VibroLink: A Wireless Vibro-Auditory Transmission System to Improve Situational Awareness During EVA

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Abstract

On earth, technicians rely on auditory or haptic cues, such as engine sounds and vibration, for a tacit understanding of complex machinery and its status. However, such vibrational cues are absent in space, potentially leaving astronauts unaware of safety-critical information about environmental changes during extravehicular activities (EVAs). This work-in-progress paper presents vibroLink, a concept for a standalone system designed to enhance situational awareness in spacewalks by wirelessly transmitting audio and vibration cues from machinery to the astronaut. Our approach employs a modular, two-component system: a transmitter (sensing) unit equipped with a piezo sensor that detects vibrations from machinery or other critical sources and a receiver unit with a vibrotactile actuator that can be attached, for example, to the astronaut's helmet to replicate the detected vibrations. A preliminary evaluation with a proof-of-concept prototype shows that our concept successfully transmits basic tactile cues, and naive users can leverage their tacit understanding of actions and materiality to identify how the cues originated.

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1 Introduction

Extravehicular Activities (EVAs) are among the most challenging tasks astronauts undertake during space missions [1]. They expose astronauts to a harsh environment characterized for a lack of oxygen, atmospheric pressure, intense radiation, and microgravity. The bulky spacesuits required for astronauts to withstand such conditions limit mobility and sensory feedback [15], depriving astronauts of sensorimotor cues that could enhance efficiency and task performance.

On earth, when operating complex machinery, sound is always a present cue. For example, when driving a car, subtle changes in its sound alert us to its condition. Through audible and tactual vibration, we develop an implicit, *tacit* understanding of the car's operative state. This contrasts with *explicit* information communicated by designed indicators like warning lights or dashboard symbols. Similarly, technicians develop tacit knowledge regarding the status of machines; for example, automotive technicians can find the defective part of a car by hearing or feeling its vibration; this tacit knowledge, apart from the explicit knowledge, is crucial when repairing such complex systems [10, 17].

However, in outer space, these vibrations cannot propagate, due to the lack of a physical medium. For example, if an astronaut is fixing equipment during a space walk, they might miss 1) the vibratory response of the machinery that may indicate malfunctions or abnormalities and 2) safety-critical environmental information (e.g., two objects colliding or similar) because they cannot be sensed.

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In this work-in-progress paper, we propose a system to enable astronauts to access sensorimotor cues in outer space scenarios. The system consists of transmitter (sensing) and receiver units. The transmitter uses a piezo sensor to gather information about the vibration of a machine or surface and wirelessly sends this data to the receiver. The receiver has a vibroactuator that plays back the vibration. Both devices are designed to have a multi-use adhesive base, allowing astronauts to place the transmitters on critical machinery or surfaces and the receivers on, for example, their helmets. This provides astronauts with additional information about their surroundings without interfering with the design and function of other systems.

The vibroLink system is designed for ad-hoc use. It operates independently and does not require integration with existing technologies, allowing astronauts to deploy it as needed. Unlike conventional notification systems that require dedicated sensors, hardware, and planned integration, vibroLink can be deployed spontaneously – for instance, when an astronaut senses that something may be wrong. It then provides both useful status feedback and reassurance.

This paper is structured as follows. Initially, we explore existing research on the challenges of EVAs, sensory cues, tactile knowledge, and the application of haptic feedback in space environments. Subsequently, we introduce the proposed scenario for the vibroLink system. This is followed by a detailed description of the system's implementation and its evaluation. Lastly, we address the limitations of the system and outline directions for future research.

2 Related Work

This work builds on research done on sensory cues for complex tasks and tacit knowledge, as well as challenges of current EVAs and, finally, the use of haptic feedback in space exploration scenarios.

2.1 Sensory Cues & Tacit Knowledge

We define tacit knowledge as non-verbalized, intuitive, and unarticulated knowledge. It is non-declarative knowledge of the world, based on embodied experience, as opposed to explicit, declarative knowledge. For example, declarative knowledge might include how to spell the word "swing"; it is the knowledge we can easily convey to others. This is in contrast to the activity of swinging. While most of us know how to swing, articulating what exactly one needs to do to set a swing in motion is challenging.

Polyani [12] introduced the term "Tacit Knowledge" to describe the ability to do something without being able to articulate how to do it: this includes riding a bicycle or playing a musical instrument, without having the ability to fully explain all details of how it is done. Polyani claims that all practical skills rely upon tacit awareness. We extend this to incorporate knowledge about the world, as this is the foundation of any skill. For example, both riding a bicycle and swinging in a swing require a tacit understanding of physics.

Such tacit understanding of the world is also related to domain-specific knowledge, for example, many technicians rely on auditory and visual cues to detect failure on complex machinery [15]. Another documented case is craftsmen from a renowned Japanese denim brand, who claim that they share a unique bond with their machines, relying solely on auditory cues to calibrate them. This tacit understanding of the machinery is built over time and has been handed down through generations [14]. Research is only beginning to explore making such knowledge explicit, for example, by training machine-learning models to identify acoustic cues for fault diagnosis [17].

In this work, we assume that astronauts have a rich body of tacit knowledge of materiality and physics, which includes understanding vibration feedback, be it tactile or audible, and having the ability to infer what caused it. Our work aims to leverage such knowledge to make EVAs safer and more effective.

2.2 Extravehicular Activities (EVA) Challenges

At the time of this writing, it has been over 60 years since Alexei Leonov floated in free space on March 18, 1965. This event is considered the first human EVA – an activity conducted by an astronaut in outer space outside a spacecraft. EVAs include spacewalks as well as lunar or planetary surface exploration, such as moonwalks. According to a 2004 NASA report [5], in the four decades following Leonov's EVA, humans spent approximately 900 hours in microgravity and over 160 hours on the lunar surface performing EVAs. The same report highlights the following key areas for improvement in future EVAs: (1) all subsystem designs should prioritize simplicity and reliability based on fundamental principles, favoring these over added functionality in case of trade-offs; and (2) methods are needed to support and maintain high levels of mental performance during EVAs.

Conducting EVAs is extremely mentally challenging. A large part of EVA training focuses on cognitive preparedness, often described as "putting on your EVA brain." Success relies heavily on planning actions and movements in advance [4]. Several factors contribute to these challenges. For example, vibration and auditory cues are absent in the vacuum environment. Additionally, bulky suits constrain movement and act as sensory insulators. The design of current space suits – ranging from 10 to 30 mm in thickness and composed of up to 16 layers – significantly reduces both audible and tactile feedback [8]. These limitations impair the astronaut's ability to perceive non-visual cues, grasp objects, and maintain proprioception. As a result, cognitive performance can decline, increasing the risk of accidents [15].

In contrast, access to sensory feedback has been shown to improve task performance and reduce cognitive load in complex environments [16, 9]. Based on this, researchers have explored ways to reintroduce sensory input in space contexts. For example, Berengueres [2] demonstrated that enabling sound transparency during Intravehicular Activities (IVAs) can mitigate sensory deprivation and improve cognitive performance. However, their approach requires complex instrumentation of the astronaut's environment.

We propose the vibroLink concept as a way to enhance sensory access and improve situational awareness during EVAs. The system provides EVA pilots with a means to leverage their tacit material knowledge and supports sustained high-level mental performance.

The vibroLink units will be designed to operate fully standalone, adhering to the principle that subsystem designs should prioritize simplicity and reliability. Keeping the units independent avoids the complexity of integration with other systems.

2.3 Haptics in Space Exploration

Hearing and vision are distal senses – we perceive objects that are located away from the body. According to Katz, touch is different in that it involves both distal and proximal aspects [7]. For example, when we feel the rumbling of a machine, we perceive something that originates at a distance. But unlike hearing and vision, touch also has a proximal aspect: when we touch a material, we perceive the stimulus directly on the skin, at the point of contact.

The extreme conditions of space significantly limit direct physical interaction, restricting astronauts' ability to perceive their environment, be it distally or proximally. To address this challenge, researchers have been exploring the development of haptic feedback systems.

These systems aim to enhance interactions by providing tactile sensations. Their goal is to bridge the sensory gap created by the harsh extraterrestrial environment and the limitations of current spacesuit technology.

There is a large body of research on improving textiles for space exploration (e.g., [3]), which includes space suits with integrated tactile feedback [11]. The suit proposed by Wicaksono uses various sensors, such as piezoelectric and conductive fabrics, to detect external tactile cues. It then relays this information to the astronaut's skin through vibration motors, creating dynamic tactile experiences that correspond to the materials outside the suit [11]. Similarly, ExoSkin is a proposed haptic layer for the space suits' gloves. This layer would allow haptic cues from the external environment to be transferred to the astronaut's skin using small free-moving pins. These pins adapt their shape based on surface contact, providing haptic feedback to the fingertips [13].

Existing systems are aimed at augmenting proximal tactile perception. Our approach aims to enhance sensory access to remote locations. Placing a patch on a solar panel, provides an EVA pilot with a distal experience of the vibration conditions at that panel.

In addition to the system aiming to augment a different type of experience, existing systems also have the drawback of requiring complex integration with future space suits. Our vibroLink concept, however, is designed to seamlessly augment existing EVA equipment, without requiring complex technological integration.

3 Envisioned Scenario

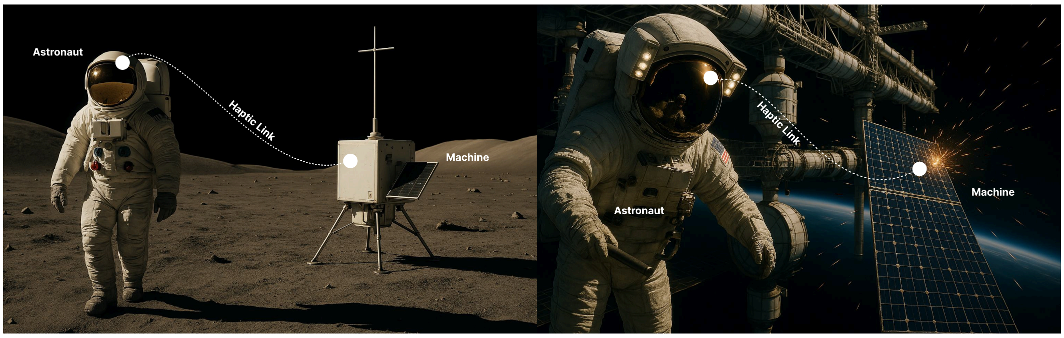

Figure 1 Envisioned scenarios for the vibroLink system include practical applications such as monitoring machine status remotely during repairs or detecting micro asteroid collisions during solar panel maintenance. *Notice: The images were generated by AI.*

We envision vibroLink being used during EVAs to improve situation awareness and facilitate machinery repair for astronauts. The system consists of two components: a receiver and a transmitter. As the astronaut performs machinery repair or maintenance and needs to monitor the status of a particular machine or surface, they can simply attach the transmitter unit to the chosen surface and the receiver unit to their helmet. This will vibrate the air inside the helmet, enabling the perception of the sensed vibration. The sensing unit will automatically transmit vibration data from the surface to the helmet as the astronaut continues with the proposed EVA plan. This vibration data can be used to assess the condition of the machinery and identify any problems or abnormalities, such as impacts, or strain.

3.1 Scenario 1 - Space Station Repair

The astronaut leaves the space station through the airlock and carefully maneuvers along the exterior using handrails for locomotion and security. Upon reaching the solar panel area, they attach their tether for safety. The astronaut performs a visual inspection to look for any visible damage. They check the joints and electrical connections, making adjustments or repairs as needed.

Here the astronaut might attach a transmitter unit to the base of the tether, so that they are aware of any mechanical problems with the tether.

3.2 Scenario 2 - Assembly of a Satellite

Two astronauts exit the spacecraft, carrying satellite components and required tools. They move toward the assembly location – first using tethers and handrails, then with astronaut #1 operating a robotic arm to position astronaut two correctly. Astronaut #2 begins by aligning the satellite's base with its mounting structure and securing it with bolts or clamps. One by one, they attach additional components such as antennas or sensors, while astronaut #1 adjusts their position relative to the satellite using the robotic arm. After each connection is checked for proper fit and stability, the astronaut powers up or tests parts of the satellite.

Here, astronaut #1 might request astronaut #2 to place a transmitter unit on the satellite itself, allowing astronaut #2 – equipped with a receiver unit – to gain better sensory access to the ongoing assembly process. Additionally, astronaut #2 may place a transmitter unit on the robotic arm's motors. Since the arm is frequently used to change position, this setup helps them distinguish whether relative motion between themselves and the equipment is caused by drift or by the arm's movement.

3.3 Scenario 3 - Soil Probe collection

The astronaut exits the planetary lander and steps onto the moon's surface. Moving slowly and carefully, they walk toward a designated location for sample collection. Upon arrival, they unpack a probe tool from their equipment, insert it into the ground, and collect a soil sample. Once the task is complete, the sample is secured in a storage container.

In this scenario, the astronaut might attach a transmitter unit to a piece of machinery inside the lunar lander. The purpose of vibroLink here is not strictly utilitarian. In the harsh and unfamiliar environment, the familiar vibration pattern from the lander's machinery provides a sense of comfort and orientation. It offers the astronaut a subtle but reassuring cue that their way back home is secure, even if the lander is temporarily out of sight, and supports their emotional wellbeing.

4 Implementation

The vibroLink system is designed to be a simple yet efficient tool for deployment during EVAs. It compromises two main components: a receiver unit and a transmitter unit (see Figure 2), each equipped with an adhesive backing for effortless attachment to different surfaces or equipment. This section provides an overview of the system.

The transmitter unit features a generic piezoelectric sensor that detects surface vibrations in real-time. Piezo electrics sensors are well-suited for this purpose, offering exceptional tolerance to extreme temperatures, as well as high sensitivity and resolution, making them ideal for measuring vibrations in spacecraft [6]. The transmitter unit also incorporates a PAM8302 amplifier and an off-the-shelf AirBorne Wi-2.4-GHz Bluetooth transmitter module.

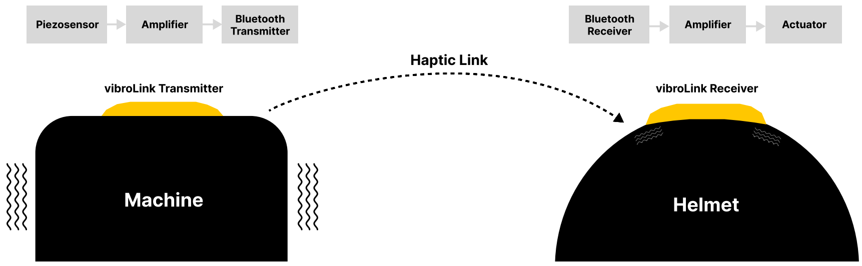

Figure 2 The vibroLink system.

Meanwhile, the receiver unit – designed to be affixed to an astronaut's helmet – includes an off-the-shelf AirBorne Wi-2.4-GHz Bluetooth receiver module, a PAM8302 amplifier, and a Vybronics VG1040003D Linear Resonant Actuator (LRA) as vibroactuator. This transmitter senses the vibration data from the designated location, treating it as audio data. It is transmitted to the receiver, which plays back the same signal, again treating it as audio. As the system operates in near real time, this enables the astronaut to feel the vibrations as they occur. Both units are intended to be powered by lightweight, thin-film lithium-ion batteries, enhancing their portability and practicality for EVA applications.

5 Evaluation

To assess the usefulness of the information transmitted through basic tactile cues provided by our system, we conducted two preliminary explorations with six participants using the vibroLink prototype. They were aimed at identifying if the system functioned, in principle (Exploration #1), and to understand if participants, without prior instruction, can implicitly identify different materials and actions (Exploration #2).

In each exploration, participants sat on a chair with a receiver unit, their index finger touching the vibroactuator, guided by Experimenter #1. Simultaneously, in a separate room, Experimenter #2 generated various stimuli on the piezoelectric sensor in the transmitter unit.

5.1 Exploration #1: Number of Knocks

Participants were tasked with identifying the number of knocks perceived through the vibroactuator's feedback. Experimenter #2 knocked on the piezo sensor using a rigid plastic piece in a separate room while participants felt the vibratory feedback and identified the number of knocks. Each participant completed one trial, which consisted of four stimuli (1, 2, 3, or 4 knocks) presented in a randomized order.

Participants correctly identified the number of knocks with an overall accuracy of 95.83%. Five out of six participants achieved 100.0% accuracy, while one participant made one error.

5.2 Exploration #2: Discrimination of different materials

Participants were asked to identify both the material and the action conveyed through the tactile feedback. The experiment used two materials (soft and hard) and two actions (scratching or knocking the piezoelectric sensor), resulting in four distinct pairs of stimuli: (soft, knocking), (soft, scratching), (hard, knocking), and (hard, scratching). Experimenter #2 performed the stimuli using a rigid object from Study #1 as the hard material and a piece of sponge as the soft material. Each participant completed one trial in which the four pairs of stimuli were presented in a randomized order. Before the experiment, participants were familiarized with the tactile feedback of all four combinations once.

Results showed an overall accuracy of 87.50% in identifying the stimuli. Four participants achieved 100% accuracy, while P1 misidentified a material, and separately P2 misidentified a material and an action.

5.3 Discussion

Current EVA operations rely heavily on visual information. The bulkiness of EVA suits and the vacuum of space shield astronauts from the vibrations of their surroundings. However, these vibrations are important to our tacit understanding of materiality and actions. vibroLink addresses this problem by offering an implicit, continuous information stream that can operate in parallel with visual tasks. Our preliminary evaluations indicate that such a link can indeed be used to transmit tacit information. Untrained participants were not only able to decode explicit tactile signals such as the number of knocks, but also to differentiate between materials and actions through vibration alone. This suggests that the information provided by vibroLink can effectively support a better understanding of one's environment during EVA activity.

A system such as vibroLink likely has other benefits related to EVA operations. A central issue during EVA is sensory deprivation due to the isolation provided by the space suit, which can degrade cognitive performance and increase the risk of errors. Our system may mitigate such cognitive effects by increasing sensory access to the astronaut's environment.

A common concern identified in the literature is the potential complexity of integrating haptic feedback systems into existing suits – generally, added functionality is seen as something that may compromise the safety and reliability of equipment. Many proposed solutions require extensive integration with existing technology stacks. We avoid this issue by proposing that vibroLink operate independently, requiring no integration with existing subsystems. Furthermore, the components are deployable ad hoc and can be integrated into deployment procedures and best practices. This simplicity directly responds to the requirement that EVA tools prioritize reliability and ease of use.

Despite its promise, our prototype still faces technical limitations. The piezo sensor in the transmitter lacks sensitivity to low-frequency vibrations, which we have found important for detecting subtle mechanical anomalies. This limits the system's applicability for more complex diagnostic tasks. We propose combining the piezo sensor with an accelerometer to expand the frequency range, though this introduces new challenges in signal fusion and actuation algorithms that will need to be addressed.

Additionally, testing with expert users and under more realistic conditions is necessary to validate the system's relevance in situ. Open questions include whether vibroLink requires any form of longitudinal training for astronauts to fully benefit from it, and whether there are conditions under which the information it provides could be perceived as distracting rather than helpful. Another consideration is whether the current one-to-one transmitter–receiver pairing should be maintained – with all its benefits for creative deployment – or upgraded to a multi-sensor system connected to a single receiver, which may be less flexible but better suited for certain tasks.

In sum, vibroLink offers a lightweight, flexible, and cognitively compatible solution to well-documented EVA limitations. By reintroducing tactile cues through a standalone, easily deployable system, vibroLink addresses both technical and cognitive challenges identified in prior work, and opens a path toward more embodied interaction in extreme environments.

6 Conclusion

This paper introduced vibroLink, a concept and initial proof-of-concept prototype of a wireless vibro-auditory transmission system designed to enhance situational awareness and facilitate machine repairs during EVAs. This system enables astronauts to wirelessly receive tactile cues from various sources, such as machines or surfaces, allowing them to detect possible failures or critical environmental changes during EVAs.

The system is designed to operate independently of existing EVA infrastructure, meaning it does not require complex and potentially costly integration with other systems. It consists of two units: a transmitter that can be attached to any surface or machinery, and a receiver unit intended to be mounted on the astronaut's helmet.

We tested a proof-of-concept prototype vibroLink in two explorations, which confirmed its functionality in transmitting basic tactile cues and that naive users can leverage their tacit understanding of actions and materiality to identify how the cues originated.

References

1 B. Belobrajdic, K. Melone, and A. Diaz-Artiles. Planetary extravehicular activity (eva) risk mitigation strategies for long-duration space missions. *npj Microgravity*, 7:16, 2021. doi:10.1038/s41526-021-00144-w.

2 Jose Berengueres, Maryam AlKuwaiti, Maha Abduljabbar, and Fatma Taher. Adding sound transparency to a spacesuit: Effect on cognitive performance in females. *IEEE Open Journal of Engineering in Medicine and Biology*, 4:190–194, 2023. doi:10.1109/OJEMB.2023.3288740.

3 Juliana Cherston and Joseph A Paradiso. SpaceSkin: development of aerospace-grade electronic textile for simultaneous protection and high velocity impact characterization. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2019*. SPIE, March 2019.

4 Matthew A. Gast and Sandra K. Moore. A glimpse from the inside of a space suit: What is it really like to train for an eva? *Acta Astronautica*, 68(1):316–325, 2011. doi:10.1016/j.actaastro.2010.08.015.

5 Stephen J. Hoffman. Advanced eva capabilities: A study for nasa's revolutionary aerospace systems concept program. Technical Publication NASA/TP-2004-212068, S-922, National Aeronautics and Space Administration, Johnson Space Center, April 2004. Document ID: 20040200983. URL: https://ntrs.nasa.gov/citations/20040200983.

6 Hadi JAHANSHAHI and Zheng H. ZHU. A comprehensive review of tactile sensing technologies in space robotics. *Chinese Journal of Aeronautics*, page 103423, 2025. doi:10.1016/j.cja.2025.103423.

7 David Katz and Lester E Krueger. *The world of touch*. Psychology press, New York, 2013.

8 Mohammad Amin Kuhail, Jose Berengueres, Fatma Taher, Mariam Alkuwaiti, and Sana Z. Khan. Haptic systems: Trends and lessons learned for haptics in spacesuits. *Electronics*, 12(8), 2023. doi:10.3390/electronics12081888.

9 Matteo Marucci, Gianluca Di Flumeri, Gianluca Borghini, Nicolina Sciaraffa, Michele Scandola, Enea Francesco Pavone, Fabio Babiloni, Viviana Betti, and Pietro Aricò. The impact of multisensory integration and perceptual load in virtual reality settings on performance, workload and presence. *Scientific Reports*, 11:4831, 2021. doi:10.1038/s41598-021-84196-8.

10 Oriental Motor. Troubleshooting basics: Motor noises, February 2023. Accessed: 2025-03-16. URL: https://blog.orientalmotor.com/troubleshooting-basics-motor-noises.

11 Syamantak Payra, Irmandy Wicaksono, Juliana Cherston, Cedric Honnet, Valentina Sumini, and Joseph A. Paradiso. Feeling through spacesuits: Application of space-resilient e-textiles to enable haptic feedback on pressurized extravehicular suits. In *2021 IEEE Aerospace Conference (50100)*, pages 1–12, 2021. doi:10.1109/AERO50100.2021.9438515.

12 Michael Polanyi. *The Tacit Dimension.* Doubleday, Garden City, NY, 1966. URL: https://www.amazon.de/-/en/Tacit-Dimension-Michael-Polanyi/dp/0226672980.

13 S. A. Seah, M. Obrist, A. Roudaut, and S. Subramanian. Need for touch in human space exploration: Towards the design of a morphing haptic glove – exoskin. In J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, and M. Winckler, editors, *Human-Computer Interaction – INTERACT 2015*, volume 9299 of *Lecture Notes in Computer Science*, pages 18–36, Cham, 2015. Springer. doi:10.1007/978-3-319-22723-8_3.

14 The Mainichi. Japan's kojima, with its proud jeans street, draws fans of vintage, deep-blue denim, October 2024. URL: https://mainichi.jp/english/articles/20241002/p2g/00m/0li/036000c.

15 Alexander Thuro and Leia Stirling. Characterization of the apollo astronaut lunar extravehicular activity falls and near-falls. In *2021 IEEE Aerospace Conference (50100)*, pages 1–6, 2021. doi:10.1109/AERO50100.2021.9438263.

16 Ying Zhang, Terrence Fernando, Hannan Xiao, and Adrian R. L. Travis. Evaluation of auditory and visual feedback on task performance in a virtual assembly environment. *PRESENCE: Teleoperators and Virtual Environments*, 15:613–626, 2006. doi:10.1162/PRES.15.6.613.

17 Yu Zhang and Miguel Martínez-García. Machine hearing for industrial fault diagnosis. In *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, pages 849–854, 2020. doi:10.1109/CASE48305.2020.9216787.