Directed Audio Warning System for Reduction of Bus-Pedestrian Collisions

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Abstract

Collisions between buses and pedestrians often occur at intersections. These collisions are increasing as more pedestrians are distracted by their mobile devices, and bus drivers continue to be impeded by their blind corner. We propose a bus-pedestrian warning system that utilizes directed audio technology as a solution to this problem.

Many recent audiovisual warning systems have been successful at reducing collisions to some degree, but continue to face challenges in detecting pedestrians and emitting a targeted warning. Our paper outlines a novel directed audio warning system that is targeted, easy to install, and not disruptive of the surroundings. We discuss the design of an ultrasonic transducer array as a speaker that can emit an audible warning in a narrow beam. The warning can also be aimed electronically, without the need for moving parts.

Keywords: Bus pedestrian warning system, intersection safety, directed audio, parametric array, phased array.

Introduction

Collisions between buses and pedestrians continue to be a significant issue for transit operators and pedestrians today. These accidents often occur at the point in a city where pedestrians and vehicles most frequently crisscross – at crosswalks and intersections. In particular, these accidents occur the most when a transit bus makes a turn into a busy crosswalk. Unfortunately, these accidents often result in injury and sometimes death, leaving transit agencies to deal with the tragic and sometimes expensive consequences.

These collisions only stand to increase in frequency, as increasing numbers of pedestrians choose to block off their surroundings with such devices as headphones, smartphones, and other electronic devices (1). This decrease in awareness of surroundings, particularly at a dense urban intersection, serves to magnify the likelihood that distracted pedestrians fail to notice a turning bus in their way.

In our increasingly litigious environment, the consequences of such incidents have become much more significant, as growing numbers of injured pedestrians choose to engage in a legal battle for compensation. The Southeastern Pennsylvania Transportation Authority (SEPTA), primary transit operator for Philadelphia and the fifth largest transit provider in the United States, estimates that over $40 million per year is spent on legal fees and compensatory awards directly stemming from bus-pedestrian collision instances (2). Thus, greater financial obligations from increasing numbers of bus-pedestrian collisions, though secondary in importance to the critical issue of pedestrian injury and life loss, impact the bottom lines of SEPTA and other cash-strapped transit agencies – making critical the development of any system or method that can reduce these collisions, saving lives and money in the process.

Various bus transit operators have designed solutions that have reduced the number of bus-pedestrian collisions to some extent. However, our analysis shows that there are large areas for improvement in all the existing solutions, especially in detecting the pedestrian and emitting a warning signal. We propose a solution utilizing directed audio technology that makes significant improvements in these two aspects.

Case Studies of Existing Solutions

We first analyze two existing solutions and determine its strengths and weaknesses, and challenges for our research to focus on.

Cleveland Regional Transit Authority

The Greater Cleveland Regional Transit Authority (RTA) is the primary transit operator in the Cleveland metropolitan area. In 2009, safety protocols had to be re-examined after two fatal pedestrian collisions that occurred when a bus turned at an intersection. Following an internal investigation, RTA decided to implement a number of pilot measures to mitigate the consequences of driver and pedestrian inattention, to varying degrees of success.

RTA first required bus drivers to honk their horn when making a turn. When that proved to be ineffective, it tried to automate the warning by activating it on turn signals. Both strategies had unanticipated consequences, as noise complaints increased dramatically in the following weeks and studies showed a reduction in the use of horns and turn signals (3).

Following the second failure, RTA began the implementation of an audiovisual warning system. As part of their pilot program, 400 transit buses (approximately 83% of the fleet) were retrofitted with a turn detection sensor, wired to the steering column of the transit bus. Upon detection of a turn, the system activated a pre-recorded warning that emanated from the exterior of the bus and warned both the driver as well as pedestrians (4).

This third system ultimately became very successful, eliminating pedestrian fatalities from bus collisions since its installation. It is currently being tested with New York's MTA (5). However, at a price of $600,000, the technology used is costly, making adoption a potentially difficult choice for many agencies (4). Additionally, noise pollution by this system continues to be an issue, as the warning is still broadcast in all directions from the bus into the surrounding environment.

Portland TriMet

TriMet is the primary transit provider for the Greater Portland metropolitan region. In 2011, TriMet decided to take the initative to reduce bus-pedestrian accidents by implementing an automated pedestrian warning system. This system also employed an audio warning that was activated by a rotation of the steering column of the bus.

Upon actualization of the pilot, however, the system proved unreliable and difficult to calibrate. The system would often deliver warnings too early, too late, or in the wrong scenario, such as when a bus was turning lanes. As a result of protracted difficulties, development was placed on hold (6).

As of 2014, TriMet has begun another program that seeks to improve on the failures of the original system. This new program utilizes a combination of audiovisual warnings on the moving buses and fixed locations. Development is in conjunction with the Federal Transit Administration and is ongoing (7).

Case Study Summary

The eagerness of public transit operators to develop an effective warning system is evident in the previous case studies. However, there are significant problems to the current systems that we are working to overcome in our proposed solution. The problems are as follows:

1. High costs. The cost of installation is at a price point beyond the reach of many cash-strapped transit agencies.
2. Complexity. These systems required complex retrofitting of the bus in order for successful installation, making changes difficult and increasing maintenance costs.
3. Lack of community support. Residents have complained about the additional beeping and warnings in cities already saturated with noise.

Our Proposed Solution

We propose a solution that makes significant improvements to the challenges highlighted above. In the following sections, we discuss a pedestrian warning system that is inexpensive, reliable, and non-disruptive to the surrounding environment. The important parts of the system are explained below:

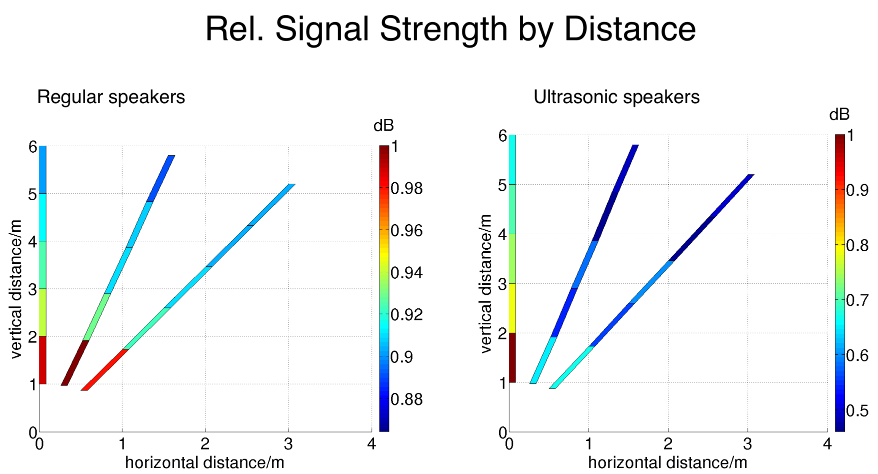
<u>Directed Audio</u>

We want to achieve a high directivity of sound, so that we can emit a targeted audio warning toward pedestrians without noisily disrupting the surroundings. A narrow beam of sound also has a startling effect on its target as compared to a regular, widely dispersing audio signal.

It is not feasible to achieve a high directivity if the warning is transmitted purely in the audible frequency domain (20 Hz – 20 kHz). The directivity of a wave increases with its frequency and length of its source. The frequency of audible waves is considerably low. Thus a very large speaker is required to achieve a high directivity for audible signals.

We thus emit ultrasonic waves at a higher frequency of 40 kHz. The nonlinearity of air acts as a mathematical transform on the wave (8). We have verified that if we transmit a Pulse Width Modulated audible signal with a center frequency of 40 kHz, the nonlinearity of air acts as a low-pass filter, demodulating it back to the audible domain with minimal distortion. This reproduced audible signal is much more directed as it is "carried" by the high frequency ultrasonic wave.

The following plots illustrate the higher directivity of an ultrasonic speaker. We transmitted an audible signal through a regular speaker, and recorded the audible signal volume at various angles. The process was repeated with an ultrasonic speaker prototype we developed. The results show that the signal from ultrasonic speakers attenuates more rapidly at greater angles from normal. This proves its higher directionality.



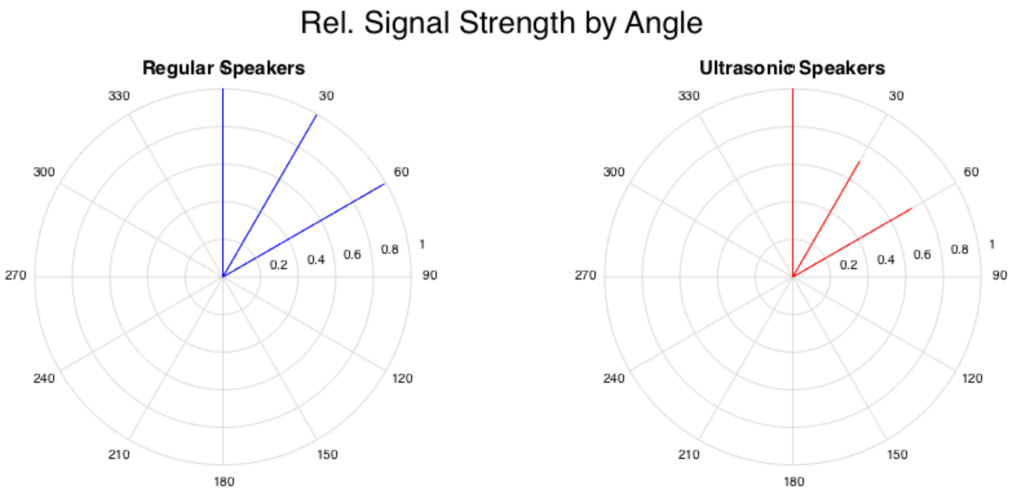
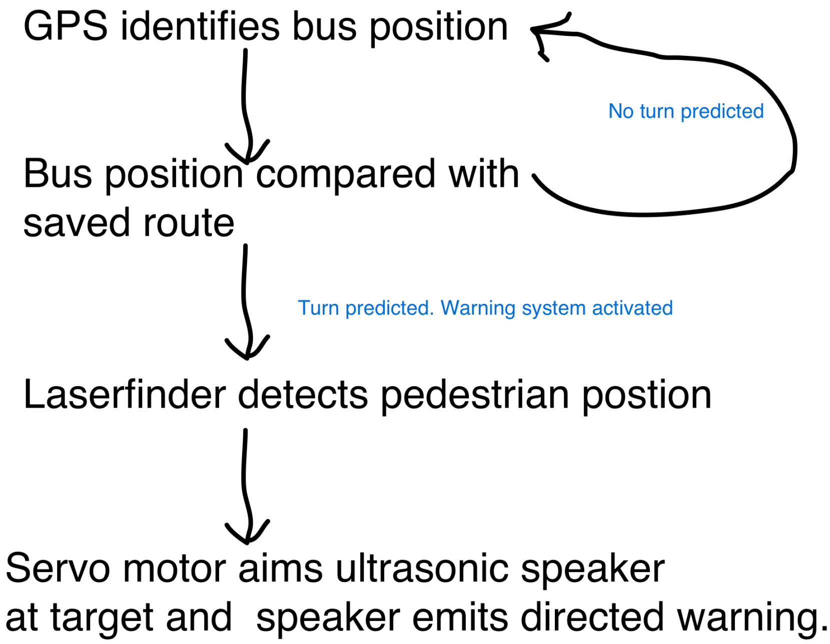


Figure 1: Comparison of relative signal strength at various angles for a regular speaker and an ultrasonic speaker

Current Architecture

Our team from the University of Pennsylvania proposes a pedestrian detection and warning system as follows:



Further description of each individual part discussed below:

Location Detection System

The location detection system determines when a turn will be made. Once this criterion is met, it sends a signal to activate the warning system.

The system is comprised of a global positioning system (GPS) and inertial motion unit (IMU) sensor. Both of these sensors provide information on the bus's location. GPS does so through the use of a global network of satellites, while IMU uses more local data gathered on the bus (e.g. the bus's direction and velocity). These onboard sensors feed their real-time data into an Unscented Kalman filter (UKF) to produce a filtered, weighted output that is more accurate in determining the bus location than either individual sensing system alone.

The output from this filter is compared with a defined bus route. If the system predicts that a turn will be made soon, it will send a signal to activate the warning system.

Warning System

The warning system is comprised of two components: a pedestrian detection component, and an array of ultrasonic transducers. The pedestrian detection component scans for pedestrians in potential danger, and forwards the location and coordinate data of the target to the ultrasonic array, such that the array is pointed directly at the target location in time to deliver an appropriate warning.

Pedestrian Detection

The current pedestrian detection setup we are using involves a Hokuyo laser scanner. The scanner pings across 270° field of vision to detect obstacles at up to 30 meters away. When such an obstacle enters the field of detection, the sensor registers the direction and coordinates of the obstacle and forwards this data to the warning system.

Ultrasonic Transducer Array

This array takes advantage of non-linearities in the air medium to produce an audible warning from an ultrasonic output. The array itself is comprised of a number of rows of ultrasonic transducers. When a specific ultrasonic waveform is fed to this transducer array, the output result is a directed beam of audible sound.

The array is mounted on a servo-equipped axis, such that movement can be achieved in all directions, thus steering the beam. The warning system takes directional input from the pedestrian detection rangefinder, and then utilizes the servos to steer the array in the appropriate direction.

Benefits

The advantages of our system are threefold. First, we utilize standard, off-the-shelf components with a target cost of $500 or less, which is many times less expensive than the systems utilized by the transit agencies in the aforementioned case studies. Second, our system is easily retrofitted onto existing buses, without the need for complex disassembly of portions of the bus. Third, our system minimizes noise pollution in the urban environment by targeting and delivering audible noise only to targeted locations while minimizing noise output elsewhere.

Areas for Improvement

The following section outlines a number of concerns that we hold regarding the current iteration of our system.

Moving Parts

As mentioned previously, the directionality of our array comes from the directed nature of the audio beam as well as the servo system that will mechanically steer this beam. However, transit buses are exposed to many extremes, such as low temperature and mechanical vibration, as they navigate an urban environment. We must consider the additional risk of unreliability if we are to implement a system that contains various moving parts to accurately pinpoint a relatively small target.

Single Target

Perhaps the biggest drawback of our system in its current iteration is its sequential nature of targeting; due to the mechanical nature of the servo configuration, only one target can be pointed to at any given time. This is a cause for concern, particularly at busy intersections where there may be multiple targets that require a directed warning at the same time.

Sensing of the Target

The current setup of the pedestrian detection system utilizes a Hokuyo laser scanner, a component, which by itself exceeds our target goal for overall system cost. An improved, more cost-effective system must be found if we are to create a product that is within the reservation price of transit agencies. Additionally, the laser rangefinder provides fast, but primitive data about its surroundings. The only characteristic that the laser rangefinder can determine is the actual position of the target object relative to the rangefinder itself; it offers no additional information regarding object type, which could be a potential hindrance to identifying only targets that actually require a warning.

Current Research: Phased Array Ultrasonic Speakers

In our current speaker system, a sensor detects the position of a target person, and a motor swivels our directed speaker to face the target. To eliminate moving parts in our system, we are working to implement a phased array speaker, which would steer sound electronically.

A phased array speaker consists of an array of sound sources, with each consecutive element delayed increasingly. The effect of the constructive and destructive interference of sound would result in a maximum sound peaks at an angle from normal.

Consider the following simple illustration with just 2 sound sources. When the 2 sources have a uniform phase, the maximum is found right in its center. If the source on the right is delayed however, the wavelet peak from the left source travels further and meets a peak from the right source to right of the center.

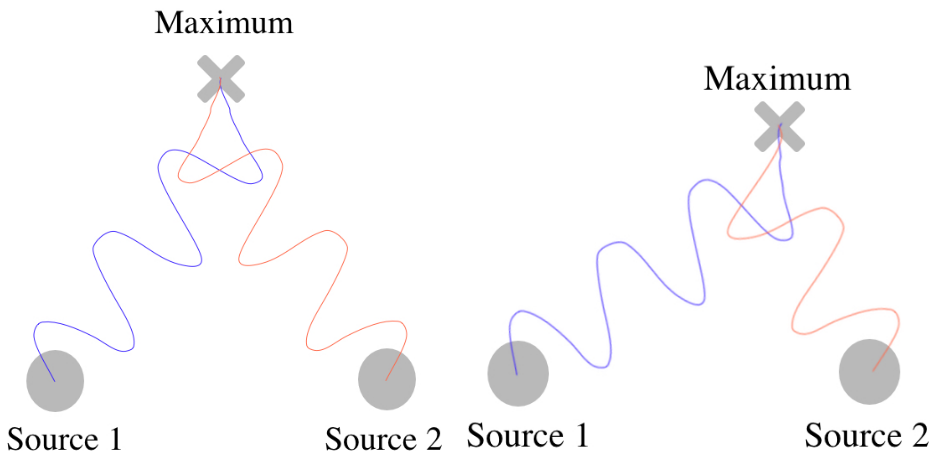


Figure 2: Position of maximum with uniform-phase sources and out-of-phase sources.

We employ this principle to steer the beam in our directional speaker. We have not collected actual data from the hardware implementation, but we simulated a MATLAB model of the sound output to test its feasibility.

The following model results are based on an actual board configuration with 10 separate sound columns. The dimensions of the board are based on physical transducer sizes. The separation between transducer elements was reduced as much as possible to eliminate side grating lobes. Theoretically, based on the formula $\sin(\theta) = \frac{\lambda}{d}$, where θ is the angle between normal and line to the second maximum, and *d* is the separation between sound sources, if $d < \lambda$ then the grating lobes would be eliminated. The wavelength of an ultrasonic 40 kHz wave in air is about 8.5 mm. A limitation in the physical layout is the transducer diameter, which was 16.2 mm. We thus arranged the board such that the spacing between each speaker column is approximately half a transducer length:

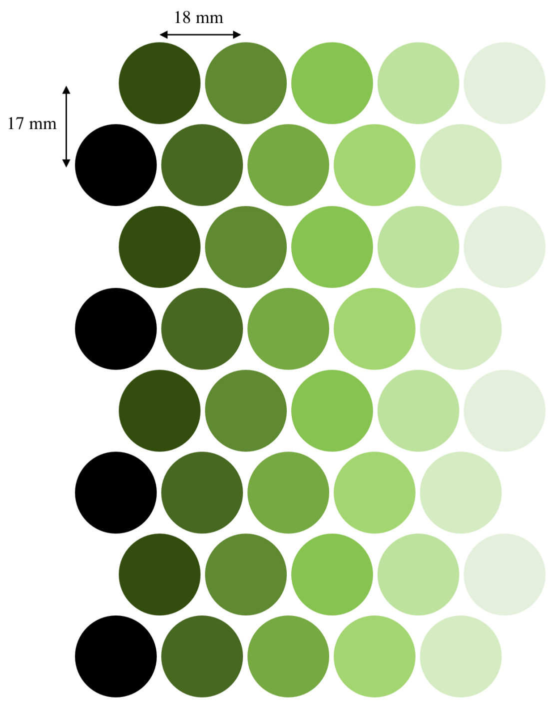


Figure 3: Transducer spacing for phased array speaker. Speakers with uniform phase are the colored uniformly.

During simulation, a fundamental phase difference ϕ was chosen. Then *n*th speaker column was delay by a phase of $n\phi$. The results can be summarized in the following diagrams:

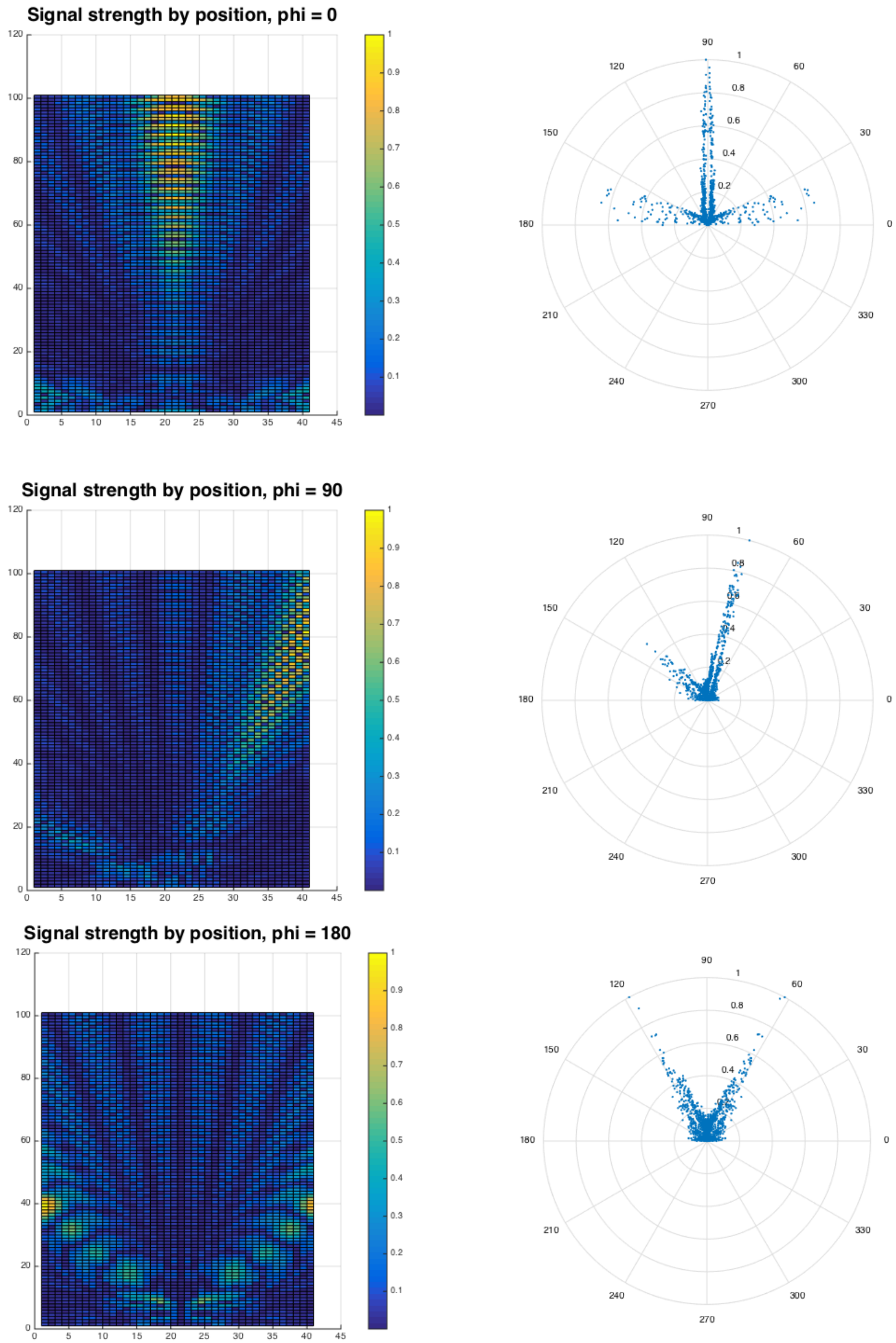


Figure 4: Beam directing with different phase delay angles

When the phase was increased further between 180° and 360°, the beam was steered left between 90° and 120° from horizontal. This simulation shows that by principle, with a realistic board dimensions, a beam of sound that can be steered with a 120° range. This has great potential to be used on the directed speaker installed on buses.

Collaboration between the University of Pennsylvania and Protran Technology

A recent partnership has allowed us to pursue a new direction with our pedestrian warning system. The research team at the University of Pennsylvania is working with Protran Technology, a transit safety company that specializes in pedestrian bus warning systems. We want to produce a hybrid product that incorporates the directed audio beam technology with Protran's existing turn-activated warning system.

This collaboration is significant in many ways. First, it will integrate research in directed audio technology into an existing commercial system, allowing us to save development time and overhead. At the time of writing, we have already made plans with to incorporate our prototypes into an upcoming pilot test with buses from SEPTA, which are being fit with Protran's Safe Turn Alert system (9). Thus, we will be able to quickly test our prototype in real-world conditions and make changes as necessary on a much quicker schedule than would otherwise have been possible.

Second, this hybrid combination successfully addresses the flaws of previous systems. The integration of our directed audio beam will allow for minimal noise disruption to the urban environment, an important accomplishment that addresses the needs of community stakeholders. Additionally, the incorporation of our system will allow for lower unit costs, higher reliability, and a lower complexity than was previously possible with either of the two standalone systems.

Conclusion and Future Work

Our overarching goal was to design a warning system that would reduce bus-pedestrian collision in a way that is effective, targeted and robust. The various experiments, simulation and prototyping we have done with the ultrasonic directional speaker provide a promising solution.

The prototype speaker we produced is low-cost. It consists of electronics and hardware that are cheap and readily available. The audible sound that is reproduced is also clear enough that a transmitted speech signal is discernible by a listener.

Current work is being focused on developing the phased array speaker. This would make the beam directing more precise as moving parts are eliminated. Much work is being put into signal processing that will split a signal and delay it consecutively. This phase would also need to change as a function of time, so that the beam is focused on a target as the bus turns.

For future work, we could develop a cheaper and more accurate person detector. Our current sensor is a laser rangefinder, which is expensive and gives false positives when any thin and tall object is detected. One possible solution would be computer vision. We could use a standard 2-D camera and then employ facial recognition or depth calculation algorithms to identify a pedestrian in the way of a bus. These algorithms would involve high-speed comparison of picture frames to detect the person. The interesting challenge would be to perform all this in on a lightweight system that is robust and installable on buses.

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