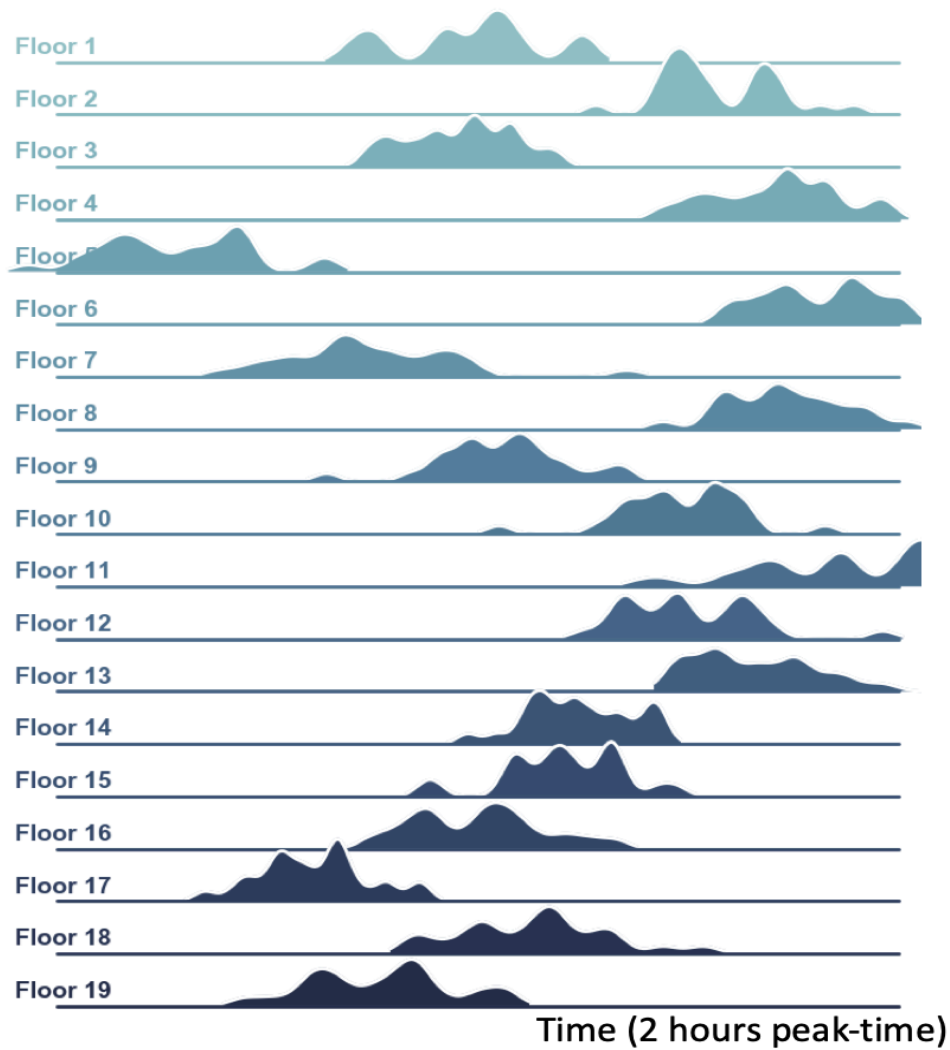


Figure 6.12: The figure shows the traffic flow with fluctuation on peak-time

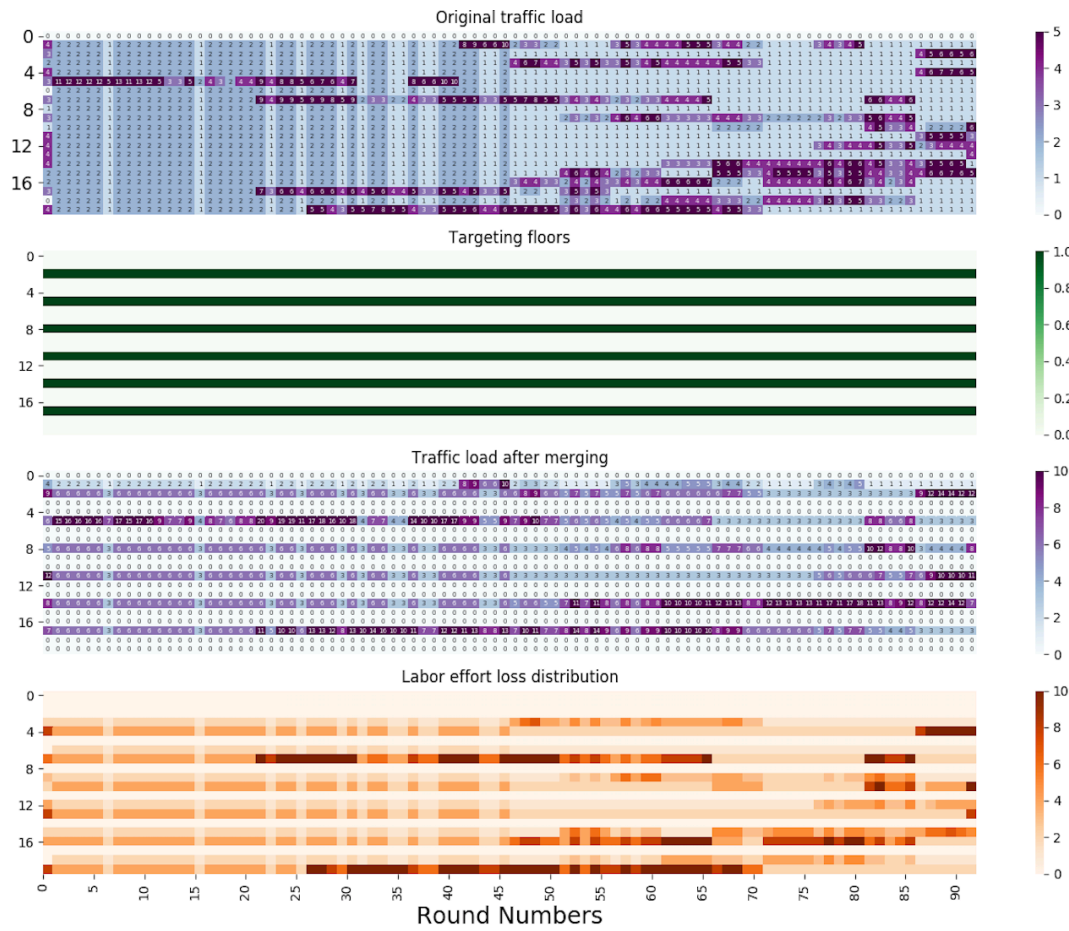


Figure 6.13: An example shows traffic managed under FR method

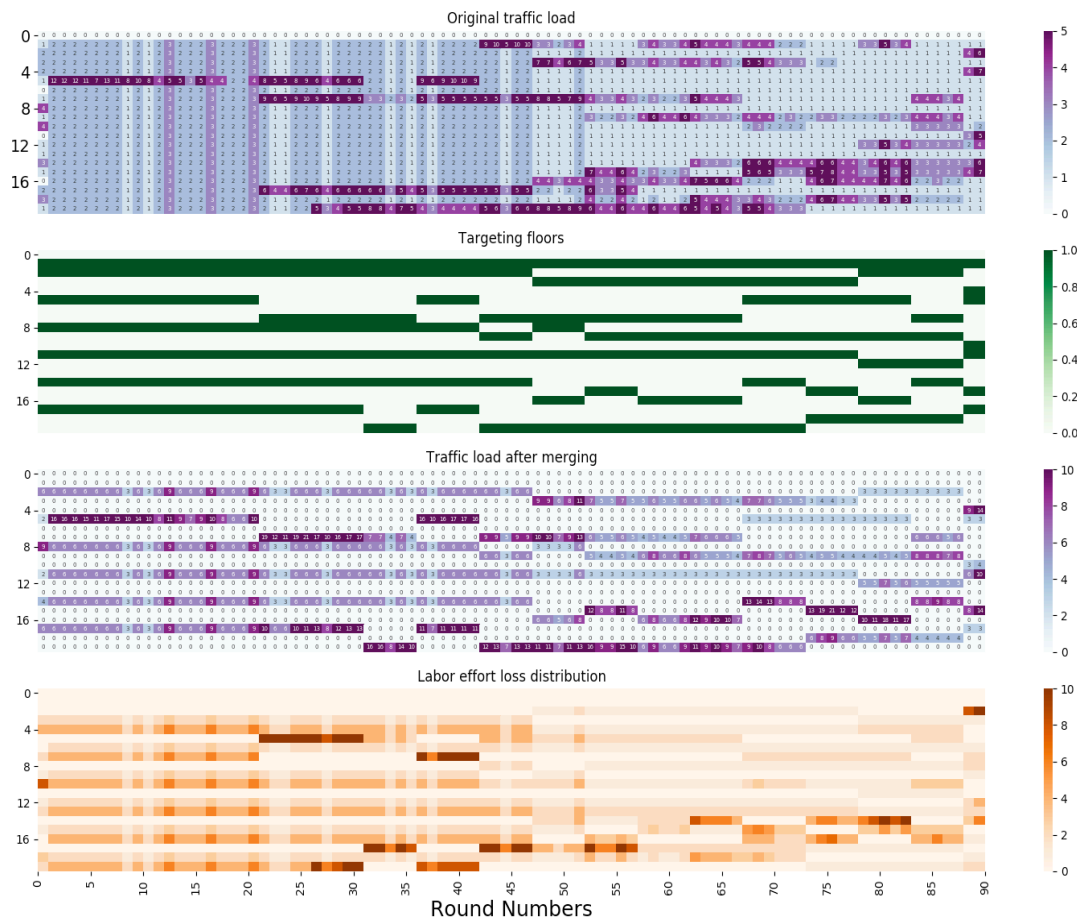


Figure 6.14: An example shows traffic managed under DT method

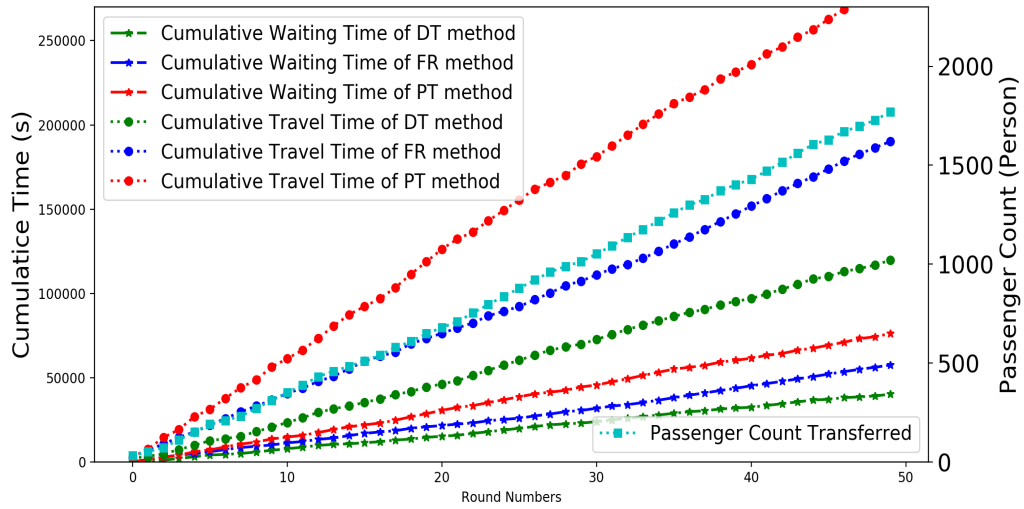


Figure 6.15: Comparison of cumulative time and transported traffic flow of the three methods

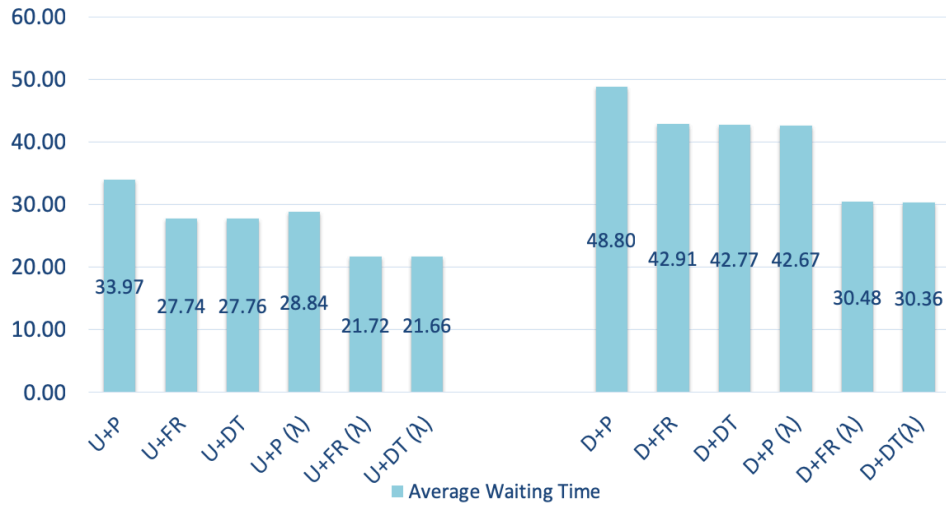


Figure 6.16: The results of average waiting time

Table 6.4: Performance of different methods on the evaluation (in seconds)

Pattern	Methods	AWT	ATT	Duration	LL sum	Max	Max	Waiting time	journey time
Up-peak	PT	33.97 (0.53)	92.81 (1.42)	6456 (519.9)	0	75.18			51.43
	FR	27.74 (0.16)	63.70 (0.17)	6701 (343.5)	3600 (0.0)	59.77			36.02
	DT	27.76 (0.17)	68.75 (0.73)	6601 (360.5)	3482 (42.3)	59.76			36.01
	PT+ λ	28.84 (0.30)	101.95 (3.5)	5530 (146.9)	0	75.83			52.08
	FR + λ	21.72 (0.20)	67.81 (1.47)	5243 (109.9)	3826 (127.2)	60.25			36.50
	DT + λ	21.66 (0.15)	67.43 (0.33)	5254 (93.4)	2443 (21.0)	60.41			36.66
	PT	48.80 (0.11)	94.84 (0.62)	5606 (36.6)	0	75.22			51.47
	FR	42.94 (0.17)	64.28 (0.21)	5578 (40.10)	3600 (0.0)	59.81			36.09
	DT	42.77 (0.12)	65.10 (0.20)	5591 (26.87)	3524 (36.4)	59.81			36.06
Down-peak	PT+ λ	42.67 (0.89)	98.00 (3.10)	5418 (152.14)	0	68.90			45.15
	FR + λ	30.48 (0.43)	66.80 (1.37)	5023 (197.78)	3770(88.5)	48.08			24.25
	DT + λ	30.36 (0.51)	66.41 (1.92)	5095 (179.20)	2424 (14.7)	48.18			24.43

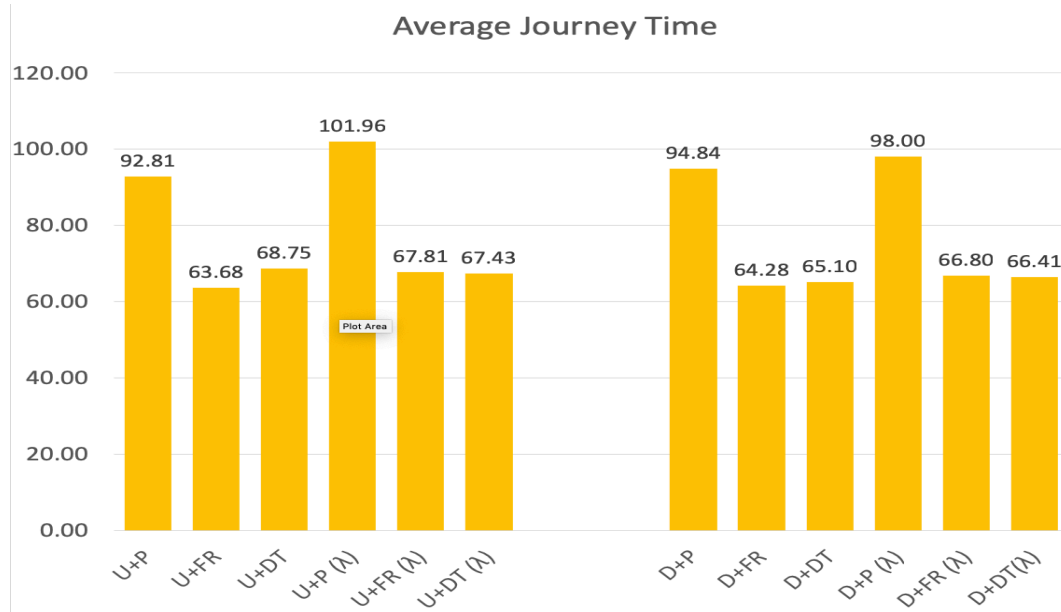


Figure 6.17: The results of average journey time

With regard to time-saving, Figure 6.16 presents the detail on the average waiting time (AWT). Overall, there is yet to be any significant difference in the performance of waiting time reduction between FR method and DT method. Despite this, as compared to non-peak-fluctuation, the advantage of time-saving becomes more apparent in case of under the peak time fluctuation.

To be specific, while under Up-peak, the proportion of saved-time increased from 18% to 25%. At the same time, the amount of saved-time increased from 13% to 30% while under down-peak. In down-peak time (the origins were distributed in different floors while the destination was centralized to the lobby floor), being merged at the lower floor would extend the time spent on waiting for elevator to arrive. It leads to the average waiting time (AWT) of the down-peak pattern being relatively prolonged compared with the one of the up-peak pattern .

The specifics of average journey time (AJT) has been indicated in Figure 6.17. While in the absence of peak-time fluctuation, FR delivers marginally superior

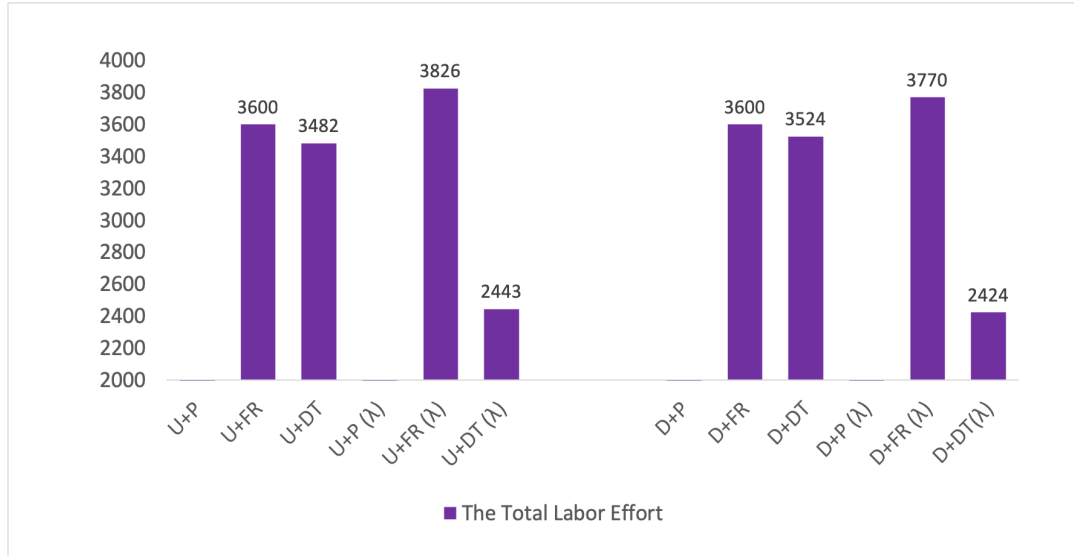


Figure 6.18: The results of total labor effort loss

performance. Because the FR method always merged the traffic load to the lowest floor which obtains the lowest average journey time. However, while in case of peak-time fluctuation, there is no noticeable distinction between FR and DT methods. Besides, regarding the percentages of saved-time that improves from 31% to 33%, it is showed that the advantage of down-peak is relatively insignificant. Nevertheless, while under up-peak pattern, the advantage of time-saving increases significantly from 25.8% to 34%.

Concerning labor effort loss, as indicated in Figure 6.18: Overall, PT method that is passive to undertake transport task, no labor effort is required. FR method results in a substantial amount of total labor effort. As the FR method is consistent in merging traffic to the lowest floors in the absence of real-time traffic prediction. DT method shows the most desirable performance as it takes into account the traffic prediction in real-time. Moreover, while under peak time fluctuation, the advantage of DT on labor effort-saving increases noticeably: under up-peak, the percentages of labor-effort saving increases from 3.2% to 36%; likewise, while under down-peak, the percentages improves from 2.1% to 37.3%

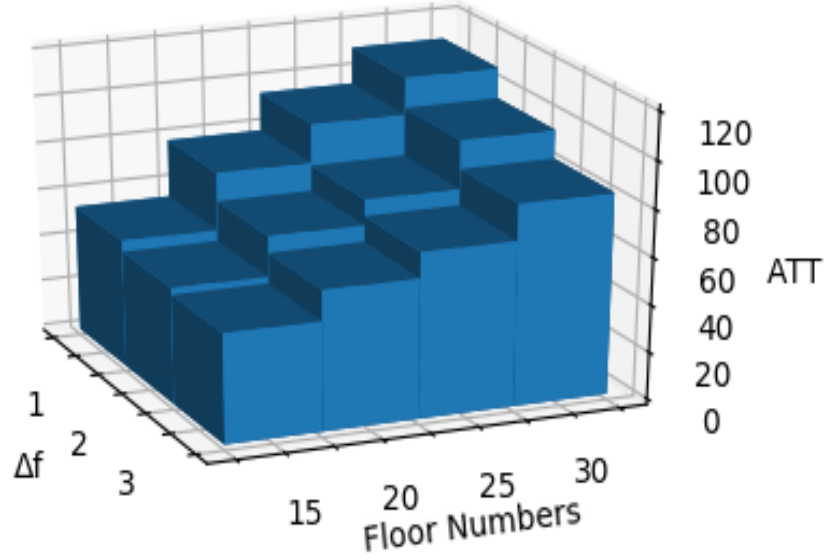


Figure 6.19: Average journey (travel) time based on setting of floor number vs Δf

To conclude, the simulation exhibited the transport efficiency of our proposal based on the comparison of the three methods. Regarding time-saving, there is no substantial disparity between the FR method and the DT method. However, concerning labor-effort loss, DT method dictates the optimal floor based on real-time traffic flow prediction requires minimal labor effort. In respect of the trade-off on time-saving and labor-effort loss, the DT method displays the comprehensively best performance.

The correlation between the results and environment parameter setting

In addition, to confirm the correlation between Δf (floor window for grouping) setting and system performance, we set the total floor number N from 15 to

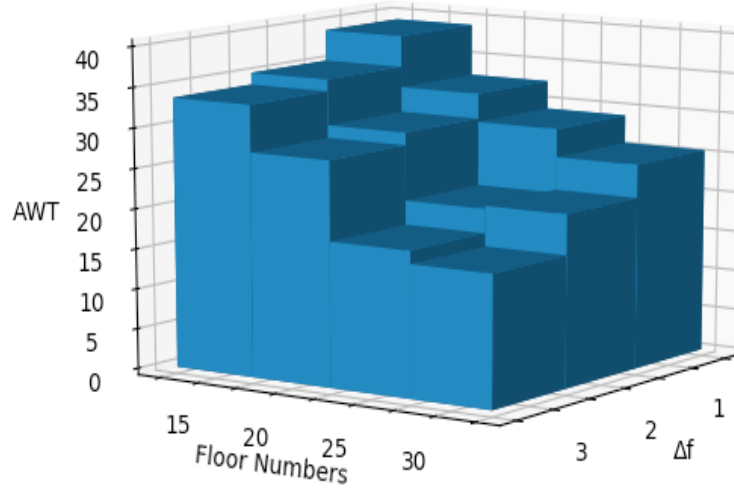


Figure 6.20: Average waiting time based on setting of floor number vs Δf

30, as well as the Δf from 1 to 3, for simulation of the results under both two traffic patterns. The quantitative result has been presented in the Figure 6.19 and Figure 6.20.

As the floor number for grouping is on the rise, the elevator time efficiency also increases accordingly. Because the percentages of time-saving increase with the rise in the overall floor numbers, a conclusion can be drawn that, the higher the building, the more noticeable the time-efficiency improvement could be made.

6.5 Limitations

Experiment Environment

This building where the user study was conducted is a small size built, with 5 floors and about 100 hundred resident users inside. Although sometimes the held events or lectures could cause momentary large traffic flow, there is no definite and

regular peak traffic patterns on the elevator. As such, at the most time the waiting time of participants are always within 20 seconds, means the elevator moving from within 4 floors for picking up exclusively. This situation of the building could not provide participants a comprehensive user experience on the elevator, for example, providing the long waiting time for more than 2 minutes, which is common during peak time at a tall building.

Besides, the user study was personal-oriented. If pursuing a more sufficient experience on the elevator usage, the user study should be conducted by more comprehensive conditions, such as extremely long waiting time for heavy traffic flow, people crowd while waiting outside the elevator or riding inside the cabin. The different experience leading to various feedbacks should be explored and compared, thus for clarifying more factors affecting the user experience on the elevator system.

Internal scheduling have been discounted from this paper

In the simulation, the traffic flow was generated, managed and transported in iteration, without taking into account the internal scheduling of multiple elevators. As explained in Chapter 2, various scheduling algorithm optimizations have been proposed in the past. However this proposal, Intellevator system concentrates on the proactive adaption on the user interface with the further management of the traffic flow. Consequently, it excludes the internal scheduling optimization from this research scope.

Besides, given that the internal scheduling would make the simulation more complicated, it would cause difficulty in converging the result objectively. Based on these considerations, the simulation was designed to primarily verified the efficiency increment following traffic load management, as well as the correlation between the result and building environment setting.

6.6 Summary

In this chapter, Intellevator is presented, a practical elevator system integrated with the smart building framework. The key novelty lies in the consideration given to the complex algorithms, control methods, or the advanced decision rules to be implemented in the controllers of the stand-alone elevator is insufficiently flexible for intelligence and efficiency. The facts that the user experience of the elevator system have been subject to challenge for the past decades, which had negative effect on vertical mobility.

We developed the proposal - Intellevator was developed for an end-user oriented novel elevator system. Intellevator enables visualization of useful contents of elevator using, simplified operation as well as the supportive advice for time-saving. As a consequence, it is effective in improving user experience on elevator usage.

We conducted experiment with Intellevator through the integration with a real conventional elevator and carried out a user study by 22 participants attended for evaluation. The system usability and acceptance of Intellevator have been verified in the user study. The results demonstrated that the system usability and user experience of the Intellevator are superior to that of the current conventional elevator. Moreover, valuable feedback for the system to offer advice-making and context visualization have been collected; they will serve as an informed reference for the development of the futuristic elevator system.

In addition, evaluation of the system performance was conducted by a further simulation. The efficiency improvement of Intellevator has been quantitatively validated. Moreover, the detailed correlation between elevator environment setting and the optimization result has been identified as well.

Chapter 7

Discussion

In this chapter, a final discussion on our research is conducted. The results obtained from this research is not only to make improvement to system performance or user experience but also to give an in-depth insight into the futuristic optimal mobility platform development for the smart building.

7.0.1 Who is the ICT Service Provider?

The indoor environment of the building is semi-public open. Even though it is an essential requirement from the public perspective to develop the mobility infrastructure which covers across the barrier-free navigation, robot way-finding and emergency evacuation with high interoperability, it remains difficult to ascertain who should take on the responsibility for providing this sort of mobility service. The potential ownership of offering indoor mobility service is possibly undertaken by whoever is among stakeholders: a building developer, owner, device or facility manufacture, architects, or other information system provider.

In addition, the cause of difficulty in determining who (which stakeholder) ought to be responsible for providing this new trend of ICT (information and communication technology) service, lies in the lack of a direct economic incentive. It is also challenging for industries to undertake this program on their own. Because the

Table 6-1. Costs of Inadequate Interoperability by Stakeholder Group, by Life-Cycle Phase (in \$Millions)

Stakeholder Group	Planning, Engineering, and Design Phase	Construction Phase	Operations and Maintenance Phase	Total
Architects and Engineers	1,007.2	147.0	15.7	1,169.8
General Contractors	485.9	1,265.3	50.4	1,801.6
Specialty Fabricators and Suppliers	442.4	1,762.2	—	2,204.6
Owners and Operators	722.8	898.0	9,027.2	10,648.0
Total	2,658.3	4,072.4	9,093.3	15,824.0

Figure 7.1: Cost of inadequate interoperability by stakeholders, reprint from [7]

required effort to accomplish this mission and to put the approaches into practice is characterized as very multi-disciplinary and academic support necessary.

Nevertheless, as revealed by the report published National Institute of Standards and Technology (NIST), inadequate interoperability adds the cost burden placed on construction industry stakeholders and results in the opportunities being missed that could bring significant benefits to the public [7]. Figure 7.1 shows a large number of financial costs of inadequate interoperability of the building construction. The problem of which construction phase would be cost-less to launch this sort of mobility platform is worthy of further discussion.

In conclusion, a primary reason that currently none of organizations has willingness to provide such a beneficial indoor mobility service to the public, is understood to be the lack of direct economic incentive for industries. Innovations that are beneficial to both the elevator and the building are necessary but a strong commercial pull is required [92].

Eventually, the current situation sacrifices the continuously being ignored personal time-wasting, individual frustration. Moreover, under the urbanization de-

velopment, the height of the building as well as the population to live and work at higher altitude are increasing. The challenges arising from secure, efficient, comfortable indoor mobility also increase massively within larger and more complex buildings.

At the meantime, life safety first is accepted as a common sense and the relevant research indicated that the existing technologies and procedures could be conducive to improving indoor environments for increasing human safety and health [93]. However, considering the occurrence rate of emergency, it makes the mobility computation for emergency risk and efficient evacuation remains lacking in the actual operating system in the building.

7.0.2 Increased Physical Demand is NOT a Pain

It is essential to note that, according to the result of NASA-TLX evaluation on Intellevator, we do not consider the increase in physical demand and effort as a pain. The prevalence of sedentary lifestyles has occurred when human populations start to concentrate in urban areas, and the popularity of transportation-related occupational physical activity is falling [94]. The physical inactivity is further amplified by the risk it conveys and the significance of frequent exercise have been recognized[95]. Relevant research demonstrated that existing technologies and procedures can improve indoor environments in a manner that promotes human health indoors[93].

The benefits of walking on health management also have been validated by the related research [96]. It is hoped that optimal vertical moving plan provided by Intellevator which guide passengers to walk to another floor for taking a ride could be a considerable by-side product for increasing the frequency of indoor exercise, finally could make contribution to improving the physical health of users.

Passenger experience ought to be viewed in the context of both the individuals

and larger populations. Concerning the vertical mobility bottleneck within tall commercial buildings, balancing the passenger experience of a group of passengers with the concerns of overall time-efficiency could be rational.

7.0.3 Mobility as a Service (MaaS) Concept

Mobility as a Service (MaaS) is a mobility concept recently perceived, which gave rise to an emerging phenomenon or a new transport solution, integrating the different available transport modes and mobility services [26]. MaaS is put forward as a technology-enabled mobility management service where the multiple-mobility services are required to be incorporated into a single interface [97].

Distinct from stairs or escalators, the elevator is equipped with user interfaces for interacting with end-user. After developed with IoT and AI technologies, it also enables itself to perform the task of delivering the optimal mobility service to the end-user. These potentials bring significant possibilities for the elevator. For instance, the interface of the elevator system could be taken as a reasonable media for providing floor map reference or integration with dynamic authorizations for supporting indoor users to move in an efficient and comfortable way.

Based on this concept, the optimal but mixed vertical plan (a combination of stairs, elevator, escalator, etc.) computed by Intellevator would be regarded as reasonable because it brings benefits in respect of both time-efficiency and health management.

7.0.4 Optimizing the Planning of Elevator Deployment

As urbanization expands, the mobility of the complex indoor environment or the vertical dimension is made as equally significant as that in the outdoor horizontal dimension. Apparently, the challenges arising from the high-rise building

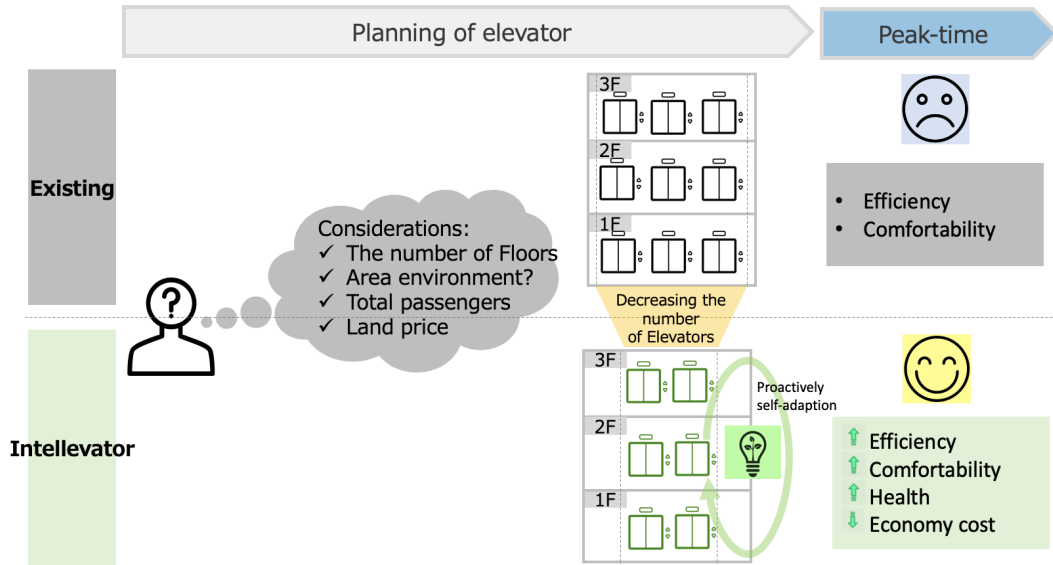


Figure 7.2: Elevator deployment planning

highlight the significance of elevator deployment. Concerning the deployment of the elevator system, as shown in Figure 7.2, traditionally, when elevators are installed, it starts with an analysis conducted of traffic demand by floor numbers, total area, building tenants, etc., before planning the numbers and specification of elevators.

The elevator specification can be made variable that need to be determined based on the requirement of building. Among the influencing factors, a significant factor is the land price that imposes restriction on the elevator numbers to be equipped. Therefore, while faced with the peak-time congestion problem, the elevator system is possible to be overload and incapable of ensuring the efficiency and comfortability of vertical movement for passengers. The problem is challenging for the reason that office building is comparatively larger and higher.

Concerning the vertical mobility problem in the continuous urbanization development, there is a necessity to balance the design, construction, and technology equipping of the building and vertical transportation systems with improvements for people that may make radical change to the move behavior to improve the

comfort, health, convenience, and time-efficiency while consequently reducing the anxiety and frustration.

The desirable system ought to provide a natural interaction with building ecosystem for a safe, efficient, intelligent, personalized experience, balancing the system performance improvement and user experience enhancement, finally providing passengers a delightful vertical motion every time.

As a means to address problem, our proposal - Intellevator system is effective in improving overall transportation efficiency based on self-adaption and proactive management. This proposal enables the elevator system to be proactive in optimizing the traffic distribution according to the status of congestion. In essence, it brings the possibility of reducing the number of elevators to be installed prior to the construction of the building, thus minimizing the economic cost and ensuring the efficiency and comfort of the uses in vertical movement as well.

Chapter 8

Conclusion

In this chapter, a final conclusion of the dissertation will be made. Besides, the future work will be described at the end.

8.1 Conclusion

This dissertation presents the research for enhancing the indoor mobility of smart building, which was conducted into indoor mobility enhancement for smart building is presented. The research problems are categorized into two perspectives: (1) the overall accessible mobility perspective and (2) the efficient vertical mobility perspective. Figure 8.1 shows the simplified diagram illustrating these two perspectives. A number of proposals comprised of fine-grained spatial modeling, accessibility semantics measurement, and dynamic facility control have been made.

Firstly, to enhance the overall indoor mobility, we proposed a fine-grained spatial model for structuring the semantic and dynamic environment. Based on the model design, we also proposed a routing mechanism that takes into consideration the accessibility semantics for context-aware routing. We implemented a systematic approach to generate path descriptions with the varying granularity of mobility-assistive information.

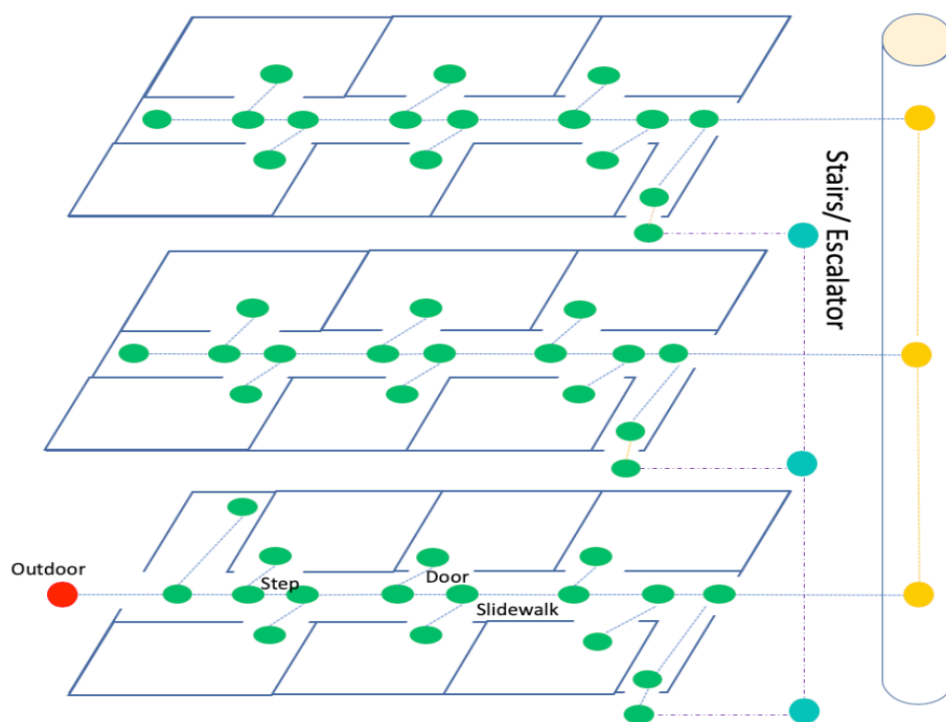


Figure 8.1: A simplified diagram shows proposals for enhancing indoor mobility

To validate the above proposal objectively, we conducted a user study with six visually impaired attended. In the user study, we also designed an effective interface to provide useful interaction and referable guidance for assisting the participants move in an efficient and smooth way. As a result, the path description with fine-grained mobility-assistive information which extracted from our proposed model made a substantial contribution to enhancing the mobility for those visually impaired participants. Besides, the designed interface also has received relatively good acceptance.

Secondly, from the perspective of efficient vertical mobility, we also proposed elevator-centric control optimization to enhance vertical mobility. Elevator plays a significant role in vertical mobility. However, the limited elevator physical capacity and the momentary traffic increment during the peaktime give rise to the persistent problem of vertical traffic bottleneck. Furthermore, the internal mathematical optimization on the controller makes the insufficient efficiency improvement.

In the research, we came up with the elevator-centric control optimization to improve the indoor vertical mobility. Upon the development of IoT-enabling hardware as a first step, an agent server architecture was suggested to enable elevator computation capability. Based on this fundamental architecture, we developed two implementations to ensure the indoor vertical mobility enhancement for the end users.

One implementation is called PrecaElevator, which is integrated with the localization platform for location-aware on the passenger side. The proposal makes passengers able to pre-register elevator call when they have the intention for using the elevator. We conducted experiment with the proposed system in the real smart building environment. The effectiveness was verified by simulations of learning waiting time from the historical data over five months, which demonstrated the massive potentials for reducing passengers' waiting time. Different from the previous works, this proposal made attempt to allow pre-registration of elevator call by

applying the context-aware platform to the agent server with no addition of any off-line sensors. Therefore, the minimum cost incurred from hardware development and flexibility were made possible.

Another implementation is named Intellevator, premised on a more advanced user interface for the provision of information visualization, simplicity in operation, and intelligence for the end users. Meanwhile, to seek the time-efficiency, Intellevator system has the capability to make real-time prediction of the upcoming fine-grained traffic flow, then to enforce proactive management of the traffic distribution based on self-adaption on the designed user interface. For passengers, other time-efficient plans would be presented for vertical moving by the Intellevator system. We carried out experiment with the Intellevator by integrating with a conventional elevator system and performed both a user study and simulation to validate the effectiveness of our proposal. As a result, both the user acceptance of the novel usage and system improvement were validated quantitatively, which indicated that our proposal was effective.

8.2 Future Work

In this dissertation, the novel approaches to indoor mobility enhancement for smart building is proposed. There remain some areas that this research has yet to cover. In the long run, we are going to develop the upper-layer mobility enhancement applications for a variety of potential users.

One of the major directions is robot navigation in the smart building by providing assistance in support of indoor mobility for robotic devices, such as personal transporter. Our future research is aimed at combining environmental modeling with robotic mobility. This advancement will provide inspiration for other novel aspects in the area of indoor robotic mobility computation, which will help achieve the ultimate objective of empowering fine-grained context-aware indoor navigation.

With regard to elevator-centric vertical mobility in particular, at present, there remains a lack of the mechanism for automatic interaction between robot and elevator. This causes robot to be incapable of making assessment of the typical elevator. In some specific environment, such as warehouse, the interaction between elevator and robot could take place under the local machine to machine (M2M) specification. Nevertheless, the feasibility and applicability of the solution has been restricted.

The research of opening the framework for assisting the robot's autonomous movement on the elevator is regarded as a crucial requirement for the mobility platform development of the smart building. Smart buildings themselves are in the best position to find the solutions, considering their own dynamically changing physical and semantic environment in real-time. Shortly, we are going to conduct the research into indoor robotic authorization and mobility management from the perspective of smart building supervision to provide more practical insight into the society, which hopefully contributes to the further development of the indoor mobility research.

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