The A20: Musical Metaphors for Interface Design

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ABSTRACT
We combine two concepts, the *musical instrument* as metaphor and *technology probes*, to explore how tangible interfaces can exploit the semantic richness of sound. Using participatory design methods from Human-Computer Interaction (HCI), we designed and tested the A20, a polyhedron-shaped, multi-channel audio input/output device. The software maps sound around the edges and responds to the user's gestural input, allowing both aural and haptic modes of interaction as well as direct manipulation of media content. The software is designed to be very flexible and can be adapted to a wide range of shapes. Our tests of the A20's perceptual and interaction properties showed that users can successfully detect sound placement, movement and haptic effects on this device. Our participatory design workshops explored the possibilities of the A20 as a generative tool for the design of an extended, collaborative personal music player. The A20 helped users to enact scenarios of everyday mobile music player use and to generate new design ideas.

KEYWORDS
Generative design tools, Instrument building, Multi-faceted audio, Personal music devices, Tangible user interfaces, Technology probes

1. INTRODUCTION
We are interested in creating tangible user interfaces that exploit the semantic richness of sound. Our research draws from two disciplines: Human-Computer Interaction (HCI) and NIME instrument design. The former offers a number of examples of the use of sound in graphical interfaces, including Buxton et al.'s [2] early work, Gaver's auditory icons [5] and Beaudouin-Lafon and Gaver's [1] ENO system. These systems focused primarily on sound as a feedback mechanism, with an emphasis on graphical rather than tangible user interfaces.

We draw upon HCI design methods, particularly *participatory design* [7][12], that emphasize the generation of ideas in collaboration with users. In particular, *technology probes* [9] engage users as well as designers to create novel design concepts, inspired by the use of the technology *in situ*. This *generative design* approach challenges both users and designers to explicitly question traditional ways of thinking and open up novel design directions. Our goal was to create a technology probe that focuses on the sonic aspects of tangible interfaces, using participatory design to create and explore the possibilities of a working prototype.

We also draw on the *instrument building* approach from NIME, which offers a similar notion of generative design. Musical instruments are developed as open-ended systems that allow the creation of novel compositions and interpretations, while *idiomatic composition* recognizes that limitations are imposed by the characteristics of the system or instruments. We use this instrument building metaphor as one of the foundations for our generative design approach: the limitations of the instrument serve to both define and constrain the design space, with respect to the given research problem.

Figure 1. The A20 is a working prototype of a technology probe for exploring music and sound in a tangible interface.

This paper describes the design and development of the A20 (Figure 1), a polyhedron-shaped, multi-channel audio device that allows direct manipulation of media content through touch and movement, with various forms of aural and haptic feedback. During a series of participatory design sessions, both users and designers used the A20 to generate and explore novel interface designs. The easily modifiable software architecture allowed us to create various mappings between gestural and pressure inputs, producing specific sounds and haptic output. Meanwhile the flexibility of the A20 as an interface allowed users a range of interpretations for any given mapping. The A20 was never intended as a prototype of a specific future system. Instead, we sought to use it as a design tool to explore the potential of music and sound in tangible interfaces. Our participatory design workshops served to both evaluate the A20 itself and to explore novel interface designs, including social interaction through portable music players.

2. RELATED WORK

Since our goal was to maximize the user's ability to explore new forms of interaction, we needed a generic shape that would maximize the user's freedom of expression and could be easily adapted to a variety of types of interaction, preferably through direct manipulation of a topological display. The D20 **Error! Reference source not found.**, co-designed by one of the authors, is a design concept for a visual interface embodied as an icosahedron. An icosahedron is a nearly spherical polyhedron with 20 discrete triangular facets. Figure 2 shows how this shape permits a variety of display options and modes of rotation-based interaction, such as around the *equator*, as slices of a *pie*, or simply as *binary* choices (Figure 2).

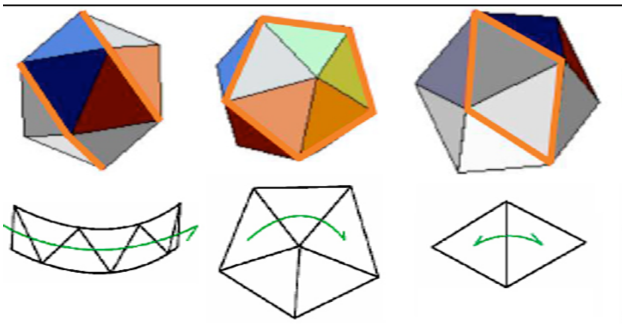

Figure 2. The D20 interaction modes that emerge from three facet patterns: *equator*, *pie* and *binary*

The D20 was created as a design concept, using a computer simulation that emphasized the visual display properties of the icosohedron. We decided to adopt the same form but this time as a functional prototype, focusing on its audio and haptic possibilities.

Several other researchers have created omni-directional spherical sound output devices. For example, Warusfel [17] controls radiation patterns from a single sound source across a spherical matrix. Freed et al. extended this to a multi-channel approach that simulates acoustical instrument propagation [4]. SenSAs [16] add sensors to create a form of electronic chamber music performance. The primary focus of these projects was to recreate multi-directional sound radiation patterns that approach those of acoustic instruments: they create non-frontal forms of amplified sound reinforcement so as to better situate electronic sounds in context with acoustic sources. However, none have used a spherical form factor to play multiple sound sources in the context of end-user music devices such as MP3 players.

The other relevant research relates to generative design methods. For example, cultural probes [6] provide people with unusual artefacts in various settings, with the goal of inspiring novel ideas. The idea is to move from the more classical HCI approach, in which users are viewed as a source of data, and engage in activities in which users become a source of inspiration. Technology probes [9] also focus on design inspiration with users, but in an explicitly participatory design context. Technology probes are founded on the principle of *triangulation* [11] which fulfills three "*interdisciplinary goals: the social science goal of understanding the needs and desires of users in a real-world setting, the engineering goal of field-testing the technology, and the design goal of inspiring users and researchers to think about new technologies*".

Technology probes were originally designed to study human-to-human communication and were tested in the homes of remote family members. Most focused on the exchange of visual information, such as the VideoProbe [9] which snaps a picture from a webcam in the living room – but only if the person does not move for three seconds – and shares it with a VideoProbe in the living room of a remote family member. Another device, TokiTok [10] explored communication via simple sounds: users could transmit 'knocks at a distance', which conveyed simple information such as 'I'm home' but also allowed participants to establish more elaborate codes to stay in touch. However, sound and music have not been the focus of technology probe research thus far.

The A20 project seeks to leverage the complementary aspects of music research and user interface design methods. We use the notion of technology probes to understand users and draw inspiration, but in simulated settings in design workshops rather than in the real world. We also take advantage of techniques from NIME, with the inherently expressive properties of musical instruments, to explore this design space.

3. CROSSING DESIGN TRADITIONS

3.1 IDIOMATIC WRITING AND SEAMFUL DESIGN

Musical instruments are built to be vehicles of expressive communication. An instrument is generic in the sense that many kinds of music can be composed for the same instrument. At the same time, an instrument is idiosyncratic in that it is capable of specific modes of articulation, limited melodic range and harmonic combinations. An instrument is not necessarily designed to have a set of limitations, but a successful musical work must take into account these characteristics. A musical composition that respects and plays upon the idiosyncratic nature and limits of an instrument is considered an example of *idiomatic writing* [15]. This approach to creative musical use of acoustical properties and limitations applied to digital interaction properties is one of the core research areas of NIME.

In the field of HCI, various design methodologies exist to create useable or efficient user interfaces. This can include performance optimization in the technical sense, or taking into account the end-user's needs in the design process as in the case of User-Centered Design. A technique similar to that of idiomatic writing in music exists in HCI, whereby limitations of a technological system are used as part of the design process. This is called *seamful design* [3]. Chalmers argues that accepting all of a system's "physical and computational characteristics [whether they are] weaknesses or strengths" not only offers more robust system design, but may also inspire novel interface ideas.

Composing idiomatic music for an instrument can be considered an act of *seamful design*: we can make a link between making a composition that takes into account an instrument's limitations, and creating an interface that takes advantage of a system's characteristics. In the user-interface design process, seamfulness helps define the *creation* of a design space, while open-endedness helps in *interpreting* the design space. Here we apply the duality of seamful composition and open-ended instrument to create a tool for generative user interface design.

3.2 INSTRUMENT METAPHORS FOR INTERFACE DESIGN

In the development of the A20, we sought an application-neutral approach that would yield a flexible interface. The design of the A20 is not a direct response to specific interface design questions. Instead a metaphor-based conceptual development allowed us to pursue an open-ended process to explore the design space of audio interfaces. We called upon three metaphors from the musical tradition: *instrument building, composition,* and expressivity of *interpretation*.

When building digital musical instruments, unlike acoustic instruments, we must define the mappings between input and output [8]. For a given system specification, we can conceive of many mappings to create a variety of input and output connections. This range of mappings turns the system into a potential family of instruments or corpus of articulations for a given instrument. This contrasts with most user interface design, in which the goal is to find the single optimal mapping of input and output that will create the desired interaction for a specific design problem.

We also draw from the metaphor of musical instrument *composition* which emphasizes expressivity and interpretation. A composition exists as a musical structure that can be executed and re-interpreted in the context of a musical performance. These two metaphors, musical instruments and composition, encourage us to re-examine the traditional user interface design concept of a scenario and redefine it as a compositional abstraction that can be executed on that tool/instrument. In a participatory design process, scenario creation and scenario enacting can be seen as composition and interpretation. These metaphors serve to situate and enrich our interaction scenarios, while also guiding the design specification of the system.

The metaphors of *instrument*, *composition* and *interpretation* correspond to two levels of abstraction of the A20. At the lower level of abstraction, the *instrument* is defined by the hardware specification (form factor, sensors, audio output) and software specification (mapping between input and output). As a design tool, the A20's hardware establishes the first set of constraints for the design space, including gestural and pressure input on the one hand and multidirectional and multi-channel output capabilities on the other hand. The software defines the 'elements of interaction' that turn the A20 into an instrument. For example, the user can create a sound that moves around the device and then make it stop by shaking the device.

The upper level of abstraction comprises *composition* and *interpretation,* which allow the user to play the device in the context of a specific design scenario. Different interpretations can be seen as different instantiations of an open-ended interaction mapping. For example, shaking the device could be interpreted as a gesture to validate playlist creation, to send a song to a friend's device, or an action in a collaborative music game. The expressivity of the resulting instrument allows a wide range of interpretations and instantiations for different design questions. The software that defines the A20's interaction is highly flexible, which enables us as user interface designers to invent and invite users to 'play' a diverse set of instruments and understand both the problems and potential of each.

4. A20 INSTRUMENT DESIGN

4.1 Hardware

The first version of the A20 was a simple cube, which helped us to develop the software for integrating sound-processing and sensor data. The second version was an icosahedron, which we used in our studies with users.

Figure 3: The A20 frame (left) consists of 20 triangles, 16 of which hold flat speakers. Transducer and Force Sensing Resistors (right) fit under each speaker.

Figure 3 shows A20's frame on left, built with rapid prototyping stereo-lithography. An audio interface and sensors were housed within the structure (Figure 3, right). The icosahedron had 14 cm edges, resulting in a diameter of approximately 22 cm. We attached commercially available lightweight flat-panel loudspeakers along the outside of the frame, with each panel cut to a triangular shape. The assembled, working version can be seen in Figure 1.

The sixteen flat speakers are driven independently with two USB 8-channel 16-bit sound cards with a 44.1 kHz sampling rate. Thus, only 16 of the faces are able to display independent sound. Sensors include a Bluetooth Six-Degrees-Of-Freedom (6DoF) inertial sensor pack with a triaxial accelerometer and a triaxial gyroscope for rotation [18]. Force Sensing Resistors (FSR) are integrated under each speaker transducer, with a 10-bit analog-to-digital conversion processor on a separate micro-controller-based acquisition board[1]. The micro-controller acquires the pressure sensor data with 12 bit resolution which is then sent over a standard serial port. Figure 4 (lower box) illustrates the hardware architecture.

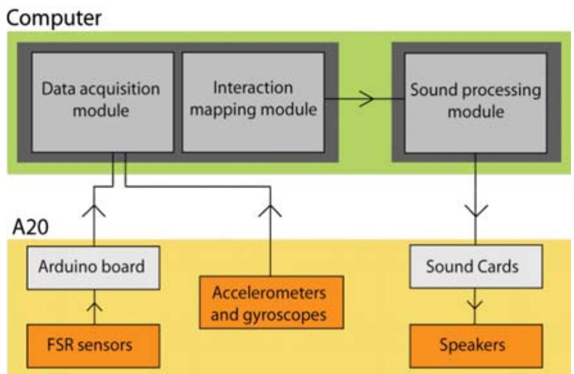

Figure 4. A20 hardware and software architecture

4.2 SOFTWARE

The software architecture is based on a client/server model and consists of: sensor acquisition and interaction mapping modules and an audio engine, shown in Figure 4 (upper box). The data collected from the A20's sensors is broadcast to a control module on the computer, which integrates the sensor data and

[1] *www.arduino.org*

defines the interaction mappings. A second module is in charge of audio processing and sends data back to the A20. Both modules communicate via Open Sound Control[2]. We chose the UDP protocol for its efficiency in time-sensitive applications.

The A20 interaction mappings are implemented in C^{++} as a server process that aggregates data from the accelerometer, gyroscope and pressure sensors. We used the OpenGL graphics library to program a visual representation of the physical prototype for debugging interaction mappings and to accelerate matrix operations during real-time sound mapping on the device. We vectorized sound location across the surface of the icosahedron in a way similar to Pulkki's work on vector-based sound positioning [13]. Vector-based audio panning extends the principle of stereo panning with an additional dimension, making it useful when the listener is not fixed at a sweet spot or in cases where sound distribution includes a vertical dimension.

In the control software, 3D vectors represent sound sources. The origin of a 3D coordinate system is the center of the object, in this case, the center of the A20. Each face and corresponding speaker is represented by a vector from that origin to its center. The control software outputs, in real time, a vector angle for each sound source. The audio engine can then calculate amplitude levels given the angular distance between the vectors representing the sound sources and those representing the speakers. The control software dynamically calculates the source vectors, resulting in sounds moving across a series of faces. After audio processing, this results in a gradual multidimensional panning between those two faces, giving the impression of sound moving across the surface of the object.

This software can be adapted to a range of different shapes. The vectors representing the faces are computed according to the number of speakers and their placement. The audio engine is then configured with the proper number of speakers and data relative to their output capabilities, such as physical size and amplitude range. Thus the same software works for the original cube-shaped prototype and for the 20-sided icosahedron.

The audio engine is written in Max/MSP and is divided into two parts. The main control program is the master of two slave patches, each controlling a sound card. The audio engine manages multiple sound streams that can be placed on different positions on the device according to location attributes sent by the control software. This software allows us to use synthesized sounds as well as samples of recorded music in MP3 format. Post-treatment algorithms are applied to achieve acoustical effects from the real world. For example, Doppler shift changes the sound pitch as it moves closer or further, and filtering effects change the sound timbre as the sound moves behind obscuring objects, thus enhancing the effect of sound movement around the device.

5. EVALUATION

In order to evaluate the A20, we invited non-technical users to the third in a series of participatory design workshops. The first two sessions, not reported here, focused on an interview-based exploration of existing personal music player usage, and structured brainstorming on communicating entertainment devices, respectively. Evaluation of the A20 was comprised of two activities. The first type of evaluation focused on its perceptual characteristics as a multi-faceted multi-channel audio device. The second type of evaluation used the A20 as a technology probe and an instrument, to inspire and explore different forms of interaction with a tangible audio device.

5.1 Multi-faceted Audio Perception

The purpose of the first set of tests was to assess the users' ability to perceive different modes of audio display on the A20, including their ability to perceive sound position, motion around the device, and haptic patterns. We also wanted to familiarize them with the A20 so they could participate in the second set of participatory design exercises.

Figure 5. Testing how a user perceives the A20

We asked 16 participants to perform a set of tests, in individual sessions lasting approximately 10 minutes each. Each participant was given the A20 (Figure 5) and asked to perform the following tasks:

Test 1: Localizing Sound
Impulse sounds were played randomly on one of the facets and the participant was asked to identify the source facet without touching the A20. (Repeated five times.)

Test 2: Detecting Direction of Movement
An impulse train was panned around the equator of the device to simulate a moving sound source with a circular pattern. The participant was asked to identify whether the direction of movement was clockwise or counter-clockwise, without touching the A20.

Test 3: Distinguishing Static from Dynamic
We combined the first two tests to determine whether the participant could distinguish a moving sound from a static sound. The participant was presented with four conditions: two static sounds were played (derived from Test 1) and two moving sounds were played (counter and counter-clockwise) in a counterbalanced presentation sequence.

Test 4: Distinguishing Haptic Stimuli
We combined the auditory and haptic channels to create various combinations – some where the two modes were synchronous, reinforcing perception of a single source, and others that presented two distinct sources, one in each modality. The haptic channels were presented on the lateral faces under the participant's hands whereas the auditory channel (a musical excerpt from a well-known pop song) was presented on the 'pie' zone at the top of the A20. In some combinations, the haptic channel corresponded to the music being heard, while in others the haptic and audio stimuli were independent. The participant was asked to indicate whether or not the haptic and audio signals were the same. In cases where the haptic signal was derived from the music, several variations were made to bring more or less of the music into the haptic range. This included generating the haptic signal from the amplitude envelope of the music, or low-pass filtering the music before generating the corresponding haptic stimulus.

[2] *www.opensoundcontrol.org*

Test 5: Distinguishing Haptic Stimuli
Participants were asked to hold the A20. We generated two different haptic stimuli, one under each hand. These were low frequency vibration patterns that were not in the audible range (using pulse width and frequency modulation). The participant was asked whether or not the two patterns were the same. For each task, trial order was counterbalanced across participants.

5.2 Results

Figure 6 shows the results of each of the five tests. Participants were reliably able to locate the position of a sound on the device (Test 1, 85% accuracy), to detect the direction of motion (Test 2, 77% accuracy) and to perceive whether the sound was moving or not (Test 3, 79% accuracy). However users had greater difficulty determining whether the haptic stimulus under their hands was a filtered version of the music being heard (Test 4, 69% of accuracy). Participants were particularly successful in distinguishing among haptic stimuli (Test 5, 91% accuracy).

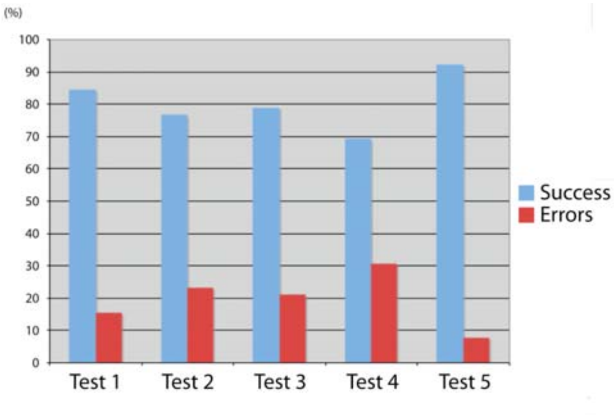

Figure 6. Results of simple perception tests

5.3 Participatory Design Workshop

We organized the workshop into four major design activities. The first asked participants to create personal scenarios that address the theme of mobile social interaction through music. The second and third activities were conducted in parallel. In the second activity, small groups collaborated on creating a scenario that combined and deepened the individual scenarios from activity one. During this time, we invited individuals to test the A20, as described in the previous section. When all the members of a group had completed individual perception tests, we used the A20 as a design tool to help each group imagine novel interaction scenarios. We implemented three interaction mappings that allowed participants to play with thee different forms of gesture-based interaction:

1. Flick the A20 left or right to change the current music track playing on the top of the device.
2. Press on a facet to make a sound rotate around the equator, starting from the pressed speaker and then fading away.
3. As the user physically turns in a circle, compensate by panning the A20 so that the music stays fixed relative to the surrounding space.

The fourth activity (Figure 7) asked pairs of participants to create a meta-scenario that incorporated their newfound interpretations of A20 interaction mappings and design a user interface that exploited its sound properties. The resulting scenarios were sketched out on storyboards, acted out, and videotaped.

Figure 7. Working with cardboard mockups and drawing storyboards to illustrate shared scenarios.

5.4 Results

One of our constraints was that we had only one working prototype of the A20, which meant that participants played with it at different points in their design exercises. However, this enabled us to observe how the A20 affected their designs, and compare designs from those who experienced it early or late in their design processes.

As one would expect, people had various interpretations of the A20 and incorporated its features differently into their designs. Some were directly influenced by the interaction elements that they experienced in the perceptual tests. For example, one group's concept emerged from the first interaction mapping: They extended the idea of flicking the A20 to navigate through sounds and created a collaborative music game. One user would perform a succession of back-and-forth flicks to create a sound sequence. The remote player would then execute the same sound sequence, adding one new sound at the end. As they play, the sequence becomes successively more difficult to master, until one player cannot reproduce the sequence.

Another group imagined a file browsing technique that involved manipulating the sound source directly. This exploited the whole-object interaction and audio-only nature of the A20. One participant applied this functionality to common MP3 players by adding gestural input and spatialized sound. This modified the concept of the playlist so that it was no longer a textual representation of the music, but the music itself, sequentially laid out across the faces of the A20.

The second interaction mapping allows users to send a sound around the equator of the A20, so that the sound moves from the pressed face to its opposite face. Although presented only as an abstract interaction element, several participants seized upon the idea of generating sonic feedback when sending a music file to someone else. One participant imagined a scenario that combined the second and third interaction mappings. He would turn physically in space with the A20 so as to orient himself with respect to his distant correspondent, effectively associating a physical person in real space to the topology of the A20. He would then select a piece of music from a particular face to share with the other person.

The third interaction mapping inspired another group to propose a device that acts like a sound memory compass: *"The A20 can be a recorder for use while traveling, to capture impressions from different places. Each face saves a sonic snapshot from a place I visit."* They attached sounds to virtual objects in the environment and proposed navigating through this collection of objects by pointing the A20 in different directions in the space.

Other users imagined scenarios that exploited the A20's form factor. For example, one group proposed throwing the A20 "*like a die onto the floor*", which would turn on shuffle mode and "*fill the living room with sound*". Another group proposed using groups of A20's like stackable bricks, to create a variety of different sound or music effects. These examples illustrate some of the richness and innovation of the ideas generated by non-technical users, which go far beyond the creativity we saw in previous workshops, when they had no specific instrument on which to play and explore ideas.

6. CONCLUSION AND FUTURE WORK

Our goal has been to use the expressivity and open-endedness typical of musical instruments to create generative design tools, encouraging both users and designers to imagine new interfaces using the evocative richness of sound. In workshops, users experienced, tested and explored design ideas, immersed in the context provided by the workshop theme and the A20's specific sound characteristics. We feel that the A20 successfully acted as an expansive platform for generating and exploring new sound interaction ideas.

The icosahedron form served as a generic interface that could be reinterpreted in different ways. The A20 constrained the design space to gestural input and multi-directional sound output and the idiosyncratic form factor influenced some participants' scenario interpretations. However, since the sound control software can be easily adapted to work on other form factors, different shapes could be used depending upon the design questions to be treated, allowing us to transpose on the design space. This could be achieved by creating a wider range of simple forms or even using Lego-like building blocks to create a shape around the multidirectional sound source.

In our future work, we plan to extend the output and networking capabilities of the A20. We found the preliminary perception tests with haptic patterns interesting and we also plan to explore audio-haptic correlation and audio-to-haptic information transitions and add these features to another instrument interface. This would allow user interface designers to take the haptic capabilities of audio displays into account and to further explore the multimodal potential across sound and touch together. We hope to develop a fully wireless lightweight version of the A20 and would also like to add networking features so that multiple A20's can communicate with each other and encourage diverse form of musical collaboration among its users.

7. ACKNOWLEDGMENTS

This project was developed at Sony Computer Science Laboratory Paris. Our thanks to the project interns, Emmanuel Geoffray from IRCAM and Sonia Nagala from Stanford University and to Nicolas Gaudron for the icosahedron structure.

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