

An Application of Parametric Speaker Technology to Bus-Pedestrian Collision Warning*

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Abstract—The purpose of this research is to address the problem of frequent bus-pedestrian accidents in dense urban areas through the creation of an intelligent pedestrian warning system. Our proposed system uses visual detection and parametric speaker technologies to provide a concise, focused beam of sound that reaches only a focused target while minimizing the amount of disruption and disturbance to neighboring areas. We believe that this solution will provide a minimally invasive, cost-effective method for reducing bus-pedestrian collisions and substantially reducing the loss of life and property. In this paper, we first present a review and analysis of the relevant technologies and current implementations. Then, we provide a detailed overview of the system that we have developed, and discuss our tests and data collected. Finally, we conclude with a brief discussion of future engineering and cost considerations for implementation of this system in a practical setting.

I. INTRODUCTION

Fatal bus and pedestrian collisions have been a continual headache for transit operators and agencies over many decades. As reported by many transit agencies, most of these accidents happen while buses are turning at dense urban intersections – precisely the type of intersection where vigilance and attention to one’s surroundings is absolutely critical [1]. Additionally, collisions have become increasingly common between buses and pedestrians, as more and more pedestrians engage in “distracted walking” while crossing streets – in other words, walking while occupied with earphones, smartphones, and other electronic devices [2].

In our increasingly litigious world, such collisions have become far more of a liability for transit operators, as growing numbers of pedestrians that have been injured choose to file suit. For instance, it is estimated [3] that such claims cost the Southeastern Pennsylvania Transit Authority (SEPTA), the primary transit provider for the Philadelphia metropolitan region, over \$40 million per year in compensation and legal fees. Thus, the financial losses from increased collisions, though secondary to the critical issue of pedestrian injury and life loss, are nonetheless growing in importance to SEPTA and other cash-strapped agencies – making critical the development of a system which can prevent such accidents from

occurring.

II. LITERATURE REVIEW

This project is not the first to propose a pedestrian warning system triggered by the turning of buses. Commercial systems are generally available (see for example [4], [5], [6], as well as [7] for an overview) and generally involve modifying the steering column of the bus in order to trigger a warning during a turn. The warning is delivered to the bus driver, the pedestrians external to the bus, or both. However, the external warnings are not directional – in some cases they may simply be the vehicle’s horn. Since the system is unaware of a vulnerable pedestrian’s exact position, or even whether there is a pedestrian in the path of the bus, the only choice is to broadcast a warning loud enough to cover the entire area around the bus (see section II-D). At busy intersections, loud warnings may come from several directions at once, confusing pedestrians (as well as drivers). Pedestrians could become desensitized to the constant noise, or attend to irrelevant alarms while missing an actual imminent collision – both highly undesirable outcomes for a system designed to prevent collisions. Clearly, it is necessary to design a system that effectively grabs the attention of only the pedestrians in danger of a collision, so a wide-area notification is not ideal. One method for targeting the notification is a directed speaker. Though there are other possible alerting technologies, which we must consider (especially in the case of pedestrians who are deaf or otherwise unresponsive to an audio-only warning), in the current paper we will focus on our proof of concept implementation using a directed audio speaker.

A. Case Study: Cleveland RTA

The Greater Cleveland Regional Transit Authority (RTA) is the primary provider of multimodal public transportation services to the Cleveland metropolitan area. Its reach spans an estimated population of over 1.5 million people, and its service sees over 1.6 million annual departures, with an average of 200,000 boardings on a typical weekday.

RTA is also a primary employer of the region, with over 2,000 employees collectively responsible for the management and application of a \$350 million annual budget towards regional transit needs [8]. The agency manages dozens of bus lines, heavy and light rail lines, a BRT line, and paratransit services in compliance with the Americans with Disabilities Act [9].

In 2009, the RTA was forced to re-examine safety protocols after two fatal pedestrian collisions that both occurred

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when a bus turned at an intersection. An external investigation determined the cause to be both operator and pedestrian inattention.

Following an internal audit, RTA quickly began the implementation of a number of pilot measures designed to reduce the chance of distraction.

The first pilot measure was a procedural fix that advised bus drivers to blow a horn when turning. The measure proved to be effective at keeping the attention of pedestrians and drivers, but had some unanticipated consequences. Complaints to the city increased significantly due to the increased noise pollution. Additionally, driver compliance with this procedural fix hovered below 60 percent [10].

The second pilot measure sought to reduce the human factor. Turn signals were connected to the backup alarm, resulting in a loud beep whenever turn signals were activated. The consequences of this solution were drastic and unanticipated – again, complaints to the city increased almost immediately, and drivers stopped using turn signals [11].

After the aforementioned failures, RTA then commenced with the implementation of an audio and visual warning system. The stated purpose of the system is to warn pedestrians when a bus is about to make a turn, and to warn bus operators to stay alert when turning at an intersection.

As a part of the pilot and implementation process, 400 transit buses (approximately 83% of RTA’s transit bus fleet) were retrofitted with a steering-column wired turn detection sensor that activates speakers on transit bus exteriors when a turn radius exceeding 45 degrees is detected. The total cost of the retrofit was approximately \$600,000, most of which was funded through existing federal stimulus money [12].

Upon activation (through realization of the turning radius), the system’s speakers (located on the interior and exterior of the bus) play a pre-recorded message that warns pedestrians to be alert for the bus as it turns. The alert also serves to keep the driver more alert as he or she makes the turn [13].

By some indications, the Cleveland RTA warning system has been a success. However, at a price of \$600,000, the technology may remain out of reach to more sparsely funded transit agencies. Additionally, the use of the steering column as the sensing input complicates installation and maintenance, both of which require a disassembly of the steering column [12].

In the context of this paper, the RTA system differs from our design in the degree of integration with the vehicle, as well as the warning delivery mechanism. Our chief innovation is the use of a directed speaker so as to avoid the noise complaints and confusion that arose in Cleveland.

B. Case Study: Portland TriMet

The Tri-County Metropolitan Transportation District of Oregon, more commonly known as TriMet, is the primary transit provider for the Greater Portland metropolitan region in Oregon. The agency operates a mixture of buses, light-rail, and demand-responsive paratransit services, and in 2013 handled over 100 million trips [14].

In 2011, TriMet decided to take the initiative to reduce bus-pedestrian accidents due to distracted walking after the death of two pedestrians in a bus accident. Using Federal Transit Administration funding, TriMet began testing an automated pedestrian warning system that used both audio and visual cues to alert pedestrians to a turning bus. The pilot program called for the retrofitting of 10 buses across two routes that spanned various land uses, including commercial, residential, and industrial [15].

Additionally, TriMet considered three other possibilities to warn pedestrians of oncoming buses - audio only, visual only, and fixed-location warnings. The audio-only option involved the broadcasting of an audio warning when a bus operator made a turn. The visual-only warning system used the same activation criteria, but flashed an exterior light to warn pedestrians. The fixed-location warning involved the placement of a flashing “BUS” sign on the side of the street. In all cases (including the first), the bus operator had to rotate the steering wheel at least 45 degrees before the system would activate [7].

However, such systems proved to be unwieldy or unreliable for TriMet, resulting in the ending of the pilot demonstration [16]. Because of the complexity of the pilot approach (wiring a sensing system into a bus’s steering wheel), calibrating the warning deployment became an issue. The warning delivery had various timing issues – occasionally, the warning would be delivered too early, too late, or at the wrong time. The problem was twofold: the sensing would often detect turns too late, resulting in a shortening of the required degree of steering wheel rotation; however, reduction of the minimum turn angle would result in numerous false positives, which often occurred when a bus was changing lanes. As a result, the program was abandoned [16].

As of 2014, TriMet has commenced work on a new and improved version of the turning column safety system in conjunction with the Federal Transit Administration. Research and development is ongoing [7].

C. Parametric Speakers

There is a rich literature in the last several decades on directed audio systems, that is, the process of producing a collimated beam of sound analogous to a laser beam. In principle, this could be done with a phased array of regular speakers. However, the emitters in a phased array must be spaced at a distance comparable to the output frequency. In the context of a warning system, it is instructive to examine the frequencies of common siren systems, which are generally between 1-4 kHz to optimize for human hearing sensitivity and localizability [17]. Under normal conditions (speed of sound ≈ 343 m/s), this corresponds to a wavelength of 8.5-34cm, which is an impractical size for an array to be mounted on a moving vehicle.

However, there is a way out of this conundrum. Intuitively, a system which produces audible sound needs a speaker in the audible range. But this turns out not to be the case, due to the nonlinear nature of the sound propagation medium

(that is, air). Since air is a nonlinear medium, signals passing through are subject to non-frequency-preserving transformations, including sums and differences. Therefore, we can use a phased array at a higher frequency (ultrasonic), which allows a smaller array, and rely on the air itself to produce audible sound.

These ideas are discussed and demonstrated at length in Frank Pompei’s 2002 thesis [18].

D. Psychophysical Considerations

A successful collision warning system must grab the attention of a pedestrian against both the normal background noise of a city intersection (which varies based on location and time of day) as well as any activity that is engaging the pedestrian (i.e., causing him or her not to notice the oncoming bus). The pedestrian may be wearing headphones, in which case a stimulus must be much louder than the ambient noise, in fact by an unknown amount. For an easier case, consider a pedestrian who is visually distracted, for example by a smartphone. In this case, the warning merely needs to jolt the pedestrian enough to trigger an attempt to localize the source of the noise, which will be the bus. In some studies (e.g. [19]) typical car noise is approximated at 65 dB SPL, so the warning should at least be louder than that in order to be heard at an intersection. Our proof of concept does not currently achieve this level, but ongoing work is in enhancing the sound amplifier, and the next revision will be rated for higher power, which will enable sufficient sound volume.

III. SYSTEM ARCHITECTURE

Our proposed pedestrian detection and warning system is comprised of three portions - a sensing, processing, and warning component. Overall control of the system is coordinated using a pre-programmed microcontroller. Figure 1 shows a diagram providing a visual interpretation of the system.

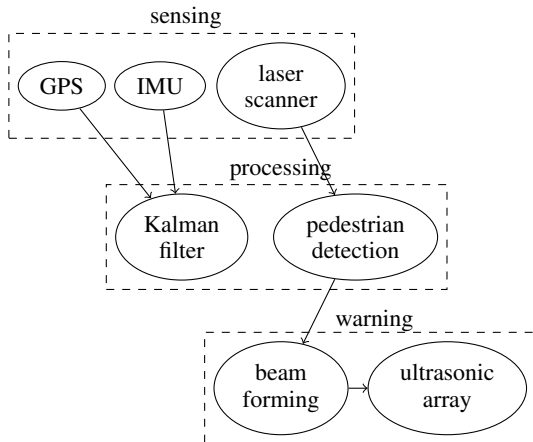


Fig. 1. System architecture diagram

A. Sensing and Processing

There are two primary sensing inputs to our system: detection of the bus’s location, and detection of pedestrians

in front of the bus during a turn. The following section details the hardware that is used to accomplish these tasks.

1) *Bus Location Detection:* In order to detect the location of the bus, the system gathers raw data from onboard GPS and IMU sensors.

The onboard sensors feed the data into a Unscented Kalman filter (UKF) to produce a filtered output. This process occurs in real-time, and continues for as long as the system is in operation. Kraft [20] describes a robust algorithm for tracking position in 3D space using multiple sensors.

The output from the Bus Location Detection component is compared with the defined bus route. It is assumed that the bus will follow its predetermined bus route for the duration of the system’s operation. If the comparison to this route reveals an impending turn (as suggested by the route), the Pedestrian Detection portion of the system will activate.

2) *Pedestrian Detection:* This portion of the system activates only after a turn is detected by the Bus Location Detection component. It currently utilizes a Hokuyo scanning rangefinder to detect objects up to 30 meters away within a 270 degree range of vision.

When an obstacle such as a pedestrian comes within range, the sensor registers the direction and distance of this obstacle and forwards this data to the processor. The processor then activates the warning system by passing on the distance and directional values reported by the rangefinder onto the warning system.

B. Warning Delivery

The warning system is comprised of an array of parametric speakers. As mentioned in a previous section, the array takes advantage of non-linearities in the air medium in order to produce an audible warning. The array itself is mounted on an axis that contains a number of servos, which allow for significant range of horizontal and vertical motion. The warning system takes the directional and distance inputs from the processor and activates the servos, which position the array to deliver localized sound at the approximate distance and in the appropriate direction of the detected obstacle.

Our array, fabricated on a custom printed circuit board (PCB), contains 198 ultrasonic emitters in a rectangular array (see Figure 2). They are all connected in parallel, broadcasting the same waveform. At a center emission frequency of 40 kHz, the large number of emitters in a small area has the effect of focusing the ultrasound into a cone much more directional than that of a normal speaker. (See section IV-A for data on the directionality achieved in our proof of concept.)

IV. EXPERIMENT

A. Range and Direction Testing.

The proof-of-concept directional speaker was compared with a commodity speaker system to test the range and directionality properties. While playing a test waveform (white noise), measurements of sound pressure level (SPL)

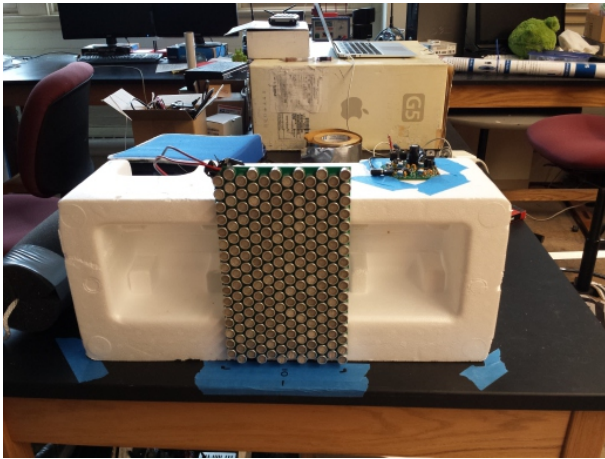


Fig. 2. Experimental setup with PCB array

were obtained at various points in front of the speakers. In Figure 3, the points are marked with the \times symbol.

Figure 4 shows the results. Three lines are plotted, showing the average sound pressure level as the measurement point moves away from the emitter. Clearly, the directional speaker is still audible from the side, but much less so, with 3 dB attenuation on average between 0° and 45° , and 5 dB attenuation between 0° and 90° . In an urban environment, background noise can wash out the attenuated sound and create the (useful) illusion of increased directionality.

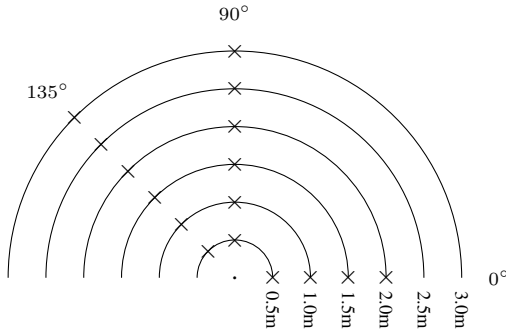


Fig. 3. Measurement points for directionality experiment.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have provided an overview of a novel pedestrian warning system designed to reduce the incidence of bus-pedestrian collisions at urban street corners. We compared our design with other approaches to the same problem, and demonstrated a proof of concept.

One of the goals of our system, which differentiates it from other approaches, is extreme low cost. Our cost target is \$500 or less per vehicle. To meet this objective, the major component which will need reworking is pedestrian detection. Laser rangefinders and scanners currently on the market are simply too expensive for practical use in a system like this one. Cheaper alternatives include sonar and cameras, but both alternatives have drawbacks. Sonar systems have

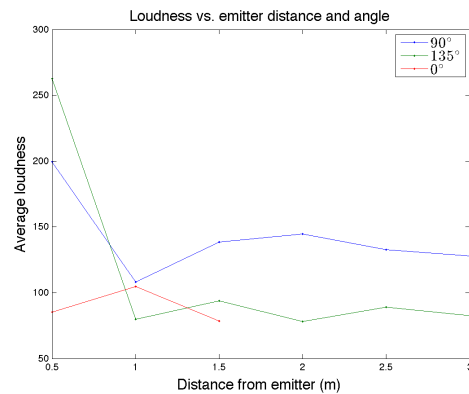


Fig. 4. Results of directionality experiment.

limited range and accuracy, and are prone to interference. On the other hand, computer vision presents its own set of challenges, and there may be public resistance to adding more cameras in public spaces. However, none of these objections are insurmountable – and because cost reduction is a primary concern, exploring these options will be a priority for this research going forward.

Another task for future work is system integration and hardening for use in the real world. Outside the lab, a practical device must be easy to install and maintain on a bus, without supervision by an attending team of researchers. Such a system would additionally need to demonstrate resilience to a wide array of environmental conditions, including rain, snow, wind, and jarring vibrations due to bus movement. SEPTA is a potential partner on this front as the development of our system moves forward. Our research team has been in communication with the SEPTA general management team, and we expect to roll out a pilot program in the near future that will see the installation of a number of prototype warning systems on a portion of the SEPTA bus fleet, allowing us to refine our system in a real-world setting.

Overcoming these challenges and improving the proof of concept to the point where it can be demonstrated on a real bus is the next target of our research program. With judicious use of these new technologies, we can reduce pedestrian casualties and make the city intersections safer places for everyone.

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REFERENCES

- [1] K. K. Pecheaux, J. Bauer, S. Miller, J. Rephlo, H. Saporta, S. Erickson, S. Knapp, and J. Quan, *TCRP Report 125*, 2008. [Online]. Available: http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt.125.pdf

- [2] D. C. Schwebel, D. Stavrinos, K. W. Byington, T. Davis, E. E. O'Neal, and D. de Jong, "Distraction and pedestrian safety: how talking on the phone, texting, and listening to music impact crossing the street." *Accident; analysis and prevention*, vol. 45, pp. 266–71, Mar. 2012. [Online]. Available: <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3266515&tool=pmcentrez&rendertype=abstract>
- [3] C. Karnash and O. Liebermann, "8 Charged With Faking Injuries After Minor SEPTA Accident In 2009," Oct. 2012. [Online]. Available: <http://philadelphia.cbslocal.com/2012/10/11/8-charged-with-faking-injuries-after-minor-septa-accident-in-2009/>
- [4] B. Electronics, "Sensing Danger." [Online]. Available: <http://brigade-electronics.com/product/ultrasonic-obstacle-detection/overview-uod>
- [5] ProTran Technology, "Safe Turn Alert Bulletin," 2014.
- [6] Clever Devices, "Clever Devices Pedestrian Warning System," 2014. [Online]. Available: <http://www.cleverdevices.com/pedestrian-warning.htm>
- [7] R. Altstadt, "Distracted walkers listen up and look up: Talking buses to begin running on five TriMet bus lines," 2014. [Online]. Available: <http://news.trimet.org/2014/03/pedestrians-listen-up-and-look-up-talking-buses-to-begin-running-on-five-trimet-bus-lines-the-week-of-march-3/>
- [8] Greater Cleveland Regional Transit Authority, "Annual Report for the Year 2013," 2013. [Online]. Available: http://data.axmag.com/data/201403/20140313/U115884_F269429/index.html
- [9] G. C. R. T. Authority, "About RTA," 2012. [Online]. Available: <http://www.riderta.com/about>
- [10] D. Sims, "RTA works to reduce left-turn accidents," 2009. [Online]. Available: <http://blog.cleveland.com/metro/2009/01/rta-works-to-reduce-leftturn-a.html>
- [11] D. Kramer, "That beeping and honking you hear is coming from RTA buses that are turning," 2009. [Online]. Available: <http://blog.cleveland.com/metro/2009/03/that-beeping-and-honking-you-a.html>
- [12] K. Farkas, "RTA to install an audible system on buses to warn pedestrians at crosswalks," Cleveland, OH, Oct. 2009. [Online]. Available: <http://blog.cleveland.com/metro/2009/10/rta-to-install-an-audible-syst.html>
- [13] G. C. R. T. Authority, "Implementing a Safety Management System: Eliminating Bus Collisions through Innovative Technology," 2012.
- [14] TriMet, "TriMet At-a-Glance," Tech. Rep., 2014.
- [15] —, "TriMet tests audible pedestrian warning system," 2011. [Online]. Available: <http://trimet.org/news/releases/mar1-audible-test.htm>
- [16] —, "TriMet halts test of audible pedestrian warning system," 2011. [Online]. Available: <http://trimet.org/news/releases/may27-ped-warning-canceled.htm>
- [17] R. A. De Lorenzo and M. A. Eilers, "Lights and Siren: A Review of Emergency Vehicle Warning Systems," *Annals of emergency medicine*, vol. 20, no. 12, pp. 1331–1335, 1991. [Online]. Available: <http://www.emergencydispatch.org/articles/warningsystems1.htm>
- [18] F. J. Pompei, "Sound From Ultrasound: The Parametric Array as an Audible Sound Source," Ph.D. dissertation, Massachusetts Institute of Technology, 2002.
- [19] H. Uchiyama, M. Unoki, and M. Akagi, "Improvement in Detectability of Alarm Signals in Noisy Environments by Utilizing Spatial Cues," *...of Signal Processing to Audio ...*, pp. 74–77, 2007. [Online]. Available: <http://ieeexplore.ieee.org/xpls/abs.all.jsp?arnumber=4393017>
- [20] E. Kraft, "A Quaternion-based Unscented Kalman Filter for Orientation Tracking," vol. 1, pp. 47–54.