Managing Uncertain Location with Probability by Integrating Absolute and Relative Location Information

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ABSTRACT

Location information is expressed by various formats that depend on services. Location information is divided into two categories: absolute location information (such as latitude/longitude and address), and relative location information (such as distance and direction). Each service that utilizes location information defines location information system individually. Therefore, sharing location informations between the services is difficult. Consequently, reusability of location information decreases. Then, we consider new common location information system, which can be converted from location information of various systems and expresses location more flexible. In this study, we propose probabilistic location information, which expressed as a combination of area and existence probability. Moreover, we propose the algorithm which calculates probabilistic location information based on geographic coordinate information and pass-by information (PLPA-GP).

CCS CONCEPTS

• **Information systems → Location based services**; **Global positioning systems**; • **Human-centered computing** → Ubiquitous and mobile computing systems and tools;

KEYWORDS

location information, geographic coordinate, pass-by, probabilistic location information

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1 INTRODUCTION

With the recent development of IoT (Internet of Things) and the sensor technologies, positioning location information becomes easier for consumers. Therefore, many value added services which utilize location information of objects are developed and utilized widely around the world.

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Examples of services utilizing location information are shown below. " Uber[3] " can dispatch a taxi near the location of the user. " Life360[2] " can trace location information of child for monitoring for crime prevention. " To-haku Navi[4] " can explain nearby exhibit automatically with a smartphone at Tokyo National Museum.

Location information is expressed by various formats that depend on services. The location information is divided into two categories by type of coordinate **system** belonging. These categories differ in a relationship between object and subject. The first one is **absolute location information**. Absolute location information is location information expressed in an absolute coordinate system which points to an absolute place. An absolute coordinate system is such as latitude/longitude and address. The second one is **relative location information**. Relative location information is location information expressed in a relative coordinate system which indicates a positional relation between two objects. A relative coordinate system is such as distance and direction. Absolute location information is detected by positioning systems which measure location directly such as a Global Positioning System (GPS). " Uber " and "Life360" utilize absolute location information. By contrast, relative location information is detected by near field radio communication system such as Bluetooth and ad hoc mode of Wi-Fi when two objects approach. " To-haku Navi " utilizes relative location information.

Each location information service defines location information system individually. This fact causes differences in such as expression format, and representability of spatial or temporal resolution between each system. Therefore, sharing location informations between the services is difficult. Consequently, reusability of location information decreases. Furthermore, different location information systems cannot refer to each other. A simple way to solve these problems, constructing unified location information system which is independent the services is enumerated. Nevertheless, characteristics required for location information are different between each service. Thus, it is difficult to integrate expression of location information. Here, we consider new common location information system. This new system can convert from location information of various systems. This new system can expresses location more flexible. Because of this new system, inferring unknown location of a object becomes possible by calculating based on an absolute location of other objects. Moreover, a location information that is uncertain in a single system can be complement by location informations of other systems. In addition, the new system can express a location information with various spatial or temporal resolution.

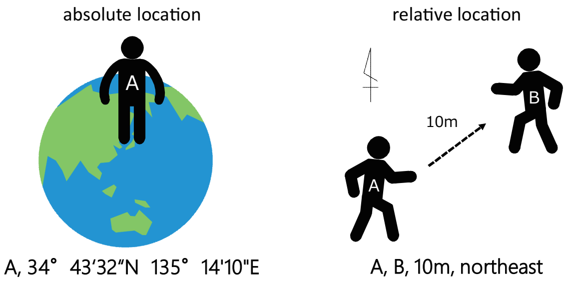

Figure 1: Examples of information informations

In this study, we propose **probabilistic location information system** as the above new common location information system. Probabilistic location information can express a location with one format. This format expresses the location information of an object by a combination of area and existence probability. Then, for the realization of calculating probabilistic location information, we consider the method which calculates based on a combination of different location systems. In this paper, in particular, we consider the method of calculation based on geographic coordinate information and pass-by information. Geographic coordinate information consists of latitude and longitude. And pass-by information expresses approaching of two objects.

2 PREPARATION

2.1 Location information

Location informations are expressed by various formats. The format of the location information is different between each service. The location informations are divided into two categories. These categories differ in a relationship between object and subject. Examples of information informations are shown in Figure 1.

Absolute location information

Absolute location information is expressed by an absolute coordinate system which points to a place in a positioning system. Examples of absolute coordinate systems include latitude/longitude and address are utilized. On mobile devices, absolute location informations are detected by positioning systems which measure location directly such as a GPS. In this paper, an absolute location of object A at time t is expressed $\mathrm{Pos}(A, t)$. In addition, an absolute location information of object A at time t at place P is expressed $\langle A, t, P \rangle$.

Relative location information

Relative location information is expressed by a relative coordinate system which indicates a positional relation between two objects. Examples of relative coordinate systems include distance and direction. We define an event that objects get close in an arbitrary distance within an arbitrary period of time as *pass-by*. The pass-by information is indicated as relative location information. Relative location informations are detected by near field radio communication systems such as Bluetooth or ad hoc mode of Wi-Fi when objects do pass-by. BLE and Wi-Fi can measure distance between objects from the attenuation degree of radio waves, however, these technologies cannot measure a direction between objects. In this paper, a relative location of object A and B at time t is expressed $\mathrm{Rel}(A, B, t)$. In addition, a relative location information of object A and B at time t at positional relation R is expressed $\langle\langle A, B, t, R \rangle\rangle$.

2.2 Problems of location information

When multiple absolute location systems have a different basis of absolute location, an expression format of location informations which are expressed by each system are different. Moreover, relative location information cannot convert into absolute location information. From these reasons, location information systems cannot refer to each other. In addition, location information systems differ in a representability of spatial or temporal resolution. Therefore, when plural location information systems which have the same basis differ in setting, these cannot refer to location information of each other. Thus, reusing location information between services is difficult.

Here, we consider new common location information system which can be converted from location information of various systems. The new location information system realizes that services can utilize location informations which are recorded by various information system indirectly. Moreover, this system can express an uncertain location which cannot be indicated by one point. This system can absorb a difference in spatial or temporal resolution of location information by complementary utilization of various location information system. Therefore, by utilizing this system, services can refer to location information of various time as compared with utilizing a single location information system. Furthermore, we can infer an absolute location of an object that records only relative location information by absolute location of other objects.

3 PROBABILISTIC LOCATION INFORMATION

Probabilistic location information expresses a location of an object at an arbitrary time with a combination of area and existence probability. A probabilistic location information has multiple absolute location informations which mean an area. These absolute location informations include values of probability (such as number and " high " or " low ") that an object exists at this absolute location. By utilizing values of probability, we can calculate an area where an object exists with an arbitrary probability.

The outline of utilizing probabilistic location information is shown in Figure 2.

A probabilistic location positioning algorithm calculates a probabilistic location information by utilizing location informations of various location information system. For services utilizing location information, it becomes possible to refer to probabilistic location information as a unified expression format regardless of positioning methods. In addition, spatial or temporal resolution of the location information becomes adjustable. Moreover, location information recorded by various services becomes mutually referenceable indirectly. Thus, reusability of location information is increased.

By utilizing probabilistic location information, we can refer to areas where an object exists with high probability at a time when

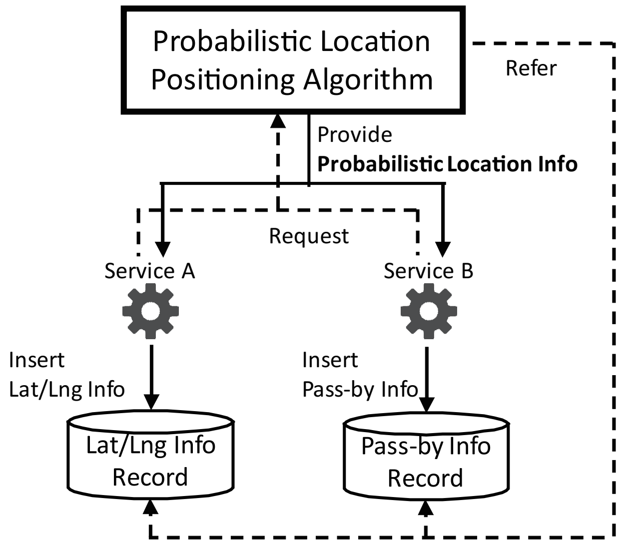

Figure 2: The outline of utilizing probabilistic location information

absolute location information was not detected. The probabilistic location information algorithm infers location information from absolute location information of times near the designated time. On the other hand, we can refer to probabilistic location information of an object which detects only relative location information. Then, the algorithm can infer absolute location by referring to absolute location information of an another object in the relative location information.

3.1 Data structure

Probabilistic location information consists these following elements.

- **objectId**
- **time**
- **location**
  - Expresses the location where the object exists at the time
  - Be list structure
    - ⋆ **place** (element of location)
      - Expresses an area or a point geographically
      - Be defined as a shape which expresses an area such as a circle
    - ⋆ **score** (element of location)
      - Expresses values of probability which an object exists on the place
      - The value is such as number and " high " or " low ".

3.2 Calculation methodology

In the probabilistic location positioning algorithm, the process of calculating probabilistic location information of object A at time t occurs in two steps. First, the algorithm infers location information from transitions of absolute location informations of object A at times near t. Second, the algorithm combines a relative location information of object A and object B, and an absolute location information of object B. The algorithm can calculate location by summing up areas which are calculated by the above two steps. The algorithm utilizes the speeds of each object. Hereafter in this paper, the speeds of A and B are called v_A and v_B. In this section, we assume that v_A and v_B are inferable.

3.2.1 Inference from transitions of absolute location informations.
The algorithm infers an area where an object exists at an arbitrary time from transitions of absolute location informations.

For example, we consider location information of object A at time t_3. We assume that two location information ($\langle A, t_1, P_1\rangle$ and $\langle A, t_2, P_2\rangle$ ($t_1 \leqq t_2 \leqq t_3$)) are recorded. We calculate v_A by distance and time difference between these location informations. Therefore, we can express a location information of object A at time t_3 as " A exists at place where A can go from the place P_2 by time $(t_3 - t_2)$ at speed v_A ".

3.2.2 Inference from combination of absolute location information and relative location information.
In certain cases, we can infer an absolute location of an object from relative location information of the object. In these cases, an another object in the relative location information records absolute location information. By combinations of these location informations, the algorithm can infer an area where an object exists with high-probability at an arbitrary time.

For example, we consider location information of object A at time t_3. We assume that two location information ($\langle B, t_1, P_1\rangle$ and $\langle\langle A, B, t_2, R\rangle\rangle$ ($t_1 \leqq t_2 \leqq t_3$)) are recorded. In the case of $t_1 = t_2$, we infer that A exists at a new place P_2 where it is positional relationship R from P_1 at time t_2. Therefore, we express a location information of object A at time t_3 as "A exists at place where A can go from the place P_2 by time $(t_3 - t_2)$ at speed v_A ". In the another case of $t_1 < t_2$, we infer that A exists at a new place P_3 where B can go from the place P_2 by time $(t_2 - t_1)$ at speed v_B at time t_2. Therefore, we express a location information of object A at time t_3 as " A exists at a place where A can go from the place P_3 by time $(t_3 - t_2)$ at speed v_A ".

4 PLPA-GP

4.1 Outline

In this section, we propose **PLPA-GP** (Probabilistic Location Positioning Algorithm based on Geographic coordinate and Pass-by). PLPA-GP is an algorithm which can calculate probabilistic location information based on geographic coordinate informations and pass-by informations. PLPA-GP calculates a location of a designated object at a designated time from a movable area from a known location at time near the designated time. The movable area is expressed by a circle area of which becomes larger corresponding to moving speed of the object. In addition, PLPA-GP calculates multiple circle areas by utilizing the location informations of other objects which detect pass-by with the designated object. PLPA-GP calculates probabilistic location information by utilizing these circle areas.

Algorithm 1 Calculating probabilistic location information based on circular area

```
1:  // Function which calculates ProLoc(A, t)
2:  function PLPA-GP(A, t, hop)
3:      // Declare of circular areas
4:      Set⟨Circle⟩ circleSet_A;
5:      if Pos(A, t) != null then
6:          return Pos(A, t);
7:      end if
8:      if Pos(A, t′) ( (t − t′) < δ) != null then
9:          // Add movable area as a circle from the latest geographic coordinate information of A
10:         Circle c = new Circle(Pos(A, t′), v_A × (t − t′));
11:         push (circleSet_A, c);
12:     end if
13:     if hop > 0 then
14:         // Get object B_i which records pass-by information at time near t
15:         pbSet = {B_i|⟨⟨A, B_i, t_i, l_i⟩⟩ AND (t − t_i) < δ}
16:         for B_i in pbSet do
17:             // Get ProLoc(B_i, t_i) recursively
18:             proLocBi = PLPA-GP(B_i, t_i, hop-1);
19:             // About each circle of ProLoc(B_i, t_i)
20:             for Circle c : proLocBi.getCircleSet() do
21:                 // Add movement distance (t_i to t) to radius of circle
22:                 c.addRadius(v_A × (t − t_i) + l_i));
23:                 push (circleSet_A, c);
24:             end for
25:         end for
26:     end if
27:     // Return circleSet_A as probabilistic location information.
28:     return circleSet_A;
29: end function
```

4.2 Algorithm

The pseudocode of PLPA-GP is shown at Algorithm 1. The pseudocode includes recursive calls. Therefore, this algorithm sets parameter **hop** which means depth limit of the recursive calls. In the algorithm, relative location information which means pass-by information of object A and B_i at time t_i at distance l_i is expressed as $\langle\langle A, B_i, t_i, l_i\rangle\rangle$.

At L3-L8 of Algorithm 1, the algorithm explores absolute location information Pos(A, t). If location information exists, the algorithm returns Pos(A, t).

At L9-L13 of Algorithm 1, the algorithm explores past absolute location informations from $t - \delta$ to t. δ means reference time interval for limitation of explored time. circleSet_A adds the circle which means the movable area from past absolute location.

At L14-L27 of Algorithm 1, the algorithm explores past pass-by information from $t - \delta$ to t. About each object B_i ($i = 1, 2, \ldots$, the number of objects which detected pass-by with A) which recorded pass-by with A, the algorithm explores location information Pos(B_i, t_i). Then, circleSet_A adds the circle set which means the movable area from Pos(B_i, t_i).

At L19, the algorithm calls PLPA-GP recursively to refer location information of object B_i at time t_i. If the hop $\geq$ 1, the algorithm calculates the probabilistic location information of object B_i. When the algorithm calls recursively, the algorithm sets the hop of called-out side decremented. Because of the recursive call, the location information of object B_i at time t_i is calculated as a probabilistic location information. We can infer that Pos(A, t) exists at a place where is to less than distance $v_A \times (t - t_i)$ from Pos(B_i, t_i). To calculate this area, the algorithm extends ProLoc(B_i, t_i). The algorithm add length $v_A \times (t - t_i) + l_i$ to the radius of each circle area of ProLoc(B_i, t_i). Then, circleSet_A adds all circles of ProLoc(B_i, t_i). Similarly, the algorithm calculates probabilistic location information of all B_i ($i = 1, 2, \ldots$, the number of objects which detected pass-by with A). Finally, the algorithm returns circleSet_A as ProLoc(A, t).

The probability of existing Pos(A, t) at every point within one circle region is uniform. As the circle area is larger, the probability of existing at an arbitrary point in the circle becomes lower.

To check the probability of the arbitrary point in the circle, we can calculate **score** which express the probability of a point. The bigger score of a point in the area of probabilistic location is, the higher the probability is of existing at the point. A score of the point is calculated by summing up reciprocals of circle's area which includes the point.

4.3 Example

An example of calculation process by PLPA-GP is shown in Figure 3. In the figure, there are some persons and some beacons. Beacon is a radio station that broadcasts a directional signal. Persons moves at a regular speed. In contrast, beacons are fixed at one location point. In the figure, both A and B_3 are persons, and move at a regular speed v_A and v_{B_3} respectively. The movement locuses of both A and B_3 are displayed by arrow marks respectively. Both both B_1 and B_2 are beacons. The person A cannot find own geographic coordinate information; however, person B_3 can find own geographic coordinate information at regular intervals. On the other hand, geographic coordinate informations about both of beacons B_1 and B_2 are known. The process of PLPA-GP for calculating probabilistic location information of A at t_4 is shown below.

When $t = t_1$, A detects a pass-by information with B_1 ($\langle\langle A, B_1, t_1, l_1\rangle\rangle$). PLPA-GP infers that A is exist within distance $v_A \times (t_4 - t_1)$ from Pos(B_1, t_1). This inference is shown in Figure 3 as the $v_A \times (t_4 - t_1)$ radius circle which center on Pos(B_1, t_1). Similarly, when $t = t_2$, A detects a pass-by information with B_2 ($\langle\langle A, B_2, t_2, l_2\rangle\rangle$). Therefore, PLPA-GP infers that A is exist within distance $v_A \times (t_4 - t_2)$ from Pos(B_2, t_2). This inference is shown in Figure 3 as the $v_A \times (t_4 - t_2)$ radius circle which center on Pos(B_2, t_2). In addition, when $t = t_3$, B_3 detects a geographic coordinate information ($\langle B_3, t_3$,Pos(B_3, t_3)$\rangle$). After that, A detects a pass-by information with B_2 ($\langle\langle A, B_3, t_4, l_3\rangle\rangle$). Therefore, PLPA-GP infers that A is exist within distance $v_{B_3} \times (t_4 - t_3)$ from Pos(B_3, t_3). This inference is shown in Figure 3 as the $v_{B_3} \times (t_4 - t_3)$ radius circle which center on Pos(B_3, t_3). The area where these circles overlap more includes Pos(A, t) with higher probability. The area expressed by the set of these circles as probabilistic location information ProLoc(A, t_4).

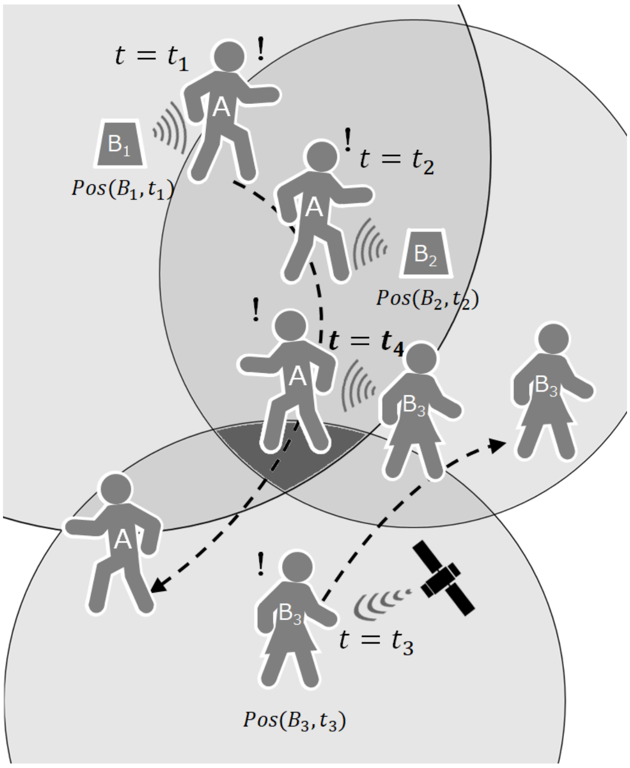

Figure 3: An example of probabilistic location information calculated by PLPA-GP

5 CONSIDERATION

The area which is calculated by PLPA-GP assumes that the object exists with uniform probability within the area. Nevertheless, actually the probability distribution within the area has a bias. In order to infer location information which has the higher probability, we should consider utilizing some methods such as machine learning.

By utilizing probabilistic location information by applications, we can refer location information of devices which do not have positioning system. In particular, the probabilistic location is benefical for searching lost articles or missing persons.

6 RELATED WORK

The technology named " Dead Reckoning[1] " proposed for inference of location. This technology can infer the present location of an object by measuring movement distance. The movement distance is calculated based on sensor data which records the condition of the object. The research of " Dead Reckoning " has a different approach from this study in calculating based on the movement distance.

So far, on uncertain location information, many study has been conducted[5–7, 10]. Bernad et al. [5] considered about handling location uncertainty by probabilistic location. They propose that uncertain location information is expressed by " uncertainty location granule " . They tried to deal with location information flexibly by an approach different from the approach of this study.

In addition, in the field of location estimation, some research of estimating location while utilizing relative location from base stations has been conducted[8, 9]. These research assumes that the locations of the base stations is known. Unlike their research, the system of this study utilizes relative location information from the object whether the location of the object is known. Moreover, in this study, the inferred location is not fixed to one point.

7 CONCLUSION

In this study, we proposed probabilistic location information which is converted from various location information and combine various location information. Because of utilizing probabilistic location information, we can infer and express location information of a person at arbitrary time. In addition, we proposed the Probabilistic Location Positioning Algorithm based on Geographic coordinate and Pass-by (PLPA-GP).

Our future work includes the development of PLPA-GP on actual word, prototype service which utilizes PLPA-GP, and evaluation PLPA-GP about practicality.

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