Sensor Localization with Lateral Inhibition & Statistical Inference

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Abstract—Lateral inhibition plays an important role in biological sensory systems. When a sensor network is connected such that neighbors exert an inhibitory effect on one another proportional to the distance between them, relative localization of elements is easy and sensitivity to targets is enhanced. This report demonstrates how lateral inhibition works and some of its important properties. The method uses radio signal strength as an indication of distance, but is robust to reflection interference because it uses pooling of multiple sensor output. The contribution of this work is a new tool for sensor localization, useful alone or in combination with other methods. A Java™ application provides the figures shown here, and is available for demonstrating lateral inhibition for different signal strength, sensor layout, and reflectivity values. Computational algorithms are available on request.

1. Introduction

In order to be useful in a real-world application, sensors in a distributed network must have locations that are known or can be inferred. Some sensor nets must also be able to detect and localize a specific target with high spatial accuracy. There are many localization methods that work flawlessly, but are unattractive in light of key sensor requirements such as minimization of power and onboard resources (CPU/Memory) and the number and processing power of anchors, maximization of robustness, maintainability, and ability to use ad hoc or random placement. See [2] for an excellent review.

The best localization schemes today use a combination of acoustic and radio information. Difference in arrival time of simultaneously-emitted radio and acoustic signals gives distance, and adding a small number of base stations allows triangulation. However, such methods require multiple base stations and high-frequency acoustic emitters and receivers which tend to be expensive in hardware and power usage [3]. Radio signal strength (RSS) is a method that should work in principal, but its usefulness has well-known problems that make it ineffective as a direct measure of distance: 1) signal strength can vary unpredictably at the source, 2) multipath reflections can create spurious signals, and 3) signal strength differences are difficult to detect at very close range.

This report describes a method for sensor localization and signal enhancement based on a biological algorithm for processing signal strength. It uses a simple RSS-based preprocessor at each sensor and lightweight statistical inference at a base station. It is also potentially robust to source variability and multipath ambiguities.

2. Biological Signal Processing

Biological systems have evolved to deal with the problem of identifying and locating the source of sensory input. For example, human vision is capable of detecting spatial offsets of as small as 1.2 arcsec [1], despite the fact that light waves arrive at the retina from a variety of angles, some reflected and some direct, and that neural tissue (receptor axons) passes between the incident light and the photo-sensitive regions of the receptors, which point backwards at the retinal surface instead of outward toward the incident light [4]. Signal processing in biological systems proceeds in three main stages: At the periphery, receptors and closely-associated neurons filter noise and boost the informative aspects of the signal. Then the signal is sent into the brain where it may be filtered or aggregated with other signals so as to detect primitive features. The filtered/aggregated signal then goes to a probabilistic classifier that determines if the signal indicates the presence of an external object, and if so, indicates the object's most likely identity and location.

3. Lateral Inhibition

Chief among the peripheral biological mechanisms is lateral inhibition. Every receptor has an excitatory response to the target it is designed to detect, and an inhibitory response to signals from other receptors. The influence of neighboring receptors declines as a function of distance, so nearby sensors have stronger interactions than distant ones. Figure 1 shows the spatial response profile of an individual sensor, which is well characterized by a Difference of Gaussians filter. A target (e.g., beam of light) hitting the sensor directly causes a large positive response, but a target shifted slightly to right or left causes a negative response. This has the effect of sharpening boundaries between target and non-target signals.

Lateral inhibition is particularly powerful when it operates over a large area or array of sensors, because the pooling effect of many sensors outputs tends to stabilize the overall output of the system, and minimize ambiguities that might arise in a single sensor due to noise, source variability, or multiple signal paths.

![Figure 1. Sensor response profile with lateral inhibition.](image)
4. Simulations in Java™

This idea has been implemented in a Java™ application. It uses lateral inhibition over a regular or randomly-jittered array of sensors (4, 8, 12, or 16 square). Figure 2 shows a 12x12 regular array and Figure 3 shows one of many possible 12x12 random arrays. The irregular version starts with the regular array then perturbs each sensor's x,y coordinates by a randomly-chosen amount. The control panel on left provides controls on signal intensity, spacing, and other parameters.

Figure 2. Java™ simulation: Regular Sensor Array.

Figure 3. Java™ simulation: Irregular Sensor Array.

4.1 Finding Edges and Corners

Localization using lateral inhibition uses one or more calibration runs in which sensors send signals one-at-a-time in a fixed or prearranged sequence. Each sensor sends a signal at a fixed strength, and each non-sending sensor listens and keeps a sum of the signal strengths received from all other sensors over the course of the run. At the end of the run, each sensor sends the base station the sum of signal strengths received. The base station subtracts the received-signal total from each sensor's starting excitation level and (in this Java™ implementation) assigns a brightness value to the sensor based on the result. All sensors start with the same initial value, but after the calibration run, sensors in the center with many neighbors have received more inhibition than sensors near the outside, with fewer neighbors (Figures 4 and 5).

Figure 4. Regular array after calibration run. Darkened sensors are inhibited by surrounding neighbors.

Figure 5. Irregular array after calibration run. Darkened sensors are inhibited by surrounding neighbors.

Figure 6 shows the result of a simple statistical inference performed by the base station. An "edge" is defined as any sensor whose value falls between the array mean and 1 standard deviation above the mean. Edges are colored orange in the simulation. A "corner" is any sensor whose value is greater than 2 standard deviations above the mean. Corners are colored red in the simulation. The result is perfect for a regular array, and promising for an irregular one.

It should be noted that results depend on signal strength, with the best inference for the irregular array requiring a larger base signal strength than for a regular array.

4.2 Reflections & Interference

Radio signals in real environments suffer from reflection and interference, and it is important to understand how they impact localization by lateral inhibition. A simple reflection calculation, assuming a single reflective surface, is described here. During a calibration run, a receiver will receive two signals from each sender, one direct signal and one ghost signal by way of the reflective surface. The direct signal and ghost signals sum and subtract according to phase relationships that depend on the wavelength of the signal and the spacing of the sensors as follows:

\[ A = \frac{a_0^2}{r_s^2} + \frac{a_0^2}{r_g^2} + \frac{a_0^2}{r_s r_g} \cdot 2 \cos \left( \frac{2 \pi \Delta r}{\lambda} \right) \]

where \( A \) is the amplitude of a sender's signal measured at the receiver, \( a_0 \) is the amplitude of the signal at the sender, \( r_s \) and \( r_g \) are the distances, respectively, of sender and ghost from the receiver, \( \Delta r \) is \( r_s - r_g \), and \( \lambda \) is the wavelength of the signal.

Figure 7 shows the results for a single reflective surface positioned to the left of the green sensor array. Reflection sources are shown as gray "ghost" sensors with positions jittered randomly to represent irregularities in the reflective surface. This demonstration assumes a 2.4-ghz radio signal.
(wavelength = 12.5 cm or 4.9 inches), and shows the effects of reflective interference for three different inter-sensor spacings of 1 m, 12.5 cm (2.4-ghz wavelength), and 1 inch:

![Image](image1)

**Figure 7.** Reflective interference for three inter-sensor spacings: 1 meter (top), 12.5 cm (middle), and 1 inch (bottom).

Reflective interference has a disruptive effect for these array spacings, but the highly-simple inference used here retains a fair amount of accuracy. More sophisticated statistical methods (e.g., bayesian inference) would improve these results, especially in the more complicated situation of multiple reflective surfaces.

5. Calibration Scenarios

After the edges and corners have been identified, further calibration can find local neighborhoods using lateral inhibition in conjunction with a source of sensor stimulation. The source can be a target object that stimulates the array in a prearranged fashion, or a signal from the base station telling a particular sensor to send out a strong signal.

Target Fly-Over Method: Suppose that an airplane drops a number of sensors at a remote desert location and before returning to base it flies a stereotyped pattern over the sensor array, sweeping a collimated light beam over the array. As the light is detected by successive clumps or lines of sensors, they send signal spikes and simultaneously inhibit their neighbors. Figure 8 shows the target as a blue vertically-oriented rectangle. Sensors under the target are given extra stimulation, and as a result they inhibit their immediate neighbors (e.g., sensor response function shown in Figure1). The resulting contrast is easily detected by the base station. Assuming the airplane is flying a known path, then the base station can use the direction and speed of the light path to determine geo-spatial directions and thus orient the array correctly in real space.

![Image](image2)

**Figure 8.** Target fly-over for array calibration. Target is blue rectangle. Sensors under target are bright while neighboring sensors are dark.

Strong Signal Method: The base station sends a strong signal to individual sensors, in sequence. The target sensor lights up and sensors around it go dark. This defines a neighborhood. Combining this with knowledge of edges and corners, a relative map can be built. Figure 9 shows results for the regular and irregular arrays. While the results for the regular array are more visually impressive, statistical inference proved to be equally good with the irregular array.

![Image](image3)

**Figure 9.** Strong signal array calibration. Sensor receiving strong signal is bright while neighboring sensors are dark.

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References


