Applied Acoustics 129 (2018) 92–103

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Improving accuracy of elephant localization using sound probes

Chinthaka M. Dissanayake [a,*], Ramamohanarao Kotagiri [b], Malka N. Halgamuge [c], Bill Moran [d]

[a] Department of Infrastructure Engineering, The University of Melbourne, VIC 3010, Australia
[b] Department of Computer Science and Software Engineering, The University of Melbourne, VIC 3010, Australia
[c] Department of Electrical and Electronic Engineering, The University of Melbourne, VIC 3010, Australia
[d] School of Electrical and Computer Engineering, RMIT University, VIC 3000, Australia

ARTICLE INFO

Article history:
Received 5 June 2017
Accepted 11 July 2017
Available online 24 July 2017

Keywords:
TDOA estimation
Elephant localization
Sound speed estimation
Vocalization detection

ABSTRACT

Localization of elephants in the vicinity of villages is an important issue in mitigating human-elephant conflict. This paper proposes an inexpensive, effective and non-invasive framework that employs a sound probe technique with an acoustic sensor network to localize elephants. Incorporation of probes in our sensor network eliminates the requirement to explicitly measure temperature and wind velocity for accurate determination of sound velocity. A sensor network has been built and experiments performed by replaying recorded elephant sounds under three different environmental conditions. The results overall show that the system is capable of providing remarkable accuracy under distinct wind and temperature conditions. An identical experimental set up was used to localize wild elephants in Sri Lanka. Our approach enabled localization of wild elephants at a distance of over 500 m from the sensors to within 30 m, providing adequate time for the villages to take appropriate safety measures.

1. Introduction

Changes in social and ecological conditions precipitated by human needs are resulting in serious depletions in certain animal populations. Human-elephant conflict (HEC) is one such problem resulting in deaths of members of both species. Humans are clearing large areas of land for food production, increasing pressure on traditional elephant habitats. This results in migration of elephants to villages to fulfil their food requirements and ensuing HEC. In Sri Lanka, HEC has is causing more than 60 human deaths and over 200 killings of elephants, annually [1].

Various strategies have been implemented to mitigate HEC. These include implementing electric fencing systems and using satellite imaging and radio and Global Positioning Systems (GPS) collars to detect the presence of elephants [2].

Electrified wire fences are used to restrain elephants into the forest areas. This is an expensive option due to high installation and maintenance cost. In practice, the long-term success with anti-elephant fences has often fallen well below expectation. This is basically because of deficiencies in meeting the considerable demands of meticulous routine maintenance. In addition, wild elephants have low resistance to these barriers as they have learned to demolish the fences using tree branches and thereby enter into the protected areas [3].

Tagging elephants with radio and GPS collars for understanding the behavioural aspects is presently conducted in many parts of the world. However, this methodology is impractical for real-time monitoring of wild elephants due to the battery power limitations in collar systems and the cost of GPS data retrieval. In addition, capturing elephants and fitting GPS collars to these animals is a complex and dangerous procedure which risks lives of both elephants and personals involved. Therefore, it is in practice even impossible to collar elephants which are deemed problematic.

With the advancements in technology, satellite imaging is also proposed as a methodology for tracking wildlife [4]. However, thick vegetation and environmental factors hinder this sophisticated and expensive technology for real-time monitoring of wild elephants.

Recently, interest has grown in the detection of elephants through their low-frequency calls, commonly referred to as "rumbles" [5]. This technique is a safe, practical and non-intrusive methodology to detect these highly social animals that use rumbles for long distance communication. Once the elephants are detected at a sufficient distance from the village boundaries countermeasures such as the use of firecrackers, broadcasting of noise through loudspeakers, and warnings to the local population can be deployed.

* Corresponding author.
E-mail address: c.dissanayake@pgrad.unimelb.edu.au (C.M. Dissanayake).

http://dx.doi.org/10.1016/j.apacoust.2017.07.007
0003-682X/

However, the variations in environmental conditions seriously affect the performance of such systems [6,7]. This is due to the sound speed dependency on several environmental phenomena such as temperature, water vapour mole fraction, atmospheric pressure and CO_2 content in the air. Cramer [8] has proposed a closed form equation for the relationship between speed of sound and the above environmental factors through a laboratory experiment. However, the speed of sound mainly depends on temperature and effects of other variables are insignificant. The speed of sound in air can be expressed in terms of temperature as $C_{Sound_T} = C_{Sound_0}\sqrt{\left(1+\frac{T}{273.15}\right)}$ where $C_{Sound_0} = 331.45\ \text{ms}^{-1}$ is sound speed at 0 °C [9]. In addition, wind causes to movement of the propagation medium which effectively alters the propagation sound speed between sound source and the receivers [10].

In [6] the possibility of using an acoustic sensor network to detect and localize elephants has been extensively analysed. Wind and temperature variations are identified as the main cause for the deterioration of the performance of the above approach [6,7]. For instance, a uniform wind velocity of $20\ \text{ms}^{-1}$ results in about a 100 m (20%) error at a distance of 500 m. An additional temperature variation of 4 °C can result in an increase in the error to over 175 m (35%) [6].

In this paper we propose a technique to correct the errors arising from variations in sound speeds due to environmental effects. We propose a system to implement the algorithms that have been developed and describe the results of experiments, under three different environmental profiles, using a sensor network system that we designed. Then, we implement our system in a village area in Sri Lanka and test it for the real application of wild elephant monitoring. Our contribution is to present an effective solution that significantly improves localization accuracy over a conventional acoustic sensor network, and which does not require explicit wind and temperature sensors to compensate for the environmental effects on sound speed.

The remainder of the paper is organized as follows. In Section 2 we summarize the localization algorithm that will be utilized in our proposed system. In Section 3 the technique used to correct the speed of sound to mitigate temperature and wind velocity effects is described in detail. In Section 4 we describe the corresponding experimental setup for tests we conducted in open field and forest environment. Section 5 outlines the experimental results and discusses them further. Section 6 concludes the paper.

2. Localization algorithm

We consider an acoustic sensor network with N sensors that listen to elephant vocalizations. In consideration of the long propagation range of infrasonic rumble signals [11], it is assumed that all sensors receive an attenuated and noise corrupted replica of a call generated by an elephant (source). Let the time of arrival measurements at sensor S_i be t_i where $i = 0, 1, \cdots, N-1$. The infrasonic acoustic sensors are deployed at predetermined coordinates (x_i, y_i). It is necessary to locate the source position (x_s, y_s). The arrival time measurements at sensor S_i can be modeled by $t_i = T_0 + R_i/c_i + \epsilon_i$ where T_0 is the signal emitted time by the source, R_i is the distance between source and the ith sensor, c_i is the sound propagation speed and ϵ_i is the normally distributed measurement noise with zero mean and σ^2 variance. It should be noted that the c_i between the source and each sensor could vary because of environmental effects such as wind and the temperature. The distance from source to ith sensor R_i is given by $R_i = \sqrt{(x_s - x_i)^2 + (y_s - y_i)^2}$. The time T_0 of signal emission is unknown, and so it is appropriate to perform a time-difference-of-arrival (TDOA) estimation. TDOA information is obtained by performing pair-wise cross-correlations between the observation sound signals at each sensor pair. TDOA measurement between the pth and qth sensors denoted by Δt_{pq} is given by $\Delta t_{pq} = t_p - t_q + \epsilon_{pq} = R_p/c_p - R_q/c_q + \epsilon_{pq}$, where $p = 0, 1, \ldots, N-2$ and $q = p+1, p+2, \ldots, N-1$, $\epsilon_{pq} = \epsilon_p - \epsilon_q$ (see Fig. 1).

Let the measured TDOA ranges be

$$\mathbf{m} = [m_{2,1} \quad m_{3,1} \quad \cdots \quad m_{n,1}]^T = \mathbf{d} + \boldsymbol{\epsilon}$$

where

$$\mathbf{d}(\theta) = [r_{2,1} \quad r_{3,1} \quad \cdots \quad r_{n,1}]$$

and $r_{p,q} = R_p - R_q$. The probability density function [12] of $\mathbf{m}$ given θ is

$$f(\mathbf{m}/\theta) = 2\pi^{-n/2}(\det \mathbf{Q})^{-1/2}\exp\{-J/2\}$$

where

$$J = [\mathbf{m} - \mathbf{r}(\theta)]^T \mathbf{Q}^{-1}[\mathbf{m} - \mathbf{r}(\theta)].$$

The Maximum Likelihood Estimate (MLE) is the $\theta(x_s, y_s)$ that minimizes J. This can be reduced to minimizing the non-linear least square problem [13] of

$$f(x_s, y_s) = \arg\min_{x_s, y_s} \sum_{p,q} (h_{pq} - g_{pq})^2. \tag{1}$$

where $h_{pq} = c \times \Delta t_{pq}$ and $g_{pq} = R_p - R_q$.

The solution to (1) gives the unknown source location. However, to locate the source accurately the above system needs the correct sound propagation speeds between the source and each sensor, which is affected by wind and temperature variations. Our approach to estimate sound speed with mitigated temperature and wind velocity effects is presented in the next section.

3. Average sound speed estimation methodology

Our goal is to estimate the approximate speed of sound that signals propagate with respect to each sensor. In order to build a solution that attains the above sound speeds in a real world environmental scenario we first develop a model assuming uniform environmental conditions. Then the model is extended to real world comparable, non uniform and totally unknown environmental conditions.

To locate the elephants accurately, acoustic sensors and some specific sound (chirp) signal generators are deployed at predetermined location coordinates. These sound generators are referred to as “probes” in the remainder of the paper. The chirp signal generation time schedule is predefined and known to both devices. Therefore, by listening to the signal, each sensor can determine the time of flight (TOF) from probes to the sensor. Then, the approximate speed of sound between the source and the sensors is estimated in two different models as presented below.

Model A: *The temperature over the area is assumed to be uniform but unknown. The wind speed and the direction over the area are assumed to be uniform but unknown.*

Here we estimate the wind information and the uniform temperature over the area completely depending on the probe technique without incorporating additional sensors. Consider that the ith sensor (S_i) receives the signal from the probes P_l, P_m, P_n as depicted in Model A in the Fig. 2. The temperature affected speed of sound between S_i and P_z is $V_{P_zS_i}(T)$ where $z = l, m, n$, and, so the measured speed of sound $V_{P_zS_i}$ between S_i and P_z is given by