Chapter 6
Conclusions and Future Directions

This thesis showed how simply looking at and/or visualizing HRTF data in different ways can suggest new ways of handling spatial audio and HRTF data. In particular, the present work discussed how different visualization techniques revealed different structures in HRTF data which can be exploited for both engineering and artistic goals.

The main contributions of this thesis are:

1) A visualization study of HRTF data in four different domains: time, frequency, space, and volume. We introduced Spatial Frequency Response Surfaces (SFRS's) and volumetric techniques, along with a custom-built visualization and sonification tool to explore these domains.
2) An analytical treatment for the error analysis of HRTF's measured with complementary (Golay) codes. We showed that the Golay code system identification procedure is fairly robust with respect to additive noise and DC contaminants, but is quite vulnerable to mild time-varying effects due to head rotation during HRTF measurement. We derived, proved the existence of, and gave a concrete example of a class of Golay codes

which, when used as acoustic stimuli for measuring HRTF's, can eliminate all errors in HRTF estimates induced by DC contaminants. We developed a model which explained some artifacts found in i) HRTF measurements made by the author at a custom-built HRTF measurement facility at the Naval Submarine Medical Research Laboratory (NSMRL) Groton, CT, and ii) HRTF measurements made elsewhere in the literature as reported by Pavel Zahorik (Zahorik 2000). We also suggested why these contaminants are not found in HRTF measurements made by another popular procedure involving Maximal-Length Sequencues (MLS's).

3) An adaptive extension to an existing beamforming model for HRTF's which models the ear as an array of spatially distributed sensors. We suggested that an adaptive beamformer could model some of the dymanic properties of human directional hearing, such as a cognitive frequency shift, spatial disorientation, and the "cocktail" party effect.

4) An original HRTF interpolation algorithm which produces perceptually acceptable HRTF's.

5) *Fishbowl*, an original piece of binaural, electro-acoustic music containing moving sound sources synthesized from interpolated HRTF's. We developed several binaural compositional techniques used to realize the artistic goals in this piece, and we documented these techniques with sound examples which can be found on the accompanying CD.

There are many different ways to extend the present work. For example, the hotspot structures found in SFRS's described in Chapter 2 suggest a new way to parameterize HRTF's. Unlike pole-zero and principal components analysis parameterization strategies, modeling the hotspots with appropriate structures such as 3-D Gaussians or spherical harmonics may prove to be more intuitive and perhaps more economical than previous parameterization attempts.

The HRTF measurement techniques in Chapter 3 may also be improved by designing stimulus signals which reduce the amount of error introduced by head rotations. Similarly, although Golay codes were constructed that eliminate errors in HRTF estimates due to DC contaminants, these codes were never used to measure HRTF's from live subjects. Furthermore, it would interesting to perform listening experiments to see if the artifacts discussed in this chapter affect the perceptual quality of HRTF's. Other HRTF measurement techniques could be explored as well, such as measuring HRTF's by requiring the subject to move his/her head during system identification.

The beamforming work in Chapter 4 could be extended by designing a spatial array which more closely matches beampatterns suggested by SFRS's across several frequencies instead of only one frequency. The beamformer geometry and the adaptive algorithm could be better fine-tuned to produce better results.

Although the HRTF interpolation algorithm in Chapter 5 produces acceptable HRTF's, it is necessary to perform a comparison between this and other HRTF interpolation algorithms to evaluate its relative performance. The present algorithm is also fairly compute intensive, and deriving a fast algorithm to accomplish real-time interpolation is necessary if the algorithm is to be used in practical sound spatialization systems. Finally, the electro-acoustic musical technique discussed in Chapter 5 can be expanded to explore different kinds of sounds and other forms of “modulations” between different spatial trajectories.

Head-Related Transfer Functions (HRTF’s) and directional hearing are currently very fashionable topics of research. Psychoacousticians, engineers, defense contractors, video game designers, hearing aid specialists, musicians, and even cellular phone technologists all have very different agendas for spatial audio. Accordingly, the current widespread interest in HRTF’s may be due to the fact that HRTF’s are an exceptionally rich and flexible set of data, and that they can be interpreted and used in so many different ways. Thus, as industry dreams up new applications for spatial audio, researchers must keep pace by providing more creative means to interpret, process, apply, and ultimately understand HRTF’s.