Relative Location Information Acquisition without Direct Distance Measurement in Mobile System

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Abstract: Relative location information among multiple mobile nodes is critical for cooperative and competitive applications in mobile distributed systems. One of the effective conventional methods does not measure distances between pairs of mobile nodes directly. Angles formed by sets of three mobile nodes are achieved by camera images taken by omni-directional cameras mounted on all the mobile nodes. Search for sets of interior angles of triangles and measurement of distance between a pair of mobile nodes provides relative location information. This paper extends this conventional method to achieve the relative location information without direct measurement of distance between mobile nodes. Here, camera images are taken by all the omni-directional cameras synchronously two times, two mobile nodes are required to suspend their mobility temporarily and the other mobile nodes measure their mobility distances. The computational overhead for the proposed method is not so higher than the conventional method since the additional procedure for achieving distance between the mobility suspended mobile nodes is localized.

Keywords: Relative Location Information, Mobile Distributed Systems, Omni-Directional Cameras.
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1. Introduction

Recently, due to advances of wireless communication technologies and mobility technologies such as mobile robots, autonomous vehicles and unmanned aerial vehicles (UAVs), mobile distributed systems are widely available. Especially, in order to support large-scale mobile distributed systems, lower cost for construction and operation is critical. Hence, it is expected for adaptation of MANETs (Mobile Ad-Hoc Networks) without stationary wireless base-stations and information localization without global information sharing to be applied.

Location information of mobile nodes consisting a mobile distributed system is required for various mobile applications such as driving safety support systems (DSSS) [5] based on inter-vehicular wireless communication networks, cooperative multiple mobile robot systems, wireless sensor networks and disaster relief systems [4] including multicopters and drones. There are two types of location information. One is absolute location information, i.e., combination of latitude and longitude achieved by GPS (Global Positioning System), and the other is relative location information including distances of pairs of mobile nodes and angles formed by every three mobile nodes as shown in Figure 1. Most of the application require relative location information for cooperative and/or competitive operations. Though relative location information can be induced by using absolute location information, this paper discusses methods for achieving relative location information directly.

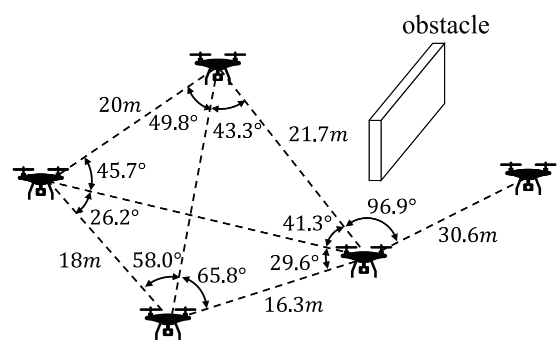

Fig. 1. Relative Location Information in Mobile Distributed System.

LiDAR (Light Detection and Ranging) [1] is one of the most widely available method to measure distance between two mobile nodes. A LiDAR device mounted on a mobile node irradiates laser to a target mobile node and receives relected laser. Then, the mobile node measures its round-trip time and achieves distance to the target mobile node. If all the distances between pairs of mobile nodes are achieved, all the angles formed by three mobile nodes can be calculated by the theorem of sine. However, in order to achieve relative location information by using LiDAR, target mobile nodes are required to be identified when laser is irradiated. Hence, for example, a camera is required to be mounted on each mobile nodes and camera images are required to be analyzed, which require additional system configuration, computation and communication costs. Moreover, it may be impossible to identify the target mobile node by camera images if shapes of all the mobile nodes are the same. e.g., in a cooperative cleaning system with multiple vacuuming robots [3].

2. Related Work

[2] has proposed a method for achieving relative location information in a mobile distributed system without direct measurement of distances between a pair of mobile nodes. Here,

each mobile node measures only differences of directions to pairs of other mobile nodes, i.e., angles formed by these three mobile nodes as shown in Figure 2. In this method, it is assumed that omni-directional cameras (Figure 3) are mounted on all the mobile nodes and all the mobile nodes can take camera images at the same instance, i.e., all the clocks in the mobile nodes are enough synchronized. In a camera image taken by an omni-directional camera mounted on a mobile node as shown in Figure 4, there are some images of visible mobile nodes. It is impossible to measure distances to the mobile nodes corresponding to the images, however, it is possible to measure angles whose vertex is the mobile node taking the camera image and formed by two visible mobile nodes. For example, as shown in Figure 4, mobile nodes A, B, C, D and E takes camera images by their own omni-directional cameras and there are images of visible mobile nodes in the camera images. Since there are three and four images in the camera images taken by A and D, respectively, three and six angles are measured. Generally, if there are n images in the camera image, $n(n-1)/2$ angles are measured. Here, only the angles are measured and no mobile nodes corresponding to the images in the camera images are identified.

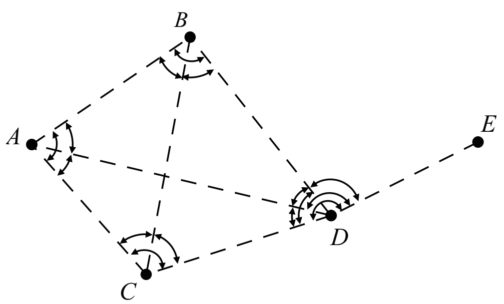

Fig. 2. Angles Formed by Three Mobile Nodes.

Fig. 3. Omni-Directional Camera.

All the angles measured in accordance with the camera images taken by omni-directional cameras are gathered and searched sets of three angles each of which is measured by different mobile node and whose summation equals to 180°. If

Fig. 4. Camera Image Taken by Omni-Directional Camera.

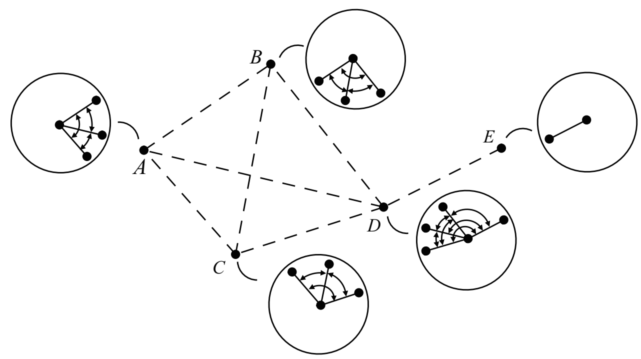

Fig. 5. Angles Achieved by Camera Images.

angles θ_A, θ_B and θ_C measured by mobile nodes A, B and C, respectively, satisfy $\theta_A + \theta_B + \theta_C = 180°$, there is a triangle $\triangle ABC$ whose interior angles are θ_A, θ_B and θ_C. In figure 9, since $72.3 + 49.7 + 58.0 = 180$ where 72.3°, 49.7° and 58.0° are measured by A, B and C, respectively, there is a triangle $\triangle ABC$ whose interior angles are 72.3°, 49.7° and 58.0°. Here, two images in the camera image taken by A forming an angle 72.3° are identified; however, correspondence between the images and the mobile nodes B and C is not clear at this moment. The correspondence becomes clear when another triangle $\triangle ABD$ is detected. Since $45.7 + 93.0 + 41.3 + 180$ where 45.7°, 93.0° and 41.3° are measured by A, B and D, respectively, there is a triangle $\triangle ABD$ whose interior angles are 45.7°, 93.0° and 41.3°. Now, two images in the camera image taken by A forming an angle 45.7° are identified. Hence, the image forming both 72.3° and 45.7° corresponds to B, the image forming only 72.3° corresponds to C and the image forming only 45.7° corresponds to D. By detection of all the sets of three angles whose summation equals to 180°, mobile nodes forming a triangle with the interior angles are detected and correspondences between images and mobile nodes are made clear. Therefore, by achieving distance between any one pair of mobile nodes, all the distances between pairs of mobile nodes are achieved by the theorem of sine.

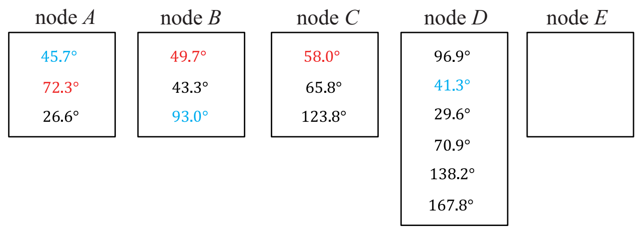

Fig. 6. Measured Angles.

3. Proposal

In the conventional method explained in the previous section, measurement of distance between any one pair of mobile nodes is required. The distance should be measured, e.g, by using a LiDAR device mounted on a mobile node, at the moment when mobile nodes take camera images. Hence, it is required for the mobile nodes to equip a mechanism to direct a LiDAR device to desired direction and to direct the LiDAR device to a target mobile node beforehand. Thus, this paper proposes a novel method for achieving relative locations without direct measurement of distance between mobile nodes.

In our proposal, each mobile node equips a mechanism to measure its mobility distance. For example, rotary encoders are used in various vehicles to measure their mobility distance and to calculate velocity as a result as shown in Figure 7. In addition, all the mobile nodes take camera images synchronously at two instances t_b and t_e. In time duration $[t_b, t_e]$, two mobile nodes suspend their autonomous mobility. Except for these two mobile nodes, all the other mobile nodes measure their own mobility distances. e.g., by using their rotary encoders. If time duration $\delta t = t_e - t_b$ is short, it is reasonable for all the mobile nodes to move straight. Here, no mobile nodes achieve their mobility directions.

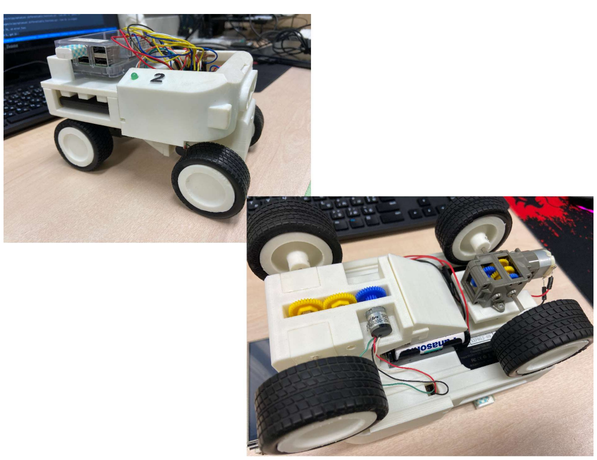

Fig. 7. Mobile Node with Rotary Encoder.

Figure 8 represents our proposal. There are five mobile nodes A, B, C, D and E and all of them take their camera images by using their omni-directional cameras at two instances t_b and t_e. During $[t_b, t_e]$, C and D suspend their mobility and A, B and E continue their autonomous mobility. A, B, C, D and E represent locations of A, B, C, D and E at t_b and A', B', C, D and E' represent locations of A, B, C, D and E at t_e. A, B and E measure their mobility distances $|AA'|$, $|BB'|$ and $|EE'|$. Same as the conventional method, each mobile node measures angles formed by pairs of images in its camera image.

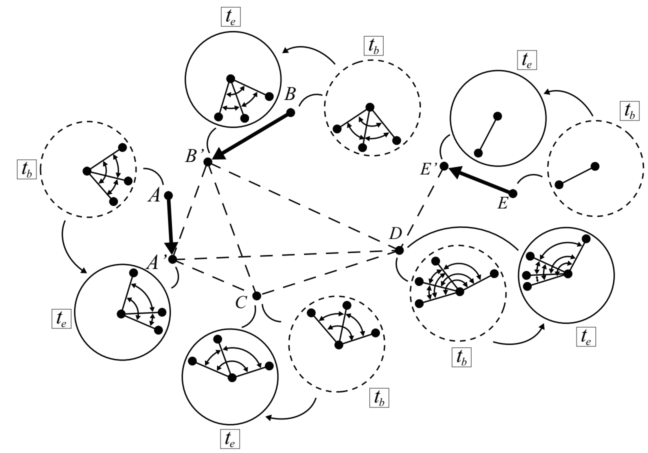

Fig. 8. Proposed Method.

Same as the conventional method, triangles whose interior angles are measured at t_e is detected by gathering angles achieved by using camera images taken by omni-directional cameras. In addition, triangles whose vertexes are the mobility suspended mobile nodes, e.g., C and D in Figure 8, are detected. For example, $\triangle ACD$ and $\triangle A'CD$ where there is a set of three angles each of which is measured by A, C and D at both time instances t_b and t_e are detected. Here, C and D are required to be visible each other. However, since the temporary suspended mobile nodes are not always visible, there may be no triangles whose vertexes are C and D. In this case, the temporary suspended mobile nodes are selected again and the proposed method is applied from the beginning.

Hereafter, mobile nodes are re-named; A and B are temporary mobility suspended nodes and C is another mobile node whose image is included in camera images taken by A and B at the both time instances t_b and t_e as shown in Figure 9. Here, angles $\theta_{AC} = \angle BAC$, $\theta_{BC} = \angle ABC$ and $\theta_C = \angle ACB$ are measured by A, B and C, respectively, at t_b where $\theta_{AC} + \theta_{BC} + \theta_C = 180°$ and angles $\theta_{AC'} = \angle BAC'$, $\theta_{BC'} = \angle ABC'$ and $\theta_{C'} = \angle AC'B$ are measured by A, B and C, respectively, at t_e where $\theta_{AC'} + \theta_{BC'} + \theta_{C'} = 180°$. In addition, $l_C = |CC'|$, mobility distance of C, is also measured.

Now, consider a x-y coordinate in Figure 10 whose origin is A and B is on the x axis, i.e., $B(L, 0)$ where $L > 0$. If $\theta_{AC} \neq \pm 90°$, an equation representing a line AC is as follows:

$$y = \tan\theta_{AC} x \quad (1)$$

If $\theta_{BC} \neq \pm 90°$, an equation representing a line BC is as follows:

$$y = \tan\theta_{BC}(x - L)x \quad (2)$$

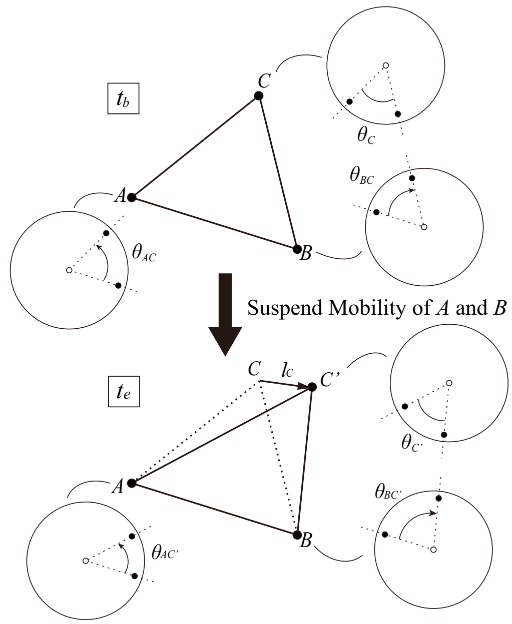

Fig. 9. Angles and Mobility Distance Measured in Proposed Method.

Since C is an intersection of lines AC and BC, the coordinate of C is achieved by solving simultaneous equations (1) and (2):

$$C\left(\frac{\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}L\,,\ \frac{\tan\theta_{AC}\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}L\right) \quad (3)$$

If $\theta_{AC'} \neq \pm 90°$, an equation representing a line AC' is as follows:

$$y = \tan\theta_{AC'}x \quad (4)$$

If $\theta_{BC'} \neq \pm 90°$, an equation representing a line BC' is as follows:

$$y = \tan\theta_{BC'}(x-L)x \quad (5)$$

C' is an intersection of lines AC' and BC', the coordinate of C' is achieved by solving simultaneous equations (4) and (5):

$$C'\left(\frac{\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}L\,,\ \frac{\tan\theta_{AC'}\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}L\right) \quad (6)$$

Since $|CC'| = l_C$, the following equation is induced by (3) and (6):

$$\left(\frac{\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}L-\frac{\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}L\right)^2 + \left(\frac{\tan\theta_{AC}\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}L-\frac{\tan\theta_{AC'}\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}L\right)^2 = {l_C}^2 \quad (7)$$

Hence, the equation (7) is solved for L as follows:

$$L = l_C\left\{\left(\frac{\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}-\frac{\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}\right)^2 + \left(\frac{\tan\theta_{AC}\tan\theta_{BC}}{\tan\theta_{BC}-\tan\theta_{AC}}-\frac{\tan\theta_{AC'}\tan\theta_{BC'}}{\tan\theta_{BC'}-\tan\theta_{AC'}}\right)^2\right\}^{-\frac{1}{2}} \quad (8)$$

Since θ_{AC}, θ_{BC}, $\theta_{AC'}$, $\theta_{BC'}$ and L_C in the right side of (8) are measured, L can be calculated in accordance with (8)[1]. By applying the theorem of sine, $|AC'| = L\sin\theta_{BC'}/\sin\theta_{C'}$ and $|BC'| = L\sin\theta_{AC'}/\sin\theta_{C'}$. Distances between other pairs of mobile nodes are also achieved by applying the theorem of sine.

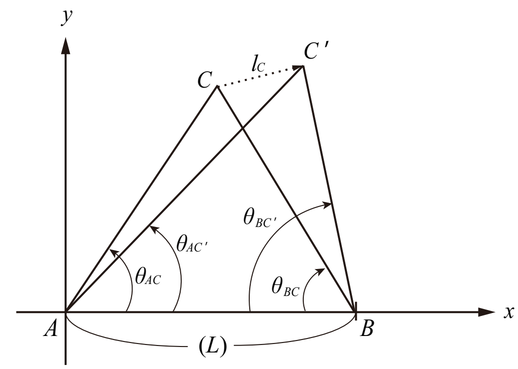

Fig. 10. Solution for Achieving Distance between Pair of Nodes.

4. Evaluation

This section evaluate our proposed method by computational complexity in comparison with the conventional method in [2]. In both the methods, since calculation of distances between all the pairs of mobile nodes visible each other is realized by simply applying the theorem of sine, the required computational complexity is proportional to the number of pairs of visible mobile nodes, i.e., $O(N^2)$ where N is the number of mobile nodes.

Computational overhead for calculation of the right side of equation (8) for achieving L is independent of the number of mobile nodes, i.e., $O(1)$ and is relatively much smaller than those for the other procedures.

The dominant overhead in these methods is for search for combinations of three angles, i.e., for sets of three mobile nodes consisting a triangle by lines of sight between them. It assumes that there are N mobile nodes $M_0, M_1, \ldots, M_{N-1}$. For each mobile node M_i, NM_i are sets of neighbor mobile nodes which are visible for M_i, i.e., whose images are in camera images taken by M_i in the conventional method. Similarly, for each mobile node M_i NM_i^b and NM_i^e are sets of neighbor mobile nodes at t_b and t_e, respectively.

For detection of all the triangles consisting of three lines of sight between pairs of three mobile nodes in the conventional method and in the proposed method for the time instance t_e, all the possible combinations of three angles each of which is measured by different mobile nodes are required to be investigated whether their summation equals to 180°. Hence,

[1] L can be calculated as $C(0, -L\sin\theta_{BC})$ if $\theta_{AC} = \pm 90°$, $C(L, L\sin\theta_{AC})$ if $\theta_{BC} = \pm 90°$, $C'(0, -L\sin\theta_{BC'})$ if $\theta_{AC'} = \pm 90°$, $C'(L, L\sin\theta_{AC'})$ if $\theta_{BC'} = \pm 90°$. However, if $L_C = 0$, it is impossible to solve (7) for L. That is, it is required for C to move in $[t_b, t_e]$.

the computational overhead is propotional to the number of the combinations as follows:

$$\Pi_{0\leq i<j<k<N}|NM_i||NM_j||NM_k| \quad \text{(in conventional method)} \tag{9}$$

$$\Pi_{0\leq i<j<k<N}|NM_i^e||NM_j^e||NM_k^e| \quad \text{(in proposed method)} \tag{10}$$

These computational complexities are evaluated as the same. In addition, in the proposed method, at least one triangle is required to be detected whose vertexes are the two mobility suspended mobile nodes M_i and M_j and one of the nodes M_k which are visible for M_i and M_j at both the two time instances t_b and t_e. That is, $M_k \in NM_i^b \cap NM_j^b$ and $M_k \in NM_i^e \cap NM_j^e$. The former is not clear in the proposed method; however, the latter has been made clear. Hence, the search area for M_k is $NM_i^e \cap NM_j^e$ and the computational overhead is proportional to the following:

$$\Pi_{M_k\in NM_i^e\cap NM_j^e}|NM_i^b||NM_j^b||NM_k^b| \tag{11}$$

This search procedure can be terminated when one mobile node M_k is detected and it is expected for $NM_i^b \cap NM_j^b$ and $NM_i^e \cap NM_j^e$ to be equal with high probability since the time duration $[t_b, t_e]$ is short. Thus, the computational overhead for the triangle search for t_b in our proposed method can be evaluated as follows:

$$|NM_i^b||NM_j^b||NM_k^b| \quad \text{for a certain } M_k \in NM_i^e \cap NM_j^e \tag{12}$$

Roughly speaking, (9) and (10) are evaluated as $O(N^6)$ and (11) is evaluated as $O(N^3)$ under the assumption that $|NM_k|$, $|NM_k^b|$ and $|NM_k^e|$ are proportional to N. Hence, the additional computational overhead for the proposed method (11) can be ignored for evaluation of total computational overhead for comparison between the two method.

5. Conclusion

This paper has proposed an extended method for achieving relative location information among multiple mobile nodes cooperatively by gathering measured angle information formed by three visible mobile nodes. Here, no direct measurement of distances between mobile nodes are required; only measurement of angles gained from camera images by omni-directional cameras and measurement of mobility distances by all the mobile nodes are required. In comparison with the original method, temporary mobility suspension of two mobile nodes and limited additional computational overhead is needed. The authors will extend the proposed method to avoid synchronous mobility suspension of two mobile nodes; i.e., development of more extended method with mobility suspension of only one node or no nodes is the current research target.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.