Asymmetrical Envelope Shapes in Sound Spatialization

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Abstract — **Amplitude-based sound spatialization without any further signal processing is still today a valid musical choice in certain contexts. This paper emphasizes the importance of the resulting envelope shapes on the single loudspeakers in common listening situations such as concert halls, where most listeners will find themselves in off-centre positions, as well as in other contexts such as sound installations. Various standard spatialization techniques are compared in this regard and a refinement is proposed, which results in asymmetrical envelope shapes. This method combines a strong sense of localization and a natural sense of continuity. Some examples of pratical application carried out by Tempo Reale are also discussed.**

I. Simulations and Patterns

Most contemporary research on sound spatialization focusses on the simulation of other spaces rather than the actual physical listening space. The idea of placing "an arbitrary (possibly time-varying) location within an illusory acoustic space that we hear but do not see" [1] was pioneered by John Chowning [2] and can be found nowadays, for instance, in the sophisticated "holographic" techniques of wave field synthesis [3, 4]. This concept tries to "hide" loudspeakers as much as possible from the listeners, in order to create convincing virtual sound locations.

On the other hand, composers may wish to use loudspeakers as "instruments" and create interesting spatial patterns between them. This approach might be defined as pattern-oriented as opposed to simulation-oriented. The authors have developed a spatialization system which originated in live electronic productions by the Italian composer Luciano Berio. His use of electronic spatialization seems to be a natural extension of the principles of his instrumental writing, where "identical notes or similar figures pass between groups that are similar in timbre, but separated in space" [5]. In this kind of musical context, a homogeneous sound quality and sonic presence is important. Spatial movements should be achieved by purely amplitude-based methods, without altering the signals using techniques such as delay, reverberation or filtering, which are generally involved in the simulation of spatial depth.

The problem of a more or less small privileged listening area (sweet spot), which characterizes simulation-oriented spatialization systems, is less relevant in a pattern-oriented approach, although patterns are usually also more evident from a central listening position. In any case, it is useful to consider not only the privileged central perspective, but to analyze what actually happens in off-centre listening positions, where the effective envelope shape applied by a spatialization algorithm to a single loudspeaker located close to the listener becomes perceptually significant.

II. Comparing Spatialization Methods

There are some advantages and disadvantages of common amplitude-based spatialization techniques that will be examined by comparing one of the most simple trajectories, a regular rotation on a circular octophonic loudspeaker setup.

In classical amplitude (or intensity) panning, transitions between adjacent loudspeakers are controlled by curves that provide a constant intensity [6]. This obviously creates a symmetrical envelope beginning at the peak of the previous loudspeaker and ending at the peak of the following one (Fig. 1). While this method works fine in a central listening position, and is also acceptable for slow movements in off-centre positions, it creates an undesirable effect of artificial interruption on the single loudspeakers when the movement becomes too fast.

Whereas the rising envelope shape is tolerable for the listener, the fast decay and the following zero amplitude have a rather disturbing quality. Belladonna and Vidolin noted this very early [7] and implemented a generic "offset" in their spatialization system (spAAce). Instead of returning to zero amplitude, a low offset amplitude is kept continuously on all speakers (Fig. 2). An interesting analogy can be observed in an implementation of the same trajectory using Ambisonics. In this spatialization technique, a sound field is constructed from directional and omnidirectional components of a previously encoded signal [8, 9]. Ambisonics implies modulations of amplitude and phase on each loudspeaker. Fig. 3 shows only the amplitude variations: depending on the weight of the omnidirectional component of the encoded signal, rather "blurred" envelope shapes are generated that never actually return to zero amplitude.

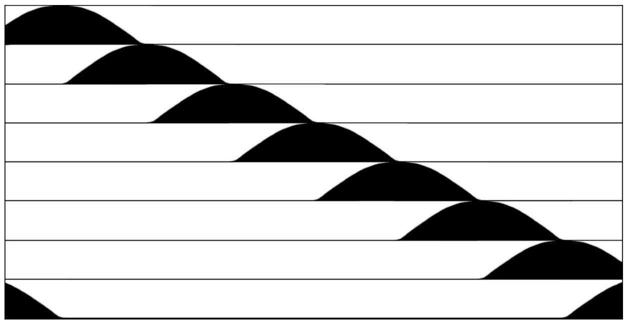

Fig. 1. Envelope shapes in classical amplitude panning.

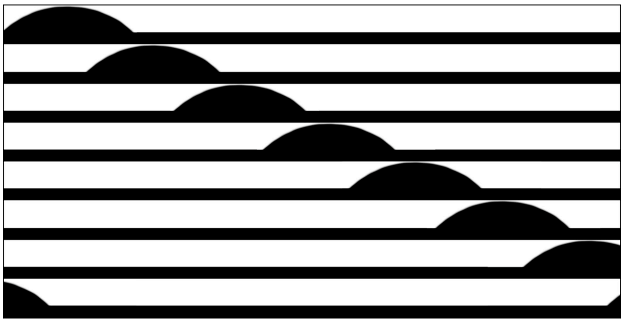

Fig. 2. Amplitude panning with offset.

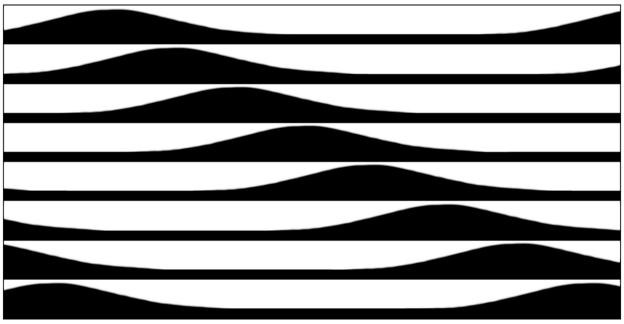

Fig. 3. Amplitude curves derived from Ambisonics.

Both spAAce and Ambisonics avoid the problem of disturbing envelope shapes at high speed on the single loudspeakers, which is typical for classical amplitude panning. But they do so by basically smoothing the movement, and therefore they lose a strong sense of localization. This is due to the fact, that in all these techniques sounds "arrive" at a certain loudspeaker in the same way they "leave" it, generating thus symmetrical envelope shapes.

III. AN ASYMMETRICAL APPROACH

Considering loudspeakers as instruments in a pattern-oriented approach, envelope shapes created by spatialization algorithms can be understood musically as "articulations". In order to achieve a strong sense of localization, the sound on each loudspeaker must be rather accentuated at the beginning, whereas the decay should be relatively long, giving way smoothly to the sound on the next loudspeaker. Therefore, asymmetrical envelope shapes with a well-defined attack and a longer decay are necessary.

At Tempo Reale a set of spatialization objects for use in Max/MSP was developed [10]. These are based on linear interpolations, which in a second instance are rescaled in order to obtain constant intensity. The gain factors G for n loudspeakers are multiplied by a rescaling factor R, which is calculated as:

$$R(G) = \frac{1}{\sqrt{\sum_{i=1}^{n} G_i^2}}$$

For efficiency reasons, R is not calculated at sampling rate, but only once for each MSP signal vector (which can be reduced to a single sample in the current MSP version). Within each signal vector, the interpolation is linear. For basic transitions between two loudspeakers, this generates a light S-like curve which very gradually rises/decays near the extreme values, whereas it is relatively steep at the centre (Fig. 4). From a listening position close to a loudspeaker, this curve is often preferable to the standard square-root or sinusoidal functions used in stereo panning, which are both very steep near zero.

In the Tempo Reale spatialization system, movements are generated by scheduled sequences of lists representing gain values. The interpolation times can be defined individually for each list. Loudspeaker patterns are usually described by pseudo-binary gain values, using "1." for the active and "0." for the non-active speakers. If a pattern has more than one active loudspeaker at the same time, the gain factors are automatically rescaled as described above: a pseudo-binary pattern such as (1. 0. 1.) would generate the effective gain factors (0.71 0. 0.71). Actually, it is possible to choose arbitrary lists of gain factors, as they only represent proportions.

A rotation is simply generated by a sequence of lists scheduled at regular intervals (Table I). It is then possible to create asymmetrical envelope shapes by defining a decay factor for successive loudspeaker configurations, producing a sort of "shadow" of the previous configurations. For each new loudspeaker configuration in Table II, the previous gain values are multiplied by a constant factor d=0.5. This list is then superimposed on the current list by selecting the higher value at each position. Fig. 5 shows the corresponding envelope shapes. Fig. 6 illustrates the envelope shapes obtained by applying different decay factors to the list atoms and rescaling the linear interpolations as described above. In all these cases the curves start rising at the peak of the previous

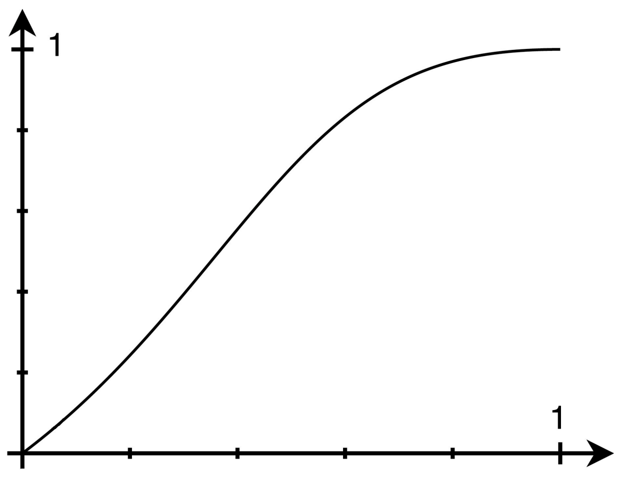

Fig. 4. S-like amplitude curve.

TABLE I.
SEQUENCE OF LISTS FOR A SIMPLE ROTATION.

	spk1	spk2	spk3	spk4	spk5	spk6	spk7	spk8
step1	1.	0.	0.	0.	0.	0.	0.	0.
step2	0.	1.	0.	0.	0.	0.	0.	0.
step3	0.	0.	1.	0.	0.	0.	0.	0.
step4	0.	0.	0.	1.	0.	0.	0.	0.
step5	0.	0.	0.	0.	1.	0.	0.	0.
step6	0.	0.	0.	0.	0.	1.	0.	0.
step7	0.	0.	0.	0.	0.	0.	1.	0.
step8	0.	0.	0.	0.	0.	0.	0.	1.
…								

TABLE II.
LISTS FOR A ROTATION WITH A CONSTANT DECAY FACTOR d=0.5.

	spk1	spk2	spk3	spk4	spk5	spk6	spk7	spk8
step1	1.	0.	0.	0.	0.	0.	0.	0.
step2	0.5	1.	0.	0.	0.	0.	0.	0.
step3	0.25	0.5	1.	0.	0.	0.	0.	0.
step4	0.13	0.25	0.5	1.	0.	0.	0.	0.
step5	0.06	0.13	0.25	0.5	1.	0.	0.	0.
step6	0.03	0.06	0.13	0.25	0.5	1.	0.	0.
step7	0.02	0.03	0.06	0.13	0.25	0.5	1.	0.
step8	0.01	0.02	0.03	0.06	0.13	0.25	0.5	1.
step9	1.	0.01	0.02	0.03	0.06	0.13	0.25	0.5
step10	0.5	1.	0.01	0.02	0.03	0.06	0.13	0.25
…								

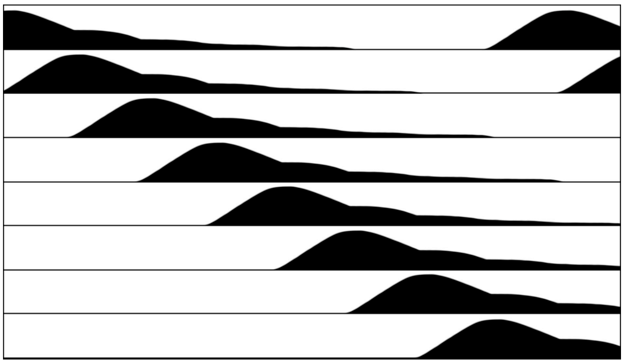

Fig. 5. Envelope shapes generated by the lists in Table II.

loudspeaker configuration, but the decay phase is more or less extended, depending on the decay factor. It can also be seen how the rising curves vary according to the gain amount distributed over the other loudspeakers.

The Tempo Reale spatialization also provides routines for generating symmetrically "blurred" gain distributions in each list, basically by applying a blur factor to adjacent loudspeakers. With a blur factor b=0.5, a list such as (0. 0. 1. 0. 0.) is, for instance, transformed into (0.25 0.5 1. 0.5 0.25). For regular rotations, this method also generates symmetrically blurred envelope shapes in time, rather similar to those of the Ambisonics example discussed above. Both methods (blurred positions and extended decays over time) can be freely combined and may create a great variety of asymmetrical shapes (Table III, Fig. 7).

IV. Some Examples

As mentioned above, the Tempo Reale spatialization system had been initially developed for Luciano Berio's live electronic projects. His approach to spatialization in his late work was extremely pattern-oriented. He developed a notation system in which he basically defined sequences of loudspeaker configurations with holding times (t_p) and movement times (t_m) for the transitions to the next loudspeaker configurations. Fig. 8 shows the notation of a sequence with continuously changing durations of t_p and t_m. Moreover, the number of active loudspeakers in each configuration varies between one and two. Applying the usual automatic rescaling mechanisms and a decay factor, the resulting envelope shapes of such a simple sequence becomes rather complex (Fig. 9). In the current implementation, the decay factor is only applied to the scheduled lists that generate the pattern. Therefore, during the holding times there is no variation of the gain factors left over from the previous configurations (the amounts of "shadow"). This emphasizes the contrast between holding and movement, but of course other implementations, which might generate more continuous decaying envelopes, may also have musical significance. As a strategy in live electronic performance practice, the decay factors are usually decided in the preproduction phase in the studio. As it is often necessary to adapt this parameter to the specific reverberation characteristics of the actual performance space, the performance system used in these productions [11] provides efficient rescaling mechanisms for the decay factors on the level of the single sequence as well as on a global level. This allows a precise adjustment of the envelope shapes during the rehearsals.

In his live electronic projects [5], Berio only once used a classical loudspeaker setup with an octophonic circle around the audience, namely in *Ofanìm* (1988–1997) for female voice, two children's choirs, two instrumental groups, and live electronics. In his works of musical theater *Outis* (1996) and *Cronaca del Luogo* (1999) he experimented with vertical loudspeaker positions. This idea can also be found in *Altra voce* for alto flute, mezzo-soprano, and live electronics (1999), where two diverging diagonal lines of loudspeakers reach from the musicians at the center of the stage to the upper left and right corners of the concert hall. This kind of geometry only makes sense in a pattern-oriented approach to spatialization. The

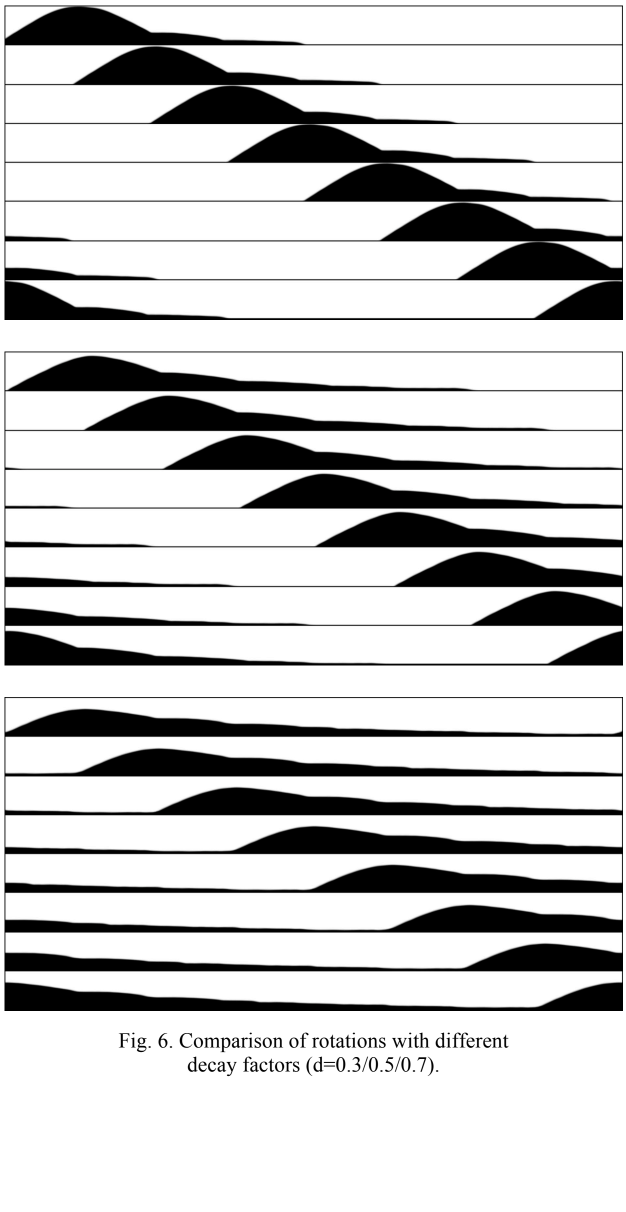

Fig. 6. Comparison of rotations with different decay factors (d=0.3/0.5/0.7).

TABLE III.
ROTATION WITH BLUR FACTOR B=0.4 AND DECAY FACTOR d=0.7.

	spk1	spk2	spk3	spk4	spk5	spk6	spk7	spk8
step1	1.	0.4	0.16	0.06	0.03	0.06	0.16	0.4
step2	0.7	1.	0.4	0.16	0.06	0.03	0.06	0.16
step3	0.49	0.7	1.	0.4	0.16	0.06	0.03	0.06
step4	0.34	0.49	0.7	1.	0.4	0.16	0.06	0.03
step5	0.24	0.34	0.49	0.7	1.	0.4	0.16	0.06
step6	0.17	0.24	0.34	0.49	0.7	1.	0.4	0.16
step7	0.16	0.17	0.24	0.34	0.49	0.7	1.	0.4
step8	0.4	0.16	0.17	0.24	0.34	0.49	0.7	1.
step9	1.	0.4	0.16	0.17	0.24	0.34	0.49	0.7
step10	0.7	1.	0.4	0.16	0.17	0.24	0.34	0.49
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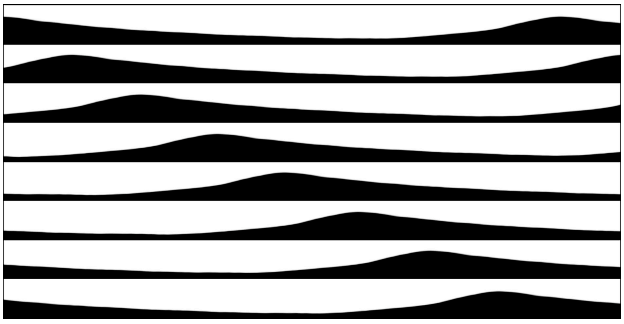


Fig. 7. Envelope shapes generated by the lists in Table III.

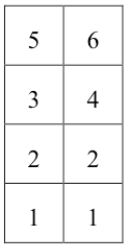
well-defined attacks of the envelope shapes are especially important in this case to make the different diagonal loudspeaker positions distinguishable to our ears.

Apart from concert productions, Tempo Reale is often also involved in projects of sound installation art, like the one realized in 2002 at the new Auditorium in Rome [12]. Only very rarely, there are central listening positions in these works: the visitors are free to move in space, in every position a valid listening experience must be possible. In most of these productions, loudspeaker distributions are chosen to create interesting relationships with particular spatial situations, emphasizing or transforming geometrical properties of an architecture. For instance, in the exhibition "Visible cities. Renzo Piano Building Workshop" (Milan, 2007), Tempo Reale realized a sound installation, entitled *Memory,* with 19 loud-speakers placed in a huge space where the central area was not accessible. The loudspeakers were hanging from the ceiling, forming different paths and listening areas (Fig. 10). Sound movements where mainly structured as linear trajectories of varying length. Even in a position directly underneath a loudspeaker, the transition to the adjacent speaker was clearly perceptible due to the clear attack of its envelope shape. At the same time the decay mechanism provided a smooth fadeout on the loudspeaker above one's head.

V. CONCLUSIONS

The Tempo Reale spatialization system is the result of practical research carried out by a team of and musicians and developers dealing with live electronic projects and sound installations. The basic effort was to overcome psychoacoustical problems of classical amplitude panning in a pattern-oriented compositional approach. Concentrating on the envelope shapes applied to the single loudspeakers signals, and transforming them with the asymmetrical methods described in this article has led to successful psychoacoustical and musical results in a great variety of situations. These strategies can be applied in a standard 5.1-channel surround sound setup, as well as with complex and non-standard loudspeakers distributions. Movements can be appreciated even in listening positions relatively close to single loudspeakers, while retaining a strong overall sense of localization.

The concept of timed sequences of loudspeaker configurations is very easy to grasp and to deal with for composers and sound artists. On the other hand, the resulting envelope shapes can be rather complex and sophisticated, having a precise control over the "articulation" of each loudspeaker by adjusting only two parameters (decay and blur factor). The flexibility of these adjustments is important, as can be understood in analogy to human interpreters: musicians more or less unconsciously change their way of playing, especially tempo, dynamics and articulation, depending on the reverberation characteristics of concert halls and their positions on stage. The possibility of easily modifying the envelope shapes of the spatialization system is a relevant new option for sound diffusion and underlines the concept of loudspeakers as "instruments". Furthermore, the very nature of a pattern-oriented approach is to avoid conflicts between a virtual space and an actual physical listening space, which may have very particular characteristics on its own.



	step	t_p (s)	t_m (s)
	1	6	1
	2	3	1
	3	2	0.5
x3	4	1.5	0.2
x3	5	1	0.2
x3	6	0.5	0.2
x3	5	0.8	0.2
x3	4	0.2	0.2
x3	3	0.4	1
	2	7	1

Fig. 8. Notation of a spatialization pattern by Luciano Berio.

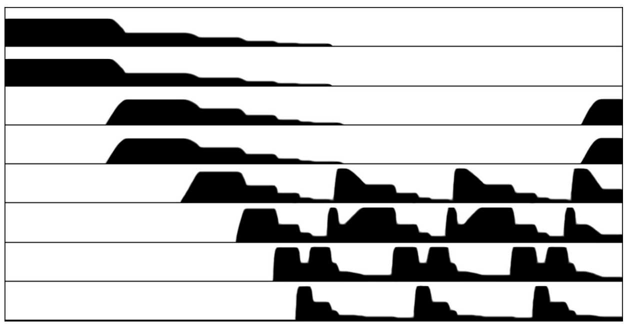


Fig. 9. Envelope shapes corresponding to Fig. 8.

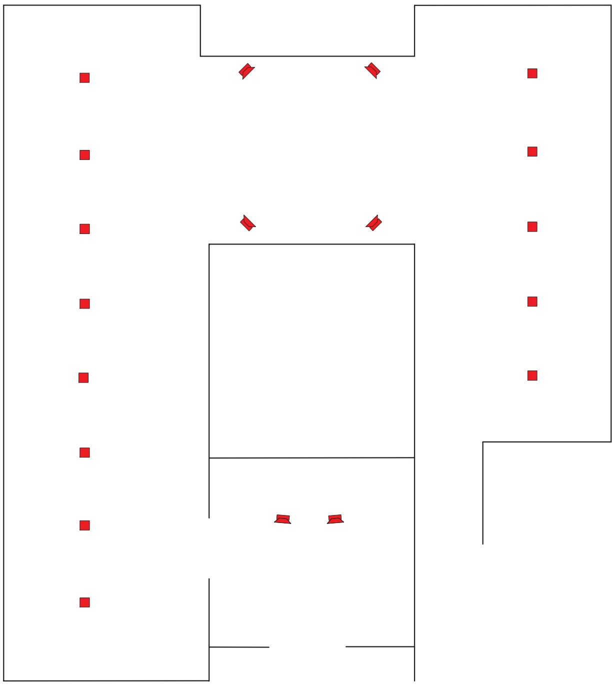


Fig. 10. Loudspeaker configuration for the installation *Memory*, realized for the exhibition "Visible cities" by Renzo Piano.

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