Enabling Intentional Sound for Construction Cobots

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***Abstract*— As collaborative robots (cobots) enter the field of construction, successful multimodal communication will be essential to safe and effective human-robot cooperation. Auditory communication holds particular promise for successful interaction, but this topic in human-robot interaction is not well understood, and many robots lack the audio systems needed for this type of communication. We present exploratory work on audio system design and integration for the Husky robot. In these efforts, we designed, built, and tested an speaker system appropriate for equipping the Husky robot with audio communication capabilities suitable for construction environments. The prototype system uses 59 W to produce broadband sound at up to 107.9 dB measured 1 m from the robot, though the frequency response and sound pressure level vary depending on the recording location. Robot designers and researchers may benefit by implementing similar systems with additional consideration for speaker placement, power supply interfacing, and broadband sound alarms.**

Fig. 1: *Top Left:* a single speaker. *Bottom Left:* the prototype audio system, unmounted. *Right:* the prototype system mounted on the Husky robot. A 61 cm long measuring stick is included for scale.

I. Introduction

Collaborative robots (also known as cobots) are becoming increasingly common in industrial settings, and recent work aims to introduce cobots to the construction site [1]. These robots, which are often not bounded by a cage or otherwise separated from human coworkers, require strong multimodal communication abilities (e.g., audible sound cues, legible motion, and communicative lights) to safely and capably work alongside people [2]. The case for auditory communication is particularly salient; sound cues such as back-up warning alarms and horns are required by regulatory agencies for construction vehicles and machinery [3], [4]. Yet, robots intended for construction sites often lack speakers or other audio systems [5]–[7]. Thus, the work presented in this paper focuses specifically on enabling and beginning to evaluate the auditory communication needed by construction cobots.

Although gaining access to commercially available audio system components is relatively easy, identifying and satisfying specifications for auditory communication in a construction environment requires considerable effort. Producing sound that can be heard is challenging; the background sound typical of a construction site includes high levels of noise, contains variable peaks and frequencies, and takes place in different acoustic environments [8]. Prior work in alarm systems shows that our audio system may also need to challenge the norms of existing construction site sound. For example, [9] demonstrates that tonal sounds (e.g., the typical truck back-up warning) may be worse warning indicators to humans than broadband sounds. Even once robot audio signals are perceptible, formative human-robot interaction work on intentional robot sound (e.g., [10]–[12]) leaves abundant open questions about robotic auditory communication unanswered. Accordingly, we aim to create adaptable audio systems for robots that are capable of being heard on construction sites and emitting promising intentional sounds informed by future research steps.

This paper presents our initial efforts to prototype and validate the proposed type of audio system. We present a custom audio system mounted to a typical construction robot: the Husky robot shown in Fig. 1. After a description of related work in Section II, Section III describes the design methods and system specifications. We present the preliminary system evaluation in Section IV. The conclusions in Section V may inform those who wish to use auditory communication in their own robotic systems.

II. Related Work

Sound in Construction: Although noise at construction sites is regulated for worker safety, the general sound level is high in this type of environment, and important safety communications rely on further sounds. Construction sites have high ambient noise throughout the day: depending on the type of construction site, trade, activity, and equipment used, average noise exposure levels vary from 81 to 113 dBA [8]. In the United States, the permissible exposure limit is an 8-hour time-weighted average exposure level of 90 dBA [13].

In order to promote safety, vehicles and other machinery often include alarms that can project over the typical construction site noise [3], [4]. These tonal alarms are widely available commercially. However, research has found that workers can notice and localize other alarm alternatives (e.g., broadband sound alarms) more effectively than traditional

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1 kHz tonal alarms [9]. Also, counter to the traditional design, hearing is most sensitive between 2 kHz and 5 kHz [14]. Further, broadband alarms may lessen the need to exacerbate worksite noise levels; traditional tonal alarm loudness ranges between 97 and 112 dB [15], but commercial broadband sound alarms at 107 dB claim equal effectiveness to 112 dB tonal alarms [16]. In our work, we consider typical construction site sound levels and state-of-the-art alarm techniques as sound design specifications.

Sound for Cobots: Human-robot collaboration in construction ranges from cobots assisting in the transportation of heavy wheels to mini-excavators helping to install curtain walls [17]. In this type of collaboration, we envision sound playing several meaningful roles. Sound has been found to affect the ability of humans to localize robots [18], the proxemics of interacting with a robot [11], and the capability of robots to convey urgency in cooperative tasks [2]. Auditory cues have also been shown to help facilitate communications between autonomous vehicles and pedestrians [19]. Despite the potential for sound to improve the effectiveness of robots, robotic systems for construction largely lack built-in speakers [5]–[7]. The present work aims to address this gap and yield more collaborative and capable construction robots.

III. Methods

We designed the proposed audio system for the Husky robot, a representative system for use in construction robotics and logistical monitoring applications [20], [21]. This robot was selected because of its applicability to the identified problem and availability within our research lab. With appropriate updates to electronic connections and physical interfaces, our audio system can integrate with additional construction robots of interest in the future. Specifications and design steps for the present system follow.

A. System Specification

In order for an audio system to succeed as an auditory communication device on a construction site, we know that the audio system must:

1) Withstand common environmental conditions.
2) Produce sound at an audible level.
3) Interface with existing components.

The concrete specifications associated with each of these design requirements appear below.

Withstanding Environmental Conditions: All external components of the system must be robust to construction environmental conditions. Commercially available buzzers and alarms designed for construction environments have Ingress Protection (IP) ratings of up to IP 68 [16]. The Husky robot, a rugged unmanned ground vehicle, has a maximum rating of IP 55 [6]. Thus, the audio system should have a rating of at least IP 55, and ratings of up to IP 68 are reasonable.

Producing Audible Sound: Commercially available worksite buzzers and alarms guided our specification of the sound level needed to produce audible warnings on a construction site. Our audio system should produce a maximum sound pressure level (SPL) of at least 112 dB if its sound is tonal or at least 107 dB if its sound is broadband [15], [16].

Interfacing with Existing Components: The Husky robot offers power interfaces at 5 V, 12 V, and 24 V with 5 A fuses. Additionally, the onboard computer offers common computer peripherals, such as USB ports and a 3.5 mm audio jack [6]. The audio system should receive power directly from the available power interfaces and receive audio input from the onboard computer through its peripherals.

B. System Design

Based on devices commonly used for producing audio, we considered buzzers, surface transducers, and speakers as the best options for adding intentional sound capabilities to the Husky. The buzzer option would limit the available sound frequencies, while surface transducers may not be usable for construction robots generally due to their reliance on having a suitable surface for vibration and sound production. Accordingly, we determined that a speaker-based system would be best.

A speaker system generally includes the following:

1) A speaker driver, which converts an electrical audio signal into sound.
2) A speaker enclosure, which affects the loudness and frequency response of the speaker driver.
3) An amplifier, which increases the power of audio signals for the speaker driver.

Figure 2 shows our selection for each of these required components, as detailed further below.

Speaker Driver: In order to identify an accessible speaker driver, we considered alternatives on Digi-Key. General-purpose and full-range speaker drivers can produce broadband or tonal sound, so based on the past promising work on broadband sound and the associated specifications, we sought a speaker driver that could achieve a sustained SPL of approximately 107 dB at 1 m. Based on the aforementioned specifications for speaker type, IP rating, and sound level, we selected the FRS 10 WP [22], which has an IP of 65 and sound level further explained below.

Fig. 2: *Left:* the speaker enclosure and mounting plates, disassembled. *Top Right:* the FRS 10 WP speaker driver, soldered to 14 ga speaker wire. *Bottom Right:* the TPA3116D2 amplifier module, with auxiliary audio input, 5.5 mm barrel jack power input, and screw terminal outputs.

Based on the speaker driver's specifications of 25 W rated power and 90 dB mean SPL at 1 W and 1 m, the speaker driver can provide up to 104 dB according to Eqn. 1 (the sound power level equation). L is the SPL, P is the sound power produced, and $P_0 = 1\,\mathrm{pW}$ is the reference sound power in air [14].

$$L = 10\log_{10}\left(\frac{P}{P_0}\right)\mathrm{dB} \tag{1}$$

We anticipated that a two-speaker system, which would also allow for more complex signaling through stereo sound, would provide the required 107 dB. At the same time, we noted that the inverse square law indicates the potential for the proposed audio system to produce hazardous levels of sound (i.e., 120 dB or above) if the listener is less than 0.16 m away. Thus, we recommend the inclusion of a safety barrier or cautionary signage with the proposed audio system.

Speaker Enclosure: A speaker enclosure helps to prevent unnecessary sound cancellation, but the permissible enclosure size and needed attachment mechanism will vary from robot to robot. Generally, speaker enclosures fall into sealed or ported enclosure categories; a ported design may preserve lower frequencies more effectively than a sealed enclosure at the cost of larger cabinets, additional tubing, and openings [23]. To avoid issues with ingress and production, we selected a sealed enclosure design. A single wire-routing hole is located at the bottom of the enclosure.

We designed the enclosure to increase size without an excessive footprint. As size requirements vary based on the robot and other components, we selected a footprint of 125 mm long and 115 mm wide instead of the manufacturer-recommended enclosure volume of 2 L [22]. The enclosure was 3D-printed using polylactic acid (PLA). In order to improve the acoustics of the speaker, the enclosure was filled with a polyester filament. This addition assists in enclosure acoustics when the volume is less than optimal [24].

The speaker enclosure was designed to couple with a custom mounting plate (Fig. 2, Left) that clamped to the top mounting plate of the Husky. This design can easily be adapted to mount to other robots.

Speaker Amplifier: Our system requires an amplifier to convert low-power audio signals from the Husky computer to high-power audio signals for the speaker drivers [14]. We searched for a stereo amplifier breakout board with power specifications similar to the speaker drivers but below the maximum power output of the Husky robot to avoid tripping the 5 A fuse. This led to a maximum total power rating of 120 W from the 24 V power supply. Thus, we selected the TPA3116D2 amplifier breakout board capable of driving two 50 W outputs [25].

C. Initial Evaluation

In our first audio system evaluation, we installed the prototype design on the Husky robot. Using a Blue Snowball microphone, we recorded the system playing white noise at maximum power from three locations: 1 m from the front, left side, and back edges of the robot. The loudness, power requirement, and frequency responses at the three positions were extracted from the recording.

The microphone was calibrated by measuring the amplitude of noise with a Class 2 decibel meter at multiple volumes to determine the conversion from the microphone recording loudness in decibels full scale (dBFS), which has a digital maximum of 0 dBFS, to physical SPL in dB. We found the physical SPL to be 118 dB greater than the digital loudness.

IV. Results & Discussion

Initial evaluations of our speaker system's prospective effect in construction settings yielded the following insights.

A. Loudness & Power

The system produced white noise with a mean SPL of 107.8 dB in front of, 101.0 dB to the side of, and 97.7 dB behind the robot. Based on Eqn. 1 discussed previously, this means that the system drew at least 59 W from the robot.

Overall, the system produced the required SPL of 107 dB at 1 m away in the forward direction; however, factors such as acoustic absorption, speaker directivity, and speaker placement negatively affected SPL to the side of and behind the speakers. Additional speakers or new speaker orientations may be needed for sufficient SPL in other positions around the robot (e.g., for the system to act as a back-up alarm). Ambient worksite SPL and planned positioning of people relative to the robot are further factors to consider. For example, in a lower-noise construction environment, the current SPLs in all directions may be sufficient, and scenarios with different human-robot spacing would require updated system settings.

It is important to note that a speaker power consumption of 59 W may significantly reduce robot runtime. The Husky robot typically consumes around 160 W. Thus, with the added speaker system, the runtime will be reduced by up to 27%. Additionally, the system's 59 W draw requires the 24 V supply to avoid the risk of blowing the fuse on the 5 V and 12 V supplies. On other robots, we recommend carefully considering the power supply capabilities and points of access before installing our proposed speaker system.

B. Frequency

Acoustic reflection, directivity, and speaker placement all affected our audio system's frequency response. Figure 3 shows the frequency response of the recording in each position compared to the original broadband noise waveform being played through the speakers.

Although the system does not respond evenly, key frequency ranges needed for intentional robot sound in construction appear to be strong. For example, strong frequency response in the ranges of 400-800 Hz and 1600-3500 Hz may be useful for localization of the robot on construction sites [15]. The results also support the idea of using broadband sound for warning; peaks and troughs occur at different frequencies in all listening positions, which may undermine the audibility of tonal sound.

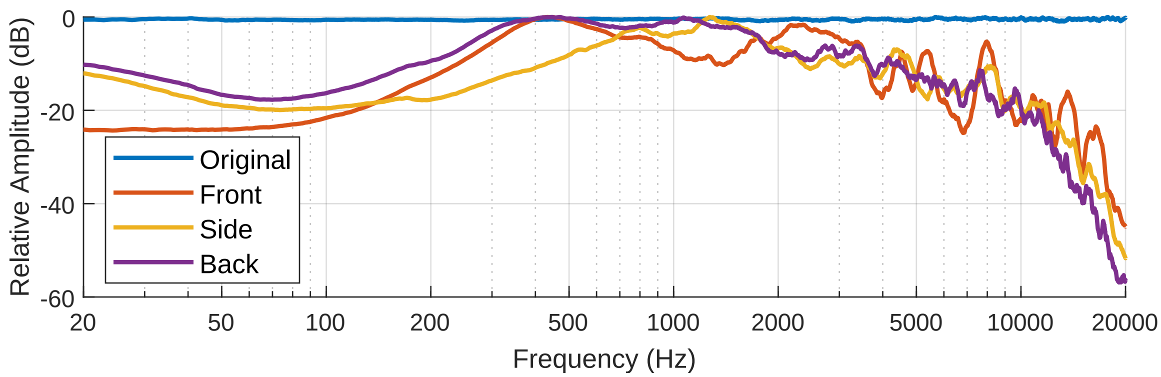

Fig. 3: The recorded frequency responses compared with the originally played broadband noise. The data was analyzed with the Plot Spectrum tool in Audacity with size 65536 and smoothed with a moving average filter with window size 100.

V. Conclusions and Future Work

This paper presented the design process and initial evaluation of a prototype speaker system for the Husky robot. The prototype produces sound of sufficient intensity to project warnings and alerts in construction environments while mounted onto the Husky. Based on our results, we recommend researchers and engineers in construction robotics to implement speaker systems that carefully consider speaker positioning and power interfacing methods and that use broadband noise. Our next research steps will include studying alternative enclosure designs, performing in-depth evaluations of the speaker system, and releasing an open-source speaker toolkit to facilitate the easy addition of intentional robot sound to a variety of platforms.

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