Robust Shock Wave Localization with Swarm-Intelligent Systems

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Abstract

Using data obtained via accelerometer readings on time-synchronized, collective E-puck robots, we propose a framework to detect in real-time the geographic epicenter of a radially-emitted shock wave. Combining techniques to obtain swarm synchronization, centralized communication and the parameters for mathematical multilateration, our research provides foundational work for more advanced detection and localization of earthquake-like vibrations in swarm-intelligent systems. With an experimental setup consisting of three immobile E-puck robots, our methodology has shown potential to provide accurate geographic localization of simple shock waves in a two-dimensional triangular arena. Unfortunately, due to hardware limitations on the E-puck robot accelerometers, actual experimental results were unattainable. This paper highlights and contextualizes our implementation and outlines the crux of the problem in order to motivate future related research.

I. Introduction and Motivation

Swarm-intelligent systems are well-suited for a number of practical applications by virtue of their relatively low cost for individual components, individual agent simplicity, and their intrinsically distributed nature. One promising application is that to the domain of seismography. Typical seismographs are solitary, expensive and often technologically complex units used to detect the onset and magnitude of earthquake vibrations [1]. On the other hand, the deployment of simple, inexpensive, geographically scattered, collective agents imbued with vibration-capturing technologies can offer a unique approach to detection of seismographic activity.

The E-puck is a miniature, mobile robot developed for educational purposes. E-pucks contain a simple three-dimensional accelerometer and communicative abilities that make it an apt candidate for swarm-intelligent seismographic acquisition. By distributing a small horde of three E-pucks at predetermined coordinate positions we will show that the geographic epicenter of earthquake-like vibrations can be isolated via application of multilateration, a popular mathematical technique used in localization for aviation and satellite systems [2].

Formulating seismographic problems with swarm-intelligent systems poses a unique set of obstacles. For instance, since determination of the epicenter depends on timing information, it is necessary to have all agents in the swarm time-synchronized. Moreover, due to the simplistic nature of each agent, implementation must circumvent any intensive processing operations. Finally, the incorporation of agent communication demands that extra care be taken in implementation for accuracy of results.

II. Project Overview – Experimental Setup

Before delving into the details of the various components of our research, we will briefly outline our modus operandi. Three E-puck robots are positioned in a right triangle to detect vibrations. These robots first undergo a time synchronization and then begin to “listen” for shock waves. At the detection of a shock wave, the robots collect a window of relevant data preceding and following the onset of the vibration. This data is then sent to a central processor who is constantly listening for information from the robots. It is then centrally post-processed using the time stamp from each robot and the received accelerometer values. The birds-eye view of the process is outlined in *Figure 1* and the experimental set up is shown in *Figure 2*.

III. Multilateration

Multilateration is a mathematical principle commonly used for object localization in global positioning, aviation, surveillance and navigation systems. By observing the time of arrival (TOA) of the same signal at numerous receivers, the time difference of arrival (TDOA) can be computed and a system of algebraic equations can be solved to locate exact coordinates. More specifically, we use the TDOA between robots to compute various hyperboloids. The intersection of all TDOA-derived hyperboloids corresponds directly to the source of the vibration.

Notationally, we define the the systems of equations according to the Bucher method [3]. In our case of E-puck vibration detection, we consider only the domain of vibrations caused by tapping or pounding on a table. That is, all source vibrations are considered to be induced in the same plane as the receivers and thus contain no third dimension, typically notated in the literature as z. This simplification was necessary as we had no mechanism by which to produce shock waves in the third dimension.

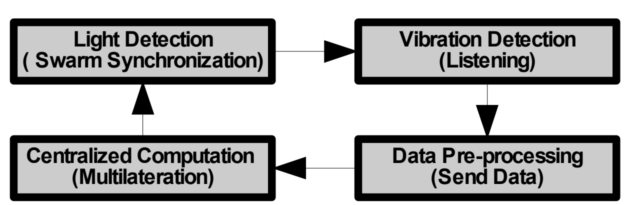

Figure 1 -- *Implementation Overview*

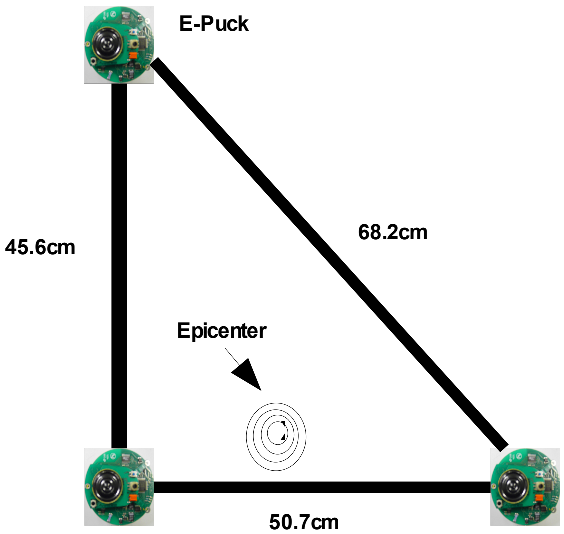

Figure 2 – *Experimental Setup*

Consider receiving robots R_1, R_2, and R_3 who receive the same signal with medium-dependent velocity of v_m. Moreover, for sake of mathematical simplicity, assume that R_2 is placed at the origin of the defined coordinate system. As such, the TOA at each robot is:

$$T_{R1}=\frac{1}{v_m}\sqrt{(x-x_{R1})^2+(y-y_{R1})^2}$$

$$T_{R2}=\frac{1}{v_m}\sqrt{x^2+y^2}$$

$$T_{R3}=\frac{1}{v_m}\sqrt{(x-x_{R3})^2+(y-y_{R3})^2} \quad (1)$$

where (x,y) represents the actual epicenter of the vibration and (x_{R1} , y_{R1}) is the first robot's coordinates. Now, we define the TDOA relations of each robot to trivially be:

$$T_{R12}=T_{R1}-T_{R2}=\frac{1}{v_m}\left[\sqrt{(x-x_{R1})^2+(y-y_{R1})^2}-\sqrt{x^2+y^2}\right]$$

$$T_{R32}=T_{R3}-T_{R2}=\frac{1}{v_m}\left[\sqrt{(x-x_{R3})^2+(y-y_{R3})^2}-\sqrt{x^2+y^2}\right] \quad (2)$$

By symmetry, the following relationships hold:

$$T_{R13}=-T_{R31} \quad and \quad T_{R23}=-T_{R32} \quad (3)$$

We hereby make the simplifying assumption that all three robots are stationary and are placed at predetermined coordinates. Not only is it unclear what advantage there would be to using mobile robots to detect earthquakes (cf. Section VII), obtaining a common, relative coordinate system amongst distributed robots further complicates the problem beyond the scope of seismography. Furthermore, we assume that the medium through which the waves propagate is homogeneous. Thus, the velocity will be a constant across equations.

Finding a Solution

Using the above assumption we now have all necessary elements to solve the system of equations. In general, utilization of *N* robots yields a system of equations containing *N-1* variables. More concretely, given three E-puck robots we should be able to solve the above system of two equations for two unknown variables x and y.

One common way to solve problems of multilateration is to apply the above-mentioned Bucher method, giving us a detailed analytical derivation of the TDOA equations. As seen above, using three robots yields two TDOA equations (2) and two unknowns. Regrettably, the solution to two equations for two unknowns is neither simple nor satisfactory due to the square root terms. The Bucher method thereby demands the addition of a fourth receiver to yield simple and elegant solutions.

Given this restriction and our inventory of only three robots, we had to change trajectory in our approach of a mathematical solution. In the end, we used Matlab's *solve()* command to generate the approximations to the solution in the form of two functions With this found solution (cf. accompanying code) we are now able to find the exact x and y coordinates of the epicenter as functions of the reported TOA from each robot. Toy Matlab graphical solutions and Bucher algorithm solutions can be seen in *Figure 3.*

IV. Time Synchronization

One caveat of using distributed systems and the method of multilateration outlined above is that all of the mathematical foundations assume perfectly time synchronized robots. That is, the TOA equations (1)-(4) demand that each robot is reporting the TOA according to the same scale. Time synchronization is a non-trivial problem in distributed systems as it requires special attention of individual agent software and hardware details to guarantee time synchrony.

Method

We begin by enforcing the prerequisite that each robot is running the same controller software and that they are homogeneous with respect to their hardware. In addition, we manually set the register values in the controllers to fix the acquisition speeds of the accelerometer and the analog-to-digital conversion sampling rate.

Next, we have to have some way to communicate with each of the robots at the same time in order for them to agree upon a ground-zero time. Communication via the Bluetooth device or manual manipulation of each individual E-puck (for instance simultaneously restarting each E-puck) are insufficient in guaranteeing time synchrony since we may have communication delays or loss, and individual robot rebooting times may slightly differ. In short, we need all three robots to wait for some signal that will be guaranteed to arrive at the same instant. Our solution is to utilize the infrared sensors on the E-puck.

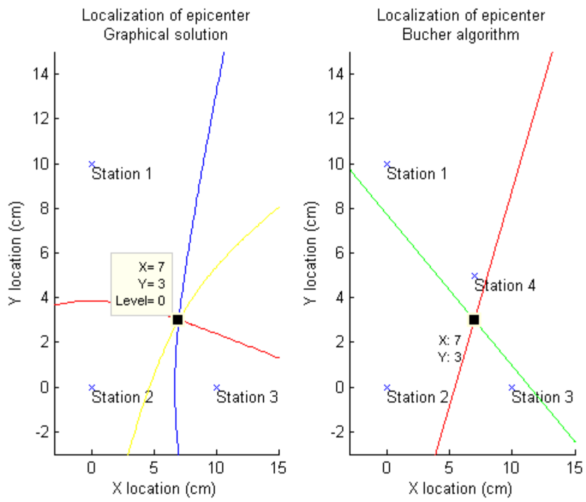

Figure 3 –
Graphical and Bucher solutions to multilateration

We begin by initializing all robots into a "light sensing" mode whereby they wait in an infinite loop for some dramatic increase in the infrared light sensor value. We can thus use an intense flash of light to begin the process of synchronization. Upon sensing the light each robot changes its mode to a "detection mode" and immediately starts an individual timer that is now assured to be started at the same time as all robots who received this signal. It should be noted that since all robots are sampling their infrared channel at the same sampling frequency, and interrupts are manually disabled before switching operation mode, we assure that the processor on each E-puck is making the same computation at the same time.

The above method carries an implicit assumption that the velocity of light is much greater than the distance between the E-pucks. Therefore, any minute time difference can be seen as negligible enough to consider the light to have arrived at the same time at each E-puck. Since we are talking about light traveling at nearly 300 km/s, the difference of time to traverse distances within than a meter are mere fractions and are thus safely considered to be the same.

V. Data Acquisition and Processing

As mentioned in the Section III, we have regulated the E-Puck behavior to sample the accelerometer at a known rate. By configuring the PIC registers for the analog-to-digital converter according to the technical specifications document, we know that each E-Puck is sampling the accelerometer values at its maximum rate of about 200 kilosamples per second [5]. This gives us the finest time resolution obtainable for later data processing.

To capture both shock wave data and light sensor data, it was necessary to come up with some methodology to define what constitutes a "flash" of light and a vibration. To do so, we have implemented to primitive types of data acquisition, each with their own advantages and shortcomings. These methods were implemented in the controller and therefore pushed some of the data preprocessing to the E-Pucks. This was the prudent thing to do since most of the data we are observing is irrelevant. Said differently, there is no reason for the central processing unit to know anything about sensor readings until it is time to compute. At this point, only data which is computationally relevant should be communicated.

The first method uses empirically determined, preset thresholds to detect the onset of light and shock waves. By collecting various experimental data from E-Pucks constantly reporting their infrared port and accelerometer values, we determined two reasonable fixed thresholds by which to consider a new sensor value as being significant. If the sensor value is found significant, the E-Puck relays the time it receives the value to the central processor. This method has the overall benefit of being computationally efficient since it requires the E-Puck to solely compute a comparison for each sample. This method was particularly adequate for light sensing since ambient light in most environments contained values well above the threshold and the flash perturbed the signal significantly.
The main pitfall to using a static threshold is that there is no implicit noise filtering. For instance, if the E-Pucks are in an environment with constant vibrations, we would like to consider the shock wave to be that value which is relatively large and not some predefined numeric value. To remedy this situation we have implemented an adaptive threshold via a running average. Upon receiving a new sample from the accelerometer, we update an ongoing mean value. By adding a fraction of acceptable noise to the current mean, we construct a window of values for which only incoming samples falling outside of the window are considered as significant. All other examples update the mean and thereby change the dynamic window.

The adaptive threshold is a more robust mechanism by which to determine whether a sample ought to be considered or discarded. However, by sampling at 200 ksps we have to be extremely cautious of what computation is being done for each sample in order to guarantee time synchrony. By dynamically updating the mean with each sample we avoided doing post-computation (i.e. calculating the mean after the fact), but had no way to avoid introducing floating point arithmetic. Since the E-Puck robot has no native floating point arithmetic it must convert floating point operations and approximate. We noted that this floating point conversion undeniably altered E-Puck timer values and led to unrealizable time synchronization.

Our final implementation was motivated by the disadvantages outlined above and consists of using a static threshold for the onset of a shock wave. It differs from the first proposed detection algorithm as it stores a window of samples before and after the sample which exceeds the threshold. This information is packaged to capture the full characteristic shock wave and is sent to the central processor for further processing. At the central processor, we can reconstruct the wave further analyze the data for threshold adaption. This also affords us post-analysis and is a prerequisite for cross-correlative detection (cf. Section VII).

VI. Results

Using a simplified version of the experimental setup outlined in Section II, we have obtained measurements for the velocity of shock waves in our particular system. Multilateration results from the triangular set up are additionally included below. Before introducing our results we first append a disclaimer in which we highlight the accelerometer deficiency and explain how it may yield inaccurate localization.

Technical Limitations

After implementing all of the individual pieces outlined in Section II we noticed that there were often incongruities in our measurements. For instance, those E-Pucks closer to the shock wave would sometimes report that they had received the shock wave after E-Pucks farther away. Sometimes two E-Pucks would report they had received the signal at the same time. Occasionally reports would follow the intuition that the shock wave would be intercepted at the closest E-Puck. Investigation as to what was happening led to the following conclusion: the E-Puck's accelerometer was filtering out important shock wave frequency data.

According to the accelerometer spec sheet, the onboard accelerometer is only capable of measuring wave frequencies up to 150Hz [7]. This embedded low-pass filter is removing important shock wave frequencies, namely those above 150Hz. With this myopic understanding of the shock wave, we are ignoring any timing information contained in the higher frequencies that reach the robot. Sampling at 200 ksps is moot because we are unnecessarily over sampling. By sampling very rapidly from a signal whose frequency can only be a small fraction of our sampling rate we obtain no new information about the wave form.

In brief, not being able to observe higher frequencies means that our TOA measurements will be inaccurate. These TOA measurements are pivotal in the multilateration configuration and without proper timing information, we are unable to obtain accurate results. By running the same experiments a number of times and obtaining different core values for the velocity through the same medium, one can clearly see that the timing will dramatically affect velocity measurements (cf. *Figure 4*).

Measuring Shock Wave Velocity Through Medium

By using two E-Puck robots and producing a colinear shock wave, we are able to use the reported TDOA between the two and the known distance to calculate the velocity of the wave through the composite wood material we are using. The results from three such experiments are outlined in *Figure 5*.

Experiment #	Measured Velocity
1	1697.1 m/s
2	802 m/s
3	752 m/s

Figure 4 –
Incongruity in Velocity Measurements

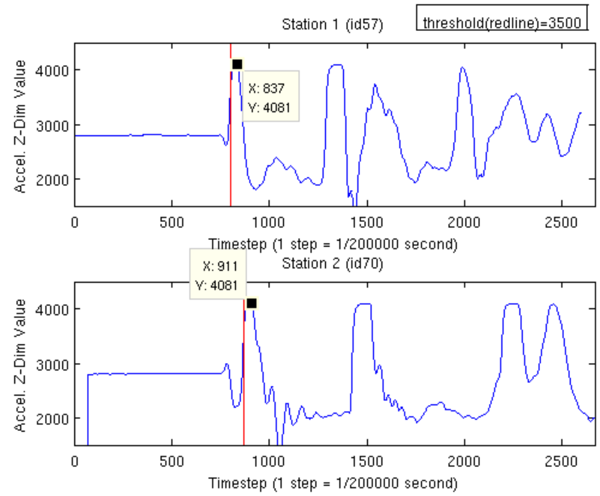

Figure 5 – *Velocity Experiment Two*

Measuring The Epicenter

Using multilateration and the triangular setup described in Section II, we have run experiments to localize the epicenter. Results of one such experiment can be found in *Figure 6*.

VII. Discussion

In short, we have presented a full framework for detecting shock waves with simple, distributed, collective agents. By collecting and submitting relevant data of three time synchronized E-Puck robots we have demonstrated how vibration epicenters can be isolated. It happened to be the unfortunate case that a pivotal hardware limitation on behalf of the E-Puck accelerometer thwarted the perfect transition between using our collected data and our implementation of multilateration, but all elements of the framework are in place for future research.

Using this preexisting framework there are numerous directions for future research. First, and most importantly, it will be necessary to use agents whose hardware enables us to capture a fuller range of vibration frequencies.

A second possibility is to explore the benefit of using mobile robots. The underlying assumption is that earthquake epicenters generally appear in relatively small geographic regions and that having detection stations closer to typical epicenters may help in preventative detection. That is, after detection of a shock the robots will localize the epicenter and then move closer to the source. Finally, they must recalculate their new relative positions for future detection.

Mathematically there are also a few things that we can improve. By simply adding one more E-Puck we could have had a simple analytical solution to the multilateration problem using the Bucher method, as discussed in Section III. Adding addition stations will increase the accuracy as we will be computing the intersection of more hyperboloids. Using these additional stations may also permit us to attempt new mathematical principles in TDOA estimates, such as cross-correlative methods. These tactics may also provide more accuracy heterogeneous environments.

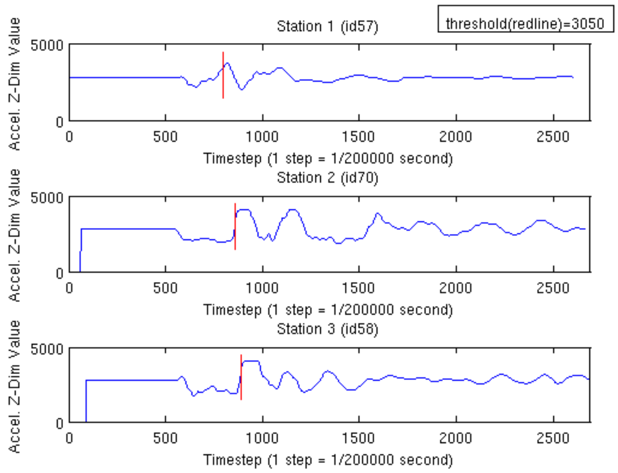

Figure 6 –
Obtained Signals in Triangular Setup

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