MULTI-HOP POSITIONING

Relative Positioning Method for GPS Wireless Sensor Network

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Abstract: This paper presents a relative positioning method, called “multi-hop positioning”, which is suitable for raw GPS data collected by densely deployed L1 GPS receivers. The wireless sensor network employing an affordable L1 GPS receiver has been developed by the authors for monitoring displacement of large civil structures with high spatial resolution. In general, relative positioning of GPS sensors are performed between a single reference point and sensor nodes. On the other hand, in the newly developed approach, relative positioning is performed between all pair of sensor nodes in the network. Then, the best set of relative position vectors is selected to determine the location of sensor nodes. Experiments have been conducted using 53 sensor nodes equipped with an affordable L1 GPS receiver and the collected data are analysed by using the proposed method in a post-processing manner. The results show that the success rate of relative position estimate is considerably improved compared with the conventional approach.

1 INTRODUCTION

Displacement monitoring of large infrastructures such as artificial island, embankment and reclaimed land is very important. This work is operated for controlling quality and ensuring safety. In general, displacement monitoring is performed by survey work or an automated monitoring system in which accurate instruments are networked with cables and the displacements are monitored remotely. Although the automated monitoring system could replace the survey work for reducing the monitoring cost, the application examples are still limited. One of the disadvantages of the current automated system is its high cost. Very expensive instruments such as a laser displacement meter or a high performance GPS (Global Positioning System) receiver is employed to detect the displacement in sub-centimetres accuracy.

For the dense displacement monitoring of large civil infrastructures, a cost-effective system should be developed. The combination of wireless sensor network and an affordable L1 GPS receiver can be a possible solution to this problem. Besides, the wireless sensor network has big advantages not only in cost but also in robustness and workability (Lynch, 2004). Therefore, we have been developing the system of wireless sensor network using an affordable L1 GPS receiver (Saeki, 2008). We call this system GWSN (GPS Wireless Sensor Network). This system consists of a central server and many sensor nodes equipped with an affordable L1 GPS receiver. Each sensor node collects raw GPS data according to the command from the central server and sends their data back to the server. The relative positions of the sensor nodes from a reference point are analyzed in the server. The displacements of the sensor nodes are estimated as the change of position from the initial state.

Since the sensor node runs using a small battery and/or additional harvested energy, the total energy consumption should be suppressed. Considering the high energy consumption of the GPS receiver, the observation time should be minimized. On the other hand, to improve the accuracy of positioning, the observation should be performed as long as possible. Clearly this system has the trade-off relationship between the accuracy and the energy consumption. Therefore we have tried to develop a new relative positioning method which gives accurate relative position with short data length.

This paper presents a relative positioning method suitable for the data collected by the densely deployed GPS receivers with short data length. In this method, the location of the sensor node is

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estimated as a sum of the relative position vectors. Relative positioning is performed between all pair of sensor nodes in the network and the optimal sum of relative position vectors is selected to determine the location of sensor nodes. To assess the performance of our method, experiments have been conducted using 53 wireless sensor nodes. The collected data are analysed by using the proposed method in a post-processing manner. The results show that the success rate of estimating the relative positions is considerably improved compared with the conventional approach.

2 RELATED WORK

GPS-less localization method for large networks of wireless sensor nodes has been intensively studied by many researchers. For example, Bulusu et al., (2000) evaluates the effectiveness of a simple connectivity metric method for localization in outdoor environments. Moor et al., (2004) presents a linear-time algorithm for localizing sensor network nodes in the presence of range measurement noise and demonstrates the algorithm on a physical network. These results show that the accuracy depends on the scale of distribution and is not high enough for monitoring displacements of large civil infrastructures, which needs a few centimetres to sub-centimetres accuracy.

Many displacement monitoring systems using L1 GPS receivers are developed and demonstrated in a real field. Gassner et al., (2002) developed a GPS-based continuous monitoring system and applied it to landslide monitoring. Shimizu, (2003) developed a monitoring system and applied it to large open quarries and landslide slopes. Seynat, et al., (2004) developed the monitoring system, which uses a low cost GPS receiver and a radio link, and applied their system to volcano monitoring. These demonstrations show that displacement monitoring using L1 GPS receivers might be possible in terms of accuracy.

In order to deploy the sensor nodes densely covering a large infrastructure, the cost for a single observation point should be decreased further. So, we have been developing the new displacement monitoring system which combines the wireless sensor network with an affordable L1 GPS receivers connected to a small patch antenna which is generally used for a mobile navigation (Saeki, 2008). This combination enables us to decrease the cost of a single observation point but brings about other problems to be solved.

One of the problems is the energy consumption of the GPS receiver. The sensor node of GWSN keeps the GPS receiver off as long as possible to save its battery. However, shortening observation time results in the accuracy deterioration. To overcome this problem, we have tried to develop a new positioning method considering the condition of dense sensor deployment.

The problem to determine the locations of many GPS receiver simultaneously is known as network adjustment (Han, 1995). In the network adjustment, variance-covariance matrix between GPS sensors is taken into account. However, it is so difficult to estimate an appropriate variance-covariance matrix in the application of a large infrastructure that network adjustment might not be applicable.

3 GPS WIRELESS SENSOR NETWORK

This section describes the outline of the present system and the conventional relative positioning method, and specifies the required technology.

3.1 Outline of the System

Figure 1 illustrates the schematic view of GWSN. This system consists of a single central server and many sensor nodes. The sensor node has a micro-controller, a small wireless communication device, a small battery and an affordable L1 GPS receiver. The sensor nodes run according to the command from the central server. After getting the command to start observation, it turns on the GPS receiver which outputs the raw binary messages to the micro-controller every one second. The micro-controller extracts the required data from the original binary message and save them to the non-volatile memory. The size of the original binary message is 266 bytes and is compressed to 28 bytes in the present system. After the sensor nodes collecting the data for several minutes (e.g. 4 minutes), the central server orders them to send their data back to itself. The locations of the sensor nodes are analysed by the central server in a post-processing manner.

In the prototype, a middle range series micro-controller PIC16F877A (Microchip Technology Inc.) is employed since any complex calculation is not required. As an affordable L1 GPS receiver, GT8032 (Furuno Electric co., ltd.) is used which is capable of outputting L1 carrier phases in a Furuno binary format. A small patch antenna is connected to the receiver for saving cost. This kind of antenna is commonly used in an automotive navigation system and never used for accurate positioning because the measured carrier phases are very contaminated by the antenna noises. The wireless communication device of the prototype is MU1-1252 (Circuit Design, Inc.) which uses the frequency band of 1252 MHz. The maximum distance of wireless communication is 600 m with a line of sight at the RF output power of 10 mW.

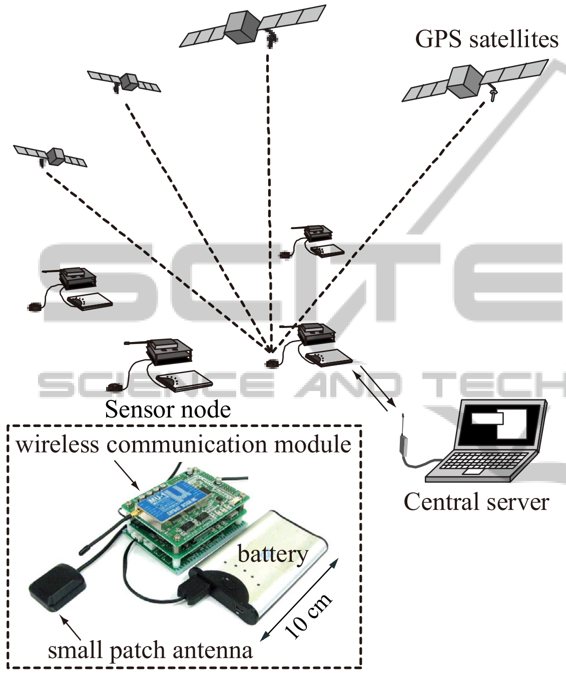

Figure 1: Schematic view of GPS wireless sensor network.

3.2 Conventional Relative Positioning Method

In the present system, the relative position vector is estimated by the static interferometry positioning method which is widely used in a practical GPS surveying to achieve centimetre-level accuracy.

3.2.1 Observation Equation

The relative position vector is estimated by analysing the L1 carrier phases. In case of short baseline, the DD (Double-Differenced) carrier phases at time t, $\phi_{ij}^{kl}(t)$, is modelled as follows (Hofmann, 2001),

$$\phi_{ij}^{kl}(t) = \frac{1}{\lambda}\rho_{ij}^{kl}(\mathbf{x},t) + N_{ij}^{kl} + \epsilon_{ij}^{kl}(t) \tag{1}$$

where $*_{ij}^{kl}$ represents the DD values for the GPS satellites k, l and the sensor nodes i, j. λ is the wavelength of L1 carrier waves, $\rho_{ij}^{kl}(\mathbf{x},t)$ is the DD ranges between satellites and the nodes, $\mathbf{x}$ is the relative position vector of a sensor node, N_{ij}^{kl} is the DD integer ambiguity and ϵ_{ij}^{kl} is the noise. Eqn. (1) is linearized by substituting $\mathbf{x} = \mathbf{x_0} + \Delta\mathbf{x}$ and applying the Taylor Expansion with respect to $\mathbf{x_0}$. Gathering Eqn. (1) corresponding to the different sets of satellites forms the following simultaneous equations.

$$\mathbf{U}(t) = \mathbf{A}(t)\Delta\mathbf{x} + \mathbf{N} + \mathbf{e}(t) \tag{2}$$

where $\mathbf{U}(t)$ is the vector of the corrected DD carrier phases, $\mathbf{A}(t)$ is the design matrix. The unknowns in Eqn. (2) are the correction terms for the position vectors $\Delta\mathbf{x}$ and the vector $\mathbf{N}$ of DD integer ambiguities. Solving Eqn. (2) through the least mean square method gives a float solution in which the DD integer ambiguities are estimated as float values.

3.2.2 Integer Ambiguity Resolution

In order to achieve centimetre-level accuracy, the DD integer ambiguities should be resolved as the integer values. This solution is called fixed solution. Denoting the float solution and the fixed solution as $\tilde{\mathbf{N}}$ and $\hat{\mathbf{N}}$, respectively, the fixed solution $\hat{\mathbf{N}}$ is estimated as the integer-valued vector which minimizes the following objective function J.

$$J = \left(\tilde{\mathbf{N}} - \hat{\mathbf{N}}\right)^T \mathbf{Q}_{\tilde{N}}^{-1}\left(\tilde{\mathbf{N}} - \hat{\mathbf{N}}\right) \tag{3}$$

where $\mathbf{Q}_{\tilde{N}}$ is the variance-covariance matrix of the float solution $\tilde{\mathbf{N}}$.

In general, the fixed solution is validated by checking the ratio J_2/J_1 where J_1 and J_2 are the minimum residual and the second small one, respectively. It is known that the larger ratio gives the higher probability of selecting the correct DD integer ambiguities. In the case that the ratio J_2/J_1 is greater than 3, the fixed solution is empirically considered a correct solution. On the other hand, the solution might be wrong with the smaller ratio, and the wrong DD integer ambiguities might give more than several centimetres to meters error to the estimated position. In the general usage of GPS, the data is logged until the ratio exceeds 3 to guarantee the quality of solution. However, in the present system, the observation time is limited to save battery energy.

3.3 Required Component Technology

As mentioned above, it is preferable to measure the GPS data longer for estimating the correct relative

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position vectors while the longer measurements results in the higher energy consumption. Since the sensor node should run for at least several months without changing battery, it is needed to develop a method to estimate the correct relative position vectors with short data length.

As considering the affordable cost of this system, the sensor nodes are expected to be densely distributed over a large infrastructure. This dense deployment might be a great advantage of the present system. Therefore, we have tried to develop a new relative positioning method considering the dense deployment of the sensor nodes. In the conventional approach, the relative position vectors are individually estimated for each sensor node. And the advantage of the dense GPS deployment is not taken into account.

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Float solution is estimated by solving Eqn. (2) with the assumption that the noise is white. The assumption could be true in some pairs of sensor nodes but could be false in other pairs. If the surrounding conditions of the sensor nodes are very similar to each other, the noises also become very similar. In the case, the noises can be cancelled out in the double difference calculation and the residual behaves as the white noise. On the other hand, when the surrounding conditions of the sensors are different from each other, the residuals of the noises are not likely to be white. In this case, the accuracy of the float solution becomes worse and the DD integer ambiguities are not correctly resolved in the minimization problem of Eqn. (3). This leads to the wrong relative position vectors. Therefore, it is very important to select a good pair of sensor nodes whose noises are very similar to each other.

4.1 Basic Idea of the Proposed Method

Suppose that three sensor nodes are there and the noises are different from each other but the noise of node 3 has some similarities to those of node 1 and 2. This situation often happens in actual observations when many sensor nodes are deployed densely. In such case, the relative position of node 2 from 1 is likely to be estimated wrong and the ratio J_2/J_1 becomes small since the noises are not cancelled out in the DD calculation. On the other hand, the relative position of node 3 could be estimated correctly and the ratio becomes larger than that of node 2. This situation is schematically drawn in Figure 2(a). Two relative position vectors and ratios are described on the figure. In this example, node 2 is unsuccessfully estimated.

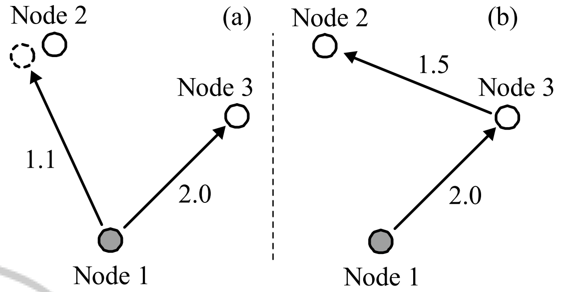

Figure 2: Simple example of the relative position vectors estimated by the conventional method (a) on the left side and the proposed method (b) on the right side.

In the above situation, the relative position of node 2 is estimated wrong from node 1. However, it can be estimated correctly by summing up the relative position vectors as described in Figure 2(b). Since the noise of node 2 has some similarities to that of node 3, some parts of noises can be cancelled out. Then it must yield better float solution and it gives higher probability of selecting the correct integer ambiguities. Then, the relative position of node 2 from node 3 can be estimated in accurate.

In a real situation, there are many candidates of the paths because many sensor nodes are distributed. And besides, the ratios J_2/J_1 might have similar values. So there is a problem how to select the optimal path with a convincing reason. To solve this problem, we introduce the success probability into the present approach. By comparing the success probabilities evaluated for each path, the optimal path can be selected convincingly.

4.2 Assumption of Success Probability

We assume that the success probability of resolving the DD integer ambiguities is represented as a function of ratio J_2/J_1. And the success probability of a path can be estimated as the products of the success probabilities of the corresponding relative position vectors. In this subsection, we empirically estimate the function relating the success probability and the ratio J_2/J_1 .

4.2.1 Experiment and Data Analysis

Figure 3 shows a look of the experiment conducted on the concrete roof of a building March 3, 2008. Since there are no obstacles over the site, it is considered as an ideal condition. In the experiment, four sensor nodes are deployed in the different manner. Two GPS antennas are fixed on the flat plane of thin concrete block (ID1 and ID2) and the other antenna is mounted on the concrete block with different height (ID3). Another antenna is fixed at the tripod (ID4). These various antenna conditions are set for causing different antenna noises. For example, the antenna noises of ID1 and ID2 are so similar that the noises are effectively cancelled out in the DD calculation. On the other hand, the antenna noises of ID1 and ID4 are apparently different and cannot be eliminated in the analysis.

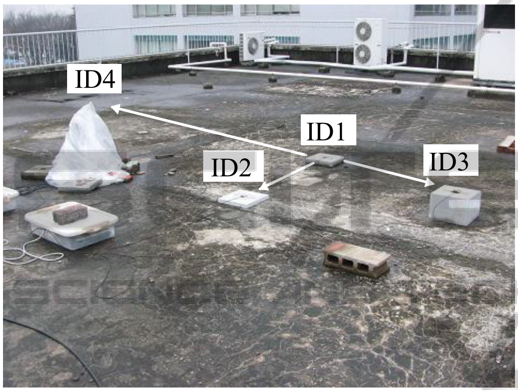

Figure 3: Photo of the experiment conducted for collecting raw GPS data with the different antenna conditions.

The raw GPS data are sampled for 24 hours at 1Hz sampling rate and are saved on a laptop. The data is analysed in a post-processing manner. In the analysis, relative position vectors of ID1-2, ID1-3 and ID1-4 are estimated.

In the analysis, the data with the length of 240 seconds is picked up from the continuous data and analysed by means of the conventional relative positioning. If the estimated location of sensor node is within 3 centimetres from the most possible position, this estimation is counted as a success. The same operation is applied to the next data shifted from the previous data by 1 second. These processes are carried out 86400 times for each sensor node. The estimated results are classified depending on the value of the ratio J_2/J_1. The success probability, which is defined as the ratio of the frequency of successes to trials in this paper, is estimated for each class.

4.2.2 Success Probability of a Single Vector

The success probabilities obtained from the above analysis are plotted in Figure 4. The marks of triangle, circle and square represent the results of ID1-2, ID1-3 and ID1-4, respectively. Three curves are the corresponding success probability functions which are estimated by the least square method. In this paper, the success probability function $P(r)$ is assumed to be the following function.

$$P(r) = 1.0 - be^{-ar} \tag{4}$$

where r is the ratio J_2/J_1, a and b are the unknown parameters to be estimated.

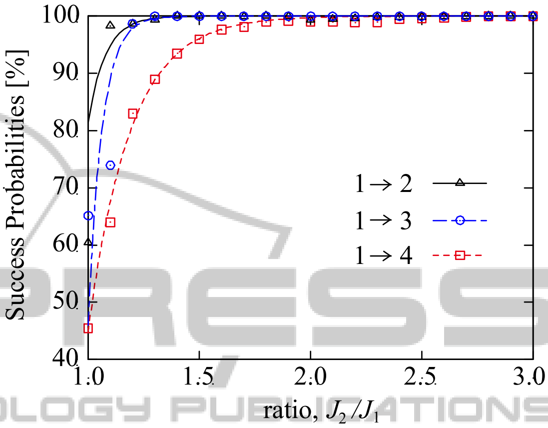

Figure 4: The relationship between the success probability and the ratio J_2/J_1.

As shown in Figure 4, the success probability of ID1-4 has smaller values compared to that of ID1-2 especially at the small ratio J_2/J_1. This means that the success probabilities depend on the conditions of antenna noises as well as the ratio. In the following simulations, the curve corresponding to the case of ID1-4 is used because it mostly represents a realistic condition among them.

4.2.3 Success Probability of a Path

In the proposed method, a relative position vector of sensor node is obtained by connecting other relative position vectors. The success probability of the path can be evaluated by multiplying the success probabilities of the corresponding relative position vectors.

$$P(r) = P(r_1)P(r_2) \cdots P(r_n) \tag{5}$$

where r_n is the ratio J_2/J_1 of relative position vectors constituting the path.

4.3 Optimal Path Finding by Dijkstra's Algorithm

The optimal path should be reasonably selected from the numerous candidates by searching the path with the maximum success probability. In the proposed

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method, Dijkstra's algorithm is used as a search algorithm (Wiitala, 1987). This algorithm is widely used in many applications such as network routing protocols or mobile navigation systems to find the shortest (or lowest cost) path efficiently.

Dijkstra's algorithm is applicable to the present problem with a small modification. In the proposed method, the optimal path is searched not for the shortest length but for the maximum success probabilities.

5 DEMONSTRATIONS

In order to investigate the performance of the proposed method, we conduct two experiments and analyse the data using both the conventional and the proposed method. This section describes the details of experiments and the results.

5.1 Experiment Described in Section 4

The data, collected in the experiment described in the previous section, are analysed. In this analysis, the sensor node ID1 is set to be a reference point and the relative positions of the other sensor nodes are estimated by using the conventional and the proposed method. The data length is set 240 seconds and the estimation is carried out 86400 times in the same manner as mentioned in the section 4.2.1. If the estimated position is within 3 centimetres from the most possible position, the estimation is counted as a success. And the success rate is estimated by dividing the frequency of successes by trials. Table 1 shows the comparison of the success rates. The success rate of ID2 slightly decreases but the other success rates of ID3 and ID4 are improved. Overall, it is said that the success rates are improved by using the proposed method.

Table 1: Comparison of the success rates estimated by analysing the data collected in the experiment described in section 4.

	Conventional	Proposed
ID1 to 2	100.00	99.94
ID1 to 3	99.91	100.00
ID1 to 4	94.99	95.70

5.2 Experiment using 53 Sensor Nodes

5.2.1 Experimental Condition

Next, we conduct an experiment using 53 sensor nodes to make sure that the proposed method works well in case of dense deployment. In this experiment, 53 sensor nodes are arranged every two meters in a grid on the rooftop of a building as shown in Figure 5 and 6. Some of GPS antennas are intentionally located in the vicinity of the obstacles (the outdoor equipment of air-conditioner shown in the right in Figure 5 and the white building behind the sensor nodes). This deployment of the antenna is for non-uniform signal environment and corresponding variety of the antenna noises. The raw GPS data are collected for 4 minutes and gathered to the central server via wireless communication.

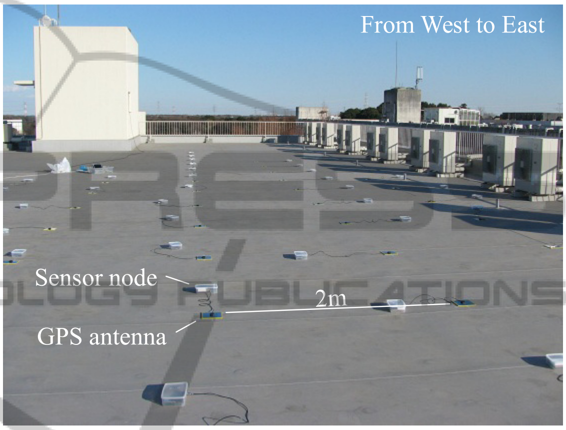

Figure 5: Photo of the experiment conducted for collecting GPS data using densely deployed GPS receivers.

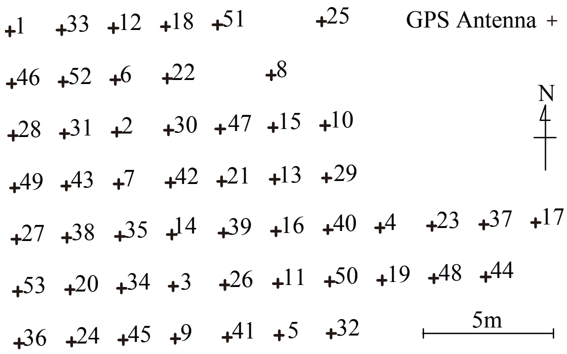

Figure 6: Arrangement of 53 sensor nodes in a grid.

5.2.2 Results of Analysis

In the analysis, the conventional and the proposed approach are performed setting every sensor node as a reference point because the results of analysis depend on the choice of the reference point. So, the position of each sensor node is estimated 52 times in this analysis. Table 2 shows the worst five success rates which are estimated using the conventional approach and the success rates of corresponding sensor nodes improved by the proposed method. All

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sensor nodes listed up on the Table 2 locates near the obstacles which cause different antenna noises. The different antenna noises decrease the success rates. However, the success rates obtained using the proposed method are all improved to 100.00% in this analysis. The multi-hop positioning method works well especially in case of dense deployment of sensor nodes because it is easier to find out the best pairs of sensor nodes which include almost the same antenna noises.

Table 2: Comparison of success rates in case of the experiment using 53 sensor nodes.

	Conventional	Proposed
ID29	43.40	100.00
ID13	69.81	100.00
ID36	86.79	100.00
ID17	88.68	100.00
ID09	90.57	100.00

One of the worst cases in case of applying conventional method is obtained if the sensor node of ID17 is set a reference point. The estimated locations are shown in Figure 7. The success probabilities calculated by Eqn. (4) are also plotted in the figure. In this estimation, 6 relative position vectors are mistakenly determined and the success probabilities are relatively small in the vicinity of obstacles. Since the antenna of the sensor node of ID17 is fixed among the white building and the outdoor equipment of air-conditioners, the antenna noises are considered to be very different from the others.

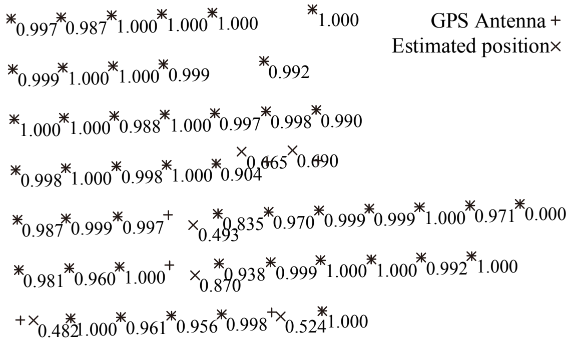

Figure 7: Locations of the sensor nodes estimated by the conventional method with the reference point ID17.

The results obtained by the proposed method with the reference point of ID17 are shown in Figure 8. We can easily see that the proposed method outputs better solution. All relative positions are correctly determined and the success probabilities are improved greater than 0.99 even though the reference point seems to be set under the noisy condition. Figure 9 describes the optimal path determined by the search algorithm. The number of connections of the relative position vectors is at most 11 in this case.

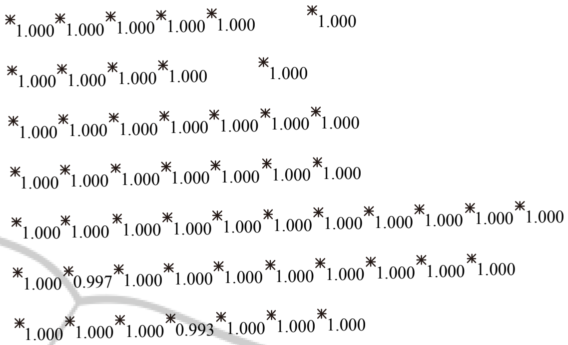

Figure 8: Locations of the sensor nodes estimated by the proposed method with the reference point being in the worst condition (ID17).

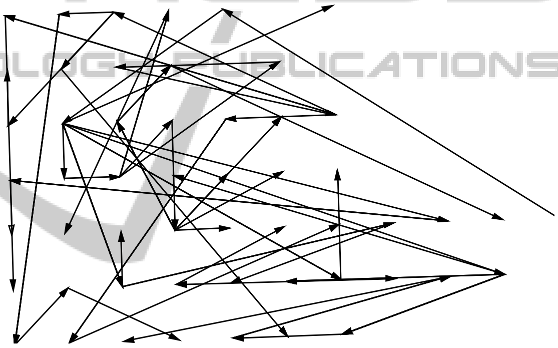

Figure 9: The optimal path found out by the search algorithm in case of setting ID17 the reference point.

6 CONCLUSIONS

This paper presents the relative positioning method, called multi-hop positioning, which is suitable for the data collected by the densely deployed GPS sensors. We introduce the success probabilities into the estimation of relative position vectors. The relative position of sensor nodes from a reference point is calculated as a sum of relative position vectors. The optimal path, which connects the relative position vectors, is selected by the Dijkstra's algorithm with maximizing the success probability. We demonstrate the proposed method analysing the experimental data. One experiment is carried out for 24 hours using 4 sensor nodes and the other experiment using 53 sensor nodes. The analytical results show that the success rates of estimating the correct relative position using the proposed method

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is considerably improved compared with the conventional approach.

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