Audiodice: an open hardware design of a distributed dodecahedron loudspeaker orchestra

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ABSTRACT

We present a new speaker array composed of five spherical speakers with 12 independent channels each. The prototype is open source and design choices are motivated here. It is designed to be a flexible device allowing a wide range of use cases, as described in more detail in the paper: simultaneous rendering with surround speaker arrays, artistic installations and acoustical measurements. The sources in the repository include filter impulse response for frequency response correction. The measurement methodology, based on sine sweeps, is documented and allows the reader to reproduce the measurement and correction. Finally, the paper describes several use cases for which feedback is provided, and demonstrates the versatility, mobility, and ease of deployment provided by our proposed implementation.

CCS CONCEPTS

• **Hardware** → **Emerging tools and methodologies**; • **Applied computing** → **Media arts**; **Sound and music computing**; • **Human-centered computing** → Accessibility technologies.

KEYWORDS

speaker array, audio spatialization, open source hardware, reuse, deployability

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1 TOWARDS AN EASIER-TO-DEPLOY AND MOBILE IMMERSIVE SPEAKER ARRAY

The use of Speaker Arrays (SAs) motivates a wide range of applications, ranging from virtual environment simulation for video games to acoustical room measurement. In the case of immersive audio for a group of participants, several creators, including creative studios, artists and auditoriums, produce immersive experiences, such as installations, movies and performances. However, large speaker arrays are not widely available and are hard to duplicate. This makes tasks like experimentation during creation and experience on tour harder to achieve, since access to the target SA remains constrained. Fortunately, several speaker placement virtualisation [4] and simulation [27] technics can be employed in order to model the targeting SA and space for more available spatial audio displays (like headphones). However, a final adaptation of the content is still required due to perceptual differences between the various SAs. We are therefore interested in this paper by easier to duplicate, deploy, and transport SAs for immersive experiences.

In order to better expose our motivations, we propose to categorize SAs into three categories:

- *surrounding*: speakers are laid out in order to surround the listener(s) and propagate sound inward
- *radiating*: speakers are laid out in order to be deployed inside the room and propagate sound outward
- *personal*: speakers are laid out in order to keep a constant relative position to the ears of a unique listener

Standards for *Surrounding* SAs are available, such as Dolby Atmos, DTS, or MPEG-H 3D Audio, and are widely deployed in places like movie theatres and planetariums. Other, more specific venues offer spaces that adapt well to a variety of listener positions, enabling spatial audio installation and live performance. These later are targeting live and multimodal content [1] and include the IEM-Cube and the MUMUTH in Graz, the MULIT in Bergen, the Motion Lab in Oslo, the SPACE in Pesaro, the Digital Media Center Theater in Bâton-Rouge and the Satosphère in Montreal. Several other immersive audio spaces allowing diffusion of an immersive audio experience to a group of listeners have been described in the literature [11, 13], in which the number of speakers offers various spatial resolutions, sometimes with acoustical control or combined with tracking or video display systems.

With the surrounding approach to spatial audio, *sweet spots* help define the listener's position where the rendered wavefield is optimal, mostly regarding both spatial and sound qualities [10].

Personnal SAs, such as personal headsets or head-mounted speaker array [14, 24] are able to provide spatial audio to a group of listeners. They are compatible with spatial audio rendering, but require as many devices as listeners, and possibly user body and head tracking if the listener is mobile in the audio scene [5].

Finally, *radiating* SAs include spherical speaker arrays like the IKO [26] or irregular loudspeaker layouts [12, 25]. This also includes custom-made speakers for sound installation [8], or smartphone speakers for collective interactions [2].

In this paper, we propose a *radiating* open hardware SA, designed as a cluster of five multichannel and spherical speakers, providing 60 audio channels. We implemented several use cases that illustrate

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various positive results of our system: device mobility, opportunity for new spatial audio composition methods and scenographies, and specific perceptive effects.

Other comparable system are described in the literature. Scott Smallwood ET AL. presented several hemispherical speakers designed for live performance during research at Princetown University [22]. Similarly, the *slork Speaker* [1] provides a Do-It-Yourself (DIY) speaker for the performer. More recently, a series of works at the (IEM) declined variation of spherical speakers, first shaped as an icosahedral loudspeaker [18, 21, 23, 26], and then with different driver layouts and fewer channels over the sphere [6, 17]. Research involving these speakers has raised several interesting results, such as the positive effect of wall (or panel) reflection on sound spatialization, composition for one or multiple speakers, and particular auditory-sculptural qualities such as directivity, contour, and plasticity [21].

In this paper, we propose our Audiodice speaker array, which distinguishes itself from previously introduced literature by simultaneously having the following characteristics:

- designed as a group of 5 radiating SAs, enabling use cases not experimented with before, according to our knowledge
- re-deployable spatial audio device with a resolution of 60 audio channels
- open source, allowing anyone to reproduce the device

The rest of this paper will describe the design (Section 2) and frequency correction (Section 3) of the Audiodice. Then uses cases (Section 4), and a discussion on use and reuse (Section 5). We will use the terminology *speaker* for a single Audiodice sphere, that is a dodecahedron providing 12 channels, and *driver* for a single channel of a *speaker*.

2 SPEAKER CONCEPTION

The design of Audiodice covers several parts of the system. First are the five boxes (speakers) that host 12 audio drivers each, the distribution system that allows a single computer to drive the entire system, and finally the mounting system. In order to be reproducible, the project plans and specification[2] are released under the Attribution-NonCommercial 2.0 Generic (CC BY-NC 2.0) licence that allows to i) share – copy and redistribute the licenced material in any medium or format, and ii) adapt – remix, transform, and build upon the licenced material.

Each speaker is designed as a generic dodecahedron, with 12 regular pentagons as faces (see Figure 1). Each of these faces is identical in shape and size and hosts a single driver/channel (model: Visaton SC 8 N). This particular characteristic was chosen in order to ensure a similar geometric configuration among all audio channels, with the hope that it will ease speaker calibration, while opening the possibility to investigate use cases involving rich radiation patterns, such as those involved with acoustical instrument [20]. This design is also employed in acoustical room measurements [15].

Boxes are made with wood, open inside (no damping material), and designed to be attached to a tripod, or fixed to a ceiling grid[3].

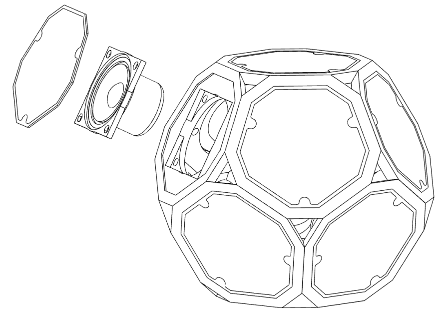


Figure 1: A single Audiodice speaker.

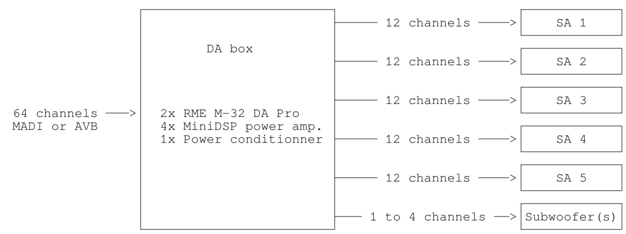


Figure 2: Audiodice audio distribution system. The system provides the distribution of 64 audio channels, available from a single computer to the five Speaker Arrays (SA), each similarly shaped as regular dodecahedrons.

The audio distribution system, shown in Figure 2 provides access to allow a single computer to access all the channels. Audio from the computer is sent to the *DA box* (for Digital Analogic audio converter) with either Multichannel Audio Digital Interface (MADI) (standardized as AES10) or Audio Video Bridging (AVB) (standardized as IEEE 802.1BA-2011) protocols, as supported by the digital-audio converter made of two RME M-32 DA pro. These two converters are connected in series. Then, audio signals are amplified by four 16-channel power amplifiers connected to each Audiodice box via speaker cables. Note that $12 \times 5 = 60$ channels are required for the Audiodice, leaving four channels that can be used for extra subwoofers or other uses. This configuration provides the user with single and simultaneous access to all the channels, allowing them to create custom audio rendering strategies, including per-driver and/or per-sphere renderings.

3 SPEAKER FREQUENCY CORRECTION

Not surprisingly, when we first plugged in the speakers, we were able to hear that the sound had a significant bias towards certain frequencies. This can be explained by the driver design, as frequency response is usually provided by the manufacturer. Indeed, some driver characteristics may affect the expected frequency neutrality: choice of material for the cone, magnet, size, and shape of the cone, among others. In addition, and probably more significantly affecting the sound, our 12-speaker cabinet is likely to provide some specific resonances, sound pressure interference, and phase alteration that affect the frequency response. In order to correct the sound quality

[1]https://ccrma.stanford.edu/~njb/research/slorkSpeaker/ (visited May 2023)
[2]Available at https://gitlab.com/sat-mtl/tools/audiodice (visited May 2023)
[3]A video demonstrating conception is available at https://vimeo.com/519938720 (visited May 2023).

of the Audiodice, we conducted measures about frequency response, and generated correction filters accordingly.

3.1 Measurement setup

Measurements were done in a semi anechoic room at Center for Interdisciplinary Research In Music Media and Technology (CIRMMT) [4] during 2 sessions of 1 week each.

We used 3 Octomic from Coresound. These are second-order ambisonic microphones, provided with individual calibration. The microphones were plugged in 3 RME Micstasy. Figure 3 is a panoramic picture of the measuring setup from the point of view of one of the measuring Octomic. The measured speaker is set in the middle of the room, on a precision rotating stand (Brüel & Kjaer Type 9640 turntable system), with 3 surrounding Octomic placed as an equilateral triangle. Each measuring microphone is set at the ear level of the Audiodice, that is the middle of the speaker, 25 cm away to diminish the room effect.

The playback and recording machine was set up in a control room, connecting the DA box and the 3 RME Micstasy along with the turntable remote. Measurements were done using the Exponential Sine Sweep (ESS) method [7] with a 20-second sweep from 0Hz to 20kHz. For most measurements, ESS was played on every speaker simultaneously. The recording is then converted from ambisonic A format to a more generic B format. Finally, the recorded sine sweep is converted to an impulse response for further analysis. More importantly, it is used to generate a correction filter with the Room EQ Wizard[5] (REW) software.

Figure 3: Panoramic view of the semi-anechoic room. The camera is set on the tripod we used for one Octomic.

This setup allowed us to create an average speaker correction. We measured the 12 drivers at once (omnidirectional pattern) with multiple microphone positions around the speaker, as described above, giving up to 3 microphone positions around the speaker. Rotating the turntable by 60° then gives 3 more microphone positions equally spaced, allowing up to 6 positions. All the measurements are averaged with REW and a single correction filter is generated that can be applied to the 12 drivers.

[4]https://www.cirmmt.org/ (visited May 2023)
[5]https://www.roomeqwizard.com/ (visited May 2023)

3.2 Measurement results

Figure 4 shows in red the averaged frequency response of speaker number 5, as measured from six microphones. This average was then used to generate a correction filter, targeting all 12 drivers. In green, we can see the measured frequency response when correction is applied. This response is also an average of multiple microphone positions. Our subjective listening confirmed the apparent flattening of the frequency response, which is actually hiding drastically the bias towards certain frequencies we initially heard.

The averaged correction method not only works for an omnidirectional pattern (12 drivers playing the same sound), but it can also be used in a multichannel mode when all the drivers play different sounds.

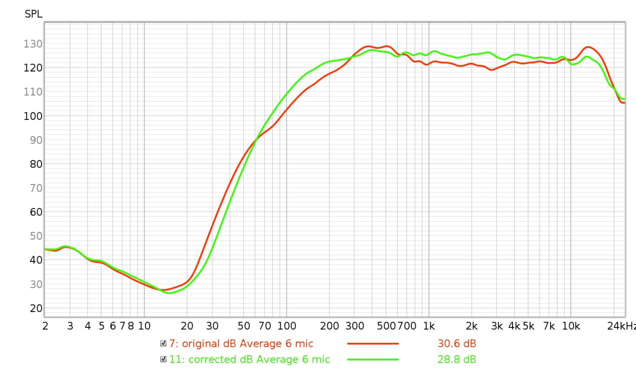


Figure 4: In red, the average frequency response. In green, measured frequency response with correction applied.

In addition, we noticed this filter removed the "boxiness" of the speaker's sound. With the correction, we found the sound more defined. This can be heard on the comparison video[6], using a string quartet recording in a room without acoustic treatment. While each of the single instruments are assigned to a single speaker, an ambisonic microphone (the Octomic from Coresound) is placed in the middle of the speakers in a square shape. The resulting recording was then converted to stereo, following Blumlein pair placement. More details about this recording are provided in Section 4.3.

3.3 Single driver correction

We also experimented with a single driver correction that required measuring every 12 drivers independently in order to generate 12 corresponding correction filters. For each measure, the microphone was placed 25 cm away in front of the analyzed driver. The ESS was played only through this driver. This measurement was then used to create the 12 corresponding correction filters for one speaker.

During our subjective listening session, we could still hear resonant frequencies. This might be caused by a misalignment of all 12 correction filters, leading to some phase shifting between the drivers, but further experiments must be conducted in order to provide evidence. Losing all phase coherence between the drivers affects the fidelity of the sound reproduction.

[6]https://vimeo.com/802032392 (visited May 2023)

3.4 Directivity

Figure 5 shows a measured directivity sonogram for driver number 1 of sphere number 5. This corresponds to the top-facing driver in Figure 3. A directivity sonogram depicts the sound intensity with respect to the listening angle. In addition to the directivity of that specific driver, it shows that the frequency response of the speaker is not flat, even on axis (angle 0°). As expected, due to the small size of the drivers, there are barely audible sounds below 200Hz. This gap in the frequency response can be easily filled with a subwoofer.

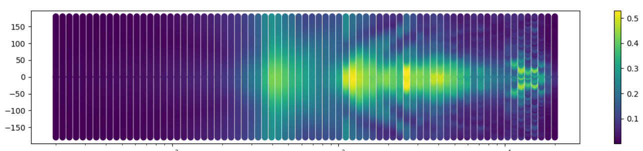


Figure 5: Directivity sonogram of driver 1 of the Audiodice. A sonogram depicts the sound intensity with respect to the listening angle for a frequency range.

We can also notice some discontinuities in the pattern, some frequencies will disappear at a certain angle and reappear at another, creating dark arcs in the sonogram. For instance, at 2.5 kHz, there is a drop in sound pressure of around 100°. Two factors can explain this observation: first, the driver 1 is not perpendicular to the microphone; second, phase cancellation due to the speaker design (sound pressure bleeding inside the box, resonances, etc.). Further studies are needed to characterize the prevalent reasons for these gaps.

4 USE CASES

The Audiodice prototype has been employed in research and artistic projects. They provided feedback about device mobility and the specifics of audio composition and scenography. This feedback is elaborated in the next section. Here are four use cases, illustrated in Figure 6.

4.1 Complement to a dome-shaped spatial audio device

Previous work in our laboratory includes a work on live spatial audio rendering for a navigable listening experience in a sound field capture of an orchestra performing in a symphonic house. This work is based on 3D game engine navigation that informs the spatialization software SATIE [3] about the parameters required for rendering the 64+ captured channels. The spatial audio engine is able to render simultaneously and independently for multiple multichannel audio display devices. Accordingly, the Audiodice, located inside the audio dome device (see Figure 6a), is employed for rendering near-field sounds, while far-field sounds remain displayed by the 31-channel dome. In this case, near-field and far-field separation is achieved with a specifically configured crossfade applied for each captured audio source. This crossfade is driven by the distance between the listener's location and the sound source's location.

As a result, the addition of our Audiodice device provides a group experience where one can walk in the orchestra while listening and therefore listen closer to any captured (group of) instrument(s) at any moment of the piece. This specific rendering for the near field is performed using five "virtual microphones" placed inside the 3D rendering engine, whose locations replicate the locations of the actual spheres of the Audiodice. These microphones are attached to the listener's location, allowing for continuous rendering adaptation when the listener is moving. A demonstration video is available[7] and further described, with more details about capture and rendering, in a previously published paper [19].

4.2 Multilocation acoustic measurements

In a previous work [16], we used each of the Audiodice spheres as omnidirectional speakers in order to scale to a significantly large number of measurements, which allows for IR interpolation and simulation of a walk into a room. These previous works demonstrated that this method was successful in reproducing the acoustics during navigation in a room[8].

4.3 Tangible audio avatars

The Audiodice being a group of 5 spheres brings the opportunity to assign one sound source per sphere and therefore reproduce the location of a group being in the same room. We used this approach for a prototype telepresence project, allowing remote audience members to be part of the audience located with the performers of an immersive show, including dancers. This is shown in Figure 6c[9].

Moreover, the multichannel capability of each sphere opens the possibility of reproducing the radiation pattern of each sound source. This has been implemented using available audio from the paper entitled "anechoic multi-channel recording of individual string quartet musicians" [9]. Fortunately, microphone placement in the work follows a dodecahedron geometry, allowing us to only remap audio channels for instrument directivity reproduction. While this allows to *walk* in the string quartet, it also allows exploration of alternative quartet dispositions.

4.4 Artistic installation

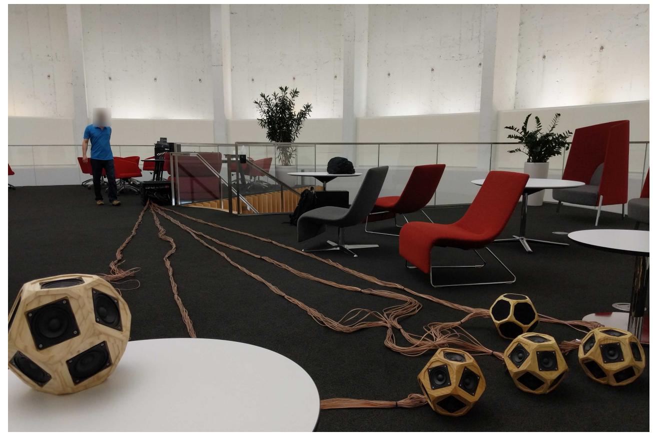
Finally, artistic use of the Audiodice system enables new approaches to spatial audio composition. Three artistic residencies and a 2-day hackathon have been conducted using the system. Several ideas were developed, but all approaches included speaker placement as part of the artistic process and, more particularly, participant walkarounds.

Here follows a description of various approaches to spatial audio composition with the Audiodice 60 channels:

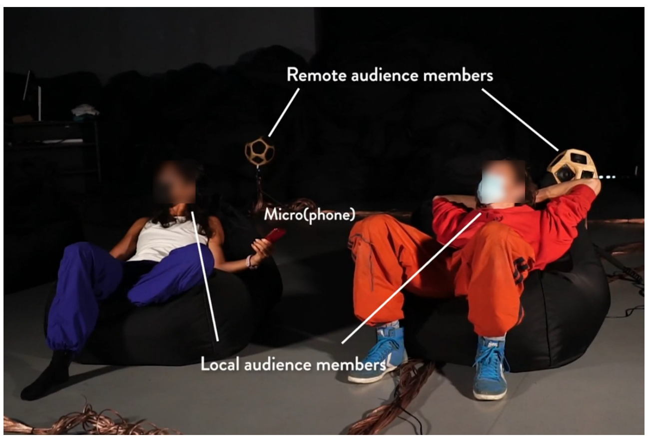
- Use of granular synthesis with random placements for each grain over the sphere channels. This, applied to a microphone with a delay, provides a user-contributed and generative sound field. Figure 6d is a picture taken of this installation.
- Use of the Distance-Based Amplitude Paning algorithm [12], applied to all 60 drivers in order to compose trajectories of sound objects

[7] https://vimeo.com/519940468 (visited May 2023)
[8] A video demonstration is accompanying the paper and is available at https://vimeo.com/697114857 (visited May 2023)
[9] A demonstration video is available here: https://vimeo.com/664359535 (visited May 2023)

(a) The Audiodice use as a near-field rendering device in complement to a 31-channel dome speaker device used for far-field audio display.



(b) Multipoint impulse response measurement with the Audiodice for impulse response based interpolation navigation in an acoustic field.



(c) Spherical speakers used as tangible avatars for hybrid interaction among remote and present participants.

(d) Audio installation in a medium-scale room, involving a microphone that provides audio for an artistic per-channel spatialization with the Audiodice.

Figure 6: Four use cases implemented with the Audiodice.

- Use of each sphere for sonification of a particular data dimension. In this case, navigation enabled pattern listening of specific data dimensions as well as experiencing the existing harmony among these dimensions by choosing the listening location among the speakers.

5 DISCUSSION ON USE AND REUSE

The several projects we conducted have provided subjective feedback about use, perception, quality improvement, and reusability. They are provided here and remain informed by the different approaches employed during both creative and technical uses.

In terms of audio display, the use of a cluster of multichannel speakers came with several lessons learned and ideas:

- Similarly to the feedback provided with the IKO-related research mentioned in the paper introduction, the contribution of room acoustics and room reflections in the spatial audio rendering is significant. For instance, our lab is located in a brutalist building with very reflective concrete. This provides us with a rich reverberated sound field in which, in turn, window reflections are sometimes perceived as a sound source. Although this provides a hard-to-control location of the wanted sound source in the sound field, we found that this elegantly integrates the diffusion space into the experience. We never experienced a similar perception of depth with audio display, either with dome multispeaker systems or with elaborated Wave Field Synthesis audio displays.
- With artistic installations employing per-audio-driver rendering developed with the Audiodice, we noticed that walking around the spherical speakers provided a continuously evolving sound field, providing each location with a specific spatial rendering. This contrasts with the usual notion of a "sweet spot" that is present in most surrounding SAs. This was made particularly obvious when we combined surrounding SAs for *far field* rendering with the Audiodice for *near*

field: moving into the space provided the feeling of a walk into a very large soundscape with the opportunity to listen to your ears.
- Scenographically, audio speakers are brought into the participant's space and encourage listeners to explore the sound field by moving or to remain static and experience the unique perspective brought by the given location.
- The assignment of sound sources or instruments to each spherical speaker allows for experiencing a specific placement and provides an unusual way of listening to music since the audience is usually put in a distance, both when musicians are on stage and when music is listened to in an already pre-determined (spatial) mix. In addition, the characteristics enable exploration of alternative sound source placements, such as string quartets, that could be of interest during various steps of composition or experience design.
- The availability of 60 channels provided sound field creators with an important spatial resolution that raised questions about the creative process and spatialization. Among them, let's mention the implementation of sound trajectories inside the listening space, the implementation of a Leslie speaker, the use of ambisonics, or the use of multichannel captured sound fields.
- The availability of five multichannel spherical speakers driven by a single computer provides, to our knowledge, an unprecedented playground for a new approach to spatial audio composition.

Finally, all these projects were temporary installations, including outside our laboratory, lasting from 1 day to 1 week. We needed approximately 30 minutes to set up the entire device and a little less to wrap it up. Most of the remaining set-up time was dedicated to adaptation of the installation to the expected scenography and adaptation to the room, including positioning the speakers according to the room acoustics. Despite the prototypical nature of the system, we were still able to conduct the experiments and installation in spaces that were not previously prepared for spatial audio.

6 FUTURE WORKS AND CONCLUSION

We presented the Audiodice, a *radiating* speaker array we built from scratch. It is composed of five spherical speakers, each composed of 12 independent channels. We introduced and open-sourced the design, along with a correction filter. According to our own listening test, the correction method provided surprisingly good results, which we shared as a video demonstration accompanying this paper.

Then, we employed the prototype in a variety of use cases that demonstrated the versatility of the Audiodice speakers. Interestingly, we observed that it could achieve near-field and far-field audio sensations when our prototype system is combined with a surround speaker array system. Other use cases demonstrated the new possibilities offered, including the use of speakers as *tangible audio avatars*, and custom spatial audio rendering methods informed by artistic projects.

With the implementation of several use cases, we demonstrated that the Audiodice is an easy-to-deploy spatial audio device with a fairly high resolution given its 60 independent channels.

Since we implemented all the use cases, we are facing a growing demand to access the Audiodice for artistic residencies, including requests for touring installations. However, the prototype remains fragile, which led us to investigate the creation of a more robust set. The new design will have the same dodecahedron shape with slightly bigger drivers and an equivalent DA box. Each driver will have its own 3D-printed enclosure and an aluminium front plate. This will allow a better separation of the sound in a multi-directional mode, and we anticipate a more accurate sound reproduction. Those 12 enclosures will combine into a dodecahedron shape, with two connectors to power the 12 drivers and an adaptable mounting system. The DA box will have an equivalent 2x32-channel DAC, but 5x12-channel power amplifier instead of a 4x16-channel one. All this added modularity will also greatly improve the repairability of the speaker system.

Future works will include authoring tools to drive this type of speaker. Many object-based sound spatializer methodologies assume only surrounding speaker arrays and personal speaker systems. We plan to develop spatial audio algorithms that will take into account the specifics of radiating speaker array, and more particularly when operating in combination with *sourrounding* one. One of our use case (cf: 4.1), a prototype of mixing a multi-person dome-shaped speaker array combined with the Audiodice, is a preliminary work towards such future works.

Other approaches to authoring will be considered, such as the beam-forming approach proposed through the work around the IKO speaker, which may provide an easier way to control sound source localization when working with object-based spatialization.

Another direction we wish to explore is making the Audiodice an even more modular hardware system. We notice that several use cases only require a subset of the 5 spherical speakers, or even may benefit from more than just 5. We will investigate a design based on a single speaker with a small dedicated DA box driven by an embedded computer such as a Raspberry Pi. This will, in turn, allow embedding authoring tools within the speaker. However, speaker synchronization and streaming will need to be investigated more, but our first investigation using low-latency streaming tools seems promising.

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