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4pEA7. Environment mapping and localization with an uncontrolled swarm of ultrasound sensor motes

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A method is presented in which a (large) swarm of sensor motes perform simple ultrasonic ranging measurements. The method allows to localize the motes within the swarm, and at the same time, map the environment which the swarm has traversed. The motes float passively uncontrolled through the environment and do not need any other sensor information or external reference other than a start and end point. Once the motes are retrieved, the stored data can be converted into the motes relative positions and a map describing the geometry of the environment. This method provides the possibility to map inaccessible or unknown environments where electro-magnetic signals, such as GPS or radio, cannot be used and where placing beacon points is very hard. An example is underground piping systems transporting liquids. Size and energy constraints together with the occurrence of reverberations pose challenges in the way the motes perform their measurements and collect their data. A minimalistic approach in the use of ultrasound is pursued, using an orthogonal frequency division multiplexing technique for the identification of motes. Simulations and scaled air-coupled 45-65 kHz experimental measurements have been performed and show feasibility of the concept.

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INTRODUCTION

In many application areas where sensing is involved, the location where the sensory input is obtained is important. Localization of spatially distributed motes in wireless sensor networks has had significant attention in the scientific community [1, 2] in the last years. Many techniques and applications have been studied and developed e.g. for underwater acoustic applications [3].

However, in difficult-to-access areas with stringent energy constraints (inaccessible for standard techniques as well as for human access), there is a lack of techniques capable of obtaining sensory information combined with location information. These areas can be e.g. underground oil reservoirs, underground water distribution systems, etc.

One way of exploring such areas is by inserting a swarm of sensor motes at one location and extracting them from a second, where sensor motes can move passively with the flow (oil, water) from one location to another. The motes perform measurements while traveling through the area of interest. In this paper we present a method, where individual sensor motes in the swarm perform ranging measurements to other motes and to environment boundaries using ultrasound. These measurements can be used to localize motes within the swarm [4] and they can provide information on the geometry of the environment. Identification of motes is based on a non-unique identifier which is used in the ranging pulse, the measured distances and the presence of neighboring motes. This non-unique identifier is introduced to limit the complexity and usage of energy in the individual motes. After retrieval of the motes, measured information can be processed using ample computing power running complex and energy-consuming calculations offline that compensate for the lack of the unique identification.

In this paper we present key design considerations and analyze key performance parameters of the method.

PROPOSED METHOD

The proposed method can be applied to any swarm of which the motes have ranging capabilities. Here, we examine motes fitted with ultrasound transducers with omnidirectional radiation patterns. The motes perform ranging measurements by deducing the time of flight (ToF) of ultrasound pulses emitted by neighboring motes as well as those emitted by themselves, after reflection on the environment boundaries. Figure 1 shows an illustrative representation of motes traversing an environment while performing measurements. No assumption is made on the way motes traverse the environment or on their orientation, the angular information of incoming pulses is discarded and only isotropic emission and reception is considered. Since the motes are operating in enclosed environments where reflections may be significant, single short pulses will be used.

In order to identify the senders of the pulses, each mote will emit a ranging pulse in a specific frequency band using orthogonal frequency division multiplexing (OFDM) [5]. Ultrasound transducers have a limited operating bandwidth,

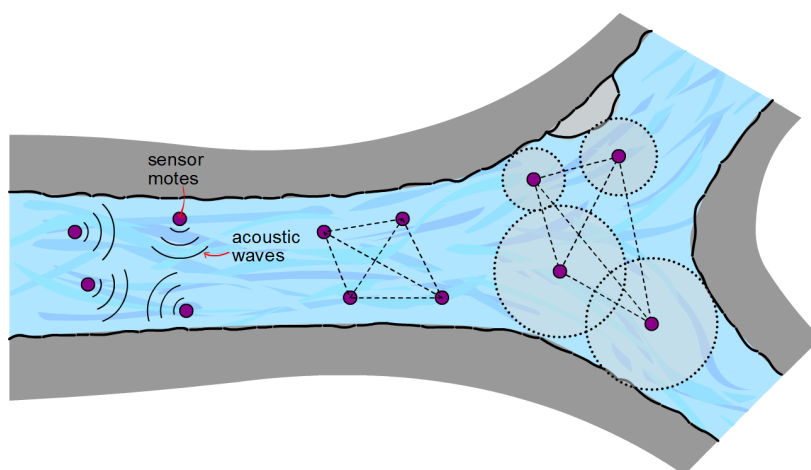


FIGURE 1. Illustration of motes in an inaccessible environment. When traversing the environment, motes measure and store the distance to each other using time of flight ranging and the distance to the environment boundaries. This information will be used in a post-processing stage to estimate the motes relative positions and to characterize the environment in which they traveled.

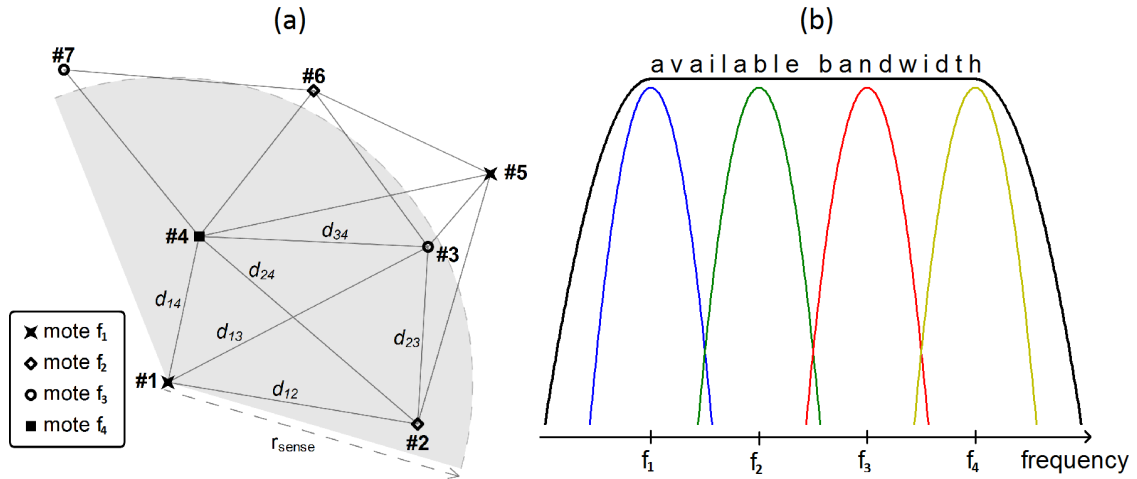


FIGURE 2. (a) A schematic of a swarm indicating motes $i = \{1, \dots, N = 7\}$ with four different frequencies f_m with $m = \{1, \dots, n_f = 4\}$ and distances between motes d_{ij} within their sensing radius r_{sense} . (b) A division of $n_f = 4$ distinguishable frequencies within the available bandwidth using Orthogonal Frequency Division Multiplexing (OFDM).

resulting in a trade-off in the amount of non-overlapping frequency bands versus the pulse lengths of the ultrasound signals, as already discussed in [6]. Since the swarm contains a large amount of motes and short pulses are requested, multiple motes will be using the same emission frequencies. Each mote will emit a ranging pulse at a specific time and will store the frequency and arrival time of received pulses from other motes within their sensing radius. Afterwards, when the motes are retrieved, their data can be analyzed.

In order to determine the relative positions of the motes, iteration techniques will be used as, for example, discussed in [4]. Iteration requires inter-mote distances and the associated motes identity. Distance can be determined from the ToF information when assuming a homogeneous medium with a known speed of sound. To determine the motes unique ID's, based only on the measured distance and associated frequencies, a matching algorithm is developed. This algorithm tries to find matches in measured distance and frequency to estimate which mote pairs have measured each other, as discussed in the following sections.

The result of this method is a set of presumed distances between identified motes, which can be fed into a localization algorithm, which tries to determine the motes relative positions, and while doing so, verifies if assigned matches and distances are correct. Incorrectly established matches, which are caused either by the non-unique nature of the method or by for example reflections, can lead to a failure in localization of specific motes or the whole swarm. Therefore, the performance of this method is also studied.

This paper assumes that the motes are synchronized and instantaneous positions of the motes are considered. Furthermore, we limit attention to the 2-dimensional case, however, the same methodology applies for the 3-dimensional case.

METHODOLOGY

A set of motes in a swarm during operations is illustrated in Figure 2a. The figure illustrates some of the used symbols and notations which will be used throughout the paper:

- N = total number of motes in swarm,
- i, j = $\{1, 2, \dots, N\}$ number, uniquely identifying a mote,
- n_f = number of orthogonal frequencies in use,
- $f(i)$ = $\{f_1, f_2, \dots, f_{n_f}\}$ emission frequency used in mote i ,
- d_{ij} = real distance between mote i and mote j ,
- r_{sense} = sensing radius of motes.

All motes $i = \{1, \dots, N\}$ have been assigned one of the n_f orthogonal modulation frequencies $f_{m=1, \dots, n_f}$ within the available frequency bandwidth, with $n_f \ll N$ due to the limitations described above. Figure 2b shows an example of a division of an available bandwidth in $n_f = 4$ orthogonal frequencies.

All motes emit their ranging pulse simultaneously. After that, motes start listening to incoming pulses and store the time of arrival of all received pulses with corresponding modulation frequency, as illustrated in Figure 3. Once the data of the different motes are collected and the time delays are multiplied by the speed of sound, measured distances and corresponding frequencies is then known for each retrieved mote. It should be noted that these measurements do not include information about which specific identifier j every neighboring mote had, only which frequency it used. As shown in Figure 3, the measurements are stored in the variable $D_{f_m}^i$ which contains for each mote i , all measured distances to neighboring motes having emitted a pulse at frequency f_m .

NEIGHBOR MATCHING

The goal of the neighbor matching method is to derive from the obtained data, $D_{f_m}^i$, the distances \hat{d}_{ij} between specific mote pairs i and j ; i.e. to assign the measured distances to the corresponding mote pairs i and j .

In order to determine which received ranging pulse belongs to which sending mote and to define \hat{d}_{ij} , matches can be established by examining mote pairs i and j , which have measured a pulse from a similar distance with each other's frequency, as illustrated in Figure 3. This condition can be expressed as $D_{f(i)}^i = D_{f(j)}^j \pm \epsilon_d$, where a distance matching tolerance ϵ_d is introduced to allow for distance determination errors. A further restriction is given¹: $f(i) \neq f(j)$.

In this first step, mote pairs are found that have potentially measured each other. But, the combination of distance and frequency is not unique within the swarm, i.e. multiple mote pairs could have measured each other at a similar distance with similar frequencies. As a result, the above method might introduce matches between motes which haven't, in reality, measured each other, or which have measured each other but at a different distance. These false matches are unwanted and can caused the localization to fail.

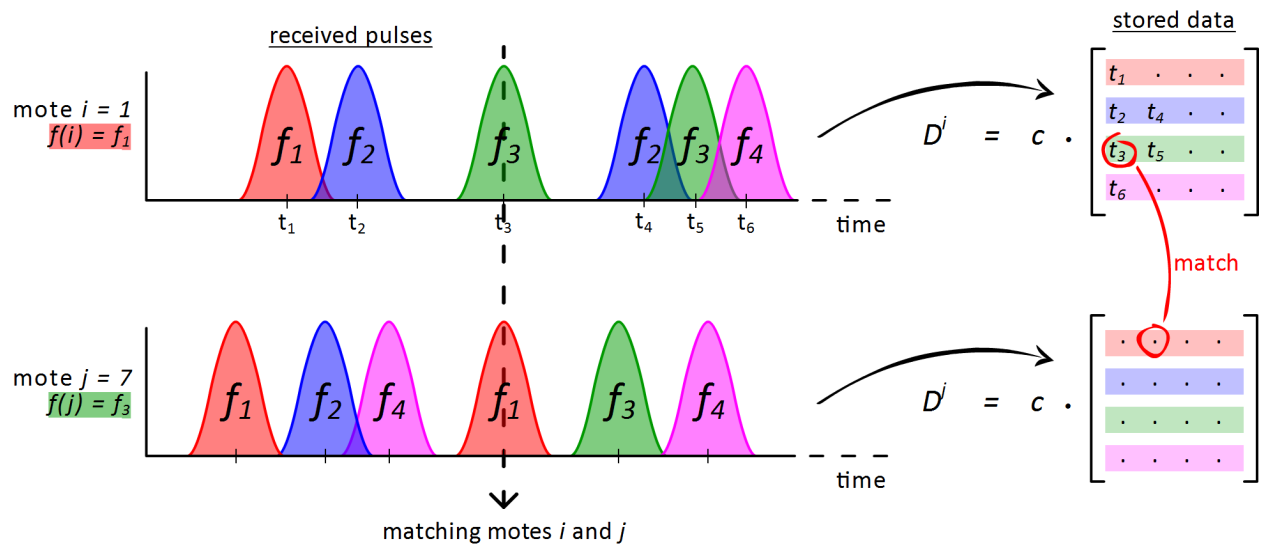


FIGURE 3. A set of received pulses for two different motes i and j . They only store time of arrival of pulses and their frequency. These two motes can be matched with each other since they potentially measured each others ranging pulse at the same time (distance). Mote $i = 1$ with $f(i) = f_1$ measured a pulse with frequency f_3 at the same time (distance) as mote $j = 7$ with $f(j) = f_3$ measured a pulse with frequency f_1 .

¹ In this paper the restriction is arbitrary and used for simplicity. It limits the amount of matches made by this method.

In order to reduce the amount of false matches, the matching condition can be applied to a group of motes instead of looking only at mote pairs. For example, distance $d_{i,j}$ can be assigned to motes i and j only if both motes measured a common third mote k which has frequency² $f(k) \neq \{f(i), f(j)\}$ and for which holds $D_{f(k)}^i = D_{f(i)}^k$ and $D_{f(k)}^j = D_{f(j)}^k$. If these motes i , j and k have measured each other, the measured distances should obey the simple geometrical constraint that they fit in a triangle:

$$\hat{d}_{ij} - D_{f(k)}^j \leq D_{f(k)}^i \pm \varepsilon_d \leq \hat{d}_{ij} + D_{f(k)}^j \quad (1)$$

When this condition is not fulfilled, it is unlikely that these motes have measured each other. When no mote k can be found which obeys this condition, mote i and j did not measure each other, or they don't have enough neighbors in order to localize them. In both cases this match can be removed and as result the number of false matches will be decreased. This neighbor matching approach can be extended to more motes with a better geometric verification to get an as accurate as possible set of matched motes with accompanying set of distances \hat{d}_{ij} .

For this paper, the algorithm creates mote pairs (matches) only if the motes are part of a group of $n_{\text{group}} = 4, 5$ or 6 motes, in which all motes have measured each other, in which no multiple frequencies exists, and all sets of 3 motes within the group obey condition 1. Since lateration in the 2D case requires for each mote to have at least 3 neighboring motes, the minimum group size is $n_{\text{group}} = 4$. Note that all possible groups are considered; motes can be part of multiple groups and, thus, can have more than $n_{\text{group}} - 1$ neighbors considered for localization.

The resulting set of distances \hat{d}_{ij} can be inserted into a lateration algorithm to estimate the positions of the motes relative to each other. Note that this method can not prevent that multiple distances are assigned to a specific pair of motes.

PERFORMANCE OF MATCHING METHOD

The information in \hat{d}_{ij} can only be used in a lateration algorithm when the amount of false entries is small in comparison with the amount of correct entries. It is therefore useful to investigate the performance of the matching method described above.

In order to test the method, numerical simulations were performed considering motes as point sources positioned at random locations in a 2-dimensional environment. The available data for further processing are the distance to neighboring motes within their sensing radius and the frequency which was used by these neighboring motes.

The performance is expressed in two parameters. First, the fraction of motes which are connected to other motes and form a group is defined to be the connectivity C , i.e. the motes for which sufficient neighbors have been matched such that they form a group of n_{group} motes, each with a unique frequency. The second parameter, Q , is a quality parameter, indicating the fraction of all grouped motes which have at least 70% of their connections correct, where a correct connection is an established match between grouped motes which also measured each other at that specific distance. The parameter Q is a measure to determine the usefulness of the data collected by the swarm. The higher this value is, the easier it is to position the grouped motes in space using the collected data.

Performance is highly influenced by the swarm characteristics (N , n_f , r_{sense} and the volume they span, V) and the accuracy of distance measurements on which the parameter ε_d is based. The parameters Q and C for two different cases are shown in Figure 4. In Figure 4a the number of motes N and the number of frequencies n_f were changed, while keeping a fixed volume V . Figure 4b shows the result of taking a fixed number of motes $N = 70$ and changing the volume V which is spanned by the motes. In both cases, r_{sense} and ε_d are fixed and $\varepsilon_d \leq 0.01 r_{\text{sense}}$. In Figure 4, a new introduced parameter, density ρ , shows the average amount of neighboring motes within the sensing volume of each mote and is depicted on the primary x-axis. In the fixed volume case (a), a secondary x-axis is showing the number of motes N .

The two different cases represent different physical descriptions of the swarms dynamics, as illustrated in Figure 5. Keeping V fixed and changing N will help in determining how many motes and how many frequencies are needed to accurately measure a fixed volume. Keeping N fixed and changing V represents the case with a fixed number of motes which are spanning a changing volume, for example when motes in a swarm begin in close proximity and disperse (over time) over the volume.

² See previous footnote.

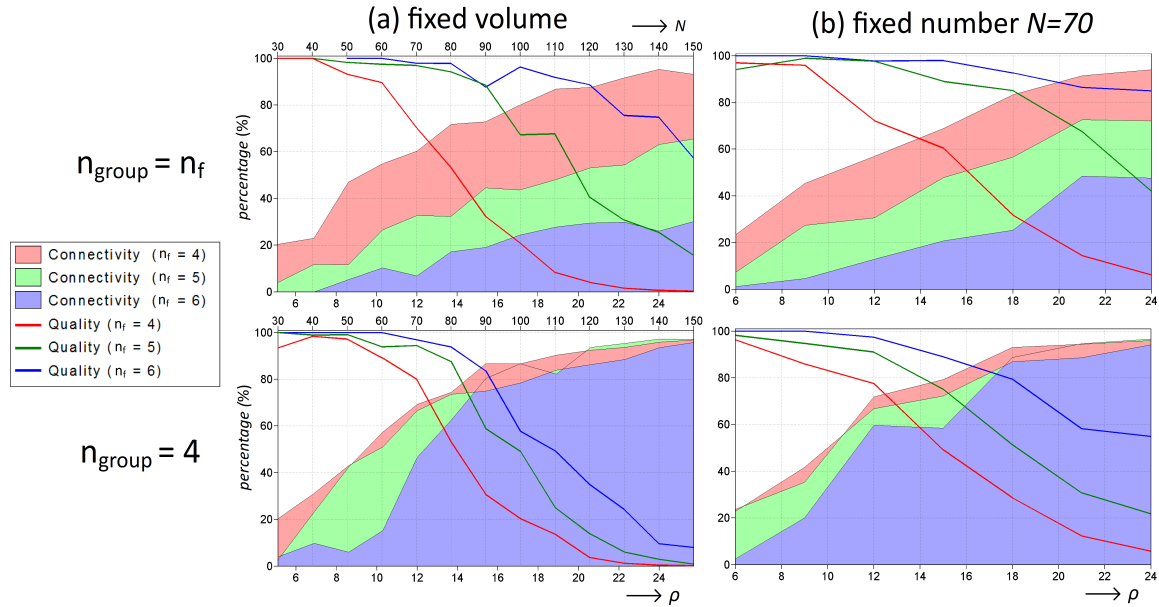


FIGURE 4. Performance parameters in two different cases: (a) the volume V which is spanned by the swarm is fixed, the number of motes N is changing; (b) the number of motes is fixed ($N = 70$), the volume V is changing. Top graphs have minimum group size of $n_{\text{group}} = n_f$, bottom graphs have minimum group size of $n_{\text{group}} = 4$.

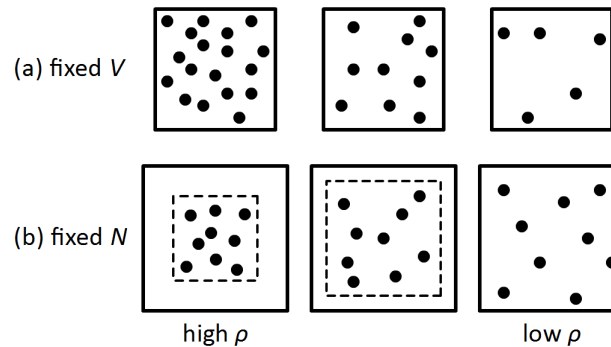


FIGURE 5. Two different cases for study into performance of method. Top: fixed volume, changing number of motes; bottom: fixed number of motes, changing volume. Representing different dynamics of swarm distribution.

The results show that in all cases when the density increases, the connectivity C increases. A larger density means that the motes will see more neighboring motes and will more easily become part of a group. On the contrary, increasing the density lowers Q . This can be explained by the fact that when more motes see each other, a larger amount of distance measurements is recorded, resulting in more possibilities to establish false distance-frequency matches. There is a clear trade-off in connectivity versus quality.

The top graphs pertain to $n_{\text{group}} = n_f$ and shows that increasing the amount of frequencies decreases C . This is so because it is more difficult with a given N or ρ to create groups of $n_{\text{group}} = n_f$ with all frequencies present. Relaxing the constraint to $n_{\text{group}} = 4$ will result in a similar C for all $n_f = 4, 5, 6$ as can be seen in the bottom graphs. The more frequencies are in use, the higher Q will be, since effectively more identification information is added in the swarm, having its limit where every mote has its own identity resulting in a theoretical $Q = 100\%$.

Furthermore, the accuracy of the distance measurement, and thus ε_d , determines where the drop-off in Q will happen. A better accuracy and smaller ε_d will result in less false matches and, thus, a higher Q .

The difference between taking $n_{\text{group}} = n_f$ (top graphs), which results in a higher Q but lower C , and taking $n_{\text{group}} = 4$ (bottom graphs), which results in a lower Q but higher C , is a decision which can be made in the

post-processing phase. Since localization works best with an optimal balance between quality of the data and the number of connections, these different post-processed quality over quantity datasets can be combined, depending on the localization algorithm requirements. Also, different post-processed datasets can be generated by allowing groups to be formed with different frequency constraints (now maximum one mote per frequency), for example to exclude certain frequencies when a mote received too many pulses of these frequencies.

The obtained results show that, when operating within the assumptions and parameters described here, the proposed method is capable of achieving adequate performances ($C = 80\%$ and $Q = 80\%$) for ratios up to 15 between the number of motes and the number of unique identifiers ($N = 90$ and $n_f = 6$).

DISCUSSION AND FUTURE WORK

A method to characterize an inaccessible environment using a swarm of ultrasound motes by estimating their relative positions using simple ranging measurements was discussed. All motes in the swarm emit a single ranging pulse in a frequency sub-band which is used multiple times within the swarm. Identification of individual motes is performed afterwards when the motes are retrieved, based on matching frequency and distance information, combined with the distribution of neighboring motes. The preliminary numerical simulations suggest the feasibility of uniquely identifying and positioning large fractions of motes in a swarm using only a limited amount of unique identifiers. In the example given here, adequate performances are obtained for ratios up to 15 between the number of motes, and the number of unique identifiers.

Several assumptions have been made in this paper, for example: time synchronization between the individual motes, motes behaving as point source/receiver and reflections are not considered. Reflections on environmental boundaries will provide information about the environmental geometry, but due to multipath propagation they will also introduce false connections. The fact that motes will have a finite size will influence mote dynamics, motes might cluster and block signal paths, and will influence ultrasound propagation. The loss of synchronization which may happen in reality, will influence how ranging measurements can be made.

These effects are the basis of the future work which is currently being pursued. An experimental setup is being developed to study, together with ultrasound propagation simulations, the effects of inhomogeneity in the omnidirectional emission pattern, reflections and the loss of synchronization.

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