Distributed Algorithm for Localization and Time Synchronization of Large Scale Sensor Network

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ABSTRACT:

This paper presents an implementation of acoustic ranging and proposes a distributed algorithm for localization of sensor network. Relative positions between sensor nodes are estimated based on acoustic ranging through the inverse Delaunay algorithm. This algorithm localizes all the nodes simultaneously, thus, the accumulation of the error in the localization is suppressed. The robustness and the scalability of this algorithm are examined through numerical simulations. Noise tolerant acoustic ranging algorithm that employs digital signal processing techniques is implemented in an off-the-shelf sensor platform (Mica2). Experiments show that this acoustic ranging algorithm is sufficient to give average range estimation error below 10 cm against 5 m of inter-node distance. In addition to the above mentioned capability of localization, ability for time synchronization is implemented. This system consists of three types of nodes, i.e., i) a time node which broadcasts time stamp, ii) sensing nodes which get data from on-board sensors and iii) a sink node. Every data from sensor node is synchronized by using broadcasted time stamps as reference. This system has been experimentally validated and found to keep synchronization within the interval of sampling upto 500Hz.

INTRODUCTION

Recent developments in sensor and wireless communication technologies make it possible to distribute sensor platform in the environment[1]. One of the final targets to apply this network sensing system is civil infrastructures. High resolution sensing and on-site simulation using dense sensor network on civil infrastructures can be regarded as a typical example of sensor embedded society. The sensor network applied to civil infrastructures should cover wide area with high spatial resolution. This results in the

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requirement for numerous sensor nodes with low cost. This cost consists of cost for sensor itself and the installation cost. Especially to reduce the installation cost, automatic localization (determination of the position) of the sensor nodes is needed.

This paper presents an implementation of acoustic ranging and proposes a distributed algorithm for localization of sensor network. Relative positions between sensor nodes are estimated based on acoustic ranging through the inverse Delaunay algorithm. This algorithm localizes all the nodes simultaneously, thus, the accumulation of the error in the localization is suppressed. The robustness and the scalability of this algorithm are examined through numerical simulations. Details of the algorithm and the results of the numerical simulations are presented in the second section.

In the third section, noise tolerant acoustic ranging algorithm that employs digital signal processing techniques is presented. This ranging algorithm is implemented in an off-the-shelf sensor platform (Mica2). Experiments for validation are also presented.

Field experiment was conducted to evaluate the performance of the localization system (i.e., combination of acoustic ranging and inverse Delaunay localization). 21 sensor nodes with acoustic ranging devices/algorithm were spread on the plane in a pseudo-random manner. Localization was performed by using measured distance among sensor nodes as input data set for the inverse Delaunay algorithm.

In addition to the above mentioned capability of localization, ability for time synchronization is also implemented. The details of the time synchronization based on broadcast time stamp is presented in the sixth section followd by the final section with conclusion and discussion.

INVERSE DELAUNAY ALGORITHM FOR RELATIVE LOCALIZATION

Each and every sensor node in the randomly distributed sensor network is localized by using inter-node distance as input data set. Since the inter-node distance is measured by inaccurate acoustic ranging devices, accumulative localization using small number of reference nodes may result in erroneous localization or even failure in localization itself. To suppress the accumulation of error and to enhance the robustness, localization should be based on local clusters[2].

In this paper, localization achieved by clustering the neighboring set of nodes with Delaunay polygons is presented. Using the observed relative distance between sensor nodes as input data, relative positions of nodes are determined by properly connecting local Delaunay clusters. This is opposite from Delaunay tessellation of a space for given arrangement of points. In this sense, this localization algorithm is called inverse Delaunay algorithm.

In the inverse Delaunay algorithm, the following characteristic of Delaunay polygon is extensively used.

Delaunay polygons on $\Re^2$ *are triangles with no point in their circumscribed circle*

This characteristic is fully utilized in constructing local clusters and for enhancement of the robustness of local clusters (i.e., toughness of the local clusters against measurement error).

Local Delaunay cluster construction

In the first step of the inverse Delaunay algorithm, a local cluster is made for each sensor node. Figure 1 shows a typical example of a local cluster. The area surrounded by thick solid lines is a local cluster. In this local cluster, the center node is surrounded by the Delaunay triangles hence this cluster is called Delaunay cluster. All the nodes are localized in the local Euclidean coordinate system with the center node set as the origin. Also, the nodes surrounding the center node (satellite nodes) are numbered counter-clockwise in the local coordinate system. This numbering determines the direction of the face of the local cluster.

Each local cluster is generated in the manner as shown in Fig. 2.

1. A node is picked up as a center node and the closest neighboring node is identified based on the measurement of the relative distance. (Fig. 2 (a))
2. Form a triangle using above-mentioned nodes and another neighboring node. Examine this triangle to see whether it is Delaunay or not. (Fig. 2 (b))
3. Local cluster is expanded by adding another Delaunay triangle. (Fig. 2 (c))
4. After surrounding the center node by Delaunay triangles, the satellite nodes are numbered. (Fig. 2 (d))

Note that Fig. 3 shows a conceptual view of the arrangement of the nodes and the local cluster. In reality, position of each node has not been identified before localization is done. All we have is the relative distance between nodes. Delaunay examination and expansion of local cluster solely depend on relative distance.

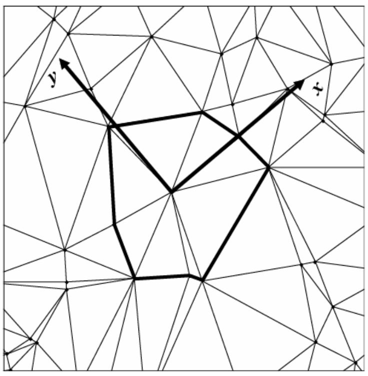


Figure 1: Local Delaunay cluster

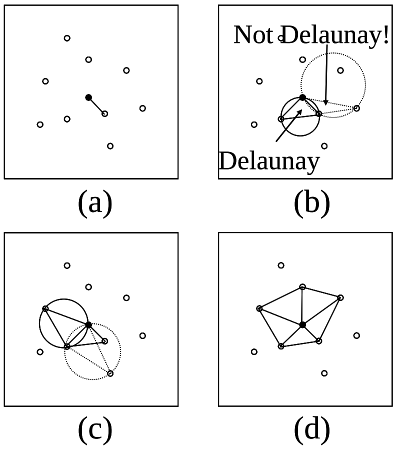


Figure 2: Delaunay cluster construction

Connecting process of local Delaunay clusters

Once the local Delaunay clusters are identified for all the nodes, those clusters should be merged together. Merging is achieved by identifying the necessary translation, rotation and flip for each cluster to satisfy consistency among local clusters with common set of nodes. The key point here is suppression of the computational cost. Since the local clusters overlap each other, cluster merging process corresponds to a jigsaw puzzle with redundant pieces. Simplest treatment of this jigsaw puzzle costs $O(n^2)$, where n is total number of nodes[2]. The following procedure results in a jigsaw puzzle with holes and its cost is suppressed to $O(n)$.

1. Clusters are divided into two groups, i.e., the atomic clusters and the bridging clusters. The atomic clusters are those with satellite nodes not being occupied by other clusters (i.e., polygons depicted by the edges with thick lines in Fig. 3). The bridging clusters are others.
2. Connect the atomic clusters (or groups) by the bridging clusters applying necessary translation, rotation and flip to the cluster or group to be consolidated.
3. Continue the second process until all the clusters are merged into a group.

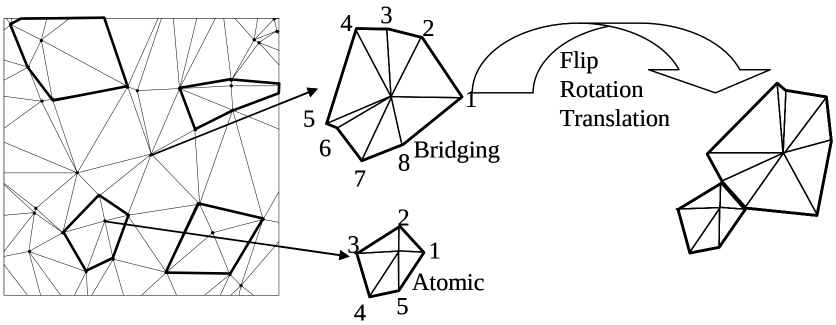


Figure 3: Local cluster categorization and merging process

Characteristics of the inverse Delaunay algorithm

One of the major advantages of the inverse Dealunay algorithm is its small computational complexity. Figure 4 shows the total number of operation (i.e., rotation, translation and flip) in the connecting process with respect to number of nodes. Figure 3 proves that computational complexity is $O(n)$ (specifically, $5n$) for merging procedure at least upto n=1000.

Another major advantage of the inverse Delaunay algorithm is its robustness against the measurement error in ranging. Consider the situation shown in Fig. 5 as a typical example. In this situation, most of the localization algorithms based on robust quadrilaterals regard this quadrilateral as a potential source of the flip ambiguity and discards this quadrilateral[2]. As a result, failure in localization of some nodes in the network is often observed. On the other hand, as shown in Fig. 5, this situation does not cause any problem to the inverse Delaunay algorithm. This is due to the bigger margin allowed in checking the Delaunay condition than that for robustness of the quadrilateral.

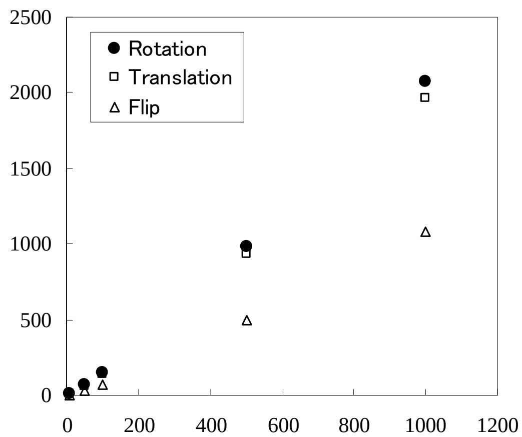


Figure 4: Number of operations

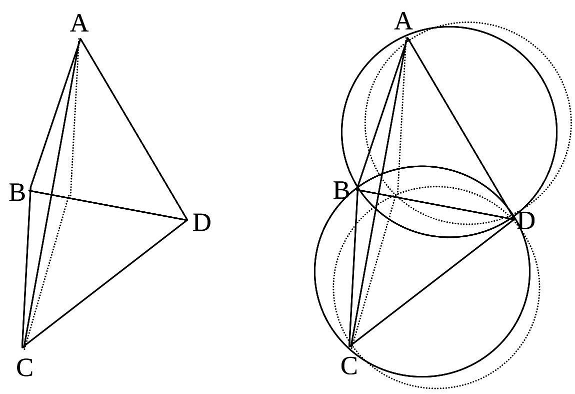


Figure 5: Robustness of Delaunay cluster

NOISE TOLERANT ACOUSTIC RANGING ALGORITHM

Relative distance between sensor nodes is one of the key information for localization. Acoustic ranging is considered to be one of the most effective tools for measuring relative distance and is actively investigated in sensor network society. This is mainly due to the limited resources in the hardware of currently available sensor nodes which is not enough for implementing ranging devices/algorithms based on TOA (Time of Arrival) of electromagnetic signals. Typical sensor node (Mica2) has only 4kB RAM and 12kB ROM with 7.3MHz microcontroller (Amtel ATmega 128L)[1]. This little capacity shows requirement for algorithms with minimum consumption of memory and computational resources. The ranging algorithm discussed in this section is based on TOA of acoustic signal and implemented in Mica2.

Basic principle of the noise tolerant acoustic ranging algorithm

The concept of acoustic ranging is based on measurement of the time of flight (TOF) of the acoustic signal between the signal source and the acoustic receiver. The range is estimated from the time measurement, assuming the speed of sound is known. In the following subsections, implementation of this principle of acoustic ranging on a commercially available sensor node (Mica2) is discussed with a major focus on algorithms for reducing the environment noise.

To locate the beginning of the acoustic signal, we need to increase the SNR (signal to noise ratio) of the samples. Since disturbances such as ambient noise are of Gaussian nature, they are independent for each chirp, whereas the useful signal content will be identical. The chirps are sampled one by one, then added together and processed as a single sampled signal. Adding together the series of samples improves the SNR by 10log(N)dB, where N is the number of chirps used. Specifically, in our implementation, by using 64 consecutive chirps in an acoustic ranging signal, the SNR is improved by 18dB.

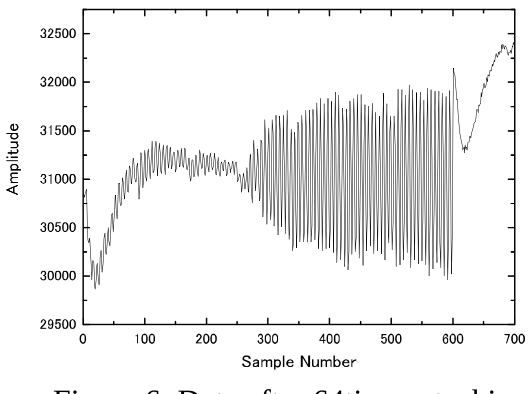


Figure 6: Data after 64times stacking

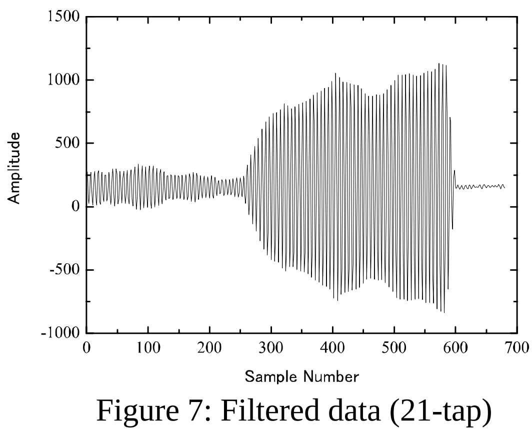


Figure 7: Filtered data (21-tap)

In addition to the external sources of the noise, analogue circuit for microphone and buzzer could contaminate the signal in low frequency range and the internal devices such as crystal oscillator could be the source of high frequency noise. Figure 6 shows the observed digital data after 64 times stacking. Remarkable noise in both low and high frequency range can be observed. To remove these noises, sampled data through ADC (analogue digital converter) is digitally processed by 21-tap FIR filter with integer coefficients in [-7, 7] interval having a rectangular window function for 4.0--4.5kHz frequency range. Figure 7 shows the filtered data. Time of arrival of the acoustic signal can be estimated from this data by identifying the intersection between the ambient noise level and the initial rising slope.

Experiment for performance evaluation of acoustic ranging method

The performance of the acoustic ranging method is evaluated in the indoor environment where we observe severe echoes as well as the moderate urban noise environment. Figure 8 (a) and (b) show the measurement errors for the indoor and the outdoor environments, respectively. In both cases, indoor and outdoor, it can be concluded that the accuracy of the present acoustic localization method is with 6cm in terms of standard deviation.

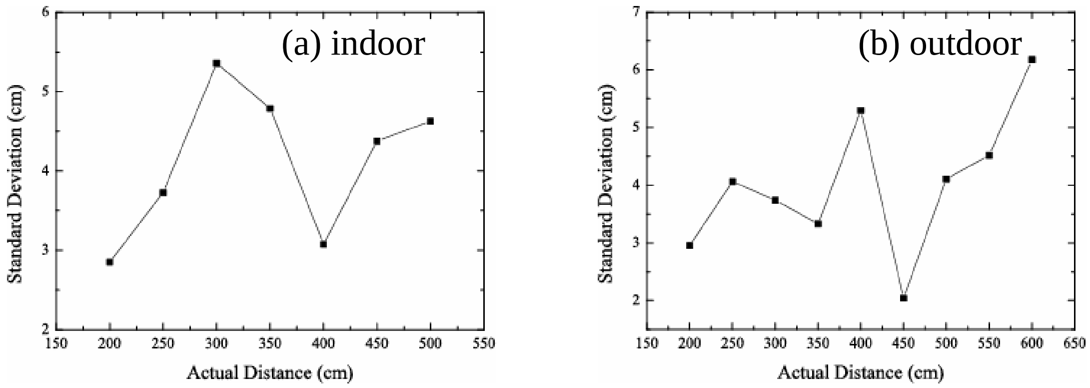
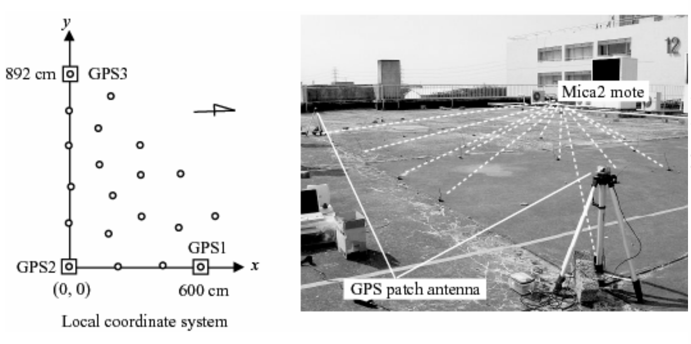


Figure 8: Measurement error in terms of standard deviation as a function of distance

FIELD EXPERIMENT FOR EVALUATION OF LOCALIZATION METHOD

Field experiment was conducted to evaluate the performance of the system for localization of sensor nodes based on the inverse Delaunay algorithm and acoustic ranging. Total of 21 sensor nodes (Mica2) with acoustic ranging devices/algorithm were spread on a plane in a pseudo-random manner as shown in Fig. 9. Each sensor node measured the relative distance among neighboring 4 to 13 nodes depending on the local arrangement of the nodes. Localization was performed by using measured relative distance among sensor nodes as input data set for the inverse Delaunay algorithm.



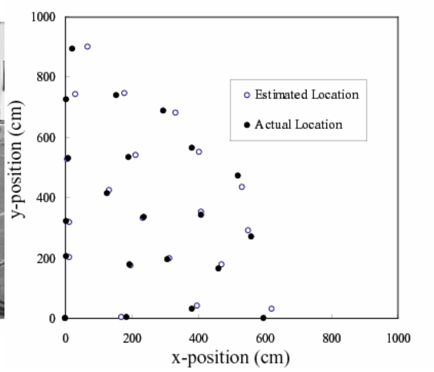


Figure9: Schematic view of sensor nodes deployment

Figure 10: Localization result

Figure 10 shows the estimated and the actual location of the sensor nodes. Since the inverse Delaunay algorithm determines the position of each sensor node upto rigid body motion (translation, rotation and flip) ambiguity as a whole, the global coordinate of the whole network of the sensor nodes is determined by GPS receivers deployed on three anchoring nodes as shown in Fig. 9. The measurement error in the acoustic ranging in this experiment was 3.8cm in average (maximum of 16.8cm) against average distance between nodes of 321.6cm. In spite of this noisy measurement of the relative distance, no node was missed in the localization and the error in the estimation was suppressed in the reasonable range. The error in the estimation of the location of the boundary nodes is relatively large. However, it should be noted that no attempt to redistribute the error throughout the domain, such as Laplacian smoothing or spring relaxation, was applied in this estimation. No sign of the flip ambiguity, accumulation of the error can be observed. Although more detailed validation such as numerical simulation on the arrangement of thousands of nodes with noise in the ranging as a controlling parameter is required, this experimental result implies the robustness of the system.

TIME SYNCHRONIZATION BASED ON BROADCAST TIME STAMP

Since time synchronization is one of the most important research topics in the field of sensor network, intensive research activity can be observed[3,4]. Among many approaches for time synchronization of wireless sensor network, we implement a method with broadcast time stamp in Mica2. The major reasons to employ broadcast time stamp are: i) time synchronization based on broadcast time stamp is suitable for devices with limited power for computation and communication, and ii) sensing of mechanical behavior of civil infrastructure has relatively relaxed requirement for accuracy (e.g., 100us -- 5ms) in time domain.

Implementation of time synchronization

The system can be regarded as a standard system for time synchronization with broadcast time stamp, which consists of "Root Node" and "Sensor Node". Time stamps are transmitted from "Root Node" periodically (1Hz-10Hz). Each time stamp has individual sequential integer number. Each "Sensor Node" starts sensing right after it receives first time stamp. It samples data from ADC at a constant sampling rate and records the information of received time stamp (see Fig. 11). All these functions are implemented on Mica2.

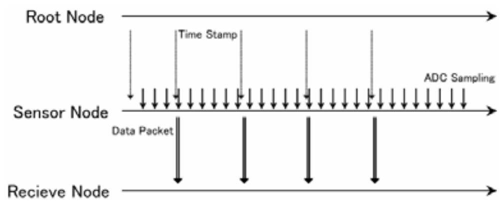


Figure 11: Time synchronization scheme

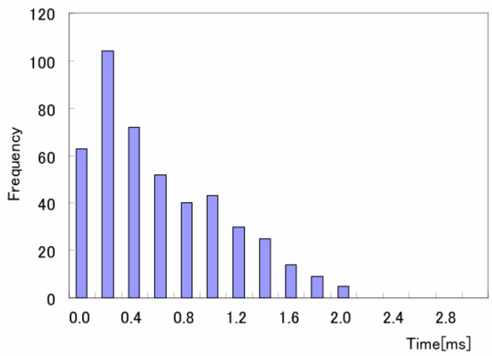


Figure 12: Event time difference

Experiment for evaluation

To evaluate the accuracy of the proposed system for time synchronization, an experiment was conducted. In the experiment, a function generator was used as a source to provide reference events. Two sensor nodes were connected (wired) to the function generator which periodically sends out pulses with fixed interval. These sensor nodes sample data with a frequency of 500Hz and stores data in on-board EEPROM. The time of the event is defined as the detection of upward zero-cross point. Together with this sampled data, when the sensor node receives broadcast time stamp, information of time stamp is also recorded on the EEPROM. After the measurement has been done, stored data is retrieved from EEPROM and decoded to shift the time of each sensor node based on recorded time stamps.

Accuracy of time synchronization is evaluated by comparing the time of detection of the event on each sensor node. Since the sampling frequency of each sensor node is 500Hz, the finest resolution in time is 2 milliseconds. A histogram of differences of detected event time between sensor nodes is shown in Fig. 12. Total number of events detected by these sensor nodes was about 450. The maximum difference of detected event time was under 2milliseconds. Difference is within the finest resolution of the current experimental setup and this shows the proposed time synchronization system works as expected.

CONCLUSIONS

The inverse Delaunay algorithm and acoustic ranging method for localization of a large scale sensor network are presented in this paper. The inverse Delaunay algorithm localizes all the nodes simultaneously, thus, the accumulation of the error in the localization is suppressed. Numerical simulation shows the scalability of this algorithm. Field experiment was conducted to evaluate the accuracy of the localization of the system. Results from this experiment validate the robustness of the proposed method.

Also, the simplest time synchronization algorithm has been implemented on a commercially available sensor platform (Mica2) and has shown reasonable performance.

As future work, improvement of time synchronization system and measurement of the actual infrastructures could be listed.

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