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Design and Development of Location Based Action Support Systems

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List of Publications

Journal Papers Corresponding to Thesis

1. Noboru Kiyama, Junko Kusuda, Sae Fujii, Akira Uchiyama, Akihito Hiromori, Takaaki Umedu, Yoshitaka Nakamura, Yasumasa Oode, Hiroshi Tanaka, Hirozumi Yamaguchi and Teruo Higashino: "An Advanced Electronic Triage System for Rescue Operations in Disasters," *IPSJ Journal*, vol. 51, no. 9, pp. 1916–1929, September 2010, (in Japanese).

2. Noboru Kiyama, Akira Uchiyama, Hirozumi Yamaguchi and Teruo Higashino: "Evaluation of Localization Algorithms Based on Accuracy of Relative Positions," *IPSJ Journal*, vol. 52, no. 1, pp. 209–219, January 2011, (in Japanese).

3. Noboru Kiyama, Akira Uchiyama, Hirozumi Yamaguchi and Teruo Higashino: "Quantifying Relationship between Relative Position Error of Localization Algorithms and Object Identification," *Wireless Networks, Springer*, October 2012.

4. Yuichi Kobayashi, Noboru Kiyama, Hirokazu Aoshima, Keisuke Shirai and Masamori Kashiyama: "A Route Search Method for Electric Vehicles in Consideration of Cruising Range and Charging Time," *IPSJ Journal*, vol. 54, no. 1, pp. 156–165, January 2013, (in Japanese).

Conference Papers Corresponding to Thesis

1. Noboru Kiyama, Yuichi Kobayashi, Hirokazu Aoshima and Masamori Kashiyama, "A Route Search Method for Electric Vehicles in Consideration of Range and Locations of Charging Stations," *Proceedings of*

the 2011 IEEE Intelligent Vehicles Symposium (IV 2011), pp. 920–925, Baden-Baden, Germany, June 2011.

Abstract

In recent years, ICT systems which support advanced and complicated social infrastructures have been developed more actively. Especially, along with the popularization of high-speed wireless networks and large-scale data processing technologies, recent ICT systems supporting social infrastructures gather the data sensed by their components, analyze them and feed the results back into the systems. Monitoring social infrastructures comprehensively enables us to support optimizations of system architectures and users' behavior. According to social demands for more intelligent systems, a variety of ICT-based social systems have been developed. Furthermore, the Japanese government has set the national agendas for the achievement of more energy-efficient, human-oriented services using ICT.

Such ICT-based systems generally need to incorporate location information of people, machines and devices to provide context-aware, situation-dependent services for service users. In this thesis, we focus on two typical key ICT-based social infrastructures that are quite essential for green and life innovations. In particular, we propose two location-based activity support systems: (i) a vehicle telematics system to aid battery-charging activities by electric vehicles' drivers and (ii) an electronic triage system that supports rescue operations of first responders in emergency sites. We discuss fundamental technologies that are required to achieve these systems, and among those technologies we particularly deal with a relative location assessment methodology.

Firstly, we describe the telematics system for electric vehicles. In recent years, electric vehicles with less impact on environments due to its energy consumption feature than internal combustion engine vehicles have become popular and got more attractions. However, there are always some concerns that their cruising range is not sufficient enough to travel long distance and that charging

stations, instead of gas stations, are not sufficiently and nation-widely installed. Thus, other low emission vehicles, such as hybrid electronic vehicles, are considered more convenient than electric vehicles today. To tackle this problem, we propose a route planning and navigation system that helps drivers to decide a route with charging stations on the way, considering the location and residual battery of electric vehicles. The system tries to search possible routes that enable the EV drivers to stop over the charge stations when more electricity is required to reach the destination. Offering such routes to drivers will eliminate a part of the major concerns in driving electric vehicles and support their comfortable travel.

Secondary, we describe the design and development of an electronic triage system, which helps a medical team to efficiently treat patients on mass casualty incidents. Triage is a process of prioritizing casualties based on the severity of their conditions when a large number of people are injured simultaneously. In current practice, a paper tag is attached to each patient to indicate his/her priority of treatment. However, paper tags do not represent dynamic change of patients' conditions, and medical team members are not able to be aware of their condition changes. In our proposed system, instead of paper tags, electronic triage tags are attached to patients, and a server aggregates their vital signs transmitted over radio signals by these tags in real time. Concurrently, this system estimates the positions of patients by using wireless network topology information. Providing vital signs data and location information of patients will support medical team members to carry out efficient medical activities under severe conditions.

Thirdly, we describe a method to evaluate the performance of different localization algorithms. Positions of people or objects estimated by localization algorithms generally contain some errors depending on the target environments. Such errors that cause mismatching between estimated positions and ground truth should be represented not only by the deviation from the true positions but also by the deviation from the true "position relationship". Although the term "relative position" partially captures the concept of position relationship, it does not take the impact on people's object identification into consideration. Hence, we propose a method to quantify the impact of positioning errors on people's identification of objects independently of specific localization algorithms.

In the proposed method, we define criteria that represent proximity and uniqueness of neighboring targets, to access the "accuracy" of the estimated positions in identifying the objects at true positions. Based on these criteria, position errors are quantified by Degree of Discrepancy in Delaunay triangulation formed on a set of estimated positions to be accessed and the corresponding set of real positions. This proposed method can support to select an optimal localization algorithm for location-based activity supports.

In summary, in this thesis, we focus on two location-based systems that support service users to make some decisions on their activities. One is a telematics system for electric vehicles to support comfortable driving and another is an electric triage system to achieve efficient treatment in disasters. Such support systems are quite essential to innovate our life in terms of energy-saving and risk reduction. Additionally, we propose a method to evaluate localization algorithms based on people's identification of objects, which is a part of essential functions in those systems. Through the design and development of those systems, we reveal the required technologies to achieve truly-innovative ICT applications that are often designed based on location of people, objects and environments. The system users and those who are engaged in severe tasks will be beneficial in determining their strategies of decision making. The goal of this thesis is to contribute to the establishment of design methodologies in these application domains that are profoundly related with locations-based systems.

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Chapter 1

Introduction

In recent years, ICTs play a key role in a variety of social systems such as large-scale vehicle traffic monitoring in intelligent transportation systems, object tracking systems for efficient logistics and smart agriculture. These systems, which we call social infrastructures, cannot be designed and developed without ICT support and ICTs allow us to construct more complicated and advanced social systems. Especially, along with the popularization of high-speed wireless networks and large-scale data processing technologies, recent ICT systems supporting social infrastructures gather the data sensed by their components, analyze them and feed the results back into the systems. Monitoring social infrastructures comprehensively enables us to support optimizations of system architectures and users' behavior. According to social demands for more intelligent systems, a variety of ICT-based social systems have been developed.

Furthermore, the Japanese government has also recommended in their proposals to utilize ICTs for the establishment of better organization of communities, more efficient social systems and more ubiquitous computing environment. For example, "fourth periodic master plans of science and technology [1]" has been proposed to use ICT for promotion of green and life innovations in order to realize the societies of stable energy supplies, low carbon and safety efficient treatments. "The 100th Council for Science and Technology Policy [2]" has mentioned that reconstructions from the Great East Japan Earthquake should be important issues solved by science and technology. Additionally, "the 108th Council for Science and Technology Policy [3]" has referred to the expectation for scientific technologies in order to diversify energy supplies and support smart mobility. “White Paper of Information and Communication in 2012 [4]” and “White Paper of Disaster Prevention in 2012 [5]” have reported the proposals to apply information technologies to achieve robust infrastructure against disasters, such as establishment of electronic local administrations and securement of lives on disasters by information distribution. Furthermore, “Strategy for New Generation of Vehicles in 2010 [6]” has referred to the long term strategy for growth of the automobile industry promoting aggressive export of next generation vehicles as the instruments of energy management systems. Accordingly, the Japanese government has set the national agendas for the achievement of more energy-efficient, human-oriented services using ICT.

Such ICT-based systems generally need to incorporate location information of people, machines and devices to provide context-aware, situation-dependent services for service users. For example, delivery management systems [7] need location information of destinations in addition to departure time, desired delivery time of each item and traffic jam information to calculate the optimal transmission order of delivery. Also, personalized advertisement services [8] may need users' trajectories and location information at stores as well as information on the users' favorite items to provide advertisements in a timely fashion.

In this thesis, we focus on two typical key ICT-based social infrastructures that are quite essential for green and life innovations. In particular, we propose two location-based activity support systems: (i) a vehicle telematics system to aid battery-charging activities by electric vehicles' drivers and (ii) an electronic triage system that supports rescue operations of first responders in emergency sites. We discuss fundamental technologies that are required to achieve these systems, and among those technologies we particularly deal with a relative location assessment methodology.

Firstly, we describe the telematics system for electric vehicles. In recent years, electric vehicles (EVs) with less impact on environments due to its energy consumption feature than internal combustion engine vehicles have become popular and got more attractions. Unlike internal combustion engine vehicles (ICEVs) which use fossil fuels, EVs only use electricity while running. Electricity generated by solar or nuclear power generation does not consume fossil fuels and emits less greenhouse gases. Also ICEVs are less efficient in energy

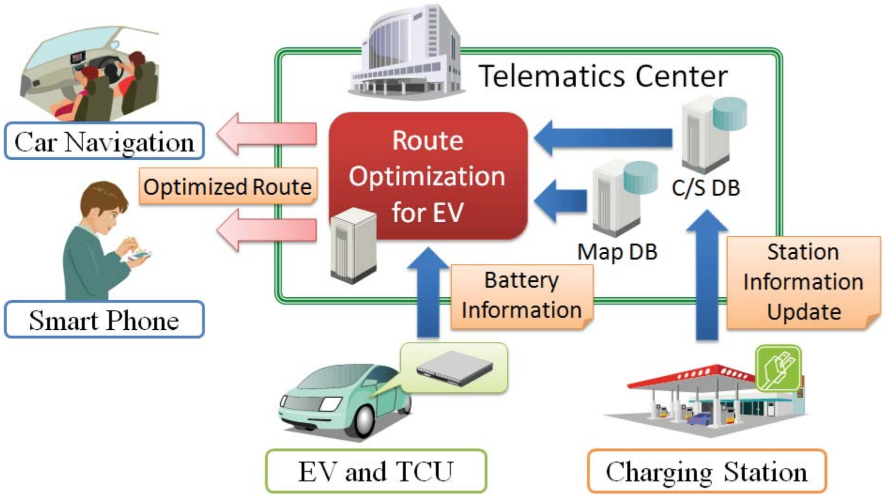


Figure 1.1: Overview of telematics system for electric vehicles

conversion than generation of electricity. Since shifting from ICEVs to EVs will contribute to ecology, governments of several countries are promoting EVs and subsidy programs for EVs are operated in Japan, the U.S., Europe and so on [9, 10, 11].

On the other hand, there are still some disadvantages of EVs. For example, (i) the cruising range of EVs, that is the travel distance without recharging batteries, is around 200km and is shorter than that of ICEVs because of the limited capacity of the batteries, and (ii) the number of battery charging stations is around 4000 in Japan, which is just one-seventh of whole gas stations in nation [12] and (iii) at least 30 minutes up to several hours are needed for fully charging battery at C/Ss. Many drivers are worry about long distance travel by EVs [13, 14] and it prevents promotion of EVs. Thus, other low emission vehicles, such as hybrid electronic vehicles, are considered more convenient than EVs today.

To tackle this problem, we propose a route planning and navigation system that helps drivers to decide a route with charging stations on the way, considering the location and residual battery of electric vehicles. The overview of the proposed telematics system is shown in Fig. 1.1. Telematics Communication Units (TCUs) which can access EVs' Controller Area Networks (CANs)

[15, 16, 17] and mobile networks are equipped with EVs. The telematics system communicates with EVs over the mobile networks and gathers the battery information as probe data, such as battery capacity and state of charge, of the requesting user's EV obtained from CANs by TCUs. The telematics system searches the route using this information of EVs in addition to the latest map information and locations of charging stations stored on the system.

In the proposed route search method, we prepare a directed graph where nodes represent the origin, destination and charging stations. We generate directed links among nodes through which EVs can drive from one node to another without exhaustion of batteries. The weight of each link represents travel time between nodes plus charging time required to arrive at the next charging station. The charging time is calculated by an electric power level that differs in charging stations. We search a least-time (minimum travel time including charging time) route from candidate routes on which EVs stop over charging stations. Such a set of routes can be obtained by applying the Dijkstra's method on this graph, and offering it to drivers will eliminate a part of the major concerns in driving EVs and support their comfortable travel.

Secondary, we describe the design and development of an electronic triage system which helps a medical team to efficiently treat patients on mass casualty incidents. Triage is a process of prioritizing casualties based on the severity of their conditions when a large number of people are injured simultaneously. When applying triage, the priority of each victim for treatment and transportation is decided on the basis of his/her vital signs. Triage aims to save as many victims as possible by deciding the order of treatment under the situation where medical resources such as medical staff are limited. In current practice, a paper tag is attached to each patient to indicate his/her priority of treatment. However, paper tags do not represent dynamic change of patients' conditions, and medical team members are not able to be aware of their condition changes. It is required to check patients' conditions continuously in order for avoiding sudden worsening, while limitation of medical resources causes serious problems.

Thus, we propose an electronic triage system to support medical team members to carry out efficient medical activities under severe conditions. The overview of the electronic triage system is shown in Fig. 1.2. In our proposed system, instead of paper tags, electronic triage tags are attached to patients.

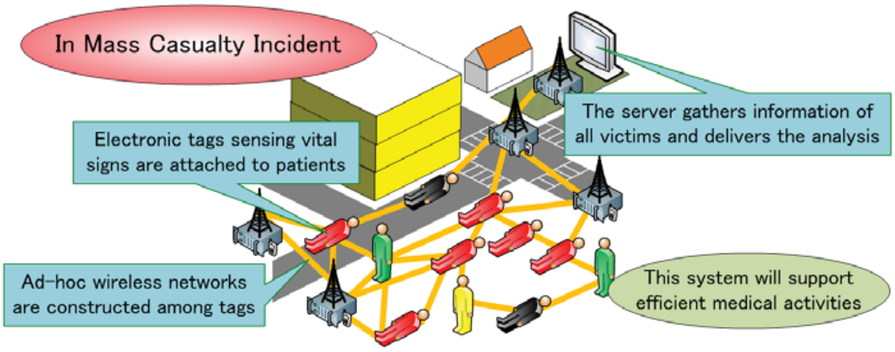


Figure 1.2: Overview of electronic triage system

This tag senses vital signs of each person and transmits the data to a server which is installed at a disaster countermeasures office via ad-hoc wireless networks. The server gathers information of all victims and delivers the analysis data to dedicated terminals kept by medical staff members. Concurrently, this system estimates the positions of patients and medical team members by our ad-hoc localization algorithm using wireless network topology information. A disaster countermeasures office and medical team members can check patients' vital signs and positions by their own specific devices. Such terminals enable medical team members to monitor dynamic change of victims' physical conditions in real time and to decide priorities of treatment and transportation of victims by comparing all of their vital signs and positions. Additionally, the disaster countermeasures office can provide appropriate instructions to medical staff members based on obtained vital signs and location information. Providing vital data and positions information of patients will support medical team members to carry out efficient medical activities in the situation where medical resources are limited.

Thirdly, we describe a method to evaluate the performance of different localization algorithms. Positioning systems have been investigated so far for location-aware services such as outdoor/indoor navigation and personal object identification in rooms. Positions of people or objects estimated by localization algorithms generally contain some errors depending on the target environments such as node densities and a number of landmarks. Such errors that cause mismatching between estimated positions and ground truth should be represented not only by the deviation from the true positions but also by the deviation from the true "position relationship". Although the term "relative position" partially captures the concept of position relationship, it does not take the impact on people's object identification into consideration. In the case of the electronic triage system, for example, if estimated positions of patients do not represent position relationship accurately, medical team members may mistake a patient who requires treatments for another patient.

Hence, we propose a method to quantify the impact of positioning errors on people's identification of objects independently of specific localization algorithms. Given a set of estimated positions of target objects and the anonymous set of their true positions, we propose criteria to access the "accuracy" of the estimated positions in identifying the objects at true positions. The proposed accuracy criteria can be used in design, development and evaluation of localization algorithms that are used to tell people the location of objects. To define the criteria without ambiguity, we prove that (i) neighbor proximity and uniqueness are significant factors to identify objects and the Delaunay triangulation captures these properties, and (ii) grouping of nearby neighbors should also be considered and properly-designed clustering captures the property. Then "position relationship dissimilarity" is defined by the Degree of Discrepancy (DoD) of Delaunay triangulations on estimated and true positions considering clusters. The proposed method can support to select an optimal localization algorithm for location-based activity supports.

In summary, in this thesis, we focus on two location-based systems that support users to make some decisions on their activities. One is a telematics system for electric vehicles to support comfortable driving and another is an electric triage system to achieve efficient treatment in disasters. Such support systems are quite essential to innovate our life in terms of energy-saving and risk reduction. Additionally, we propose a method to evaluate localization algorithms based on people's identification of objects, which is a part of essential functions in those systems. Through the design and development of the proposed systems, we reveal the required technologies to achieve truly-innovative ICT applications that are often designed based on location of people, objects and environments. The system users and those who are engaged in severe tasks will be beneficial in determining their strategies of decision making. The goal of this thesis is to contribute to the establishment of design methodologies in these application domains that are profoundly related with locations-based systems.

This thesis is organized as follows. In Section 2, we address the related work and contributions of our methods. In Section 3, we describe route search methodology and algorithm to provision the proposed telematics service, which calculates an optimal route considering the locations of charging stations and residual batteries. In Section 4, we propose an electronic triage system for rescue operation on disasters. In Section 5, we propose a method to quantify the relationship between position errors of localization algorithms and human object identification. Section 6 concludes this thesis.

Chapter 2

Related Work

2.1 Localization Algorithm Classification

In this section, we briefly address the classification of localization algorithms. We note that this section is not intended to survey individual localization algorithms, but to categorize existing localization algorithms.

Range-based localization techniques rely on distance estimation by received signal strength (RSS) to distance mapping, Time Of Arrival (TOA) by ultrasound or audible sound, Time Difference Of Arrival (TDOA) in ultra wide band or simultaneous use of RF and ultrasound [52] and so on. Directional antennas are often used to estimate Angle Of Arrival (AOA). Based on the ranging technique, this category can further be categorized into two different types of localization algorithms. Single node localization uses tri- or multi-lateration where distance or angle information from at least three reference points is used to determine the location (GPS falls into this category). Wi-Fi and/or cellular fingerprinting such as [53] also fall into this category. On the other hand, MDS-MAP [54] is a known algorithm for localizing multiple nodes simultaneously. It uses shortest path information or other ranging techniques to estimate the distance, and uses “multidimensional scaling” to determine their positions.

Range-free techniques are cost effective alternatives since they only require a communication capability. Amorphous [55] is a well-known range-free algorithm that utilizes hop counts from landmarks, where each node estimates its coordinates by finding coordinates that minimize the total squared error between the calculated and estimated distances. TRADE [56] is a constraint-based algorithm to localize mobile nodes. It constrains regions to be searched for node positions from temporal-spatial information about wireless connectivity and movement, and estimates likely points from the regions that satisfy the constraints.

In following sections, we mention some works of action support systems using location information, which are related to our proposal systems. We also describe contributions of our methods.

2.2 Telematics System for Electric Vehicles

2.2.1 Services for Electric Vehicles

In order to eliminate concerns of users about short cruising range or shortage of charging stations and to enhance the convenience of driving by EVs, many telematics services, such as accurate cruising range calculation and route search for EVs, have been proposed so far [18, 19, 20, 21].

Refs. [22, 23, 24] propose methods to determine optimal locations to construct new C/Ss based on driving history, called probe data. In Ref. [22], optimal locations are decided on the basis that EVs can also drive the same routes, which ICEVs could have driven, without battery down in a case that new C/Ss are allocated to existing gas stations. In Ref. [23], firstly states of EVs are separated into three states: (i) driving to destination, (ii) driving to C/Ss, (iii) charging at C/Ss. Optimal locations are calculated by evaluation based on charging time, travel time to stop over C/Ss and equalization of electricity consumption at each C/S.

Additionally, Ref. [25] proposes an optimal location method for particular C/Ss, which have batteries for EV' charge, do not need to connect to power grids and can move. At normal time, these C/Ss are gathered at facilities for charging. These C/Ss are located at optimal locations by tracks according to charging demand of driving EVs. Optimal locations are determined by the number of EVs which can reach to the candidate locations with their current remaining battery level.

In Refs. [26, 27, 28], the authors have proposed optimization methods for charge/discharge schedules considering power limits or available time of power grids. Ref. [26] mentions a method using an evolutionary algorithm to optimize an EV charge or discharge schedule in consideration of power limit of grid, electric bills, battery degradation, and user requirements of charging amount and origin time. Ref. [27] describes a method to determine charging or discharging time of each EV for electric-load leveling based on user requests of charging start time, charging stop time and amount of charge.

Refs. [29, 30, 31, 32, 33, 34] propose methods for EVs to search routes which have minimum power consumption from the origins to the destinations. Ref. [29] describes the fast calculation method to search minimum power consumption routes by pre-calculating costs of roads. In pre-calculation, amounts of electrical energy production of regenerative brakes on each road are estimated based on the map information including altitude data. In Ref. [30], a minimum energy consumption route is derived by solving a shortest path problem with constraints of SoC and battery capacity. In this calculation, travel costs of each road are defined as energy consumption or generation in consideration of regenerative brakes.

Furthermore, Refs. [35, 36] propose methods to display reachable areas of EVs on maps dynamically. In addition to map information included in car navigation systems, the methods consider information such as air temperature, wind velocity and gradient managed at telematics centers for calculation of reachable areas. These methods calculate accurate reachable areas by applying optimal driving models [37, 38].

2.2.2 Our Contributions

In order to enhance the convenience of driving by EVs, many works have proposed optimization of C/S allocation, charge-discharge schedule optimization methods and route search methods for EVs. These methods reduce concern about short cruising range and shortage of charging stations. However, these methods do not eliminate concern about battery down during long-distance travels by EVs. Under present circumstances, users are forced to worry about remaining battery level and locations of charging stations by themselves while long distance driving. Therefore, the above existing methods are not comprehensive solutions.

In this thesis, firstly we select optimal stopover C/Ss depending on EVs' cruising range, travel time and charging time before we search the route from the origin to the destination. After that, we calculate some routes via selected stopover C/Ss, where there is no need to concern for battery down during driving EVs. Offering such routes to drivers eliminates a part of the major concerns in driving EVs and contributes to the spread of EVs.

2.3 Action Support System for Rescue Operations

2.3.1 Triage System using Electronic Tag

In the United States, some projects by NASA, FEMA and NLM (The National Library of Medicine) have investigated advanced medical support systems using wireless communication technology. AIDN (Advanced Health and Disaster Aid Network) [39, 40] uses a sensor platform called CodeBlue [41, 42] developed by Harvard University. CodeBlue is composed of small sensor nodes called Motes, and provides vital sign gathering and estimated location information of nodes. Localization is based on fingerprinting, which requires building a database of radio characteristics at each location beforehand. In addition, miTag presented by AID-N project in 2008 is capable of providing location information of nodes by an embedded GPS chipset. Similarly, WIISARD (Wireless Internet Information System for Medical Response in Disasters) [43] by Tech Specs also investigates an advanced medical support system by using wireless networks.

By contrast, in Japan, NICT and JAXA have collaborated on a demonstration experiment for evaluation of a disaster prevention application using mobile phones with satellite communication [44]. Additionally, in a special project of Ministry of Education, Culture, Sports, Science and Technology in Japan for earthquake disaster mitigation in urban areas, they have attempted to construct an infrastructure with high ability to respond to disasters in cooperation with rescue robots [45]. Ministry of Internal Affairs and Communications in Japan has suggested that electronic tags should be applied to disaster damage tracking and support triage in the report [46]. In Ref. [47], a case of applying IC tags to triage is reported. But any localization technique to detect patients is not incorporated. With respect to localization of wireless IC tags, for example, Ref. [48] proposes a method to estimate positions of tags under the situation where each tag is allocated in a mesh pattern.

2.3.2 Our Contributions

In this thesis, we show the design of eTriage and an overview of helpful functions. Different from the existing approaches, we have designed two types of electronic triage tags and tested our system in cooperation with doctors at an emergency department. In the existing systems such as CodeBlue, GPS devices or ultrasonic devices with dedicated base stations are needed to estimate tags' positions indoors. By contrast, in consideration of requirements for weight saving, prolonged operation and cost saving, eTriage provides a location service platform and an algorithm which only assumes connectivity information among nodes obtained by vital sign transmission.

2.4 Evaluation Method for Localization Algorithm

2.4.1 Relative Position Accuracy

There have been several researches that deal with relative position accuracy [49, 50, 51] in different research domains. For example, Ref. [51] in the computer vision research considers the correctness of relationship between two objects by shapes or directions in 2D or 3D space. However, these approaches do not consider the correctness of position estimation in terms of object identification.

Relative positioning accuracy analysis has been achieved in wireless sensor network localization by several papers like Refs. [49, 50]. Most of these papers dealing with relative positioning accuracy have focused on the *errors from the measurement*. Since the anchors are not concerned in relative positioning, errors are usually defined as deviation from the measurement such as distance, angles and RSS. Therefore, these approaches are different from ours since they do not take the impact on people's object identification into account. In other words, they are defined independently of application context.

2.4.2 Delaunay Triangulation for Similarity Quantification

Pattern matching problems in image recognition deal with quantifying relationship between two objects. The basic algorithm usually consists of two processes; feature extraction and identification. The former process extracts significant points (e.g. a nose or eyes in facial recognition) from input data. The latter process quantifies these significant points by classifying or categorizing them. There are two types of identification in pattern matching problems. One is statistical pattern recognition which compares input data with enormous accumulated data. The other is structural pattern recognition which analyzes deployment of significant points obtained from input data. Therefore prior knowledge is not required. For example, in Ref. [57], eigenvectors are used for identification in facial recognition. In Ref. [58], singular points are used for identification in image matching. Ref. [59] obtains relationships between significant points using the Delaunay triangulations for identification in fingerprint matching.

Ref. [60] proposes an algorithm to group points using Reduced Delaunay Graphs (RDGs). It is based on the Gestalt law of proximity in Gestalt psychology [61] that suggests the law of proximity as an important factor of grouping objects in human perception.

These approaches use the Delaunay triangulation to represent the feature amount of given images. Our approach is completely different in the sense that we aim at quantifying the relationship between localization errors and object identification, and use the Delaunay triangulation and clustering for such quantification.

2.4.3 Our Contributions

To the best of our knowledge, this is the first approach that quantifies localization errors in the context of object identification. As briefly discussed in Section 2.4.1, the existing approaches that have dealt with relative position accuracy [49, 50] are different from ours in the sense that they consider relative position errors, which are defined by distance among objects and relative angles. We can intuitively understand that the "relative position errors" may represent some features of algorithm performance in object identification, though discussion has not been given and corresponding criteria have not been quantitatively defined. Meanwhile, our approach considers several features in object identification, such as proximity-uniqueness property, clustering and viewpoints. Justification has been done by experiments and subjective tests using questionnaires and a tool developed for this purpose. As stated in Sec. 2.4.2, the notion of Delaunay triangulation similarity is found in image recognition, but they use the Delaunay triangulations only to characterize point patterns. In other words, they use only the planer-graph property to characterize a point distribution on a 2D plane.

We believe that new mobile and pervasive applications like navigation of articles and people are beneficial from our approach to assess adequacy of positioning systems they use.

Chapter 3

A Route Search Method for Electric Vehicles in Consideration of Cruising Range and Charging Time

3.1 Introduction

In this chapter, we propose a route search method for electric vehicles. We aim to provide a telematics services based on the method and support the drivers of electric vehicles.

In recent years, many car companies are getting active in development and production of electric vehicles (EVs) as a measure against global warming and exhaustion of fossil fuels. Unlike internal combustion engine vehicles (ICEVs) which use fossil fuels, EVs only use electricity while running. Electricity generated by natural energy, such as wind power or solar power, does not consume fossil fuels and emits less greenhouse gases. Shift type of driving car from ICEVs to EVs should contribute to ecology. Thus, some governments are promoting EVs and subsidy/tax cut programs [9, 10] or mandatory minimum sales [11] for EVs are operated in Japan, the U.S., Europe and so on.

On the other hand, there are still some disadvantages of driving EVs. (1) The cruising range of EVs, travel distance without recharging batteries, is around 200km and shorter than that of ICEVs because of the limited capacity of the batteries. (2) The number of battery charging stations(C/Ss) is around 4000 in Japan. This is seventh part of that of gas stations [12] so that C/Ss are not common enough to be found everywhere needed. (3) Between 30 minutes and several hours are needed for fully charging battery at C/Ss. Many drivers are anxious about long distance travel by EVs [13, 14, 62] so that these problems prevent to promoting diffusion of EVs.

In this paper, we propose a new route search method for EVs to eliminate concerns of users about the short cruising range and the shortage of charging stations. In this method, firstly we prepare a directed graph consisting of the origin, the destination and charging stations as nodes. We generate directed links among each node which the EVs can drive from a starting point to an end point without battery down. The weight of each link consists of not only travel time among nodes but also charging time required to arrive the next charging station. The charging time is calculated by an electric power depending on types of C/S. And we search a least-time (minimum travel time including charging time) route from some routes which stop over charging stations by applying Dijkstra's method on this graph.

We implemented this method to evaluate reduction in travel time including charging of the route. And we compare some routes calculated by the proposed method with the method which uses only travel time for weight. Through the evaluation, it was confirmed that travel time between the origin point and destination calculated by the proposed method was slightly longer than that by the conventional method, but travel time including charging time was 62% shorter than that.

3.2 Route Planning Algorithm

3.2.1 Considering Characteristics of Electric Vehicles

As is the case with ICEVs, many types of EVs are selling and their battery capacities are different among car types. Additionally, a cruising range of each EV is different from its remaining battery level (SoC: State of Charge) and from each driver according to and his/her technique. Under the situation where EVs' cruising range is not enough, these differences greatly affect the calculation of accurate optimal routes and user's travels. Thus, in this paper, we introduce a parameter Electric Mileage (EM), a certain cruising range per $1kWh$ in order to consider the variation of types of EV, SoC and drivers. Each user's value of electric mileage can be calculated by driving history, which is transmitted to a telematics center via TCUs.

Furthermore, EVs generally have regenerative braking systems which enable to generate electric power when breaking. Thus, the values of electric mileage vary according to gradient of roads. So we should consider gradient information about the route, which users will drive, for calculating accurately the value of electric mileage. For simplification, however, we leave gradient information out of view for searching route and define that a cruising range bears a proportionate relationship to SoC.

Cruising range of each EV is calculated with the value of electric mileage EM (km/kWh) and remaining battery level BL_R (kWh). Cruising range CR_R (km) is calculated by

$$CR_R = BL_R \times EM.$$

Likewise, cruising range of each EV with full charged battery CR_F (km) is calculated by

$$CR_F = BL_F \times EM.$$

On the other hand, unlike gas stations, there are some types of C/Ss. Currently, C/Ss are mainly divided into two types, "normal charging stations" [63] and "rapid charging station" [64, 65, 66]. Normal charge is compatible with ordinary electric outlet at home. But it requires quite a longer charging time such as several hours and is not suitable for use during travel. In contrast, quick charge takes a shorter charging time, such as around 30 minutes, but it requires dedicated infrastructure of electricity. This prevents wide spread of charging stations having the rapid charging stations. For providing optimal routes, because of these reasons, our method needs to search the most cost effective route from routes with some charging stations. The cost mentioned here means a traveling distance or travel time required to move from one point to another and it will be described in detail later. That is, we should search a route via as many rapid charging stations as possible for reducing travel time including charging time. After that, we define "travel costs" as the sum of travel time and charging time of a route. Additionally, in the proposed method, the difference between

Table 3.1: Input and output data in the proposed method

Data	Parameter	Symbol
Input	State of Charge	BL_R (kWh)
	Battery Capacity	BL_F (kWh)
	Cruising Range with Current State of Charge	$CR_R(km)$
	Cruising Range with Fully Charged Battery	$CR_F(km)$
	Electric Mileage	EM (km/kWh)
	Charging Stations (Location Information)	$CS_1, CS_2, \ldots, CS_i$
	Charging Efficiency of CS_i	CE_i (kW)
	Origin Point	Dep
	Destination	Des
Output	Search Result of EV Assist Route	$EVR(Dep, Des)$
	Travel Distance	$EVD(Dep, Des)$ (km)
	Travel Time including Charging Time	$EVT(Dep, Des)$ (h)
	Stopover Charging Stations	$SCS_1, SCS_2, \ldots, SCS_j$ (km)

a normal charge station and a quick charge station is expressed by Charging Efficiency, which is equivalent to output electric power. A charging efficiency of each C/S is expected to be provided by database along with location of charging stations.

In the proposed method, we provide a route called "EV Assist Route" which allows a user to stop over some charging stations $SCS_1, SCS_2, \ldots, SCS_j$ to charge a battery before it being dead if the EV cannot directly reach the destination with the current remaining charge. After that, the EV Assist Route from the origin Dep to the destination Des is shown as $EVR(Dep, Des)$. In addition, we also calculate the travel distance $EVD(Dep, Des)$ (km) and travel cost $EVT(Dep, Des)$ (h) as a result of the EV Assist Route. Input and output parameters for the algorithm are defined as shown in Table 3.1.

These input parameters are gathered from electric vehicles, charging stations and map information by using telematics systems. In the proposed method, we search optimal routes via some charging stations based on the obtained information before departure. On the other hand, due to occurrence of new traffic jams or changes of C/S availability, the calculated routes may cause delays in travel times. Because it is difficult to predict accidents, traffic jams and all drivers' behaviors correctly, we focus on the method to search optimal routes based on the parameters which can be obtained before calculation. We also consider that optimal routes should be re-searched in the case of unscheduled events and re-calculated routes including new stopover C/Ss should be presented to EV users.

The algorithm uses a conventional route search algorithm for the search of sub routes between points on a route. A sub route means a route from the origin point to a charging station, a route between charging stations and a route from a charging station to the destination. If we take into account gradient information of maps, we should use the optimal route search method for EVs proposed in Refs. [29, 30]. In this paper, described as above, we simplify and use the conventional route search method for ICEVs. If this route search function is defined as F, input parameters for F are a start point and an end point. Output parameters of F are a route, distance of the route and traveling time of the route. Hereafter, $R(P_1, P_2)$ stands for calculated route between start point P_1 and end point P_2, $D(P_1, P_2)$ stands for route distance and $T(P_1, P_2)$ stands for traveling time. Connection of routes is described by the "+" symbol. That means a route from point S to point G via point T is described as $R(S, T) + R(T, G)$.

Details of this algorithm are to be described by three steps: (1) the method to select potential stopover charging stations according to a SoC and a distance between the origin and the destination, (2) the method to generate a directed graph consisting of the origin, the destination and charging stations as nodes, (3) the method to search a minimum travel cost route based on Dijkstra's method.

3.2.2 Selection of Potential Stopover Charging Stations

When we search an EV Assist Route, the accuracy of route search results is improved depending on the number of potential stopover C/Ss. On the other hand, increasing the number of C/Ss causes increase of executing time. For example, when we search the EV Assist Route from Yokohama station to Tokyo station, it is not suitable to consider all of C/Ss located in Japan as potential stopover C/Ss. Thus, we should limit appropriately the area located in potential C/Ss to stop over. There are many kinds of methods to restrict potential C/Ss and, in this thesis, we use a distance L in a straight line between the origin

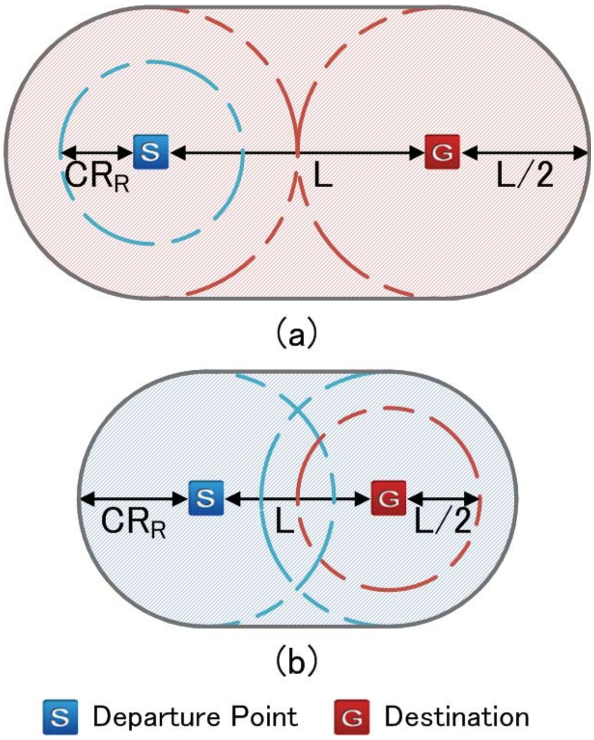


Figure 3.1: Search area for potential stopover charging stations, (a) in case of $CR_R < L/2$, (b) in case of $CR_R > L/2$

and the destination as a benchmark. In order to select optimal potential C/Ss, firstly two circles described as follows are drawn.

Circle 1 A circle having the origin as the center and $L/2$ as the radius.

Circle 2 A circle having the destinations as the center and $L/2$ as the radius.

And, we search potential stopover charging stations which are located in the area enclosed by these circles and two common tangent lines shown in Fig. 3.1(a). In this definition, however, the C/Ss which EVs can reach to with current battery from the origin are not included as potential C/Ss if $L/2$ is shorter than CR_R. Therefore, in such a case, we use CR_R as the radius of two circles and we search C/Ss which are located in the area shown in Fig. 3.1(b).

3.2.3 Generation of Directed Graph Consisting of Charging Stations

In conventional route search methods, they generate directed graphs which consist of intersections as nodes, roads as edges and travel time as weight. In order to search least-cost routes from several potential routes by conventional methods, which stop over C/Ss located in calculated area, they also need to add some C/Ss to nodes and should search the shortest path with the constraint of remaining battery level. However, these conventional methods generally need to determine a minimum travel time at each intersections sequentially. It is difficult to decide whether a target EV should stop over a certain C/S or go through because it depends on that the EV can reach the destination or next stopover charging stations.

Therefore, as a first step in the proposed method, we determine which C/Ss are suitable to stop over for least-cost routes. And then, we search an EV assist Route via these selected C/Ss. In order to select optimal stopover C/Ss, we generate a graph called "C/S graph" consisting of the origin, the destination and target C/Ss as nodes. This graph also includes directed edges between each pair of nodes, which an EV can reach from a start point to an end point, and a weight of each edge as travel cost. In order to generate C/S graphs, we use the criteria "reachable" for generation of directed edges among nodes. The reachable between two nodes here is defined as follow.

1. If node "A" is the origin, a travel distance $D(A, B)$ is shorter than the cruising range CR_R on the current remaining battery level
2. If node "A" is a certain charging station, a travel distance $D(A, B)$ is shorter than the cruising range CR_F on fully charged battery.

Because EVs can charge fully at node A, this method compares the parameter CR_F with $D(A, B)$ in a case that node A is a charging station.

This method searches routes of each pair of nodes by using route search function F and calculates distances of the routes. Then, this method generates directed edges based on that each distance is shorter than CR_R or CR_F (see Fig. 3.2). As a result, we can search some potential routes which allow a user to stop over some charging stations to charge a battery before it being dead if the EV cannot directly reach destination with the current remaining charge.

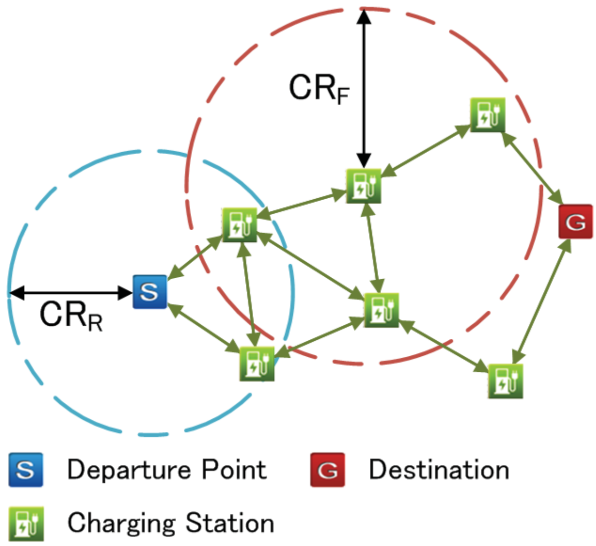


Figure 3.2: Example of "C/S graph" consisting of origin, destination and charging stations as nodes

In the next step, we calculate a weight of each directed edge. In this method, we should take into account the case that a travel cost of a certain route is reduced by taking a circuitous route for stopping over rapid C/Ss. In such case, we should compare increasing travel time and decreasing charging time by making a detour to a rapid C/S. Therefore, we calculate charging time at a C/S to charge the battery from SoC when arrival to full, and we use this time as a weight of a directed edge. When an EV travels from node A to a certain C/S CS_i, the fully charging time at CS_i, $CT(A, CS_i)$, is calculated by the formulas described as below.

1. If node A is the origin,

$$CT(Dep, CS_i) = \frac{BL_F - BL_R + \dfrac{D(Dep, CS_i)}{EM}}{CE_i}$$

2. If node A is a certain charging station CS_h $(h = 1, 2, \ldots, i)$,

$$CT(CS_h, CS_i) = \frac{D(CS_h, CS_i)}{EM \times CE_i}$$

We use the traveling cost, the sum of travel time and calculated charging time, as a weight of each directed edge. The travel cost $C(A, B)$ of driving from node A to node B is described as follows.

1. If node A is the origin,

$$C(Dep, CS_i) = CT(Dep, CS_i) + T(Dep, CS_i)$$

2. If node B is the destination,

$$C(CS_i, Des) = T(CS_i, Des)$$

3. If both node A and B are charging stations CS_h, CS_i,

$$C(CS_h, CS_i) = CT(CS_h, CS_i) + T(CS_h, CS_i)$$

We decide whether a target EV should take the long way and stop over rapid charging stations by comparing travel cost of each route.

Since the information of C/Ss such as electronic power and position are able to be given in advance, we should search previously routes among C/Ss and store the results of routes in databases. This will enable us to search an EV assist route quickly because of the reduction of calculating time among nodes.

3.2.4 Applying Dijkstra's Method on Generated Directed Graph

In the last step, in order to select optimal stopover C/Ss ($SCS_1, \ldots, SCS_j$), we apply Dijkstra's method [67] on a generated directed graph described in Sec. 3.2.3 so that the most cost effective route is searched.

The example of searching an EV assist route is shown in Fig. 3.3. In Fig. 3.3, there are two routes from the origin to the destination, Route 1 and Route 2. In Route 1, an EV will stop over two normal C/Ss. By contrast, in Route 2, an EV will drive to the destination via one normal C/S and two rapid C/Ss. In a case that we leave charging time out of consideration, we will decide that Route 1 is the shortest route because the sum of travel time of Route 1 (223 min) is shorter than that of Route 2 (302 min). In the proposed method, however, we provide Route 2 as an EV Assist route for users because the sum of travel cost of Route 2 (640 min) is shorter than that of Route 1 (871 min).

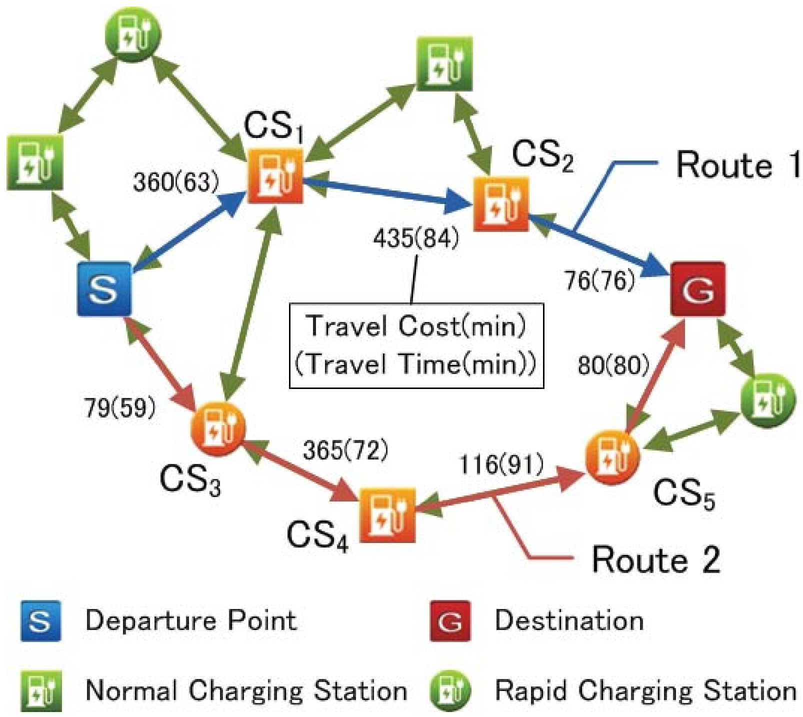


Figure 3.3: Example of "EV Assist Route" search with two or more stopover charging stations

After the stopover C/Ss $SCS_1, \ldots, SCS_j$ is selected, we calculate the EV Assist Route $EVR(Dep, Des)$, its travel distance $EVD(Dep, Des)$ and travel cost $EVT(Dep, Des)$ by route search function F described as follows.

$$
\begin{aligned}
EVR(Dep, Des) &= R(Dep, SCS_1) + R(SCS_1, SCS_2) + \cdots + R(SCS_j, Des) \\
EVD(Dep, Des) &= D(Dep, SCS_1) + D(SCS_1, SCS_2) + \cdots + D(SCS_j, Des) \\
EVT(Dep, Des) &= T(Dep, SCS_1) + CT(Dep, SCS_1) + \\
&\quad T(SCS_1, SCS_2) + CT(SCS_1, SCS_2) + \cdots + \\
&\quad T(SCS_{j-1}, SCS_j) + CT(SCS_{j-1}, SCS_j + T(SCS_j, Des)
\end{aligned}
$$

In the two cases shown below, it is not feasible to reach the destination with remaining battery charge at the origin point.

1. There is no directed edge with the origin as tail in a generated C/S graph. That is, the destination is out of range from the origin point and no charging station is available in the range.

2. There is no path with the origin as start vertex and the destination as end vertex. That is, traveling cost calculated by Dijkstra's algorithm is infinite and there is no optimal route for EVs without batteries dead.

In these cases, we decide that the target EV cannot reach to the destination with the current battery.

3.3 Simulation Experiments

3.3.1 Simulation Settings

In order to evaluate reduction travel costs of routes calculated by the proposed method, we have implemented the system that searches EV Assist Route and displays searched results based on our method. In this experiment, the origin and the destination have been selected from positions in Japan, and we have considered that C/Ss are allocated in any gas stations which are selected randomly from around 40000 gas stations existing in Japan. The number of C/Ss located in any gas stations is 2500, 3000 and 4000, according to the number of C/Ss which anyone can charge and are located outside in Japan [12] respectively in 2010, 2011 and 2012. In addition, we have defined the battery capacity as 24 kWh, EM as 5 km/kWh and SoC at the origin as 12 kWh. Thus, the cruising range with current SoC has been 60 km and the cruising range with fully charged battery has been 120 km. Furthermore, the charging efficiency of normal C/Ss is defined as 2 kW, and that of rapid C/Ss is defined as 48 kW. In this case, the fully charging time of an empty battery at a normal C/S has been 12 hours and that at rapid C/S has been 30 minutes. The parameter setting in this experiment is summarized in Table 3.2.

In the simulation, we have searched each route where the origin and the destination are any pair of 114 roadside stations located in Kanto area. The numbers of C/Ss located in Kanto area are 745, 838 and 1074 chronologically. We have obtained around 10000 results of EV assist routes which have stopped over one or more C/Ss in each year. We have also obtained search results calculated by the method which uses only travel time for weight. And we have

Table 3.2: Parameters in evaluation experiment

Parameter	Value
State of Charge	12 kWh
Battery Capacity	24 kWh
Electric Mileage	5 km/kWh
Charging Efficiency of Rapid Charging Station	48 kW
Charging Efficiency of Normal Charging Station	2 kW
# of Charging Stations (Rapid/Total in each year)	300/2500 in 2010, 500/3000 in 2011, 1000/4000 in 2012

confirmed the differences of travel time and charging time according to the number of stopover C/Ss in both two methods.

In this system, the routes among C/Ss have previously been calculated and the search results have been maintained in databases. In previous calculation, we have searched the routes between pairs of C/Ss which distance is shorter than 320 km. When this system searches an EV Assist Route, directed edges are generated among each pair of nodes, if distance between the paired nodes is shorter than a cruising range with fully charged battery (120 km in this case) by using stored data. We have also confirmed that the combination number of C/Ss we should search the route in advance is around six hundred thousand under the situation where 3000 C/Ss have been allocated in Japan.

3.3.2 Simulation Results

Fig. 3.4 shows that the averages of travel time and charging time calculated by two methods under the situation where the number of C/Ss is 2500 (in the case of 2010). These averages have been calculated in each number of stopover C/Ss. As shown in Fig. 3.4, the travel time calculated by the proposed method is tend to be around from 10 to 20 minutes longer than that of the conventional method. However, the charging time calculated by the proposed method is shorter than that of the conventional method. It is also confirmed that the charging time differences between two methods get longer according to an increase in the number of stopover C/Ss. In many cases, the conventional method may select

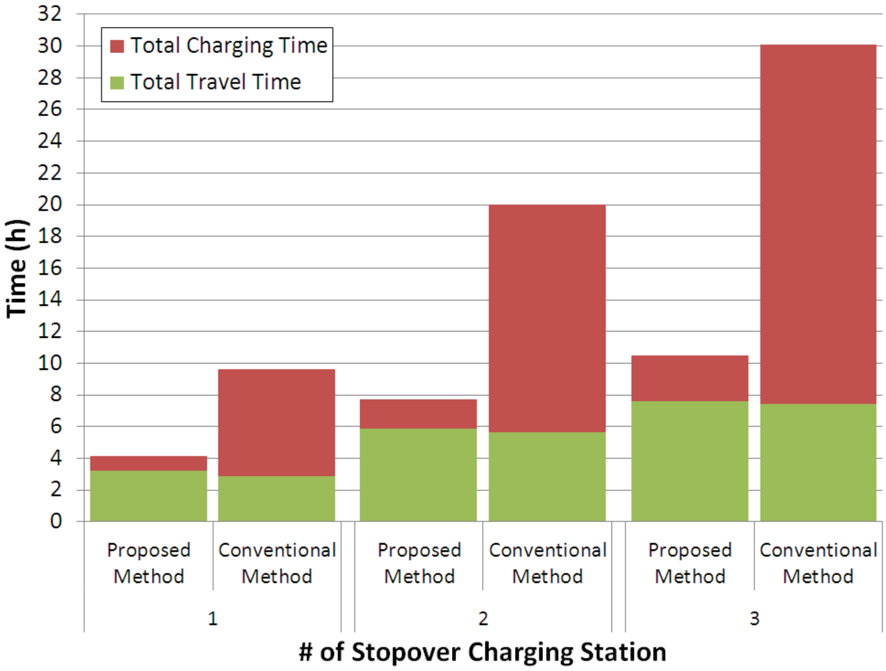


Figure 3.4: Travel and charging time according to # of stopover charging stations (in 2010)

normal C/Ss as charging points because normal C/Ss have a higher proportion of all stations allocated in Japan. In contrast, the proposed method stops over as many rapid C/S as possible in spite of taking the long way so that the charging time differences between two methods are roughly proportional to the number of stopover C/Ss.

Fig. 3.5 shows that the averages of travel time and charging time calculated by two methods under the situation where the number of C/Ss is 3000 (in the case of 2011). The travel and charging time according to the number of C/Ss denote the same tendency observed in both methods as shown in Fig. 3.4. In addition, we can observe that the charging time calculated by both methods decreases when we compare Fig. 3.4 with Fig. 3.5. In the proposed method, the number of search results via normal C/Ss, due to the fact that there is no rapid C/S allocated in the area EV can reach with current SoC, may have decreased because the number of rapid C/Ss has increased. In the conventional

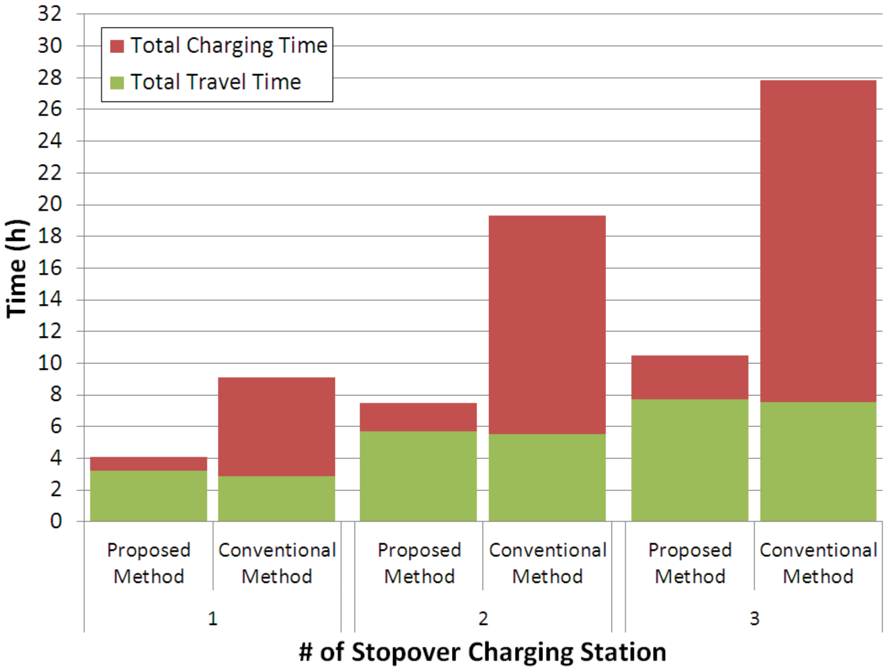


Figure 3.5: Travel and charging time according to # of stopover charging stations (in 2011)

method, the proportion of rapid C/Ss has increased from 12% (300/2500 in 2010) to around 16% (500/3000 in 2011) so that the number of search results via rapid C/Ss may have also increased.

Fig. 3.6 shows that the averages of travel time and charging time calculated by two methods under the situation where the number of C/Ss is 4000 (in the case of 2012). The travel and charging time according to the number of C/Ss denote the same tendency observed in both methods as shown in Fig. 3.4 and Fig. 3.5. We also confirmed that the averages of both travel time and charging time decreased. The reasons of decreasing the charging time are the same based on the relationship between Fig. 3.4 and Fig. 3.5. The travel time calculated by both methods may have decreased because the increased number of rapid C/Ss from 2011 to 2012 is larger than that from 2011 to 2012 so that the distances for swinging by C/Ss may have become shorter.

In any case as shown in Fig. 3.4, Fig. 3.5 and Fig. 3.6, we could confirm

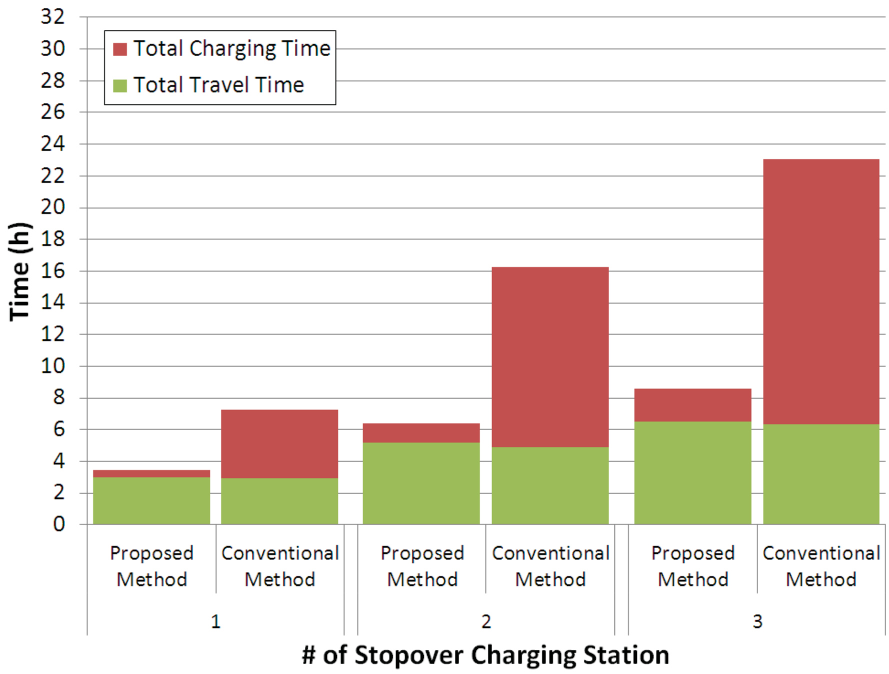


Figure 3.6: Travel and charging time according to # of stopover charging stations (in 2012)

that travel time including charging time calculated by the proposed method was 62% shorter than that by the conventional method.

3.4 Conclusion

In this chapter, we proposed a new route search method for EVs to eliminate concerns of users about the short cruising range and the shortage of charging stations. In this method, we calculated an optimal route going through charging stations to recharge its battery if the current state of charge is not sufficient to reach the destination. Through the evaluation, it was confirmed that travel time between the origin point and destination calculated by the proposed method was slightly longer than that by the conventional method. Meanwhile, travel time including charging time in the proposed method was 62% shorter than that in the conventional method.

Our ongoing works are required in some aspects of the method. There were cases that the method provided a route which made a user get off a highway halfway because the charge was running short on the highway. Thus making plan to charge before getting on a highway, for example, is expected. It may also be desirable to consider business hours of charging stations or information on charging station availability over time. In addition, taking into account some factors such as temperature, traffic information or inclination of the route which affects battery performance or electric mileage would be beneficial to improve estimation of reachable ranges. As mentioned above, we should seek further improvement of the method.

Chapter 4

An Advanced Electronic Triage System for Rescue Operations in Disasters

4.1 Introduction

In this chapter, we propose an electronic triage system to support medical staffs. We also describe a localization method applied to this system, simulation results and evaluation results of a real experiment in a disaster drill at a hospital.

In recent years, some governments and hospitals have employed triage [68, 69, 70, 71, 72, 73, 74], which is a process of prioritizing casualties based on the severity of their conditions when a large number of peoples are injured simultaneously. When applying triage, the priorities of each victim for treatment and transportation are decided on the basis of his/her vital signs. Triage aims to save as many victims as possible by deciding the order of treatment under the situation where medical resources such as medical staffs are limited.

In Japan, triage was applied for the first time in April 25, 2005 for a big derailment accident where totally 107 persons died and 562 passengers were injured. Thereafter, triage was applied to many Mass Casualty Incidents (MCIs) and some problems caused by the current triage system are pointed out in the results [75, 76, 77, 78, 79].

In current practice, a paper tag is attached to each patient to indicate the determined category (see Fig. 4.1). However, paper tags cannot monitor dy-

Figure 4.1: Triage tags in current practice

namic change of patients' condition. It is required to check patients' conditions continuously in order for avoiding sudden worsening although we cannot expect such frequent monitoring in disasters because there are not enough medical staffs. Another serious problem is difficulty in managing locations of patients and medical staffs. Medical staffs from many hospitals rushes to the disaster site, and some victims are laid on the ground without any treatment while some others may be transported to hospitals quickly. We can easily imagine it is very difficult for first responders to manage staffs and patients with respect to locations in such a chaotic situation.

Thus, we have developed an electronic triage system (eTriage) [80, 81], which is an ad-hoc wireless communication service platform for advanced rescue operations. In eTriage, electronic triage tags are attached to injured people. This tag senses vital signs of each person and transmits the data to a server which is installed at a disaster countermeasures office via ad-hoc wireless networks. The server gathers information of all victims and delivers the analysis data to dedicated terminals that medical staff members are equipped with. This terminal enables medical staff members to monitor dynamic change of victims' physical conditions in real time. Furthermore, eTriage provides locations of victims and medical staff members by our ad-hoc localization algorithm so that a disaster countermeasures office can provide appropriate instructions to medical staff members based on obtained vital signs and location information.

4.2 Overview of Triage

Triage is performed based on START (Simple Triage And Rapid Treatment) protocol shown in Fig. 4.2. Victims are categorized into one of four categories according to their degree of severity and urgency. A paper tag is also attached to each patient to indicate his/her category by a corresponding color (see Table 4.1).

Triage aims to support medical staffs for saving as many victims as possible, but some problems were reported in the evaluation after the fact as below.

1. Impossibility to deal with dynamic change of patients' condition
   In current practice, medical staffs cannot monitor dynamic change of patients' condition. Patients who are bruised severely or are compressed forcefully can get worse rapidly with time due to wound shock or crush syndrome. Therefore, patients categorized into category III (Green) or II (Yellow) firstly may change their conditions suddenly to need any treatment and transportation. However, it is difficult to check patients' conditions continuously in order for avoiding such situations because there are not sufficient medical staff members in disaster.

2. Difficulty to decide transportation order of patients categorized into the same category
   If many patients categorized into category I (Red) lie down in front of their eyes, medical staff members cannot decide the priority of patients to transport hospitals at once. In an environment that there is no instrument to compare their vital signs, rapid decision about the priority of patients for treatment and transportation is difficult.

3. Difficulty to know locations of patients and staff members.
   It is difficult for medical staff members to know locations of patients. It is also difficult for a disaster countermeasures office to know locations of medical staff members. In public places, such as airports, there are usually temporary tents to indicate the determined category for admitting patients prepared for MCIs. But medical staffs have difficulty in locating patients on a map when MCIs occur in urban areas since there is no preparation for managing treatment of patients.

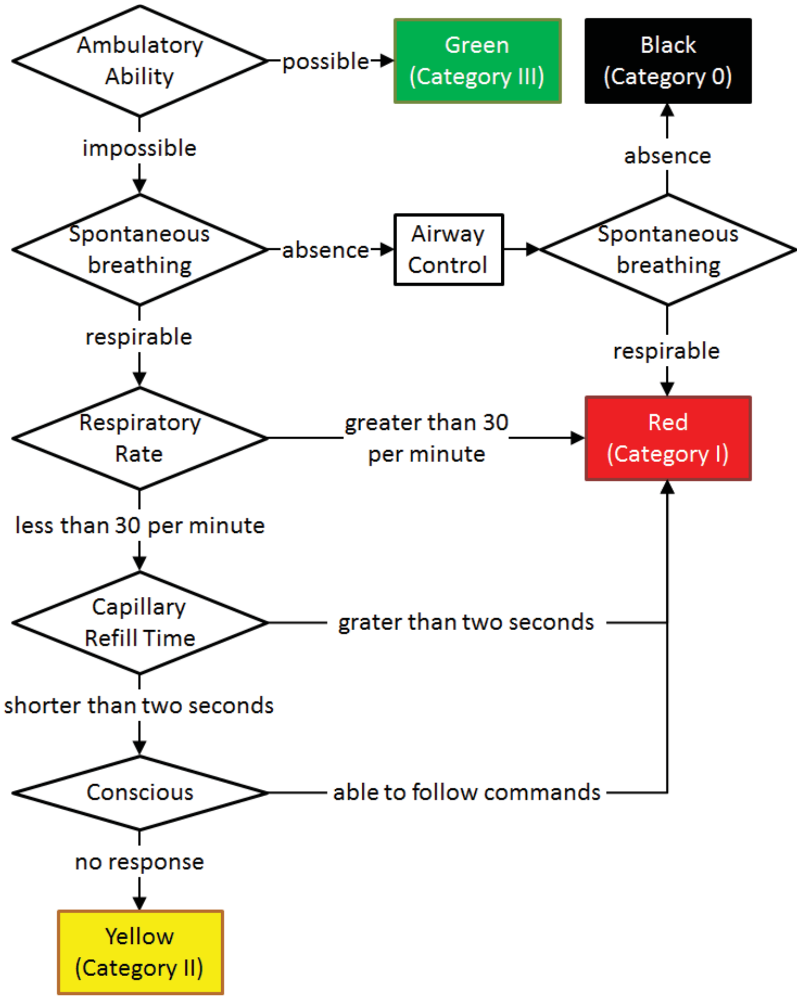


Figure 4.2: Classification of severity by START method

Table 4.1: Categories in triage

Color	Category	Severity	Priority
Red	I	Life-threatening: need immediate care	High
Yellow	II	Treatment and transportation can be delayed	-
Green	III	Those with minor injuries: less urgency	-
Black	0	Dead or dying: no care	Low

Table 4.2: Devices of the electronic triage system

Device Name	Object Person
Electronic triage tag	Patients
Medical terminal	Medical staff members
Information management server	Disaster countermeasures office
Base station for ad-hoc network	—

4. Difficulty to communicate among medical staff members
   Many disaster reports [75, 79] caution that sharing of information among medical staffs in disasters is difficult. This is partly because medical staff members from each hospital gather voluntarily at a disaster site and there is no top-down command and control management system of disaster medical care in Japan.

4.3 Design of Advanced Electronic Triage System

4.3.1 Outline

eTriage consists of four devices shown in Table 4.2 and it has four functions described as below.

Function 1 Monitoring patients' vital signs in real time

Function 2 Estimating positions of patients and medical staff members

Function 3 Providing information about vital signs and positions to medical staff members and a disaster countermeasures office

Function 4 Centralized administrative control over patients and medical staff members at a disaster countermeasures office

Each device is equipped with IEEE 802.15.4 in order to build wireless mesh networks. The vital signs are gathered via this network. This system also estimates positions of electronic triage tags and medical terminals by using wireless network topology over these devices.

The overview of eTriage is shown in Fig. 4.3. This system supports medical staffs and members in charge of a disaster countermeasures office in six steps

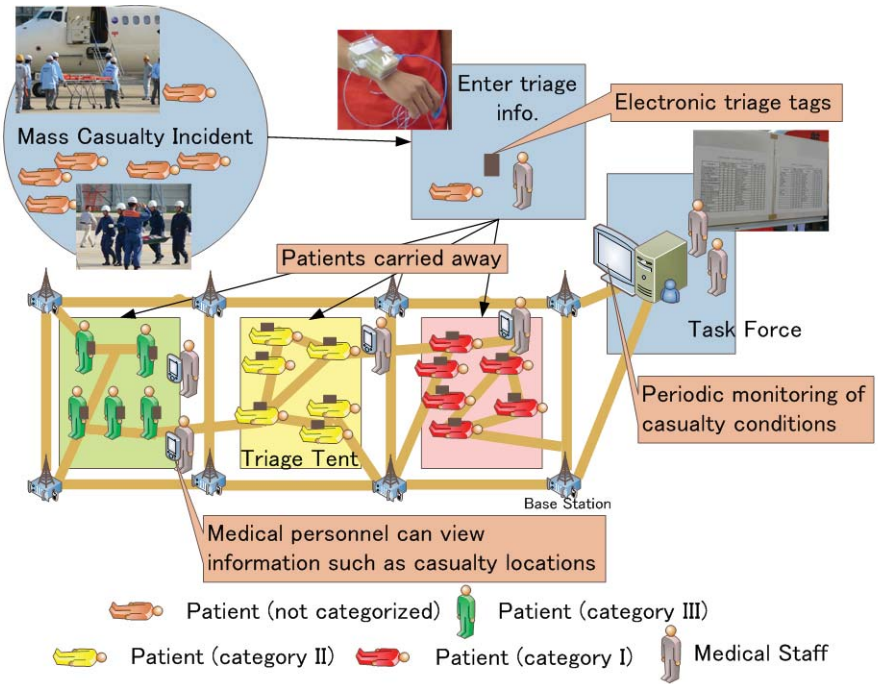


Figure 4.3: The overview of electronic triage system

from searching for victims to their transportation.

1. An injured person found by medical staff members is given first aid on the spot and transported to a tent, called a triage post, for categorization.

2. The injured person transported to a triage post receives initial treatment. Then, an electronic triage tag is attached to the patient. The patient is categorized into one of four triage categories based on his/her vital sign (first triage). This tag transmits sensed his/her vital sign to an information management server installed at a disaster countermeasures office.

3. The injured person whose category has been already decided is transported to another tent, called a triage tent, corresponding to each category. In this tent, medical staffs treat patients and decide priorities of them to transport to hospitals by comparing all of their vital signs (2nd triage).

4. All electronic triage tags consistently broadcast beacons to its neighbors

to notify their own IDs. Each tag regularly sends a set of its neighbor IDs to an information management server via base stations. Then, the server estimates the positions of patients based on the gathered neighbor ID information and displays the estimated positions on the monitors of medical terminals.

5. A disaster countermeasures office and medical staff members can check patients' vital signs and positions by the information management server and medical terminals. If they find a patient who needs immediate treatment, appropriate medical staff members can be selected to rush to the patient. After arrival, medical staff members identify the target patient from a group of patients by body area networks since the accuracy of the estimated locations may be insufficient to identify the target patient from many patients in a small area. After confirmation of the patient's vital sign, they start treatment of the patient.

6. On arrival of an ambulance, a patient with the highest priority is transported to a hospital.

These support functions solve the problems described in Sec.4.2: (1)impossibility to deal with dynamic change of patients' condition, (2)difficulty to decide the order of transportation for patients categorized into the same category, (3)difficulty to know the locations of patients and staff members, (4)difficulty of information sharing among medical staff members.

4.3.2 Description of Devices

Data flows among devices in eTriage are shown in Fig. 4.4. Each device's function and roles are described as below.

Electronic Triage Tag

An electronic triage tag is a device which is attached to each patient at a triage post. For obtaining each patient's vital sign and position, the electronic triage tag consists of a vital sensor, an IEEE802.15.4 network node and a transmitter of a body area network. SunSPOT [82] is used for the IEEE802.15.4 network node.

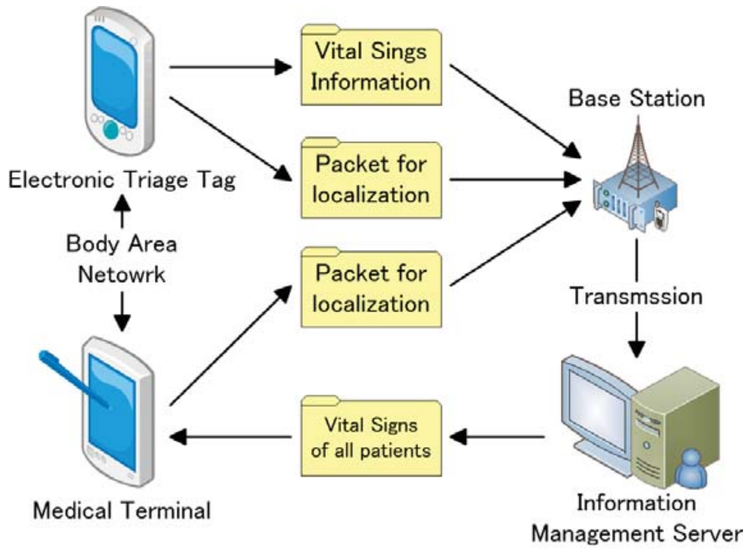


Figure 4.4: Data flows among electronic triage devices

There are two types of electronic triage tags: eTriage-Light and eTriage-Full. The eTriage-Light can be clipped to a patient's finger and its weight is lighter than the eTriage-Full. A vital sensor included in the eTriage-Light can obtain each patient's pulse rate and SpO2 (blood oxygen level). On the other hand, the eTriage-Full can be attached to a patient's arm and its vital sensor can obtain patient's breathing rate in addition to a pulse rate and SpO2. The eTriage-Full can also measure a patient's vital sign at high frequency (e.g. more than 10Hz). To prevent patients from overloading by attachments, both tags are developed as small size (eTriage-Light: width:11.7cm, height:5cm, depth:2.3cm, eTriage-Full: width:10cm, height:8.3cm, depth:2.3cm). Both tags obtain patient's vital signs every one seconds to deal with sudden change of patient's conditions. The monitored vital signs are periodically transmitted to the server via wireless mesh networks constructed over electronic tags and base stations.

Medical Terminal

A medical terminal is a device for a medical staff member to confirm patients' vital signs and positions. The terminal communicates with electronic triage tags and an information management server. This terminal consists of an

IEEE802.15.4 network node, an IEEE802.11 network node, a receiver of body area network and a touch panel. In the proposed system, we use iPod touch [83] as the IEEE802.11 network node and the touch panel. The IEEE802.15.4 network node is also developed on the basis of SunSPOT [82]. To prevent medical staff members from working on their treatment activity, Medical terminal is developed as a small-sized device (width:6cm, height:9cm, depth:2.5cm). Medical staff members can receive instructions from members in charge of a disaster countermeasures office via medical terminal. In addition, medical staff members can browse all of patients' vital sign data on an information management server by using medical terminals.

In a case that the estimated positions have errors, medical terminals have a function to access electronic triage tags via a body area network [84] and receive an ID from an electronic triage tag of a touched patient. Medical staff members only need to touch a patient to confirm his/her tag ID. Medical staff members also need to change patients' categories in response to their conditions or results of treatment. Thus, medical terminals can change patients information directly by a touch via a body area network.

Information Management Server

An information management server is a device allocated at a disaster countermeasures office. The server communicates with electronic triage tags and medical terminals. The server consists of an IEEE802.15.4 network node, an IEEE802.11 network node and a monitor. The IEEE802.15.4 network node is also developed on the basis of SunSPOT [82]. The server displays vital signs of all patients equipped with electronic triage tags on its monitor in real time. If a vital sign of a patient drops below a threshold, a warning alarm will sound and this server will turn his/her displayed name color into red. The server estimates positions of patients equipped with electronic triage tags and medical staff members who have medical terminals. Estimated positions are also displayed on its monitor with a map so that members in charge of a disaster countermeasures office can rapidly deal with change of patients' condition. Furthermore, the server works as a web server in order for providing access to vital sign data of transported patients for other hospitals and emergency care centers.

4.4 Localization Method

4.4.1 Outline

Generally, many localization algorithms estimate positions of sensor nodes by measurement of geographical relationships between nodes and landmarks. They use different types of range measurement devices such as ultrasonic equipments and directional antennas [85, 86]. Meanwhile, since each sensor node has limited power supply and equipments due to hardware costs, a localization algorithm in the electronic triage system only assumes connectivity information among nodes which can be obtained when vital signs are transmitted.

However, measurement of exact distances among nodes by Received Signal Strength (RSS) is difficult because RSS is unstable due to radiowave diffraction and reflection. Thus, we use RSS as the threshold value to relax the instability of signal. That is, if RSS from node A to node B is larger than the threshold, we estimate that a distance between two nodes is shorter than a distance corresponding to the threshold. In this system, we regard a distance between two nodes as shorter than the maximum radio range if packet forwarding succeeds between them. Therefore, the system only needs maintain neighbor information of all the nodes, which is lightweight.

The localization methods are also distinguished by their form of computation, "centralized" or "decentralized". In decentralized methods, a node position is computed by the node itself or in cooperation with other nodes. For example, APIT [87] assumes a set of triangles formed by landmarks, checks whether a node is located inside or outside of each triangle, and estimates its location. Amorphous [55] and REP [88] assume that location information is sent through multi-hop relay from landmarks, and each node estimates its positions based on hop counts from landmarks. In particular, REP first detects holes in an isotropic sensor network, and then estimates the distance between nodes accurately considering the holes. In MCL [89], each mobile node manages its Area of Presence (AoP) and refines its AoP whenever it encounters a landmark. In UPL [90], each mobile node estimates its AoP accurately based on AoP received from its neighboring nodes and obstacle information.

By contrast, these centralized algorithms use all the information about connectivity between all the nodes, the estimation accuracy is usually better than

Table 4.3: Notations

Symbols	Descriptions
R	maximum radio range
V	maximum speed of nodes
$\phi_u^{[k]}$	node u's k-th time slot
$p_u^{[k]}$	estimated position of node u in $\phi_u^{[k]}$
$P_u^{[k,k']}$	estimated trajectory of node u between $\phi_u^{[k]}$ and $\phi_u^{[k']}$ ($i.e.$, $p_u^{[k]}, p_u^{[k+1]}, \ldots, p_u^{[k']}$)
$N_u^{[k]}$	a set of neighbor node of node u at $\phi_u^{[k]}$
$D(p_u^{[k]}, p_v^{[k]})$	a distance between $p_u^{[k]}$ and $p_v^{[k]}$

decentralized methods. MDS-MAP [54] is a centralized localization that calculates the relative positions of all the nodes based on connectivity information by MultiDimensional Scaling (MDS). TRACKIE [91] first estimates positions of mobile nodes that were likely to move between landmarks straightly. Based on their estimated trajectories, it estimates trajectories of the other nodes.

The electronic triage system aims to utilize estimated positions as a mean to display locations of patients and medical staff members on medical terminals and a monitor of a management server. For developing a highly accurate localization system at low cost, we design a localization system as a centralized algorithm. Furthermore, in order to estimate positions of nodes in real time, we introduce a heuristic localization algorithm for the electronic triage system.

In the proposed algorithm, we investigate the constraints based on the connectivity information in each time slot among nodes. In addition, we assume the maximum speed of nodes and survey the constraints based on the distance between two positions of a single node at consecutive two time slots. In order to estimate positions of nodes which satisfy as many constraints as possible, we apply the spring model which exerts attracting and repulsion force on estimated position of nodes to estimate better positions in terms of satisfiability of the constraints.

4.4.2 Basic Operations

The notations are summarized in Table 4.3. We assume the maximum radio range R and the maximum speed V of all the nodes. The management server

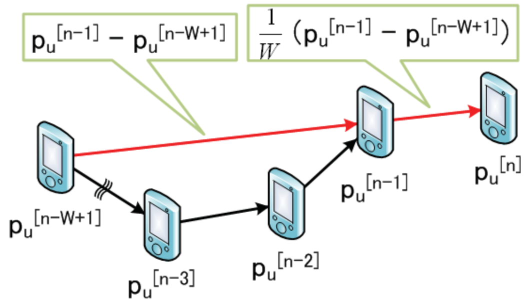


Figure 4.5: Estimation of node u's position in time slot n based on its trajectory

executes localization every time slot with time length T. We also assume that the value of T is common in all nodes.

All landmarks and nodes broadcast a hello packet every time slot. Node u's ID and transmission time t are included in the hello packet broadcast by node u. Nodes which can communicate with node u receive node u's hello packet. Each node u generates a set of neighbor node IDs $N_u^{[k]}$ and transmits the set to the information management server every time slot.

4.4.3 Position Estimation and Trajectory Update

In the proposed method, firstly the information management server estimates current positions of all nodes by using vectors in their trajectories. Then, the server updates estimated trajectories based on the information $N_u^{[k]}$ of every node. The methods to estimate positions of all nodes and to update estimated trajectories are defined as follows.

1. **Position Estimation** We denote the current time slot of node u by $\phi_u^{[\kappa]}$. In every time slot, node u predicts current position $p_u^{[\kappa]}$ from its last W estimated positions $P_u^{[\kappa-W,\kappa-1]}$ where W is a positive integer. $p_u^{[\kappa]}$ is estimated by taking the average of vectors in trajectory $P_u^{[\kappa-W,\kappa-1]}$ for the last W time slots as below (see in Fig. 4.5)

$$\begin{aligned} p_u^{[n]} &= p_u^{[n-1]} + \frac{1}{W}\sum_{k=1}^{W}(p_u^{[n-k]} - p_u^{[n-(k+1)]}) \\ &= p_u^{[n-1]} + \frac{1}{W}(p_u^{[n-1]} - p_u^{[n-(W+1)]}) \end{aligned}$$

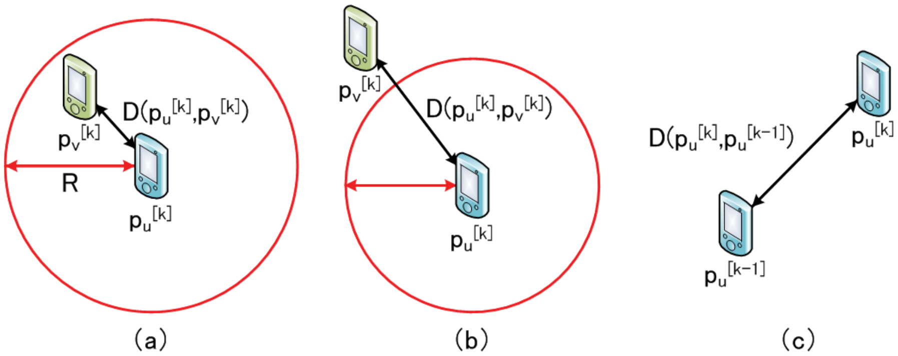


Figure 4.6: (a)positive radio-range constraint, (b)negative radio-range constraint, (c)a maximum speed constraint

2. **Trajectory Update** After the prediction of the current position, node u updates its own last L estimated positions $P_u^{[\kappa-(L-1),\kappa]}$ using (i) the estimated trajectories of 1-hop and 2-hop neighbors and (ii) the *history of neighbors* that indicates the 1-hop and/or 2-hop neighbors in each past time slot.

   To update the last L estimated positions, we consider the following three types of relationships between two nodes' positions at the same time or between the two positions of a single node at consecutive two time slots. From these relationships, we obtain three constraints: (i) a *positive radio-range* constraint, (ii) a *negative radio-range* constraint and (iii) a *maximum speed* constraint shown in Fig. 4.6. The definitions of these constraints are as follows.

   - A positive radio-range constraint: for any time slot $\phi_u^{[k]}$ and any node v, if node v is a 1-hop neighbor of node u in time slot $\phi_u^{[k]}$, the distance between $D(p_u^{[k]}, p_v^{[k]})$ must be shorter than R.
   - A negative radio-range constraint: for any time slot $\phi_u^{[k]}$ and any node v, if node v is *NOT* a 1-hop neighbor of node u in time slot $\phi_u^{[k]}$, the distance $D(p_u^{[k]}, p_v^{[k]})$ must be larger than R.
   - A maximum speed constraint: for any time slot $\phi_u^{[k]}$, the distance $D(p_u^{[k]}, p_u^{[k-1]})$ must be shorter than $V \cdot T$.

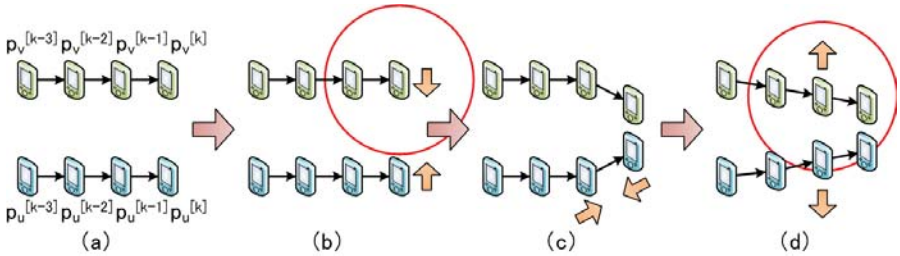


Figure 4.7: Example of localization process

Because estimated positions of nodes relate to each other temporally and spatially in terms of the above constraints, a modification of an estimated position may violate constraints on other estimated positions related to the modified position. Here, suppose that position $p_u^{[k]}$, which satisfies the maximum speed constraint, is updated by a positive radio-range constraint. This may violate the constraints on positions $p_u^{[k-1]}$ and $p_u^{[k+1]}$. Additionally, connectivity information often has errors so that there may be no result of estimated positions which satisfy all the constraints. Therefore, we employ a heuristic algorithm on localization.

In this algorithm, we calculate vectors between node positions violating constraints. Then, estimated positions are modified based on the sum of these vectors. That is, for each node u, we calculate (i) $\vec{pos} = p_x^{[k]} - p_u^{[k]}$ if there is a node x violating the positive radio-range constraint, (ii) $\vec{neg} = p_u^{[k]} - p_y^{[k]}$ if there is a node y violating the negative radio-range constraint, (iii) $\vec{mov} = p_u^{[k-1]} - p_u^{[k]}$ if there are consecutive time slots $\phi_u^{[k-1]}, \phi_u^{[k]}$ violating the maximum speed constraint. Then, we also calculate $\vec{adj}$ by the following equation and add $\vec{adj}$ to the current estimated position $p_u^{[k]}$.

$$\vec{adj} = \frac{K_{pos} \sum^x \vec{pos} + K_{neg} \sum^y \vec{neg} + K_{mov} \vec{mov}}{cn}$$

We note that cn is the number of nodes violating the constraints and $K_{pos}, K_{neg}, K_{mov}$ are constants. Continuing the updates of trajectories in last L time slots and exchange of the updated trajectories, the trajectories of all the nodes are refined asymptotically.

We exemplify the above procedures in Fig. 4.7. Fig. 4.7 shows the estimation process of trajectories $P_u^{[k-3,k]}$ and $P_v^{[k-3,k]}$. In this case, we suppose that node u met v at $\phi_u^{[k]} = \phi_v^{[k]}$. At first, node u predicts the current position $p_u^{[k]}$ based on its past moving velocity (see Fig. 4.7(a)). In time slot $\phi_u^{[k+1]}$, node u modifies $p_u^{[k]}$ to satisfy the positive radio-range constraint with $p_v^{[k]}$ based on the hello message sent from node v in time slot $\phi_u^{[k]}$ (see Fig. 4.7(b)). Since this modification violates some maximum speed constraints, $P_u^{[k-1,k]}$ is modified to satisfy the maximum speed constraints (see Fig. 4.7(c)). Moreover, $p_u^{[k-1]}$ is modified to satisfy the negative radio-range constraint with $p_v^{[k-1]}$ in time slot $\phi_u^{[k+2]}$ based on the hello message sent from node v in time slot $\phi_u^{[k+1]}$ (see Fig. 4.7(d)). In this way, the proposed algorithm iterates a modification of estimated positions to find a set of estimated trajectories which satisfies as many constraints as possible.

4.5 System Performance Evaluation

4.5.1 Communication Traffic

In this system, all of devices receive and transmit some types of packets among them on wireless mesh networks. The size of IEEE 802.15.4 packet header is $15 bytes$, and each device adds its IP address as node ID ($8 bytes$) to the packet. Moreover, in the case of a hello packet, $8 bytes$ of a timestamp is included, therefore the size of the hello packet is $15 + 8 + 8 = 31 bytes$. As described in the following section, the data transmission rate of hello packets is $31 bytes/s$ because we define the length T of a time slot as $1.0 sec$.

The sizes of the other packets are shown in Table 4.4. The size of neighbor node information depends on the number n of neighbor nodes. The size of vital signs varies according to eTriage device types. An eTriage-Light transmits $34 bytes$ of vital sign data consisting of heartbeat, pulserate and SpO2. An eTriage-Full transmits $255 bytes$ data including pulse and breathing waveforms additionally.

Data transfer speed on Zigbee networks is $250 Kbps$ theoretically. This means that all devices can communicate with each other under the environment where there are eighty eTriage-Lights, twenty eTriage-Fulls and 20 medical terminals. Although the actual throughput of Zigbee is much less than the theoretical

Table 4.4: Data transmission rate of devices

An electronic triage tag	Data transmission rate
Hello packet	$15 + 8 + 8 = 31(byte/s)$
Vital signs	34 or $255(byte/s)$
Set of neighbor nodes	$31 + (8 + 8) \times n(byte/s)$
Total	$98 + 16n(byte/s)$ or $317 + 16n(byte/s)$

Medical terminal	Data transmission rate
Hello packet	$15 + 8 + 8 = 31(byte/s)$
Set of neighbor nodes	$31 + (8 + 8) \times n(byte/s)$
Notification of communication with body area network	$26(byte/s)$
Total	$88 + 16n(byte/s)$

Table 4.5: Simulation environment

Area size	$30(m) \times 50(m)$
# of nodes	60
Node mobility	Random Way Point
Moving speed of nodes	0.25〜0.5 (m/s)
Simulation time	600 (s)
Time slot T	$1.0(s)$
W, L	10
$K_{pos}, K_{neg}, K_{mov}$	0.2

value, we consider even the half of the previous number of devices are sufficient for operating the proposed system. In addition, we have confirmed that packet loss rarely occurs in the experiment described in Sec. 4.6 where there are eight eTriage-Lights, two eTriage-Fulls, two medical terminals, one information management server and nine base stations.

4.5.2 Accuracy of Position Estimation

For evaluation of the proposed localization algorithm, we prepared patient mobility in a disaster by MobiREAL [92]. In the simulation, we used the mobility data that patients were transported from a triage post to a triage tent (see Fig. 4.8). The simulation environment and parameters of the algorithm are shown in Table. 4.5

The simulation results are shown in Fig. 4.9. We confirmed that the accu-

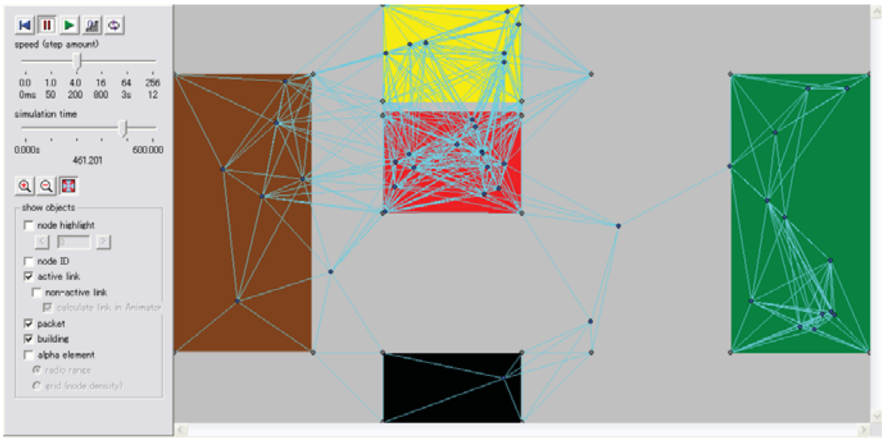


Figure 4.8: A patient mobility generated by MobiREAL for the simulation

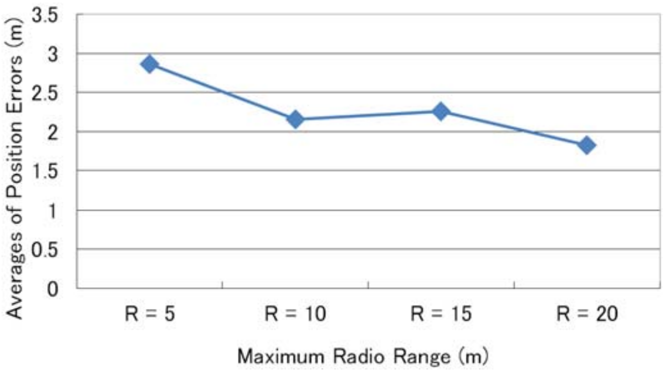


Figure 4.9: Errors of estimated positions

racy of the localization algorithm depends on the maximum radio range. In this mobility, we also confirmed that TRADE can estimate positions of nodes with errors about $2m \sim 3m$. In the case where the maximum radio range was configured as $5m$, position errors increased with decrease of the number of constraints based on positive radio-range constraints among nodes.

In this system, medical staff members can identify victims by obtained tag ID via body area networks after arrival at the target patients. Thus, accuracy of localization required for e-Triage should be shorter than about $2m$ in order to focus on several patients in highly populated areas. On the other hand, in

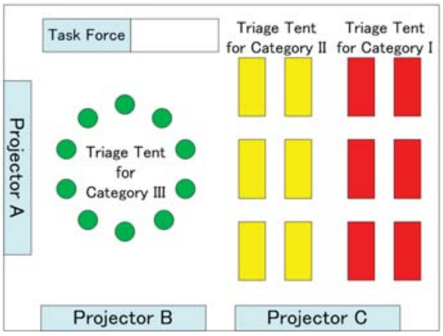


Figure 4.10: Layout of training

Figure 4.11: Scene of training

terms of battery lifetime, the maximum radio range of each device should be as short as possible. Generally, devices consume more amounts of energy when the maximum radio range increases. In this simulation, $10m$ is appropriate for R to satisfy both accuracy of estimated positions and energy consumption requirements.

4.6 Experiment on Disaster Training

In this section, we describe the experiments on a disaster training for evaluation of the proposed electronic triage system. These experiments were conducted on September 7, 2008 and September 6, 2009 in Juntendo University Urayasu Hospital in order to confirm the effectiveness of eTriage. The following section describes the training contents, opinions obtained from medical staff members and modifications required to the system.

4.6.1 Training Contents

The participants of the experiment approximately consisted of 25 doctors and nurses as subject and 15 members of the system development project team. In the training, in order to simulate the situation of MCIs, a disaster countermeasures office and triage tents were allocated. Victims categorized by START protocol and medical staff members were in triage tents. The layout plan of the disaster countermeasures office and triage tents are shown in Fig. 4.10 and the training scene is also shown in Fig. 4.11.

Figure 4.12: Electronic triage tag "Light" for fingertip

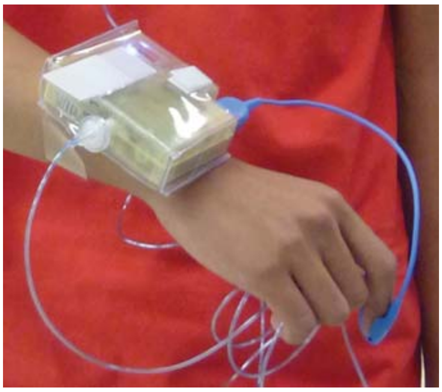


Figure 4.13: Electronic triage tag "Full" for arm

Figure 4.14: Doctors' view

In the training, as shown in Fig. 4.10, patients categorized into categories I (Red) and II (Yellow) were laid down in the corresponding treatment areas and patients categorized into category III (Green) sat on chairs. For categories I and II, six out of ten patients in each category were equipped with the electronic triage tags while the electronic triage tags were attached to two out of ten patients for category III (see Fig. 4.12 and Fig. 4.13). Vital signs obtained

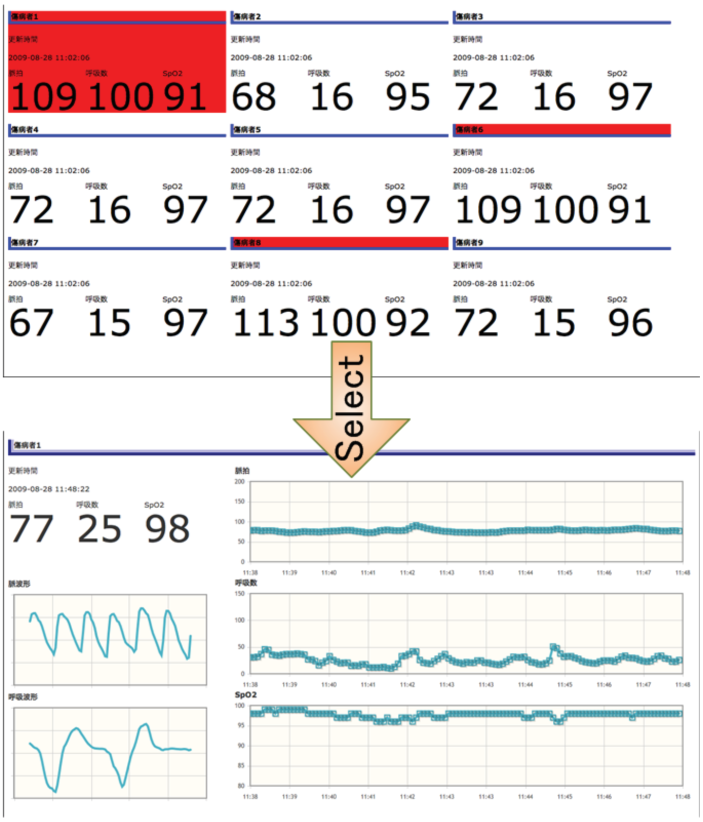


Figure 4.15: Screenshot of information management server

by the electronic triage tags were transmitted to the information management server at the disaster countermeasures office and displayed on the projectors B and C with patients' names.

As shown in Fig. 4.14 and Fig. 4.15, the medical terminals and the information management server not only display the overview of vital signs of some patients on their monitors but also indicate changes of vital signs over time. Medical terminals can also show vital data of a victim touched by a medical staff member via a body area network by highlighting the victim's data in the overview list. At the disaster countermeasures office, members in charge observed patients' vital signs and gave instructions to medical staffs when they found a sudden change of vital signs.

Table 4.6: An example patient scenario

Case 1	Dropping nameboard hit his/her head	
Symptom	(Acute Epidural Hematoma) temporal laceration and bleeding	
Vital Signs	Before condition change	After condition change
Category	Category II (Yellow)	Category I (Red)
Level of consciousness	Open his/her eyes to response someones' call	Close his/her eyes
Pulse rate	60 $times/min$	45 $times/min$
Breathing rate	12 $times/min$	4 $times/min$
SpO2	98%	88%

As the result of consultations with doctors at emergency department, we have prepared six scripts that change the conditions of patients. An example is shown in Table 4.6. In this case, we prescribed the change of vital signs over time to simulate acute epidural hematoma. In this training, we previously installed the variation prescribed by each script on an electronic triage tag, and this tag transmitted vital sign data where pulse rates and SpO2 were decreased deliberately. Then, each training scenario followed 4 steps described as below.

1. We simulate a change of vital signs prescribed by a target script on an electronic triage tag.

2. Members in charge of the disaster countermeasures office monitor all patients' vital signs on a monitor and find sudden changes of vital signs. The members select appropriate medical staff members based on estimated positions and give an instruction to the staff members to rush immediately to the target patient.

3. The medical staff members received the instruction check the estimated position and vital signs of the target patient. After that, the medical staff members hurry to the target patient and confirm his/her tag ID by a body area network.

4. The medical staff members treat the patient appropriately. After treatment, they notify the members in charge of the disaster countermeasures office of treatment completion. The members in the office confirm that

the patient's vital signs return to the normal level on a monitor of the information management server.

4.6.2 Result of Training

Participants, visitors and developers have exchanged opinions concerning the training with each other. As a result, we have obtained the opinions from medical staff members described as below.

- Electronic triage tags are small enough to attach and will not cause stress on the patients' body.
- Electronic tags enable us to shift patients' category into another category. This is an advantage compared to paper tags which do not allow us to lower patient categories.
- Medical staffs can rapidly decide next operations such as treatment because they can confirm patients' condition wherever.
- Medical terminals are helpful for making diagnoses of patients because medical staff members can confirm patients' change of vital signs easily.
- This system is also helpful in other situations, such as an emergency department in hospital, as well as in MCIs.

However, some problems of the proposed system also arose as follows.

1. The problems of electronic triage tags
    - In order to notice victims requiring treatments at a glance, instruments such as LEDs or bells should be equipped with electronic triage tags to raise an alert.
    - Electronic triage tags should detect treatment completion and notify the disaster countermeasures office of it automatically.
    - The tags are required to have water resistance to deal with bleeding patients.
    - Breathing sensors can lead to hyperventilation for injured persons categorized into category III (Green) because this sensor intensifies a sense of severe disease.

- It is required to prevent victims from removing their tags since the tags can be easily detached.

2. The problem of medical terminals

   - Connections using body area networks are not reliable.

3. The problems of the information management server

   - The colors displayed at the monitor to indicate the condition of patients should be changed to the other colors standardized for medical instruments.
   - In order for medical staffs to see the overview of vital signs, a triage post and triage tents should be equipped with monitors displaying the same screens as the monitor at the disaster countermeasures office.
   - Occasionally, the accuracy of estimated positions of patients was not sufficient.

Through the experiment in the disaster training, we confirmed that the medical staff could obtain all patients' vital signs and condition changes by the proposed system. Especially, we received a high evaluation from the medical staff on the following points: (i) the proposed system allows for early treatment of patients whose conditions suddenly change by monitoring vital signs obtained in real time and (ii) the electronic triage tags are small and can release quickly so that the tag will not cause stress on the patients' body. We also confirmed that victims were found and treated by medical staff members after changes of their conditions because of the localization system and the body area network to identify each patient individually.

In indoor environments, however, eTriage could not estimate victims occasionally because of radio reflection on walls and obstacles such as medical instruments. Furthermore, we confirmed that the accuracy of estimated positions were different according to patients' posture or movement of the medical staff. Thus, it is desirable to apply a localization algorithm specialized in indoor position estimation, which considers room shape or obstacles' positions. Currently, eTriage has been operated at the emergency department in Juntendo University Urayasu Hospital for rapid decision of treatment order of patients.

We are planning to continue the development of our electronic triage system, including improvements on the localization accuracy, coverage expansion and sustainability of network operations to achieve the practical use.

4.7 Conclusion

In this chapter, we have proposed an electronic triage system (eTriage) in order for supporting disaster relief. In the proposed system, vital signs of victims are gathered based on wireless ad hoc networks. At the same time, positions of patients and medical staff members are estimated by using topology information of ad hoc networks.

From the experiment in the disaster training at Juntendo University Urayasu Hospital, we could confirm the effectiveness of eTriage. However, some problems such as localization accuracy in small rooms were also revealed. To solve such remaining problems, we are planning to continue the development of our electronic triage system through tests in hospitals.

Chapter 5

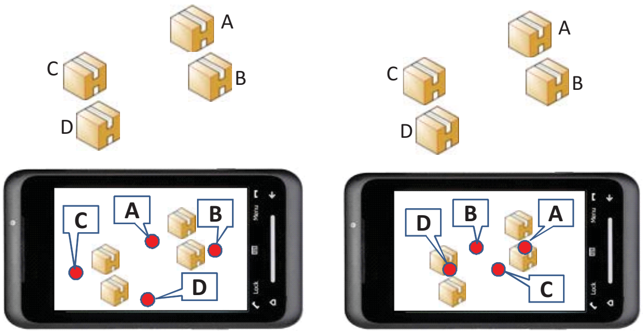
Quantifying Relationship between Relative Position Error of Localization Algorithms and Object Identification

5.1 Introduction

In this chapter, we propose a method to quantify the relationship between positioning errors of localization algorithms and people's identification of objects.

Positioning systems have been investigated so far for location-aware services such as outdoor/indoor navigation and personal object identification in rooms. GPS is the most popular global system for outdoor positioning of single nodes. For the situation where GPS is not available, localization algorithms using a variety of devices have been developed. In wireless sensor networks, cooperative self-localization is mandatory since in most cases we cannot attach GPS to small-sized wireless sensor nodes due to limitation of cost and battery lifetime. An electronic triage system shown in Sec. 4 also needs localization system to find where patients and medical staff are. Some other services such as support of social interaction [93] and indoor navigation for emergency service [94] need positioning of mobile nodes.

In those applications, the accuracy of position information is highly signifi-



(a) case 1 (b) case 2

Figure 5.1: Example of object identification in augmented reality: AR system shows article IDs over camera views by balloons using estimated positions of those articles. Most people may not be able to find the correct ID matching in (b) although (a) and (b) have similar errors from the positioning system.

cant. In particular, we focus on such applications that need identification of real objects from position information. Let us suppose an AR (augmented reality) system in a huge storehouse that shows article IDs over camera views by balloons using the estimated positions of those articles (Fig. 5.1). The errors from the positioning system may directly appear as the deviation of ID balloons from the true positions in the camera views. Although case 1 (Fig. 5.1(a)) and case 2 (Fig. 5.1(b)) have similar amounts of deviations from the true positions, most people may not be able to find the correct matching in case 2 where switching of B and C is likely to occur (or even A and B). This is obviously because the relative location of B and C (and also A and B) is quite different from the truth.

As seen, such errors that cause mismatching between estimated positions and truth should be represented not only by the deviation from the true positions but also by the deviation from the true *position relationship*. Although the term "relative position" partially captures the concept of position relationship, it does not take the impact on people's object identification into consideration (namely, it is defined independently of application context). Therefore, our approach is differentiated from existing ones that have dealt with relative position accuracy [49, 50]. In brand-new mobile and pervasive applications that associate estimated location information obtained by positioning systems with the physical things, such an impact should be considered and thus some reasonable criteria are desired for the purpose.

In this paper, we focus on how to characterize the outputs by a localization algorithm and try to quantify the impact of positioning errors on people's identification of objects independently of specific localization algorithms. Given a set of estimated positions of target objects and the anonymous set of their true positions, we propose criteria to access the "accuracy" of the estimated positions in identifying the objects at true positions. The proposed accuracy criteria can be used in design, development and evaluation of localization algorithms that are used to tell people the location of objects (augmented reality is a typical example). To define the criteria without ambiguity, we prove that (i) neighbor proximity and uniqueness are significant factors to identify objects and the Delaunay triangulation captures these properties, and (ii) grouping of nearby neighbors should also be considered and properly-designed clustering captures the property. Then *position relationship dissimilarity* is defined by the Degree of Discrepancy (DoD) of Delaunay triangulations on estimated and true positions considering clusters.

In order to validate our approach, we have analyzed properties of three localization algorithms using the proposed criteria. The results have shown that the criteria could capture the qualitative properties of each algorithm. Subjective testing has also been conducted using 120 questionnaires. Analyzing the obtained 6480 answers from 54 examinees, we have confirmed that our quantification could sufficiently render human perception.

5.2 Basic Approach

5.2.1 Concept

Position relationship dissimilarity between true and estimated positions is quantified by the Delaunay triangles in our approach. To imagine what should be considered in node identification, we introduce a simple example. Figure 5.2(a) shows real placement of nodes and Fig. 5.2(b) and Fig. 5.2(c) show two different estimations. We assume these figures are drawn in bird's-eye view. Compared with the true positions, the relative positions of nodes F and G in Fig. 5.2(c) are "opposite" from the viewpoint of node C, while those in Fig. 5.2(b) are

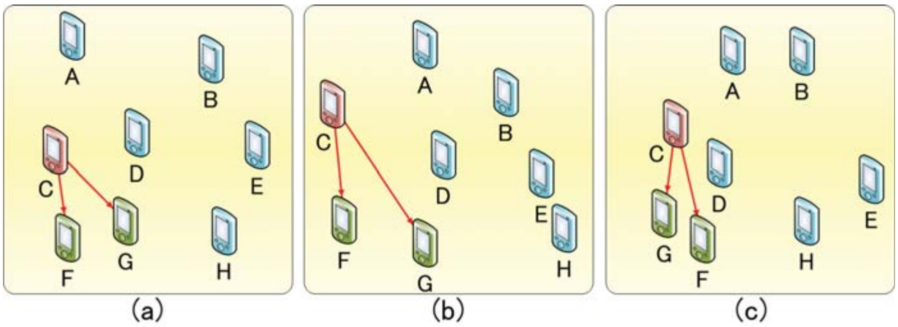


Figure 5.2: Relative positions of F and G from bird's-eye view:
(a) real position (b) "consistent" estimation (c) "inconsistent" estimation.

consistent. In terms of relationship between C and the pair (F, G), we may think Fig. 5.2(b) is "better" than Fig. 5.2(c).

We have also prepared 4 sets of node positions with errors as shown in Fig. 5.3 where the true positions are shown in Fig. 5.3(c). Each set is generated by adding $3m$ error to the true position of each node in a $20m \times 20m$ square area. Therefore, the average position errors of those sets are the same. We note that solid lines indicate alphabetically consecutive node pairs (H-A is also drawn) and arrows show the position errors. We can say that Figs. 5.3(a)–(b) have certain similarity to the true positions rather than Figs. 5.3(d)–(e) although their average errors are the same. Suppose identification of anonymous nodes at true positions by a given set of estimated positions like Fig. 5.3(a) as exemplified in Section 5.1. Obviously neither of Figs. 5.3(d)–(e) is helpful for such a purpose because the position relationship among neighbors is hardly preserved. For example, in the true positions, node O seems surrounded by the other nodes, but Figs. 5.3(d)–(e) never indicate such "relationship" among neighbors.

We try to define such position relationship dissimilarity that affects identification of nodes. The position relationship is usually defined by relations among neighboring nodes, but we need to define necessary and sufficient "neighbors" in the context of node identification.

Let us consider identifying node O in Fig. 5.4 (a) by regarding a set of its "neighbors" as reference points. The set $\{A, B, C, D, E, F\}$ where each node is

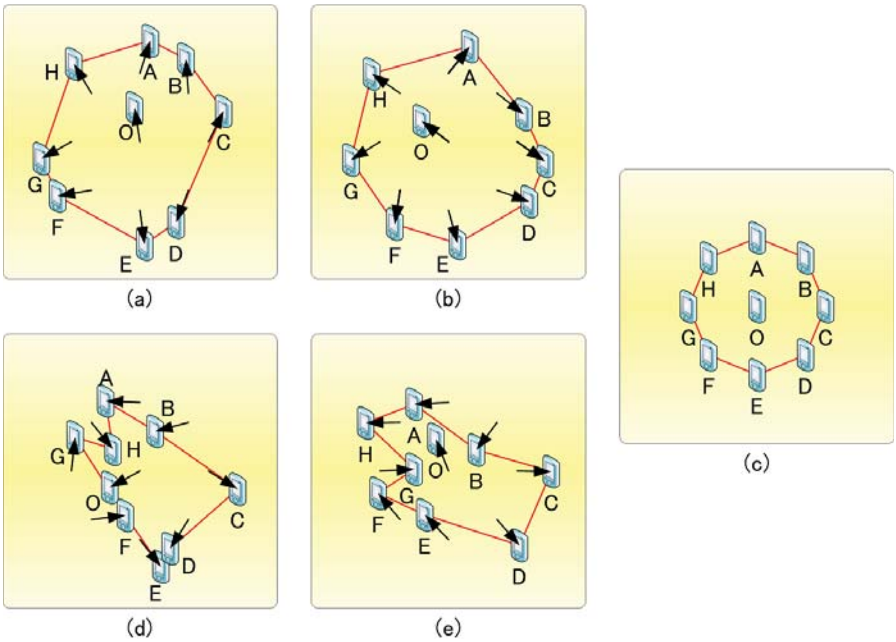


Figure 5.3: Comparison of relative positions:
(a)–(b) consistent estimations, (c) real position, (d)–(e) inconsistent estimation. Arrows indicate real positions of each node.

close to O is a possibility, but F may be redundant since having A and B in the set may be sufficient to identify O. This concept is called *uniqueness*. The uniqueness is defined for a node in a node set and the node is called *unique* if there is no alternative in the node set. In the example, the pair of A and B may be substituted for F's role of a reference point and therefore F is not unique in $\{A, B, C, D, E, F\}$. $\{A, B, C, D, E\}$ is such a set of nodes where each node satisfies the uniqueness. Even though all the nodes in a node set is unique, it does not mean the uniqueness of the node set itself. For example, different node set $\{A, C, D, E, G\}$ shown in Fig. 5.4 (b) is also such a node set. To distinguish these node sets and to choose the best one, we introduce *proximity* to O, *i.e.* the closer one to O should be prioritized. In this case, $\{A, B, C, D, E\}$ is better than $\{A, C, D, E, G\}$.

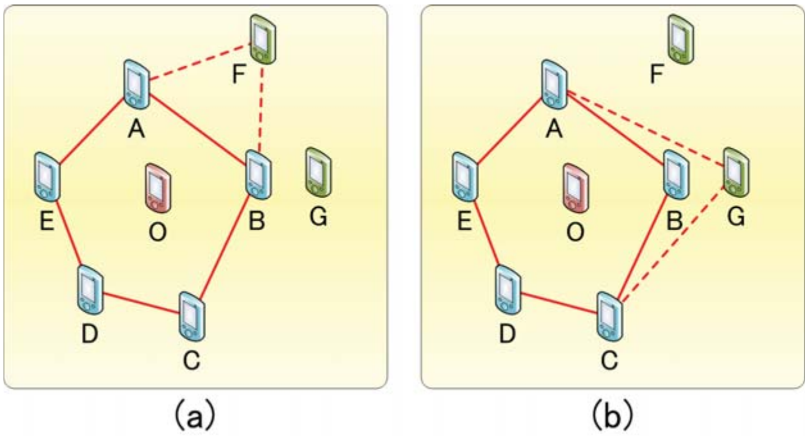


Figure 5.4: "Neighbor" sets of node O: $\{A, B, C, D, E\}$. (a) Node F is not a neighbor of node O due to node A and B, (b) Node G is not a neighbor of node O due to node B.

5.2.2 Definition of Position Relationship Dissimilarity

Based on the illustrative examples, we know that a set of neighbors that satisfies the above uniqueness and proximity simultaneously should be chosen. For this purpose, we introduce the *proximity-uniqueness* concept hereafter. We define the property of proximity-uniqueness with respect to node O as follows.

Definition 1 *Let V and $N(O)$ denote the set of all the nodes and the set of node O's neighbors, respectively. We define a necessary and sufficient condition for node X to be an element of $N(O)$ as follows.*

$$X \in N(O) \Leftrightarrow \textit{for each } Z \in V - \{X, O\},$$
$$\exists Y \in N(O) - \{X\}, f(\triangle OYX) \leq f(\triangle OYZ)$$

Let us assume that f represents X's negative "proximity-uniqueness" using some neighbor $Y \in N(O)$ (larger f means less "proximity-uniqueness"). Then the definition means that X is a neighbor if and only if the pair of X and some other neighbor Y achieve better proximity-uniqueness than any other pair of Z and Y. We regard $N(O)$ that satisfies this condition as the best set of neighbors of O.

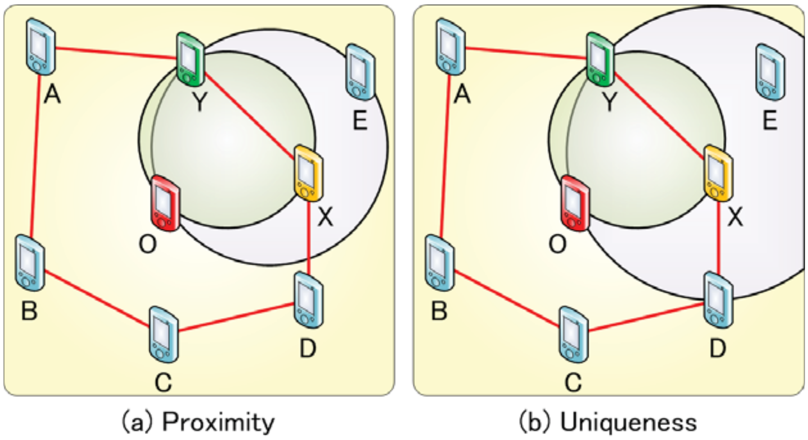


Figure 5.5: Neighbors definition based on circumscribed circles: (a) node E is not a neighbor of node O because the radius of $\triangle OYE$ is longer than that of $\triangle OYX$. (b) Node X is a neighbor of node O because the radius of $\triangle OYX$ is shorter than that of $\triangle OYD$.

Finally, we need to define function f to represent the proximity-uniqueness. More concretely, f is a function of triangles and should return the negative degree of the proximity-uniqueness of X with respect to O and Y than any other node Z. For the objective, we define the value of $f(T)$ as the circumradius of given triangle T. In this case, as shown in Fig. 5.5, X is chosen as a neighbor of O based on the proximity and uniqueness as follows.

1. (Proximity) when node E of Fig. 5.5(a) is regarded as Z in Definition 1, there exists X such that the circumradius of triangle OYX is smaller than that of triangle OYE. Therefore, E cannot be a neighbor in the presence of X.

2. (Uniqueness) when node D of Fig. 5.5(b) is supposed to be Z in Definition 1, the circumradius of triangle OYX is smaller than that of triangle OYD. Moreover, X is located in the circumcircle of OYD and no node can make a smaller circumcircle with Y and O. Therefore, X cannot be replaced by any other node due to its uniqueness to Y and O.

In order to prove validity of the proposed criteria with respect to human perception, we will show the results from real experiments based on a questionnaire in Section 5.4.

The set of triangles determined by function f which returns the circumradius is exactly equal to that of triangles derived by using the Delaunay triangulation algorithm [95]. We note that since a Delaunay triangulation is always unique for a given set of nodes, its corresponding $N(O)$ is also unique.

Therefore, we define the position relationship dissimilarity between a true position set and an estimated position set (usually given by a localization algorithm) as the *Degree of Discrepancy* (*DoD*) of Delaunay triangles formed on those sets. We define DoD by *Graph Edit Distance* (GED) [96], which represents the minimum number of edge insertion and deletion required to transform one graph into the other. GED indicates the possible number of incorrect identification.

Let E_r and E_e denote the sets of Delaunay edges in true positions and estimated positions, respectively. Also the Delaunay diagrams on true positions and estimated positions are denoted as $G_r = (V, E_r)$ and $G_e = (V, E_e)$, respectively. The GED between G_r and G_e is defined as follows.

$$Graph\ Edit\ Distance = \frac{\sum_{X,Y \in V} GED(X,Y)}{2}$$

$$GED(X,Y) = \begin{cases} 1 & if\ \ (X,Y) \in E_r \wedge (X,Y) \notin E_e \\ & \quad \vee (X,Y) \notin E_r \wedge (X,Y) \in E_e \\ 0 & otherwise \end{cases}$$

We use a normalized value of GED to define DoD. When E_e does not include any edges in E_r, GED takes the maximum value of $|E_r| + |E_e|$. Hence we define DoD as

$$DoD = \frac{Graph\ Edit\ Distance}{|E_r| + |E_e|}.$$

In the example of Fig. 5.6, common edges between G_r (left) and G_e (right) are shown by solid lines. There are three missing edges (shown by dotted lines) and three extra edges (shown by dashed lines) in G_e. Thus GED is 6 in this case and DoD becomes $\frac{6}{23} \simeq 0.26$.

We note that when DoD is equal to 0, all Delaunay edges in E_e correspond to the Delaunay edges in E_r. Thus all neighbors of each node in the estimated positions completely match those in the real positions. As DoD approaches to 1, it is harder to identify nodes from the estimated positions.

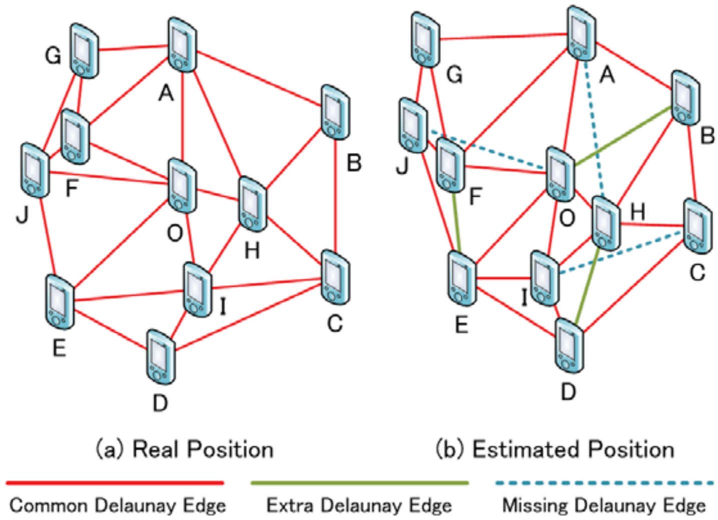


Figure 5.6: An example of discrepancy between Delaunay Triangulations: links OB, DH and BF are extra Delaunay edges and links OJ, AH, and CI are missing Delaunay edges.

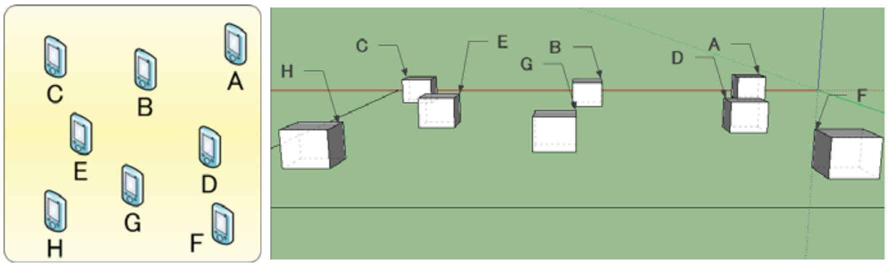
We assume there is no need to calculate DoD in real time since DoD is expected to be used for choosing the best localization algorithms before running location-based systems. Nevertheless, we discuss the computational complexity of the proposed method. The computation of Delaunay Triangulations requires $O(n \log n)$ while that of Graph Edit Distance is $O(n^2)$ where n is the number of nodes. Therefore, the computational complexity is $O(n^2)$. This indicates it is also possible to compute DoD in real time if needed.

5.3 Additional Important Criteria

In this section, we discuss other criteria that should also be considered to capture human perception as well as the Delaunay triangulation.

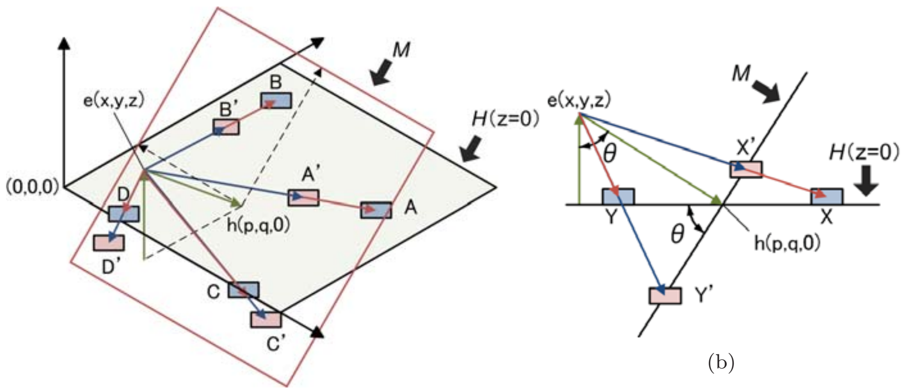
5.3.1 Viewpoint Location

We have defined DoD based on bird's-eye view (i.e. 2D-DoD). However, its 3D version (3D-DoD) should also be designed to consider viewpoint location in the real world. In applications such as a storehouse example shown in Fig. 5.1,



(a) Bird's-eye view (b) 3D view

Figure 5.7: Effect of different viewpoints



(a) (b)

Figure 5.8: Transformation with viewpoint: (a) objects A, B, C, and D on plane H are projected to objects A', B', C' and D' on plane M which is perpendicular to the line of sight. (b) Projection of A and C seeing from the side.

estimation results are shown to users in a target field. In such cases, object deployment seems different depending on viewpoints of users. The major effect of viewpoints is that distance between nearby objects appears to be longer than that between distant objects. For example, distance between node F and H is shorter than that between A and C in the bird's-eye view shown in Fig. 5.7(a). However, distance between node F and H becomes longer than that between A and C in 3D view (see Fig. 5.7(b)).

In order to define *DoD* considering such viewpoint effects, we transform the ground plane (2D-plane) to another plane in a 3D space by using the line of sight. Suppose that the target region is a ground region H where a viewpoint is at $e = (x, y, z)$ and the eyes are looking at a point $h = (p, q, 0)$ in region H as shown in Fig. 5.8(a). We introduce the oblique region M which is perpendicular to $\overrightarrow{\mathrm{eh}}$ (the line of sight) and contains h. Then node positions A, B, C, and D on H are projected onto M. We consider rays from the viewpoint e to each node position. Finally, we map node positions A, B, C, and D on H to intersections A', B', C', and D' of M and the rays, respectively. For example, Fig. 5.8(b) shows projection of A and C seeing from the side. The distance between A and h is equal to that between C and h on H. However, after projection onto M, distance between A' and h becomes shorter than that between C' and h as shown in the figure. By the above transformation, we can apply our approach to location-based applications affected by viewpoints in a 3D space.

We note that the correspondence between the bearings of real/estimated positions is assumed to be known[1]. This is usually done by referring to absolute reference points on the ground (*e.g.* buildings and signs in real world's views) or digital compasses in mobile devices.

5.3.2 Nodes in Close Proximity

In human perception, nodes in close proximity are regarded as a cluster (i.e. group) [61]. Since those nodes in the same cluster are too close to each other, they may not be necessary to be distinguished in most realistic applications and situations. Meanwhile, if *organization* of clusters in estimated positions is quite different from that in true positions, it significantly affects identification accuracy.

Therefore, we quantify the degree of discrepancy between two cluster organizations in real and estimated positions. For this purpose, we propose a clustering algorithm that fits for human perception and introduce a similar idea to the graph edit distance in the Delaunay triangulations.

We note that the existing clustering algorithms [97, 98, 99, 100] are classified into hierarchical or non-hierarchical algorithms. In non-hierarchical algorithms such as [98], the number of clusters must be specified before clustering nodes. However, since clustering based on human perception largely depends on the distribution of nodes, it is hard to specify the number of clusters beforehand, and hierarchical algorithms such as [99] are more appropriate.

[1]Without this assumption, identification becomes very hard since rotation should be considered.

Based on informal interviews with emergency medical doctors who are our collaborators in the emergency rescue support project [81] and actually need identification of injured people in disaster sites, we recognize that *inter-cluster distance* is a significant factor. We take from the existing clustering algorithm a strategy that renders this factor.

To consider inter-cluster distance, we introduce the group average method [100] which uses the average distance between nodes in two different clusters as the inter-cluster distance. Inter-cluster distance $d(C_1, C_2)$ of clusters C_1 and C_2 is defined as:

$$d(C_1, C_2) = \frac{1}{|C_1||C_2|} \sum_{p \in C_1} \sum_{q \in C_2} d(p, q)$$

where $|C_1|$ and $|C_2|$ respectively denote the number of nodes in C_1 and C_2, and $d(p, q)$ is the Euclidean distance between nodes p and q.

[Clustering Algorithm]

(Step 1) Let N be the number of nodes. Initialize the set $\mathcal{C}$ of clusters to N clusters where each cluster has one node.

(Step 2) For clusters C_1 and C_2 in $\mathcal{C}$ with the shortest inter-cluster distance, check if $d(C_1, C_2)$ is less than threshold α or not. If true, merge C_1 and C_2 in $\mathcal{C}$ and go to Step 2. Otherwise terminate the algorithm. Empirically α should be less than $1m$ and $\alpha = 0.6m$ was used in the following experiments.

We tailor DoD defined in Section 5.2.2 such that it can incorporate the clustered nodes. Firstly, we organize the clusters over real positions using the above algorithm. Then we apply the same cluster organization to estimated positions. Regarding the centroid of each cluster as the location of the cluster, we build the Delaunay triangles on real and estimated clusters and compare them to derive DoD.

5.4 DoD and Identification Accuracy Correlation

We have conducted an experiment to see the correlation between DoD and human intuition. In the experiment, we have prepared 30 pairs of real positions and their corresponding estimated positions of 10 nodes (actually they are 10 students). Eyepoints in estimation results were set to the 4 corners of the area

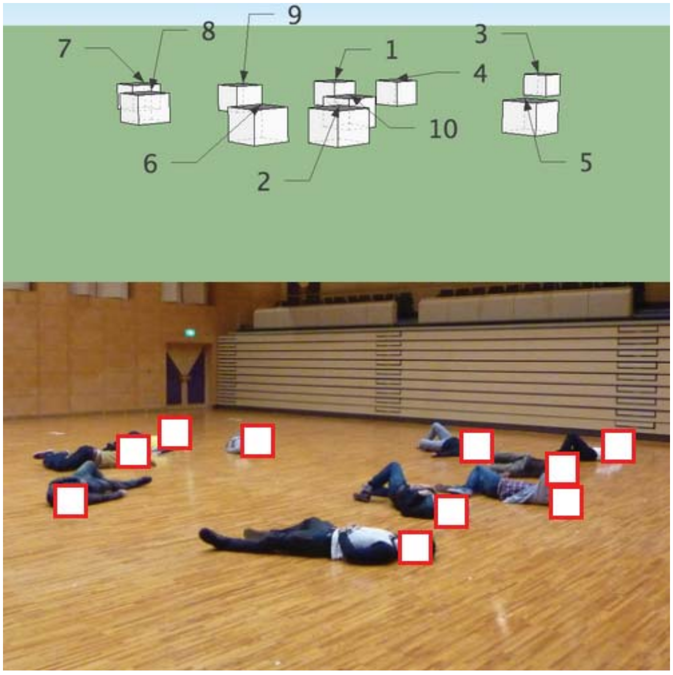


Figure 5.9: Example of questionnaire: the picture shows estimated positions of 10 objects. The photograph shows real positions of corresponding 10 persons. Subjects are required to guess ID of each person.

with 170cm height. Therefore, we have prepared 120 pairs as a total and 54 examinees participated in this experiment. As a total, we had 6480 answers for 120 questionnaires.

An example questionnaire is shown in Fig. 5.9 where node IDs were shown in the estimated positions but hidden in the real positions. For real positions, we have used the pictures of 10 students lying on the floor. Such a situation is likely to happen in emergency sites where injured persons are waiting to be treated and delivered to hospitals [81]. Given a pair of position sets, each examinee was required to identify node IDs in the real positions. The correctness of the answer is observed by the number of mis-assignments in each pair.

In order to examine the individual variability before the analysis of results, we summarized the average number of mis-assignments with error bars for each examinee. From the result shown in Fig. 5.10, we can see that the average num-

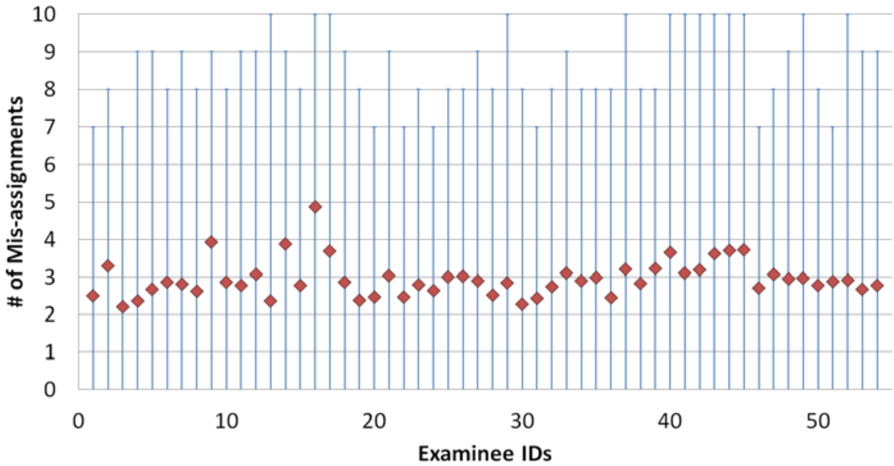


Figure 5.10: # of mis-assignments of 54 subjects. Each dot indicates the average of mis-assignments and each line shows the range of mis-assignments.

ber of mis-assignments is very similar among examinees and it is not necessary to take individual variability into account. We note that for the same questionnaire, there is of course variability among examinees. Even though it is mostly impossible to disregard such variability for different types of questionnaires, the data in Fig. 5.10 is helpful to analyze DoD trend in the followings and to justify the uniformity of the dataset among the examinees.

Fig. 5.11 shows the number of mis-assignments with error bars for each DoD value. Due to difference among questionnaires and viewpoints, the range of mis-assignments for the same DoD value seems spread. However, we can see certain trend of mis-assignment growth along with DoD where the trend more clearly appears on the average values.

In order to make this trend more visible, we have taken the averages of DoDs and the number of mis-assignments over the 13 different examinees and 4 different eyepoints. From the resulting 30 cases, we have discarded 10% to avoid outliers and finally 27 cases were left in Fig. 5.12. We have also calculated the correlation coefficient and it was 0.82, which generally indicates strong relationship.

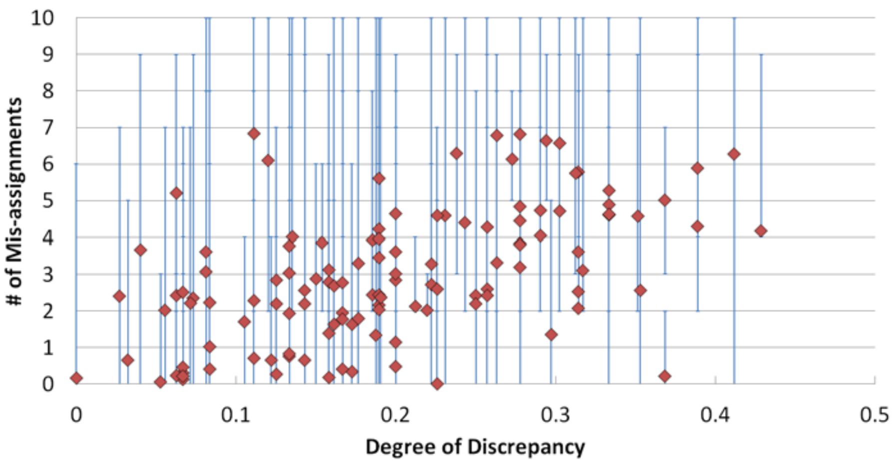


Figure 5.11: DoD vs. # of mis-assignments. Each dot indicates the average of mis-assignments and each line shows the ranges of mis-assignments.

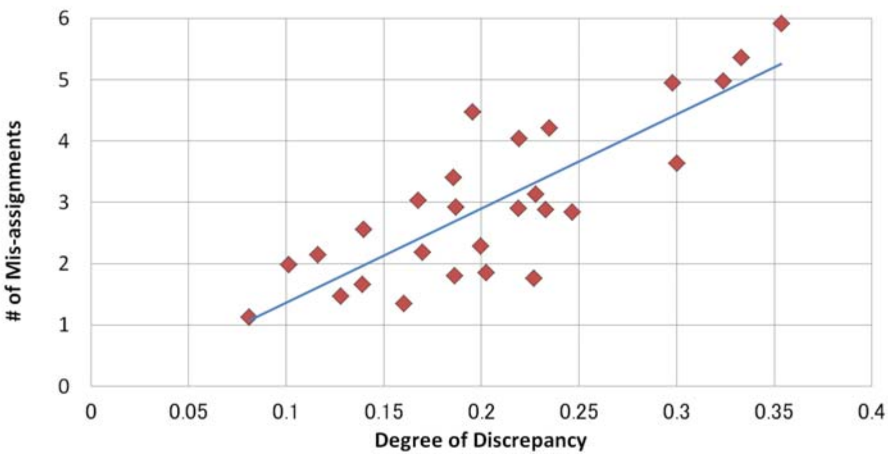


Figure 5.12: Avg. DoD vs. # of mis-assignments. The line indicates linear approximation.

5.5 Analysis of Localization Algorithm by DoD

In the last section, we have shown that DoD could capture human perception in identifying object location. Based on this, we characterize different types of localization algorithms and analyze their localization "accuracy" in terms of object identification.

5.5.1 Examined Localization Algorithms

We have selected (a) GPS as a non-cooperative, range-based positioning system, (b) MDS-MAP [54] as a multihop, range-based cooperative localization algorithm, and (c) TRADE [56] as a multihop, range-free cooperative localization algorithm that utilizes connectivity information. This is reasonable selection where we can see the characteristics of different localization algorithms on DoD through comparison between (i) non-cooperative and cooperative algorithms, and (ii) range-based and range-free algorithms. Although we have not selected an algorithm from the non-cooperative range-free category, we can suppose its characteristic from the above comparison.

In non-cooperative range-based techniques such as GPS, each node independently estimates its own position by using direct measurement from reference points.

MDS-MAP is a localization algorithm based on multi-dimensional scaling [101]. MDS-MAP exploits estimated distances between nodes based on Received Signal Strength (RSS). Then the positions of nodes are estimated by matrix calculations with constraints on distances among nodes. Euclid distance between nodes is approximated by network hop counts and estimated per-hop distance.

Finally, TRADE is a localization algorithm using internode connectivity information. Nodes in TRADE continue adjusting their positions and past trajectories to fit for spatial constraints from the maximum communication range and maximum movement speed.

5.5.2 Simulation Settings

The default values of simulation parameters are shown in Table 5.1. Four viewpoints were set at the points A, B, C, and D looking at the center of the target region in Fig. 5.13 at points are located $1m$ away from the assuming standing people.

To generate GPS errors, we have given both distance and directional errors for each true position which were randomly selected in $[0, e_g]$ and $[0, \theta]$, respectively. Then GPS has been examined with the maximum distance error

Table 5.1: Simulation parameters

Area size	10 (m) $\times$ 10 (m)
# of landmarks	4
# of nodes	30
Node mobility	Random Waypoint
Moving speed	1.0–1.5 (m/s)
Pause time	0 (s)
Simulation time	100 (s)
Clustering threshold (α)	0.6 (m)

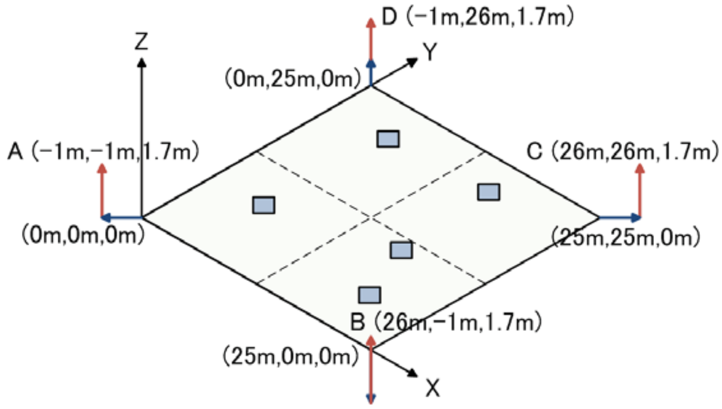


Figure 5.13: Viewpoints in simulation

$e_g \in [0.4m, 2.8m]$ with step 0.8m and the angle error $\theta = [0.5\pi, 2.0\pi]$ with step 0.5π. MDS-MAP has been examined with three distributions of measurement errors; uniform, normal and biased distributions with the "maximum measurement error" e_m, which is given as a ratio to true distances. In the uniform distribution, the measurement error was determined by randomly choosing values from $[-e_m, e_m]$. In the normal distribution, the measurement error followed the normal distribution with mean 0 and $\sigma = e_m/2$. In the biased distribution, it was determined by randomly choosing values from $[-e_m, -e_m + 0.05]$ and $[e_m - 0.05, e_m]$ (errors stick around $\pm e_m$ with 5% deviation). In TRADE, the number of nodes was selected from 20, 30, 40, and 50, and communication range r was set to $2m$, $4m$, $6m$, or $8m$.

In comparison between different localization algorithms in Section 6.4, the

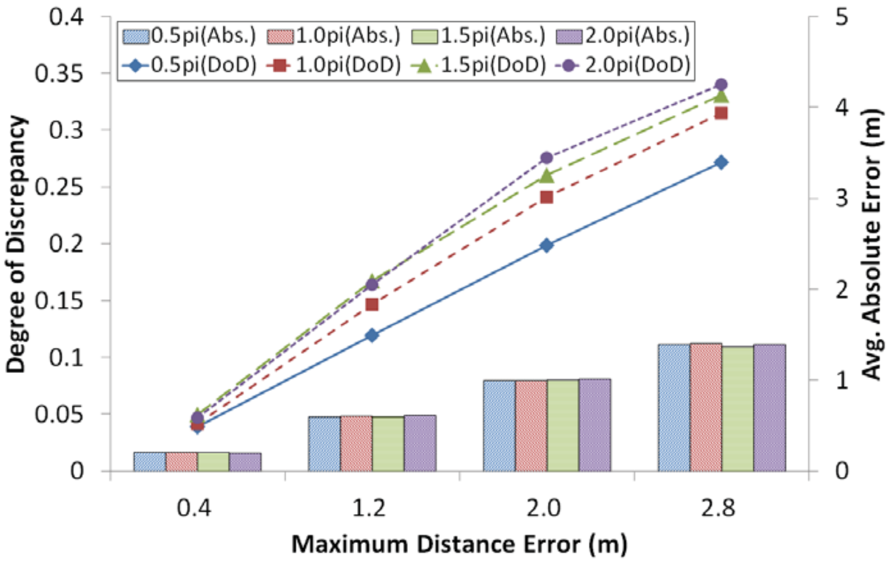


Figure 5.14: Maximum distance error e_g in GPS vs. DoD and absolute error.

area size was set to $25m \times 25m$ and the number of nodes was 20. In GPS, distance and directional errors were randomly selected from the range $[0m, 3m]$ and $[0, 2.0\pi]$, respectively. We randomly selected distance measurement errors in MDS-MAP from the range $[-10\%, 10\%]$ and used $10m$ of communication range r in TRADE.

5.5.3 DoD Characteristics of Different Localization Algorithms

Fig. 5.14 shows DoDs versus the maximum distance error e_g in GPS. The bar chart indicates the average distance errors using the right Y-axis (*i.e.* it shows not "relative errors" but "absolute errors"). The important point is that although the absolute errors are almost equal among different angle errors in $[0.5\pi,\ 2.0\pi]$, DoDs shown by the line chart using the left Y-axis show different values and trends. Since angle errors significantly affect the relative location of nodes, a larger angle error should generally indicate more rapid growth of DoD. This property can be observed in the DoD line chart, and we can say that DoD can distinguish such errors that are caused by directional errors.

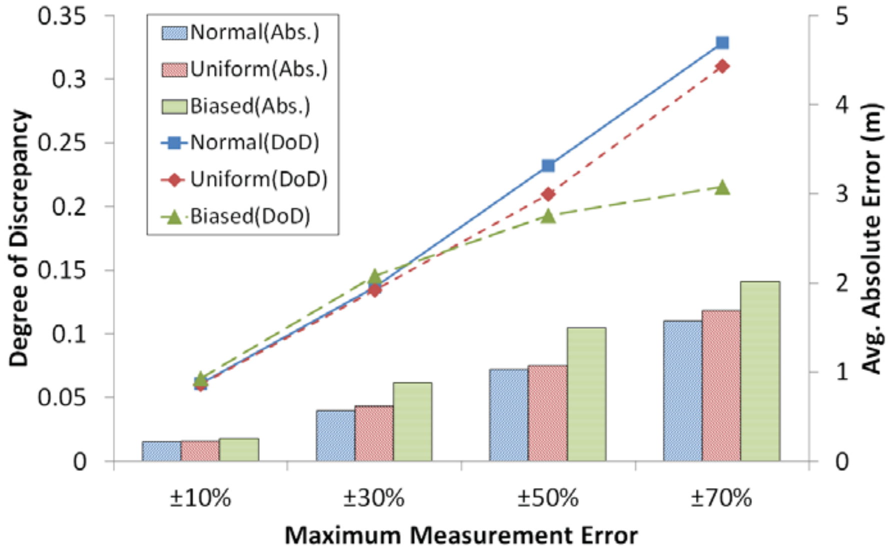


Figure 5.15: Maximum measurement error e_m in MDS-MAP vs. DoD and absolute error

Fig. 5.15 shows DoDs versus the maximum distance error e_m in MDS-MAP. Similarly with the GPS case, the absolute errors are shown by the bar chart using the right Y-axis. The interesting characteristics are found in the biased distribution where the absolute errors are largest but DoDs are smallest with larger e_m (50% and 70%). Since biased distribution generated almost two constant values as errors ($\pm e_m$ with small deviations), in the most part the position relationships were kept intact under large absolute errors. As in the GPS case, we could observe that DoD could capture such a property.

Finally, DoDs versus the number of nodes in the case of TRADE are shown in Fig. 5.16. Overall, the absolute errors of TRADE decrease with the increase of node density because the amount of spatial constraints increases. Communication ranges also affect absolute errors since a larger communication range may increase connectivity. However, the large communication range may also increase absolute errors since it may relax spatial constraints. When the communication range was 2m, the absolute error was the second worst among the four ranges because the range was too small to constrain the location of other nodes.

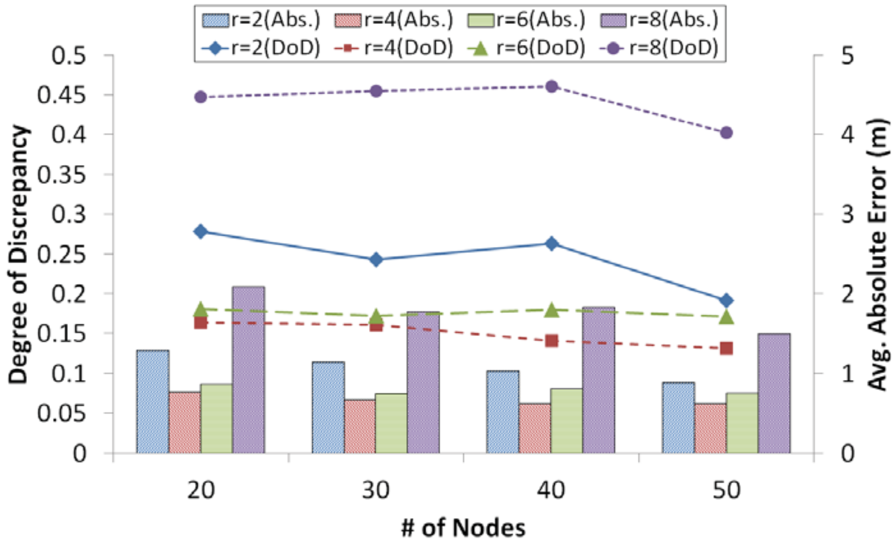


Figure 5.16: # of nodes in TRADE vs. DoD and absolute error

Here, due to the feature of range-free algorithms where relative positions are not preserved strictly, the position relationship is also affected by the evaluated factors, i.e. node density and communication range. In this context, DoDs follow the similar trend of the absolute errors, which is natural.

5.5.4 Comparison between Different Localization Algorithms

In order to see difference in *DoD* in three types of localization algorithms described in Sect. 5.5.1, we conducted another experiment. Simulation settings are shown in Table 5.2. In GPS, each estimated position was randomly chosen from points whose distances from their real positions were less than $3m$. We randomly generated distance measurement errors as up to 10% in MDS-MAP. Since node density affects the accuracy of MDS-MAP and TRADE, our simulations are done for different numbers of nodes.

Fig. 5.17 shows the absolute errors of above localization algorithms. MDS-MAP could not execute localization when the number of nodes was 10 because MDS-MAP requires the whole network to be connected and it did not work when the number of nodes was 10. The absolute errors of the compared three algorithms were almost the same when the number of nodes was 50. In MDS-

Table 5.2: Simulation parameters

Area size	25 (m) $\times$ 25 (m)
Maximum communication range (R)	10 (m)
# of landmarks	4
# of nodes	Every 10 from 10 to 70
Node mobility	Random Way Point
Moving speed	1.0–1.5 (m/s)
Pause time	0 (s)
Simulation time	600 (s)

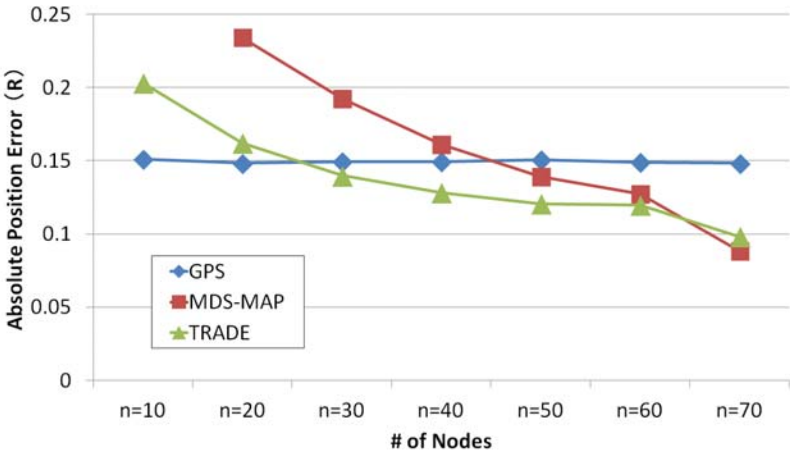


Figure 5.17: Simulation results of absolute error

MAP and TRADE, the absolute errors decrease according to the increase in the number of nodes.

Nevertheless, from the graph in Fig. 5.18, *DoD*s of the three localization algorithms show quite different characteristics. GPS is the worst in terms of *DoD* and becomes worse with the increase of node density because it does not use neighbor information. In contrast, *DoD*s in MDS-MAP and TRADE (i.e. cooperative algorithms) are rather low. The difference of *DoD*s between GPS and MDS-MAP is more than 30% when the number of nodes is more than 50. From the result, it is clear that *DoD*s in cooperative algorithms are lower than those in uncooperative algorithms because cooperative algorithms utilize

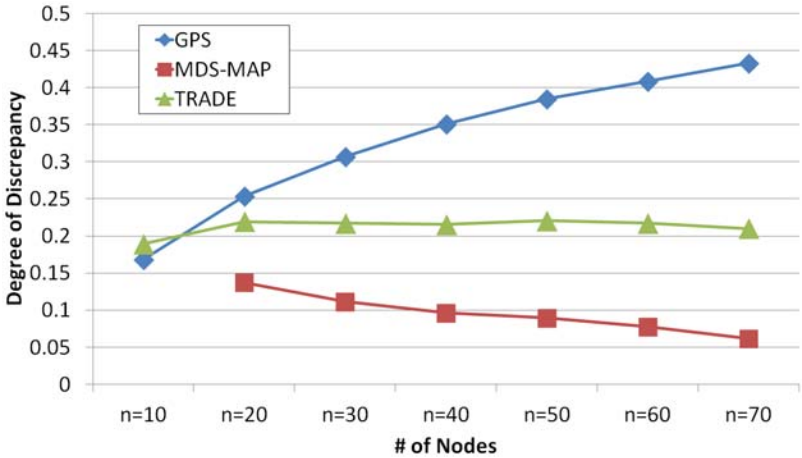


Figure 5.18: Simulation results of relative error

information from other nodes. Particularly, MDS-MAP uses measured distances between all nodes while only information from neighbors within 2 hops is used in TRADE. For this reason, DoD in MDS-MAP is the best among these three algorithms.

Figures 5.19(b)-(d) show snapshots of estimated positions of the three algorithms and their real positions are shown in Fig. 5.19(a) when the number of nodes is 20 with 4 landmarks (IDs 0-3). The absolute errors are shown by segments from each node. We can see the difference in relative positions between these algorithms, especially for nodes marked by circles in the snapshots. Relative positions in MDS-MAP (Fig. 5.19(c)) are very close to those in the real positions (Fig. 5.19(a)).

Table 5.3 also describes the absolute and relative errors at that time. Surprisingly, MDS-MAP is the best in the relative error but the worst in the absolute error. This means relative errors cannot be measured by absolute errors only. Therefore, it is important to evaluate localization algorithms in terms of relative errors depending on services and applications. From the above results, we have confirmed that DoDs could represent the different characteristics of localization algorithms in terms of position relationship.

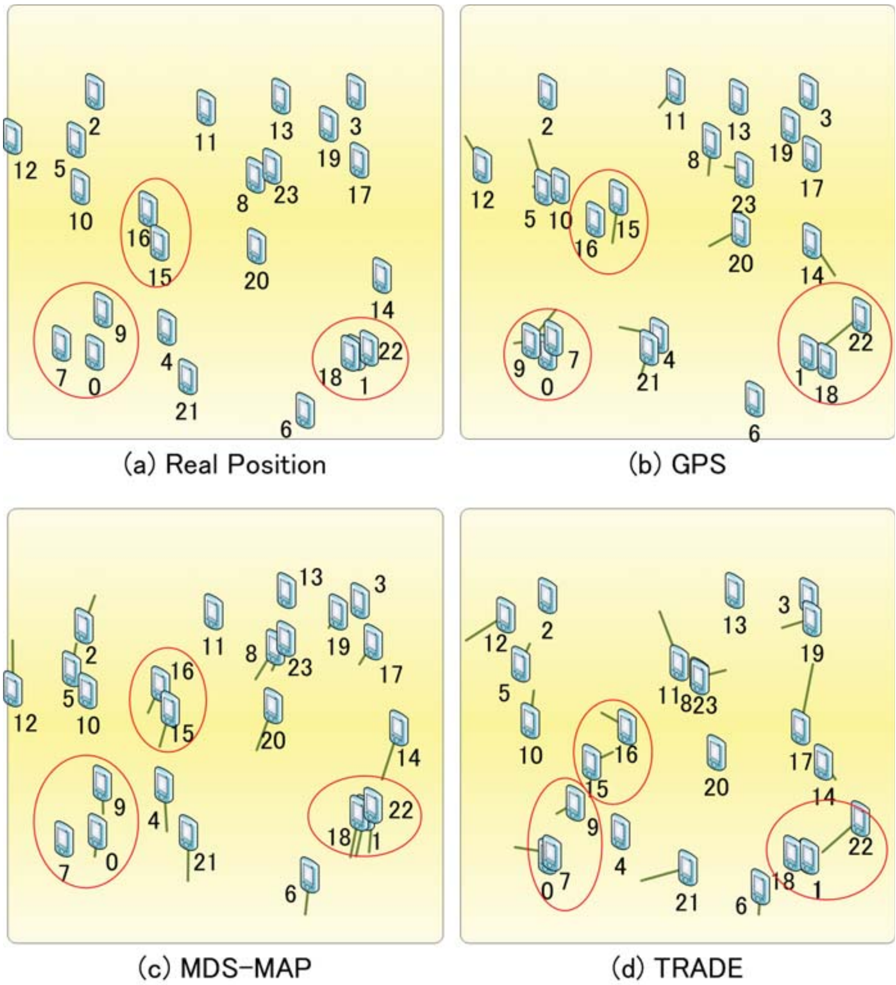


Figure 5.19: Estimated positions by different localization algorithms. Each line indicates the distance and angle error of each node in estimated positions.

Table 5.3: Position errors of localization algorithms

	GPS	MDS-MAP	TRADE
Absolute Error (R)	0.168	0.188	**0.154**
Degree of Discrepancy	0.331	**0.127**	0.246

5.6 Conclusion

In this chapter, we have proposed a method to quantify localization accuracy in terms of object identification. We have analyzed primary factors that affect object identification and have found that the Delaunay triangulation could capture such factors. We have also analyzed additional factors such as eyepoints and grouping. By subjective testing based on 120 questionnaires by 54 examinees with 6480 answers, we have justified our proposed metric, *i.e.* Degree of Discrepancy (DoD) between the real and estimated positions. Simulation results have also shown that DoD could capture the different characteristics of localization algorithms which have not been found by absolute errors. We believe that new emerging mobile and pervasive applications such as AR-based navigation are beneficial from our approach to assess adequacy of positioning systems they use.

Chapter 6

Conclusion

In this thesis, we focus on two key ICT-based social infrastructures that are quite essential for green and life innovation. In particular, we propose two location-based activity support systems: a vehicle telematics system to aid battery-charging activities of electric vehicles' drivers and an electronic triage system that supports rescue operations of first responders in emergency sites. We also discuss fundamental technologies that are required to achieve these systems, and among those technologies we particularly deal with the design of a relative location assessment methodology. Through the design and development of the proposed systems, we reveal the required technologies to achieve truly-innovative ICT applications that are often designed based on locations of people, objects and environments. The system outputs which are provisioned to customers, users and those who are engaged in severe tasks will be helpful for them to optimize their strategies of decision making. The goal of this thesis is to contribute to the establishment of design methodologies in these application domains that are profoundly related with location-based systems.

In Chapter 2, we have surveyed several researches of telematics services for electric vehicles and triage systems to show the features of our approaches. In addition, we have surveyed researches about methods to evaluate localization algorithms in terms of position relationship to address the related work and show the features of our proposed method.

In Chapter 3, we have proposed a route search method for EVs to eliminate concerns of users about the short cruising range and the shortage of charging stations. In the proposed method, we have calculated an optimal route going through charging stations to recharge its battery if the current state of charge is not sufficient to reach the destination. In the calculation, firstly we select optimal stopover C/Ss depending on EVs' cruising range, travel time and charging time before we search the route from the origin to the destination. After that, we calculate some routes via selected stopover C/Ss, which there is no need to concern for battery down during driving EVs. And we search a least-time (minimum travel time including charging time) route from some routes which stop over charging stations by applying Dijkstra's method on this graph. Offering such routes to drivers will eliminate a part of the major concerns in driving EVs and contribute to the spread of EVs.

In Chapter 4, we have designed and developed an electronic triage system (eTriage) which helps a medical team to efficiently treat patients on mass casualty incidents. We have also described a localization method applied to this system, simulation results and evaluation results of a real experiment in a disaster drill at a hospital. In eTriage, electronic triage tags are attached to injured people. This tag senses vital signs of each victim and transmits the data to a server via ad-hoc wireless networks. Furthermore, eTriage estimates positions of patients and medical staff members by our ad-hoc localization algorithm using wireless network topology information. Providing vital data and positions information of patients will support medical team members to carry out efficient medical activities in the situation where medical resources are limited.

In Chapter 5, we have proposed a method to quantify localization accuracy in terms of object identification. We have analyzed primary factors that affect object identification and have found that the Delaunay triangulation can capture such factors. We have also analyzed additional factors such as eyepoints and grouping. In the proposed method, we define criteria that represent proximity and uniqueness of neighboring targets, to access the "accuracy" of the estimated positions in identifying objects at true positions. Based on these criteria, position errors are quantified by Degree of Discrepancy in Delaunay triangulation formed on a set of estimated positions to be accessed and the corresponding set of real positions. This proposed method can helps system developers to select an optimal localization algorithm for location-based activity support.

Our ongoing work includes continuing maintenance of the proposed systems operated in the experiments. We will also reflect the opinions of our system users and enhance the function of the proposed systems to achieve the practical use. In addition, we will proceed with investigation of changing needs of social infrastructures according to rapid technological evolution, and continue the design and development of the system to respond to these needs. Although this is a long term challenge, we believe we can contribute many system developers of advanced, complicated and convenient location-based social systems.

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