The Glass Organ: Musical Instrument Augmentation for Enhanced Transparency

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Abstract. The Organ and Augmented Reality (ORA) project has been presented to public audiences at two immersive concerts, with both visual and audio augmentations of an historic church organ. On the visual side, the organ pipes displayed a spectral analysis of the music using visuals inspired by LED-bar VU-meters. On the audio side, the audience was immersed in a periphonic sound field, acoustically placing listeners inside the instrument. The architecture of the graphical side of the installation is made of acoustic analysis and calibration, mapping from sound levels to animation, visual calibration, real-time multi-layer graphical composition and animation. It opens new perspectives to musical instrument augmentation where the purpose is to make the instrument more legible while offering the audience enhanced artistic content.

Key words: Augmented musical instrument, Augmented reality, Sound to graphics mapping, Real-time visualization

1 Introduction

Augmented musical instruments are traditional instruments modified by adding controls and mono- or cross-modal outputs (e.g. animated graphics) [1, 2]. Augmentation generally results in a more complex instrument (on the player's side) and a more complex spectacle (on the spectator's side). The increased functionality and controllability of the instrument might eventually distort the perceived link between the performer's gestures and the produced music and graphics. The augmentation might confuse the audience because of its lack of transparency. In contrast, the increased functionality could enhance the perceived link.

We agree on the interest of musical instrument augmentation that extends a traditional instrument, preserves and enriches its performance and composition practices. This article focuses on a rarely stressed use of augmentation that increases the comprehension and the legibility of the instrument instead of increasing its complexity and its opacity. Our research on output augmentation follows the work on ReacTable [3], an augmented input for the control of electronic musical instruments. The ReacTable is a legible, graspable, and tangible control interface, which facilitates the use of an electronic instrument so as to be accessible to novices. Its professional use confirms that transparency does not entail boredom and is compatible with long term use of the instrument.

This paper presents the principles and implementation of the Glass Organ, the augmentation of an historical church organ to enhance the understanding and perception of the instrument through intuitive and familiar mappings and outputs. It relies on the following main features:

- the visual augmentation is directly projected on the facade of the instrument (and not on peripheral screens),
- the visual augmentation is aligned in time and space: the visual rendering is cross-modally synchronized with an audio capture and the graphical projection is accurately aligned with the organ geometry,
- the augmentation does not affect the musician's play. It can adapt to traditional compositions and deserves the creation of new artworks,
- the augmentation is designed to gain a better understanding of the instrument's principle by visualizing hidden data such as spectral sound analysis and the spatial information distribution within the large instrument.

The aim of the Organ and Augmented Reality (ORA) project was to visually and acoustically augment the grand organ at Ste Elisabeth church in Paris. This project was funded by the city of Paris program for popular science "Science sur Seine". The aim was to explain in general sound and sound in space, with specifics relating to the context of live performances. Concert were accompanied by a series of scientific posters explaining the background and technical aspects of the project. This project involved researchers in live computer graphics and computer music, a digital visual artist, an organ player and composer, and technicians.[1] ORA has been presented to public audiences through two immersive concerts, with both visual and audio augmentation. On the visual part, the organ pipes displayed a visual spectral analysis of the music, inspired by LED-bar VU-meters. On the audio side, the audience was immersed in a periphonic sound field, acoustically placing listeners inside the instrument. This article focusses on visual augmentation, the audio side is more detailed in [4].

2 Visual Augmentation of Instruments

The augmentation of a musical instrument can either concern the interface (the capture of the performer's gestures, postures, and actions), the output (the music, the sound, or non-audio rendering) or the intermediate layer that relates the incoming stimuli with the output signals (the mapping layer). Since our approach minimizes the modification of the instrument's playing techniques, we focus on the augmentation of the mapping and output layers that can be used to enhance composition, performance, or experience.

[1] In addition to the authors, participants included Nathalie Delprat, Lorenzo Picinali, and Nicolas Sturmel. Videos of the event can be found on `http://www.youtube.com/watch?gl=FR&hl=fr&v=J1YVUtJsQRk` or from the project site `http://vida.limsi.fr/index.php/Orgue_Augmentee`.

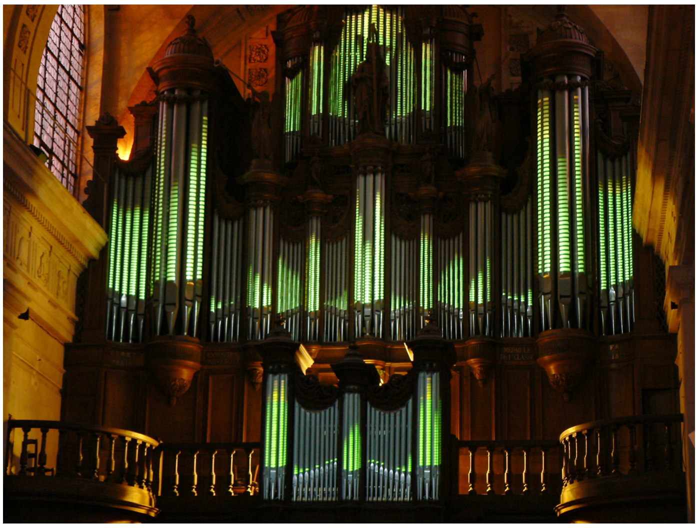

Fig. 1. ORA Concerts, May 15th and 17th, 2008

On the composer's side, Sonofusion [2] is a programing environment and a physically-augmented violin that can be used for performing multimedia compositions. Such compositions are "written" through programing, and are controlled in real-time by the performer through the additional knobs, sliders, and joystick. Whereas this work interestingly addresses the question of multi- and cross-modal composition and performance, it results in a quite complex control system. The variety of control devices yields a multiplicity of possible mappings; therefore, the correlation between the performer's gesture and his multimedia performance might seem arbitrary to the audience at times. Musikalscope [5], a cross-modal digital instrument, is designed with a similar purpose, and is criticized by some users for the lack of transparency between its visual output and the user's input.

On the audience side, the Synesthetic Music Experience Communicator [6] (SMEC) focuses on synesthetic cross-modal compositions that attempt to reproduce some of the visual illusions experienced by synesthetes. When compared with Sonofusion, SMEC has a better motivation for the graphic renderings because they are based on reports of visual illusions by synesthetes. This work however raises the question whether we can display and share deeply personal and intimate perceptions. Is it by displaying visual illusions that we are most likely to enhance the spectators' experience?

Visual augmentation can also address the human voice. Messa di Vocce [7] analyzes the human voice in real-time in order to generate a visual representation and interface used to control audio processing algorithms. The autonomous behavior of the graphical augmentation of voice almost creates an alter ego of the performer. Such an augmentation is less arbitrary than the preceding examples, because it is governed by an "intelligent" program. Within these environments, the spectators are however immersed by a complex story which they would not normally expect when attending a musical event.

3 Artistic Design

Visual Design. The visual artwork was designed to transform the instrument so that it would appear both as classical and contemporary, and so that visual augmentation would contrast with the baroque architecture of the instrument. Church organs are generally located high on the rear wall of the building. The audience faces the altar and listens to the music without seeing the instrument. Even if one looks at the organ, it is rare to see the actual organist playing, resulting in a very static visual performance experience. During the ORA concerts the seating was reversed, with the audience facing towards the organ at the gallery.

The acoustics of the church is an integral part of the organ's sound as perceived by the listeners. Through the use of close microphone capture, rapid signal processing, and a multichannel reproduction system, the audience is virtually placed inside the "organ" acoustic providing a unique sound experience. To outline the digital transformation of the organ music, VU-meters are projected on the visible pipes, making a reference to many audio amplifiers. These VU-meters dynamically follow the music and build a subtle visual landscape that has been reported as "hypnotic" by some members of the audience. The static and monumental instrument becomes fluid, mobile, and transparent.

Sound Effects & Spatial Audio Rendering. The organ is one of the oldest musical instruments in Western musical tradition. It provides a large pitch range, high dynamics, and can produce a great richness of different timbres; hence, it is able to imitate orchestral voices. Due to the complexity of pipe organ instruments, advances in organ building have been closely connected to the application of new technologies. In the twentieth century electronics have been applied to the organ (a) to control the key and stop mechanism of the pipes – the action is electro-pneumatic – and (b) to set the registration, *i.e.* the combination of pipe ranks. However, very little has been achieved so far for modifying the organ's sound itself. The ORA project directly processes the captured pipe organ sound in real-time using a multitude of digital audio effects and renders it via loudspeakers surrounding the audience. Therefore, the sound perceived by the listener is a common product of the pipe organ's natural sound, the processed sound, and the room acoustics. Spatial audio rendering is capable of placing inner sounds of the organ in the outer space, interacting differently with the natural room acoustic, which adds a new musical dimension.

Augmented Organ. Miranda and Wanderley [8] refer to augmented instruments[2] as "*the original instrument maintaining all its default features in the sense that it continues to make the same sounds it would normally make, but with the addition of extra features that may tremendously increase its functionality*". With this in mind, the ORA project aims to enrich the natural sound of

[2] In scientific articles augmented instruments are often called hybrid instruments, hyperinstruments, or extended instruments.

pipe organs through real-time audio signal processing and multi-channel sound reinforcement, to meet the requirements of contemporary and experimental music.

Audio signal processing algorithms require the capture of the direct sound of the instrument. To minimize the effects of the room acoustics, multiple microphones have been placed inside the organ's case (section 4.1). The algorithms consider that separate divisions of the organ have different tonal properties (timbre, dynamics, and pitch range) and often contrast other divisions. The microphone signals are digitally converted via multi-channel audio cards with low-latency drivers; the real-time audio processing is implemented in Pure Data [9]. Selected algorithms include ring modulation, harmonizer, phaser, and granular synthesis. Audio rendering used an 8-channel full-bandwidth speaker configuration along the perimeter of the audience area with the addition of a high-powered subwoofer at the front of the church, at the location opposite from the organ.

In recent years, a variety of multi-channel spatial audio systems have been developed, e.g. quadrophony, vector base amplitude panning (VBAP), wave field synthesis, and Ambisonics. The proposed environment uses third-order Ambisonics for 2D sound projection in space. Ambisonics was invented by Gerzon [10]. While the room acoustic provides reverberation, essential to the sound of the church organ, the presence of early reflections and late reverberation (inherent to the acoustics of churches) deteriorates sound localization accuracy. Different weighting functions, as described in [11], have been applied before decoding to widen or narrow the directional response pattern. However, the sound design mainly deals with the reduced localization accuracy by focussing on non-focused sounds and spatial granular synthesis

Musical Program. The event was designed as an organ concert, with a bit of *strangeness* added by a lively animation of the organ facade and live electronics transformations of the organ sound. The musical program followed the path of a "classical" program mixed with somewhat unusual digital augmentation. Pieces of the great classical organ repertoire (Bach, Couperin Franck, Messiaen) were alternated with a piece in 12 parts especially written by C. d'Alessandro for the event (exploiting the various musical possibilities offered by the sound capture, transformation, and diffusion system).

4 Architecture & Implementation

4.1 The Instrument

The instrument used for these performance is a large nineteen-century organ (listed as historical monument), with three manual keyboards (54 keys), a pedal board (30 keys), 41 stops, with mechanical action. It contains approximately 2500 pipes, of which only 141 are visible in the organ facade. The organ case is inscribed in a square of about 10x10 m. Pipes are organized in 4 main divisions: the "positif", a small case on the floor of the organ loft, corresponding to the first manual keyboard; the "grand orgue" and "pédale" divisions at the main level, corresponding to the second manual keyboard and to the pedal board; and the "récit" division, a case of about the same size as the "positif", crowning the instrument, and corresponding to the third manual keyboard. The "récit" is enclosed in a swell-box.

Five microphones were placed in the instrument divisions according to figure 2 left. These divisions are relatively separate and somewhat sound isolated, so that the near-field sound captured in one region was significantly louder than that received from other regions. Therefore each region could be considered as acoustically "isolated" for sound effects purposes.

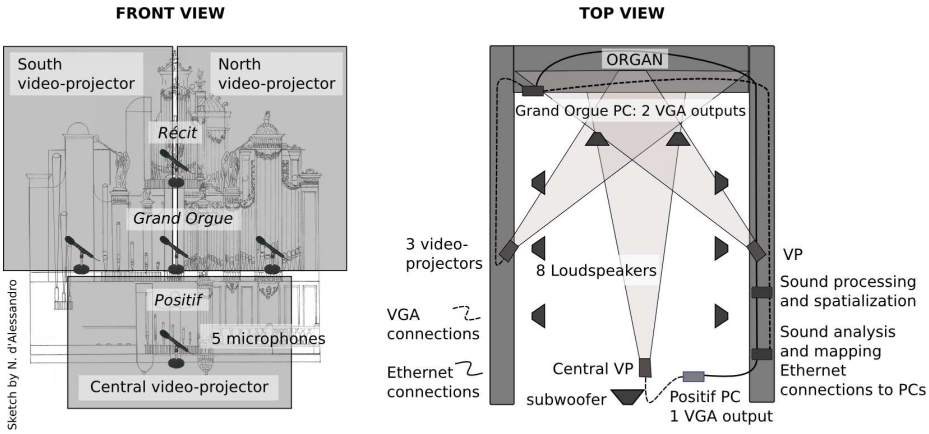

Fig. 2. Architecture of the installation: sound capture and video-projection

4.2 Architecture

Preliminary tests of video projection on the organ pipes showed that the pipes, despite their gray color and their specular reflections, were an appropriate surface for video-projection. The visual graphic ornamentation of the organ was using 3 video-projectors: 2 for the upper part of the instrument and 1 for the lower part (see figure 2 left). This figure also shows the rough locations where the microphones were placed to capture the direct sound of the instrument.

The sound captured inside the instrument was routed to a digital signal processing unit. Within this stage the captured sounds are processed and diffused back into the church as described in section 3. Traditional and contemporary organ music and improvisations were presented during the concerts. Classical organ music was spatialized and the reverberation time of the church was altered, resulting in the organ sound becoming independent from the organ location and the room sounding much larger than the actual Ste Elisabeth church. During the improvisation parts, the captured sounds were transformed and distorted applying real-time signal processing algorithms. As explained in section 4.4, sound spectral analysis and sampling were used to compute the levels of the projected virtual VU-meters. These values were sent to the 3D renderer, and used as parameters of the vertex programs to animate the textures projected on the pipes and give the illusion of LED-bars. The right part of figure 2 shows the location of the video-projectors and the main data connections.

4.3 Graphic Rendering

Graphic rendering relies on Virtual Choreographer (VirChor)[3], a 3D graphic engine offering communication facilities with audio applications. The implementation of graphic rendering in VirChor involved the development of a calibration procedure and dedicated shaders for blending, masking, and animation. The architecture is divided into three layers: initial calibration, real-time compositing, and animation.

Calibration. The VU-meters are rendered graphically as quads that are covered by two samples of the same texture (white and colored LED-bars), depending on the desired rendering style. These quads must be registered spatially with the organ pipes. Due to the complexity of the instrument and its immobility, registration of the quads with the pipes was performed manually. Before the concert began, a still image digital photograph of the projection of a white image was taken with a camera placed on each video projector, near the projection lens. Each photo was loaded as a background image in Inkscape[4] and as many quads as visible pipes were manually aligned with the pipes in the editor. The amount of effort for this work was only significant the first time. Successive registrations (for each re-installation) amounted mostly to a slight translation of the previous ones, since attempts were made to locate the video-projectors in similar positions for each concert. The resulting SVG vector image was then converted into an XML scene graph and loaded into VirChor.

During a concert, the VU-meter levels are received from the audio analysis component (section 4.4) and are transmitted to the GPU which in turn handles the VU-meter rendering. GPU programming has offered us a flexible and concise framework for layer compositing and masking through multi-texture fragment shaders, and for interactive animation of the VU-meters through vertex shader parameterization. Moreover, the use of one quad for VU-meter per visual pipe handeled by shaders has facilitated the calibration process. Frame rate for graphic rendering was above 70 FPS and no lag could be noticed between the perceived sound and the rendered graphics.

Compositing. The graphical rendering is made of 4 layers: (1) the background, (2) the VU-meters, (3) the masks, and (4) the keystone (see left part of figure 3). The VU-meter layer is a multi-textured quad, and the background and mask layers are quads parallel to the projection plane that fill the entire display. Real-time compositing, homography, and control of background color are made through fragment shaders applied on these layers. The keystone layer (4)

[3] http://virchor.sf.net

[4] Inkscape is a vector graphic editor: http://www.inkscape.org

is a quad textured by the image generated by layers (1) to (3). The keystone layer is not necessarily parallel to the projection plane. The modification of the quad orientation is equivalent to applying a homography to the final image. This transformation enables slight adjustments in order to align the numerical rendering with the organ and compensate for any inaccuracies in the calibration phase. This transformation could be automatically computed from views of a calibration pattern [12]. Elaborate testing has shown that the background, VU-meter, and mask layers were perfectly registered with the physical organ, and thus made the keystone layer unnecessary. The mask layer is used to avoid any projection of the VU-meters onto the wooden parts of the organ, and to apply specific renderings through the background layer seen by transparency.

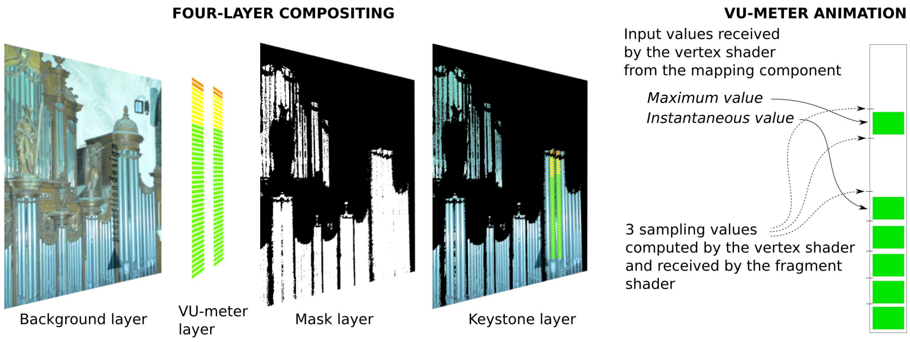

Fig. 3. Multi-layer composition and VU-meter animation through sampling

Animation. The VU-meter layer is made of previously calibrated quads exactly registered with all the visible pipes of the organ. The texture for VU-meter display is made of horizontal colored stripes on a transparent background (42 stripes for each pipe of the Grand Orgue and Récit and 32 stripes for each pipe of the Positif). The purpose of the animation is to mimic real LED-bar VU-meters that are controlled by the energy of their associated spectral band (see next section). The VU-meter levels received from the sound analysis and mapping components are sampled to activate or deactivate the bars. The level sampling performed in the vertex shader and applied to each quad was based on a list of *sampling values*. Considering that the height of a VU-meter texture is between 0 and 1, a sampling value is the height of a transparent interval between two stripes that represent 2 bars. A texture for 42 LED-bars has 43 sampling values. The sampling values are then transmitted to the fragment shader that only displays the bars below the sampled instantaneous value and the bar associated with the sampled maximal value. The resulting perception by the audience is that LED-bars are activated and deactivated.

Each virtual VU-meter receives the instantaneous value and the maximum value for the past 500ms (typical peak-hold function). They are sampled into 3 values by the vertex shader: the instantaneous sampled value, and the sampled values below and above the maximal value. These samples are sent to the fragment shader that displays the texture between 0 and the first sampled value and between the second and third sampled values (see right part of figure 3).

4.4 Analysis & Mapping

This section describes the real-time audio analysis and mapping for VU-meter visualization. Most of the approximately 2500 organ pipes are covered by organ case, while only the 141 of the facade are visible to the audience. As such, a direct mapping of frequency played to visual pipe is not relevant, due to the large number of hidden pipes. In the context of ORA, the main purpose of the correspondence between audio data and graphical visualization was:

1. to metaphorically display the energy levels of the lowest spectral bands on the largest pipes (resp. display the highest bands on the smallest pipes)[5],
2. to maintain the spatial distribution of the played pipes by separating the projected spectral bands in zones, corresponding to the microphone capture regions and thereby retaining the notion of played pipe location,
3. to visualize the energy of each spectral band in the shape of a classical audio VU-meter (as in many audio hardware amplifiers and equalizers). The display was based on the instantaneous value of the energy and its last maximal value with a slower refreshing rate.

Analysis In order to estimate the mapping of sound level values to VU-meter projection, pre-recordings have been analyzed (figure 4). This analysis allowed us to roughly estimate the overall range of the various sections and to cut these spectral ranges into different frequency bands, according to the evolution of the harmonic amplitudes over frequency. The analysis resulted in a maximum spectral range of 16 kHz for the Positif and Récit sections of the organ, and 12 kHz and 10 kHz for the central and lateral parts of the Grand Orgue.

Each spectral band is further divided into subbands corresponding to the number of visually augmented pipes, *i.e.* 33 for Positif and Récit, 20 for the lateral and 35 for the central Grand Orgue. The subbands were not equally distributed over frequency range (warping) in order to gain a better energy balance between low and high frequencies. For re-calibration the energy of the lowest subband (the largest pipe) was used as reference signal.

Mapping The real-time spectral analysis consists of three stages: estimation of the power spectral density for each subband, mapping, and broadcasting over IP. The concert mapping process is described on figure 5.

Power spectral density (PSD). The PSD is estimated via periodograms as proposed by Welch [13]. The buffered and windowed input signal is Fourier transformed (Fast Fourier Transform, FFT) and averaged over consecutive frames.

[5] Since only few pipes are visible, the exact note of a pipe was not necessarily falling into the frequency band displayed on its surface.

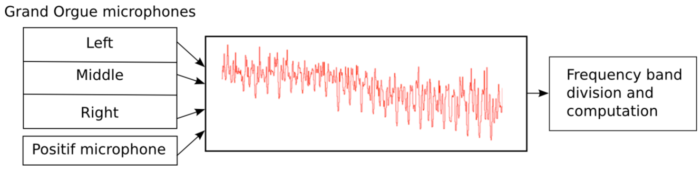

Fig. 4. Spectral sound analysis

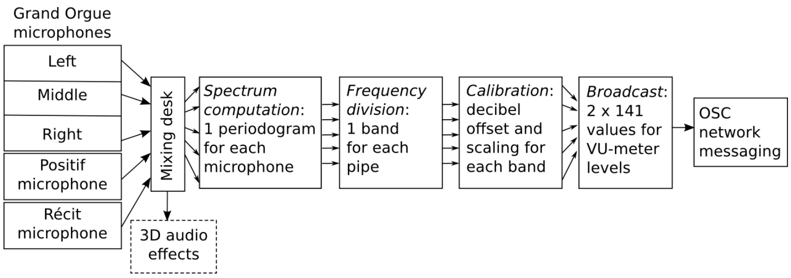

Fig. 5. Mapping between sound analysis and graphics

Assuming ergodicity the time average gives a good estimation of the PSD. One has to note, that through long term averaging the estimated subband levels are not sensitive to short peaks, they represent the root mean square (RMS) value. The decay of the recursive averaging has been set such that the VU-meter values changed smoothly for visual representation. The actual averaging was such that every incoming frame was added to the last three buffered frames.

Frequency band division. These periodograms are then transmitted as five 512 point spectra in order to correct the spectral tilt. The second part of the processing performs the division of the Welch periodograms into 141 frequency bands. Since the number of visible pipes in each section of the organ was inferior to 512 (resp. 33, 20, 35, 20, and 33) an additional averaging must be made in order to map the whole frequency range to the pipes of the organ. According to the spectral tilt, lower frequency bands (app. below 1.5 kHz) had more energy, thus only 3 frequency bands were added for the biggest pipes, whereas up to 30-40 bands were added for the highest frequency range (app. above 8 kHz).

Calibration. The third and most critical part is the calibration of the VU-meter activations through a scaling of the frequency band dynamics to values ranging from 0 to 1. The null value corresponds to an empty VU-meter (no sound energy in this frequency band), and 1 to a full VU-meter (maximum overall amplitude for this frequency band). To calibrate the output, so that 0 would correspond to no sound, we applied the pre-calculated decibel shifts computed from frequency band analysis of the initial recordings. The 1 value corresponds approximately to a 30 dB amplitude dynamic in each frequency band. After the shift, a division by 30 is made so that every VU-meter would vary from the lowest to the highest position on the associated organ pipe during the concert.

This method raised the following difficulties:

1. for each session, the microphones were located in a position slightly different from the preceding one, thus slightly changing the various amplitude levels due to the close proximity to different pipes,
2. the mixing desk dealt with both audio effects and mapping, and due to the slight presence of feedback between microphones and loudspeakers, maximum levels were configurated according to the 3D audio composition part for every concert. This turned out to change the offsets of the VU-meter calibration for each concert,
3. the dynamics of the pipes depended on the loudness of the concert pieces. These variations resulted either in a saturation or in a lack of reaction of the corresponding VU-meters,
4. the electric bellows system for pressurized air supply for the organ generated a low-frequency noise,
5. even though the microphones were inside the organ, there was some interference between the sound of the instrument and the sounds inside the church (audience applause and loudspeakers). Some of the spectators noticed the action of their hand claps on the visualization, eventually using this unintended mapping to transform the instrument into an applause meter.

To cope with these problems, before the beginning of the concert, approximately half an hour was devoted to the manual correction of the different shifts for each pipe, with the air pressurizer switched on. In order to deal with the variations of dynamics between the concert pieces, we decided to monitor the dynamics of each organ section with a slider. Last, the applause effects were cancelled through a downward shift of all the section sliders after each piece.

Broadcast. The third and last part of the process was the concatenation of all frequency band values into a list. Values were scaled between 0 and 1 and doubled, in order to give the spectator the impression of a real VU-meter with an instantaneous value and a peak-hold maximum value. Hence two lists of 141 values were sent to the visual module through ethernet (current frequency bands amplitudes and corresponding last maxima).

5 Perspectives

Technically, the geometrical and musical calibrations could be improved and automatized. By equipping the instrument with fiducials, the quads could be automatically re-aligned with the organ pipes if the video-projectors are slightly displaced. On the mapping side, the background noise detection could be improved by automatically detecting the decibel amplitudes of the different frequency bands and calibrating the lowest values of the VU-meters. Automatic individual maximum detection would allow for amplitude calibration so that the VU-meters take the full range of graphical animation during the whole concert.

The ORA project has shown that the audience is receptive to a new mode of instrument augmentation that does not burden the artistic expression with additional complexity, but instead subtly reveals hidden data, and makes the performance both more appealing and more understandable. This work could be extended in several directions. First, graphical ornamentation could be applied to smaller and non-static musical instruments by tracking their spatial location. Second, graphical visualization could concern other physical data such as air pressure, keystrokes, or valve closings and openings that would require more sensors in the instrument than just microphones. Visualization could also concern the fine capture of ambient sounds such as audience noise, acoustic reflections, or even external sound sources such as street noise.

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