氏名	松村友哉（まつむらともや）
博士の専攻分野の名称	博　士（情報科学）
学位記番号	第　２２１５０　号
学位授与年月日	平成 20 年 3 月 25 日
学位授与の要件	学位規則第４条第１項該当 情報科学研究科情報システム工学専攻
学位論文名	A Study on Embedded Implementation of 3D Sound Movement System based on Head-Related Transfer Functions （頭部伝達関数に基づく組込みシステム向け立体音像移動手法に関する研究）
論文審査委員	（主査） 教　授　尾上　孝雄 （副査） 教　授　菊野　　亨　　教　授　竹村　治雄　　教　授　山田　晃久

論文内容の要旨

With the recent significant progress in digital signal processing technologies, 3D sound effects are widely used in many application fields such as virtual reality and entertainment. In addition, there are increasing demands for 3D sound effects on mobile applications in accordance with the recent rapid widespread of mobile systems including portable A/V players, portable video games, etc. As one trend of the 3D sound technologies, a variety of 3D sound localization methods have been investigated, aiming at 3D sound effect through 2-channel loudspeakers or headphones. Generally, a 2-channel method utilizes the human ability of spatial hearing, which can be represented as a transfer function of a sound signal from the source to the listener's outer ear, referred to as head-related transfer function (HRTF). By simulating HRTFs from a sound source to both ears, 3D sound effects that give a virtual impression of incidence direction can be synthesized.

When applying these methods to portable devices, computational costs should be carefully taken into consideration. Conventional 3D sound methods intend to reproduce the overall characteristics of HRTFs throughout the audible frequency band spending too much computational costs. However, computational costs and memory capacity are severely limited in embedded systems from the viewpoint of battery life.

To solve this difficulty, Kobayashi et al. proposed a novel 3D sound movement method, which attained with low processing costs by extracting fundamental factors necessary for perception of 3D sound image. However, this 3D sound movement method for embedded systems still confronts two main issues：the reproduction of 3D sound movement at all directions in 3D space and the exaggeration of 3D sound movement for entertainment applications.

The 3D sound movement method offers limited functionalities when it is used for virtual reality applications, since the sound movement trajectory is restricted to one horizontal plane. Thus, there still remains much room for detailed measurements and feature extractions of HRTFs in 3D locations to enable sound movement in all directions.

Meanwhile, 3D sound movement method has recently become preferred in various applications, which has led

to a lot of new demands on 3D sound effects. For example, entertainment applications tend to adopt exaggerated 3D sound effects to make sound movement distinctly in order to enhance amusement rather than the accurate sound localization. The exaggeration of sound movement also solves these problems for mobile entertainment applications.

To cope with above mentioned two issues, this dissertation describes the 3D sound movement entirely for embedded systems based on feature extraction of HRTFs. First, to realize sound movement at all locations in 3D space, detailed measurements of HRTFs in 3D space are performed in this dissertation so as to extract dominant features needed for sensing sound image direction and movement. Then, an efficient coefficient storing scheme is proposed by utilizing the results of the feature extraction of HRTFs with respect to azimuth, elevation, and distance. The efficient coefficient storing scheme reduces 93% of memory size required for 1, 200 locations in 3D space. Moreover, the proposed system employs a data format to control the movement trajectory of a virtual sound source in realtime and a scheme to generate a moving sound at low computational costs. Then, a prototype system is implemented by using a field programmable gate array (FPGA) board to evaluate system performance.

Next, exaggeration method of sound movement for mobile entertainment applications is described. A novel method for exaggeration of sound movement with respect to azimuth is devised, which is gained by reproducing modified HRTFs without requesting additional computing resource. The modified HRTFs, measured by means of dummy head microphones with attached reflection plates, are used to enlarge the variation of magnitude responses. Receiving the benefit of two main results, sound movement with low computational costs is achieved, which can be used for mobile entertainment applications.

論文審査の結果の要旨

本論文は、組込みシステム向けに臨場感の高い立体音響効果を実現することを目的として、低処理量・低メモリ量による立体音像移動システムの提案と VLSI 化設計に関する研究の成果をまとめたものであり、以下の主要な結果を得ている。

⑴ 組込みシステム向け全方向への立体音像移動実現手法

３次元空間中の全方向への立体音像移動を組込みシステムで実現するために、まず３次元空間で多数の頭部伝達関数を測定し、共通的な特徴を抽出することにより、従来法に対し 93%のメモリ量を削減する効率的な頭部伝達関数の格納方法を考案している。また、移動情報の内部形式、仮想音源の現在位置更新の低演算量手法の検討を通して、立体空間上の任意の位置における連続な移動を実現している。さらに、これらの機能を Verilog-HDL 言語を用いて実装し、約３万ゲートで実装可能であることを示している。

⑵ 立体音像の移動感強調手法

移動感の強調された立体音響効果への要求に対し、組込みシステムとして実現する手法について提案している。本手法では、特に移動感が乏しい耳の真横付近の音像移動に着目し、大きな耳介モデルを用いた頭部伝達関数に基づく移動感の強調手法を考案し、追加処理を必要とすることなく、再現する頭部伝達関数を変更するのみで、移動感の強調を実現している。さらに、システムを実装したうえで、移動認知確率・最小可聴運動角を主観評価実験により導出し、提案手法の有用性を確認している。

以上のように、本論文は、頭部伝達関数に基づく組込みシステム向け立体音像移動手法に関して、回路規模・計算資源の削減、立体音響効果の向上など、多くの有用な研究成果を挙げており、組込みシステム向け立体音響技法に対し、仮想音像の全方向への実現や、その移動感の強調手法に関する知見として貢献するものと期待できる。よって、博士（情報科学）の学位論文として価値のあるものと認める。