Development of Audio System for TOYOTA "i-unit"

Akira Motojima
Masanobu Maeda
Masami Ando
Yoichi Yamaguchi
Tadashi Imamura
Shohei Yoshii
Shigeki Kato

Abstract

At the EXPO 2005 AICHI, JAPAN, the single seater "i-unit," a future concept vehicle, was submitted to the Toyota Group Pavilion for display. This i-unit is loaded with a driving support system which utilizes various types of IT technology geared towards future societies. In this project, with the aim of a fusion of humans and vehicles, a human interface has been developed which, using sound, light and vibration, provides the driver with easy-to-understand information regarding driving support. FUJITSU TEN also cooperated in this audio system development.

This document introduces i-unit audio system hardware. This introduction includes an outline of "audio contents" created with the aim of human interface enhancement, as well as an introduction regarding sound image control methods which are used to localize sound within a 360-degree circumference around the driver with two loudspeakers.

1 Introduction

At the EXPO 2005 AICHI, JAPAN, which began being held as of March 25th of this year, TOYOTA GROUP submitted to the TOYOTA GROUP PAVILION its developed "i-unit", a single seater concept vehicle for the future.

i-unit is a vehicle which includes various types of technology for realizing concrete efforts directed toward future societies, and its audio system was developed with cooperation from FUJITSU TEN. This paper introduces i-unit's audio system and "audio contents" created in conjunction with it.

2 Outline of i-unit

i-unit is a "Personal Mobility" that seeks to attain a greater balance of meeting individuals' wishes to enjoy freedom of movement and excitement of driving, harmony with society, and harmony with the Earth's natural environment.

2.1 Outline

The outline of i-unit's concept, etc., is shown in Table 1 [1].

2.2 Major functions and features

Table 2 shows a list of major functions and features.

2.3 Vehicle development theme and IT technology

The 3 development themes of i-unit are:

"Meeting the needs of individuals" "Harmony with society" "Harmony with the Earth's natural environment" Figure 1 summarizes IT technologies for the purpose of realizing each of those themes.

3 Audio system

The following describes the aim for sound for the purpose of realizing IT technologies, as mentioned in chapter 2.

①Creation of pleasant audio space

- i-unit provides you with your own private, relaxing space.

②Information provision through situation-oriented sound

- Perception is enhanced by providing information through voice and operational sounds with a sense of direction.
- In a vehicle in which warning alarms sound for courses of direction that require attention, caution and advice is provided which makes it difficult to miss important sounds.

In order to realize the target IT technology with present technology, as well as to realize the i-unit characteristic of "minimum size mobility", the least amount of hardware was used in conducting software signal processing. With the speaker system, 2 miniature speakers are set near the driver's ears, with signal processing helping to realize audio imaging control for the driver's surroundings and optional positioning.

The audio system's hardware consists of "USB unit", "power amp" and "speaker unit", which show the hardware configuration (system block) used in Figure 2. The following shows acoustic specifications for the purpose of realizing the aimed-after sound.

Acoustic specifications

- Frequency property: 300Hz to 20kHz
- Maximum acoustic pressure: 110dB (dummy head near the ears)
- Difference of left/right output: within ±3dB (dummy head, 1kHz)
- Degree of separation: 70dB or more (amp, USB)

Table 1 Outline of i-unit

Concept	" Expanding Human Abilities "	This union of driver and vehicle is intended to expand human abilities and possibilities.
Theme	" Inspire the Individual " Making a better world with mobility leading the way to a greater bond between people and the planet.	Movement expands our world by creating possibilities and encounters among nature, society, people and culture. Movement brings us new sensations, discoveries and acquaintances, enabling individuals to lead fuller lives and cultivating a sense of belonging with the planet.
Design Theme	" The Leaf "	The design, inspired by the leaf that converts sunlight into life energy, seeks to express the power of the unknown, the logic of living things and the simple beauty of waste-free functionality.

Table 2 Characteristics and outline of i-unit

Mobility with an Ultra Compact Size	The " i-unit " creates a seamless transformation between vehicle and human movement, minimizing occupied space and energy consumption with its lightweight and ultra compact size.
Variable Positioning	The i-unit has a compact size enabling the passenger to move among other people in an upright position in low speed mode, and a low center of gravity that ensures stable handling when the vehicles reclines in high speed mode.
Ease of Operation ①Drive Controller	Drive-by-wire technology and intuitive handling enable the passenger to maneuver on-the-spot turns and drive at high speed at will.
②IT Controller	A driver support information system uses sound, light and vibration to facilitate interactive communication.
Driver Support System	The driver support system features Intelligent Transport System (ITS) technology, which Toyota hopes to utilize for an accident-free society. The system permits efficient and safe autopilot driving in specially equipped lanes.
" My-unit "	A personalized recognition system can provide information and music, and body color can be customized, according to the individual 's preferences and emotions.
Environmentally Friendly Body Materials	The body is built using environmentally friendly plant-based materials such as kenaf.

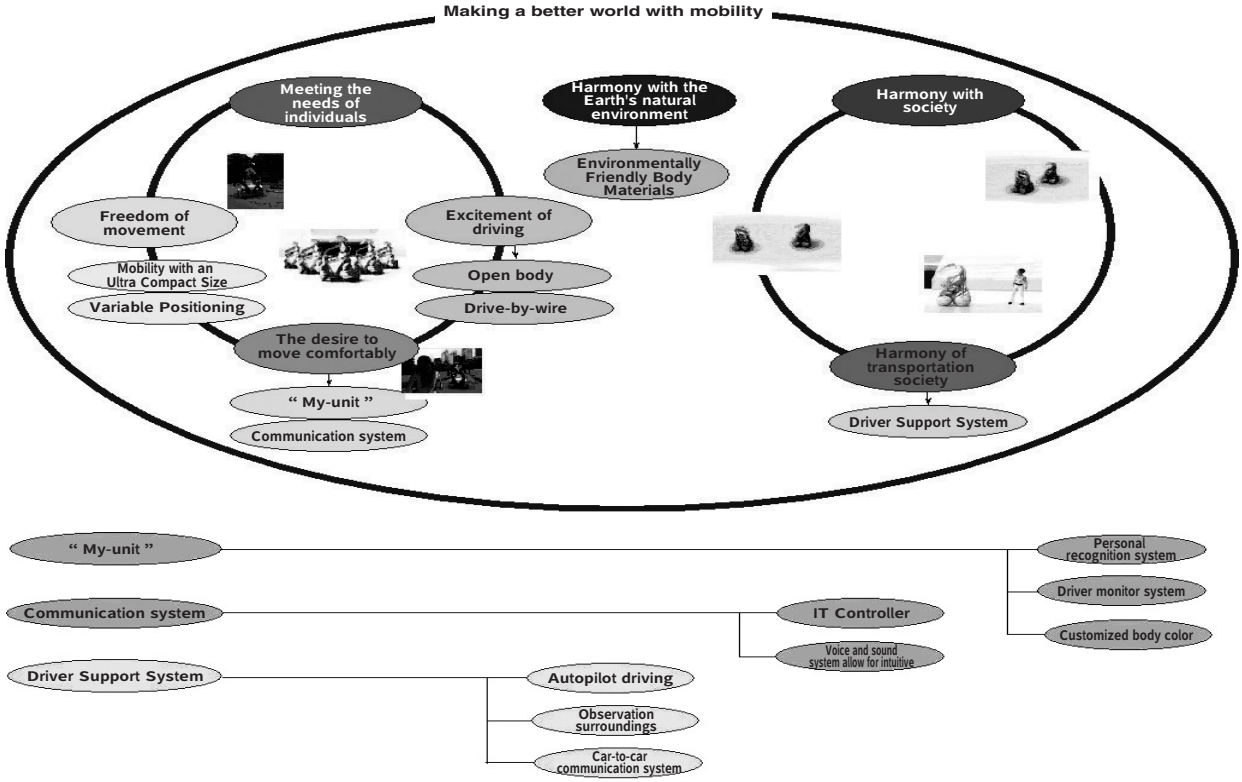

Fig.1 Outline of IT technology

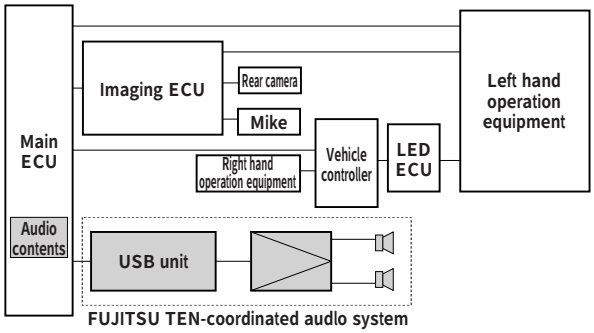

Fig.2 System block diagram

4 Hardware outline

This chapter explains about hardware units in the audio system.

4.1 USB unit

This section gives explanation regarding the USB unit, which converts digital signal to analog conversion and outputs of audio contents in the main ECU.

4.1.1 Aim and outline

Development was made in aspiration for compactness and energy conservation. Digital voice sound output from the main ECU is input via the USB cable to the main unit, which converts that voice sound data to analog signals and transmits it to the AMP unit.

4.1.2 Form

As the i-unit vehicle itself is a concept of ultra small size, focus was put on both size and weight reduction. While conducting miniaturization at the parts level, the connector portion was eliminated through the use of a fly lead connector, enabling maximum lowering of overall height. As a result, it became possible to make installation into a unique and compact vehicle.

4.1.3 Reliability

Fig.3 USB unit external features

This unit shows the following efforts that were made to secure reliability, which admittedly were unique in both objects of development and conditions of use.

①Use within the EXPO venue (indoors)

Evaluation is performed In response to wireless communications used in the venue

②Dealing with fluctuations in battery power (response to the electric automobile)

Should audio circuits lock due to a major fluctuation in power supply from the main ECU, a mechanism is set in place which restores audio output circuits by way of unit internal reset circuits without having to reset the entire system.

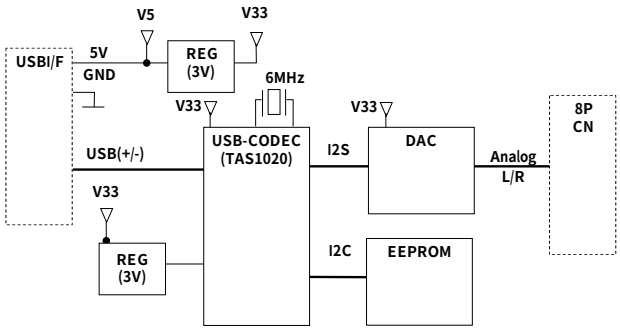

Fig.4 System block diagram of the USB unit

4.1.4 Performance

The main unit deals with sampling rate 96kHz resolution up to 24bit signal, and is able to authentically recreate digital sounds from the main ECU. One characteristic of the main unit is that it has achieved actual values which satisfy the performance target values for realizing surround sound with 2 channels.

Table 3 Electrical characteristics

Evaluation characteristic*1	TS standard *2	Target value	Actual value
Overall harmonic distortion (%)	0.2% or less	0.1% or less	0.01%
Degree of separation (dB)	65dB or more	85dB or more	91dB
Ratio of signals & noise (dB)	80dB or more	85dB or more	93dB
Left/right output ratio (dB)	0±1.5dB or less	0±2dB or less	0±0.05dB

*1 All the above are based on 1 kHz of frequency.
*2 Performance specifications for 05 audio CD/DVD portion.

4.2 Power amp

This section explains the power amp unit, which amplifies audio signals from the USB unit.

4.2.1 Aim and outline

This audio amplification device, which amplifies audio signals from USB audio for output to the speaker, represents the concept of a power amp never before heard of that deals with small spaces.

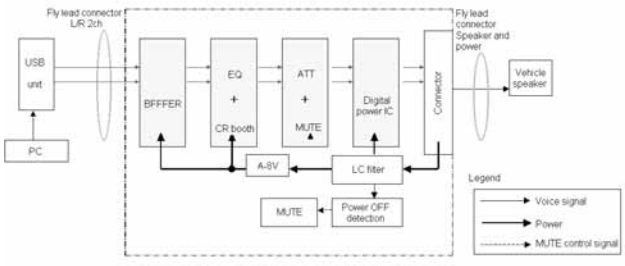

Fig.5 System block diagram of the power amp

4.2.2 Requirement specifications

Requirement specifications are following: the target specifications for this power amp.

①Output: 12 W or more compatible with 2 channel stereo

②Size: 90 mm×80 mm×20 mm or less (50% of conventional models)

③Noise reduction (S/N ratio, separation 70 dB or more)

In order to realize the above size, it is necessary to have high efficiency and miniaturization, and explanation will start from that point.

4.2.3 Miniaturization

Due to the fact that this vehicle is unique and compact, there was a demand for all of the installed units to be miniaturized as well. There were restrictions in particular on unit height, and so the slim units were designed, with a height of no more than 20 mm.

1) Content of implementation of slim dimension

①Basic concept

Structure: made slim without changing material, with further consideration given to clearance.

Parts: parts selected with focus on slim chips.

Fig.6 Audio power amp appearance

②Content of implementation

- Reduction of clearance size under the circuit board (3 mm→1 mm)
  Protection from shortage through insulation
- Use of electronic parts with low height (maximum part height: 14 mm)
  Change made, as much as possible, with electronic parts for reflow as much as possible.
- Reduction of clearance between the upper portion of the part and the lid (1.5 mm→0.8 mm)
  Using high precision parts, clearance size is reduced while maintaining the margin of the overall height.

4.2.4 High efficiency

Because this vehicle is an electronic automobile, it was necessary to realize low power consumption while also achieving the required audio output. Thus, we used digital amps.

1) Digital amp

A digital amp is a power amp which achieves high efficiency through using FET to perform switching operation for the final block. Although methods available are PWM and ⊿Σ (1 bit), due to the aspects of acoustic performance and part miniaturization, we used the ⊿Σ method.

2) Comparison of analog amp and digital amp efficiency

Figure 7 and figure 8 show the consumed current and heat generation measurement results, A cooling plate was

no longer necessary due to little heat generation, which as a result led to miniaturization.

4.2.5 Noise reduction

With i-unit, in order to realize both close placement of speakers to the drivers' ears and the after-mentioned sound image control in Chapter 5, it was necessary to achieve amp noise reduction and separation channel of at least 70 dB in the wide frequency range. Therefore, the following was given consideration in the printed circuit board design stage:

- Using multi-layer circuit boards to secure a GND exclusive layer, and to realize low impedance of power circuits and shield effect.
- Devising part layouts to realize point grounding above wiring and separation of left/right circuits.

Through the above, work was finished on an amp which was superior in sound quality and ensured target performance.

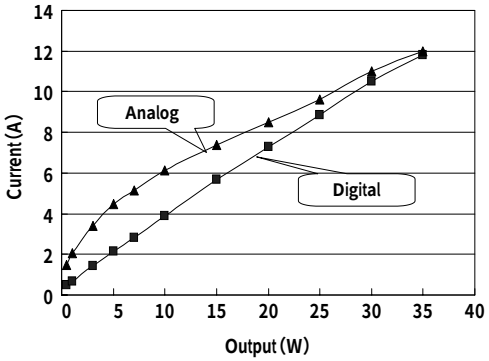

Fig.7 Graph of output power vs. current

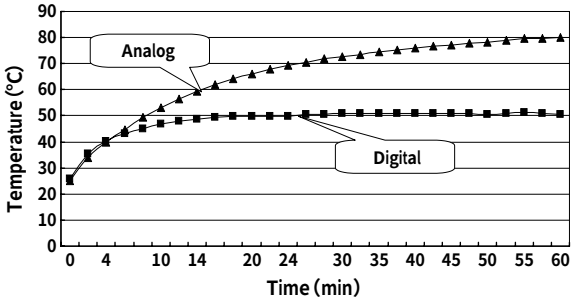

Fig.8 Graph of time vs. heat generation

Table 4 Comparison with analog amp

Item	Content
Efficiency of 1 W output	71% (digital amp), 15% (analog amp)
Consumed current	▲70% (analog amp ratio 1 W output)
Temperature increase	▲55% (analog amp ration 1 h later)
Chassis dimensions (digital amp)	85×71×20 (mm)
Chassis dimensions (analog amp)	95×110×28 (mm)
Volume comparison	▲49% (Analog amp ratio)

4.3 Speaker unit

i-unit uses an environment-friendly material called kenaf for the body panel. This section explains the speaker unit that is attached to this kenaf panel.

4.3.1 Aim and outline

We were able to install the speaker unit without We were able to install the speaker unit without losing sight of miniaturization, which is the characteristic of the vehicle, and we developed a small size oriented high-quality speaker unit which possesses the following specs suitable for directional sense control.

Target performance

- Frequency response: 300Hz to 20kHz (-10dB)
- Acoustic pressure level: 75dB/W m
- Resistant power: 3 W or more (rated)

Fig.9 The loudspeaker unit appearance

4.3.2 Conditions for speaker installation

It was necessary this time to set speakers in place without impairing speaker design, and the following restrictions in installation space were present:

- Overall speaker height: 20 mm or less.
- Installation area: within 40 mm^2

In order to ensure required sound quality within these restrictions, we dealt with strict installation conditions through the following measures:

①BOX-less speaker

By using space in the inner portion of the kenaf panel as BOX capacity, we achieved target sound quality without BOX configuration which was equivalent to quality with BOX.

②Voice coil interpolation damper

By employing new technology where the damper normally positioned in the outer circumference of the voice coil is placed in the coil's inner circumference, the speaker's contour was kept within the restriction range ((30), and a considerable amount of established credibility was ensured.

4.3.3 Development of speaker unit

There was a need to develop a micro-miniature speaker unit due to installment restrictions. To realize this, we took on dealing with further high quality sound by employing the following new technology:

①Foam rubber edge

We adopted a foam rubber edge with both high density and flexibility, securing in particular credibility regarding bass zone following ability and amplitude.

②Dome-shaped diaphragm

Making the diaphragm into a dome helped to maintain its durability. We achieved flat, treble zone properties with few peaks and dips, and sound with a sense of expansion can now be generated.

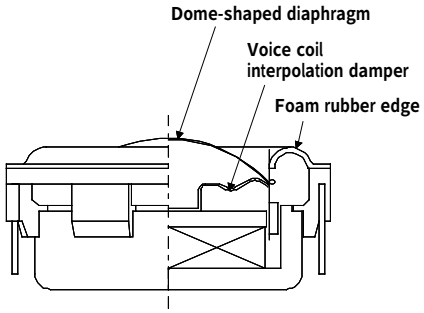

Fig.10 The loudspeaker unit structure

5 Acoustic processing

This chapter explains the signal processing method which localizes audio images for the surroundings of the driver and for optional positioning.

5.1 Installment environment

i-unit's acoustic system is used in the following environment:

I: No display

II: Speakers positioned at a close distance of approximately 30 cm from the driver's ears

III: Canopy-enclosed narrow space

In (I), there is no interface for user vision, and thus transmission of sound is indispensable. In addition, due to (II) and (III), intra-cephalic (within the head) localization occurs resembling headphone attachment, which presents the possibility of causing fatigue.

5.2 Acoustic processing outline

With consideration of eliminating fatigue and of adapting to transfer of information, we looked into a signal processing method in which sound can be perceived in an extra-cephalic (outside the head) fashion. As such a method for producing this effect, we took on an audio image localization method using HRTF (Head-Related Transfer Function). This technology was mainly examined in the field of 3-D acoustic field generation [2) 3) 4) 5)]. HRTF refers to transfer functions which include information traveling from the sound source of a certain location to the human ear, and these functions differ depending on the head and ear shape and hair of human beings. With the installed 2ch speaker , we set out for optional audio image localization using this HRTF.

General HRTF measurement is conducted using a dummy head microphone, where a microphone is mounted in the ear portion of a human head replica (refer to Figure 12) [6].

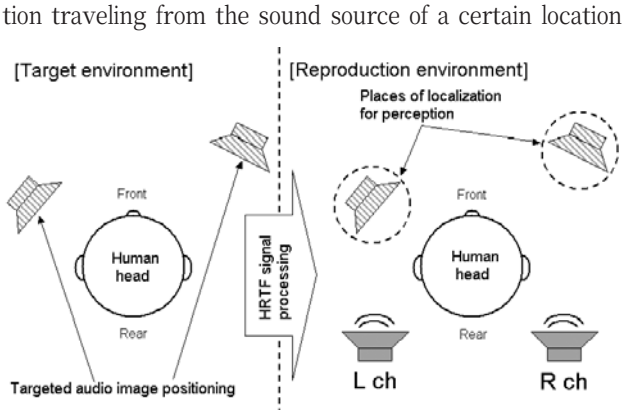

Fig.11 Outline of HRTF signal processing

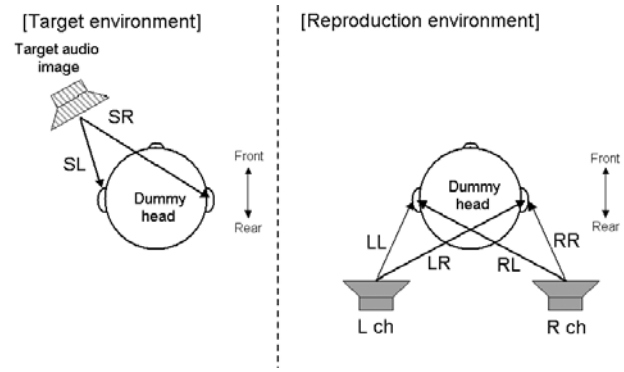

Fig.12 Measurement method for HRTF

The processing sequence is as follows:

①Measure in advance HRTF [right: SR, left: SL] for the target environment.

②Measure speaker Lch and Rch HRTF [Lch: LL, LR Rch: RL, RR] of the reproduction environment.

③Calculate the FIR filter coefficient from HRTF.

④Multiple audio signals by FIR filter coefficient.

5.3 Localization control for monaural sound

The content of basic signal processing is stated in monaural sound signals. In conducting signal processing, principle blocks are shown in Figure 13.

As just previously mentioned, the condition is appended in which RR and RL are the same as LL and LR. TL and TR in the figure are the calculated FIR filter coefficients.

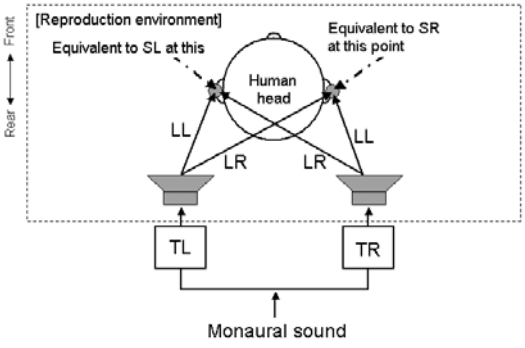

Fig.13 Principle of HRTF

The audio signals passing through TL and TR of this FIR filter reach both ears, and are guided so as to be equivalent to SL and SR of the target environment at ear position. This results in:

$$SL = TL \times LL + TR \times LR$$
$$SR = TL \times LR + TR \times LL \quad \cdots\cdots ①$$

Solving ① regarding TL, TR results in:

$$TL = \frac{SL \times LL - SR \times LR}{LL^2 - LR^2}$$
$$TR = \frac{SR \times LL - SL \times LR}{LL^2 - LR^2} \quad \cdots\cdots ②$$

Calculation is made from the HRTF in which this TL, TR is measured.

Additionally, by segmenting formula ②, expression can be made in blocks such as those in Figure 14 (additional target environment property portion, crosstalk cancel processing portion).

This concludes explanation of the basic HRTF signal processing method. Calculated examples of TL and TR FIR filter coefficients are shown in Figure 15.

5.4 Application to i-unit

Stereo signals are dealt with in music play, etc. when driving i-unit, and thus processing is necessary for multiple input signals. In addition, it is conceivable that 2 different types of sound will be localized in other directions for supply to the user. We describe the processing for such a case.

In the case of 2 voice sounds, it can be seen in Figure 11 and 12 that only the target environment is different, with no influence on the reproduction environment. Because of this, processing is enabled simply by changing only the property-added portions of the target environment in Figure 14 (refer to Figure 16). This is also the same with music stereo signals, and it also becomes possible to localize L, R signals at the different points [7) 8)].

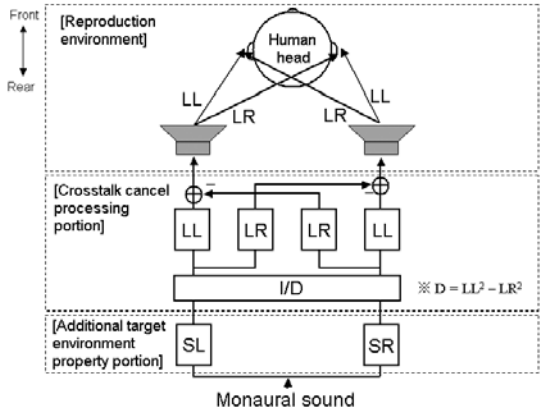

Fig.14 Block segmentation

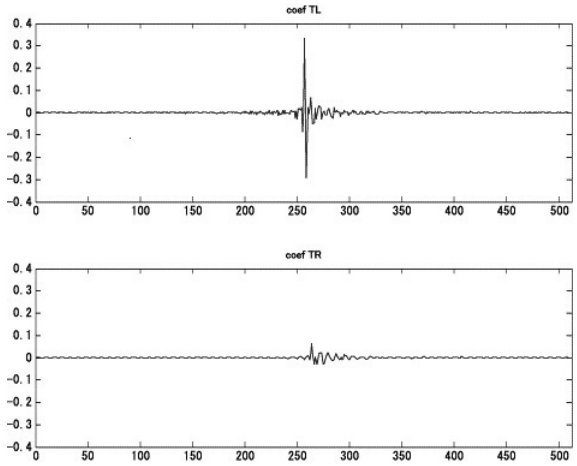

Fig.15 Examples of TL, TR computation (FIR tap length: 512)

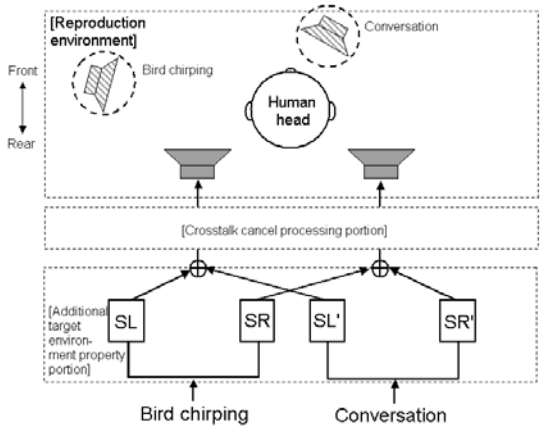

Fig.16 Processing for two different sounds

5.4.1 Creation of 360° revolving sound source

i-unit has a function for "body condition management", and so we created a sound which revolves at 360 °around the user, as a sound effect during bodily scans. In this situation, audio signals are separated into multiple frames, and they are multiplied by FIR filter coefficients TL, TR of each frame angle. Imprints from each angle were taken every 45 °and TL, TR were calculated.

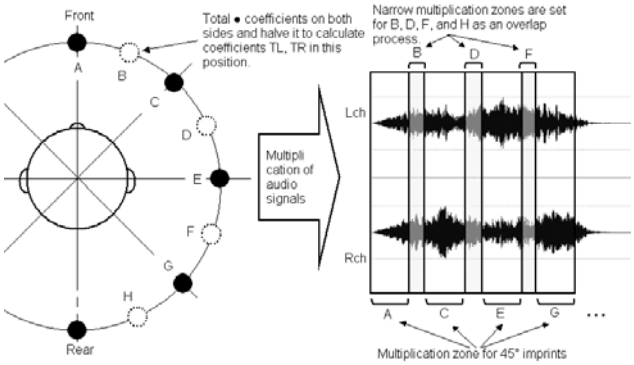

Fig.17 360° rotation processing

6 Creation of audio contents

"Audio contents" produced by the i-unit audio system include not only music and warning alarms, but also operation sounds and sound effects for making i-unit's various operations and movements easy to understand. These audio contents were created simultaneously, and so their outline is explained in this chapter.

Table 5 Sound contents

Sound category	Sound example	Outline
①Sound corresponding to i-unit switch operation	・Sound of opening and closing of canopy	A sound to inform canopy opening and closing
	・Sound for orientation change & return	A sound to indicate change of orientation between low and high speed mode
②Sound aiming for harmonization with surrounding environment	・Automatic drive sound	A sound to inform surrounding people that unmanned driving is being performed
	・Start sound	A sound to inform surrounding people that the power has been turned on
③Precaution	・Warning alarm sound	A sound to inform the passenger that surrounding objects (people, vehicles, etc.) are approaching
④BGM	・Relaxation music	A music tobe listened while driving (sound for relax the driver)

6.1 i-unit operation and audio contents

Audio contents produced by i-unit are mainly categorized into the following 4 items:

①Sounds following i-unit switch operation

i-unit has left and right hand controllers. These are for opening and closing of the canopy, an operation in which "sound", "light" and "vibration" are considered as human interfaces.

②Sounds aiming for harmony with the surrounding environment

i-unit has a function for automatic driving. It includes sounds such as warning sounds for unmanned driving, sounds which are for improving fusion with the driver's surroundings.

③Warnings

Sounds such as warning alarms and reverse sounds, for giving the driver warnings and advice.

④BGM

Music heard while driving.

6.2 Creation method

For creation of sound sources, audio direction was decided on through psychological testing, and a method was adopted for corrections through examinations on the vehicle. The basic flow of construction is shown in the following:

STEP 1. Decision on standard sound source

- In regards to one operation sound, we created sample sounds with multiple differing images (2 to 6 types), which simulated the sounds aimed for.
- Using the actual vehicle (i-unit), we implemented psychological testing in which we had evaluation done in 5 stages to determine whether or not the sound sources "matched" or "didn't match" each operational scenario. There were a total of 12 test subjects, consisting of Toyota employees and employees of companies related to i-unit development.
- Based on the psychological experiments, we decided on the direction for each sound.
- We conducted the above evaluation two times, including sound source correction, and we created base sound sources for use in examinations on the vehicle.

STEP 2. Vehicle inspection

- With the actual vehicle we made repeated adjustments in tone, time and volume, combining with "light" and "vibration", which led to the creation of the final sound sources.

6.3 Sound source outline

Among the sound sources created, two types are used as examples to explain the outline.

6.3.1 Warning alarm sounds

For safety support, the i-unit vehicle constantly monitors its surrounding area. Among its safety features, there is a function for bringing the driver's attention to people or other objects approaching the rear when the driver is getting into or out of the vehicle, and the sound produced in this situation is the warning alarm sound. Although there are various alarm sounds being used even in present-day vehicles, basically those sounds are often sine wave based. The following shows i-unit's aim in its creation of warning alarm sounds.

①Sounds comfortable for people

We maintain the sound's basic function as an alarm which alerts the driver, while making the sound one which is easy on the driver's ear.

②Control of sense of distance

The driver is informed of an object approaching from the rear according to its distance from the vehicle, in 3 stages involving "sound", "light" and "haptic controller vibration".

③Control of sense of direction

Control of sense of direction is performed in 3 stages: 45 ° to the left and right of the rear, and directly behind.

④Fusion of human and vehicle

i-unit is not considered merely a vehicle, and the sounds created give it the image of being a life form which possesses its own intellect.

As a sound for giving i-unit such an image, we sampled the short human vocal sound "toooo" and used it as a repetitive sound. With this sound as a base, we performed control of sense of distance.

In Table 6 are compiled factors in how people feel distance through sound. Table 7 shows factors considered as fluctuations in the urgency of warning alarm sounds. While continuous sounds are decided on through volume and frequency properties, cyclic sounds also have cycle length as a factor.

Table 6 Items where a person senses distance

	Sense of distance	
	Far	Near
Volume	Low →	High
Frequency property	Treble zone damping ←	
Echo	Large ←	Small

Based on the factors above, control of sense of distance for i-unit was adjusted mainly through "toooo" base sound frequencies and the difference between repetitive cycles and volume. Control done through "echo" was not used, as we simulated the inside of a room with reflecting sound.

Table 7 Characteristics of alarm and emergency levels

	Urgency	
	Little	Great
Volume	Low →	High
Frequency property	Treble zone damping ←	
Repeatcycle	Long ←	Short

A parameter was decided on with conception of long-range and short-range sounds. Sound for long distances of objects from the vehicle is sensed only to the degree of an "indicator", while the sound for short distances causes a sense of urgency. The following shows the outline for each sound source, and Figures 18~20 show the wave form and frequency properties of each sound source.

Long-range sound

- Basic frequency: 175Hz
- Repetitive cycle: 900 ms
- Volume (near the driver's ears): 77dB (A)

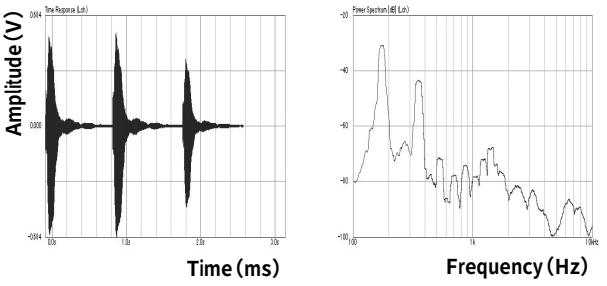

Fig.18 Waveforms and frequency characteristics of long-range sounds

Medium-range sound

- Basic frequency: 350 Hz
- Repetitive cycle: 320 ms
- Volume (near the driver's ears): 83 dB (A)

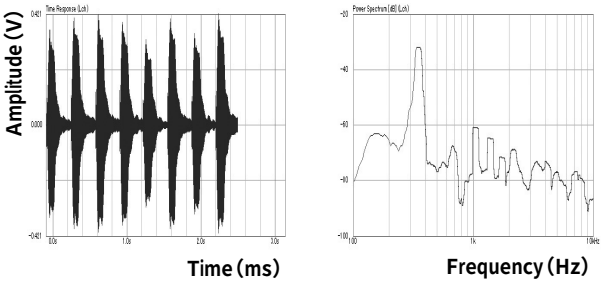

Fig.19 Waveforms and frequency characteristics of medium-range sounds

Short-range sound

- Basic frequency: 880 Hz
- Repetitive cycle: 210 ms
- Volume (near the driver's ears): 86 dB (A)

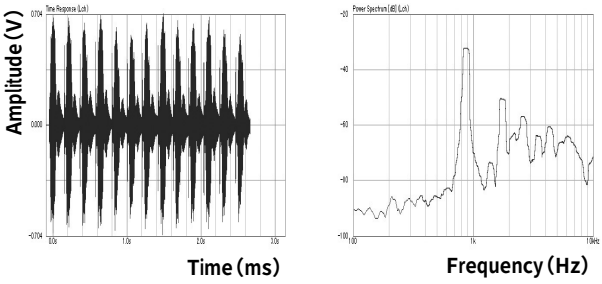

Fig.20 Waveforms and frequency characteristics of short-range sounds

6.3.2 Individual identification sounds

Before one gets into i-unit, that person goes through verification performed by the individual identification system. At this time, "identification in progress" and "identification complete" are indicated by "sound", "light" and "haptic vibration". The following explains the procedure for individual identification. (refer to Figure 21)

①The driver holds up the palm of the driver's hand to the haptic controller, which starts individual identification. He/she is informed that identification is in progress by vibration and blinking of the haptic controller and by audio sounds. (Identification is completed in 3 to 4 seconds.)

②The "identification complete" sound is produced at the same identification is finished, while simultaneously performing the following operations:

- The haptic controller moves downward.
- Colored light spreads out from near the haptic controller throughout the entire vehicle body.
- The canopy opens, and preparations for driver entry are completed.

The following shows the aims of each sound for the above operations as well as the outline of sounds. Also, Figures 22 and 23 show the sonagraphs (graphs of time, frequency and levels) for each sound source.

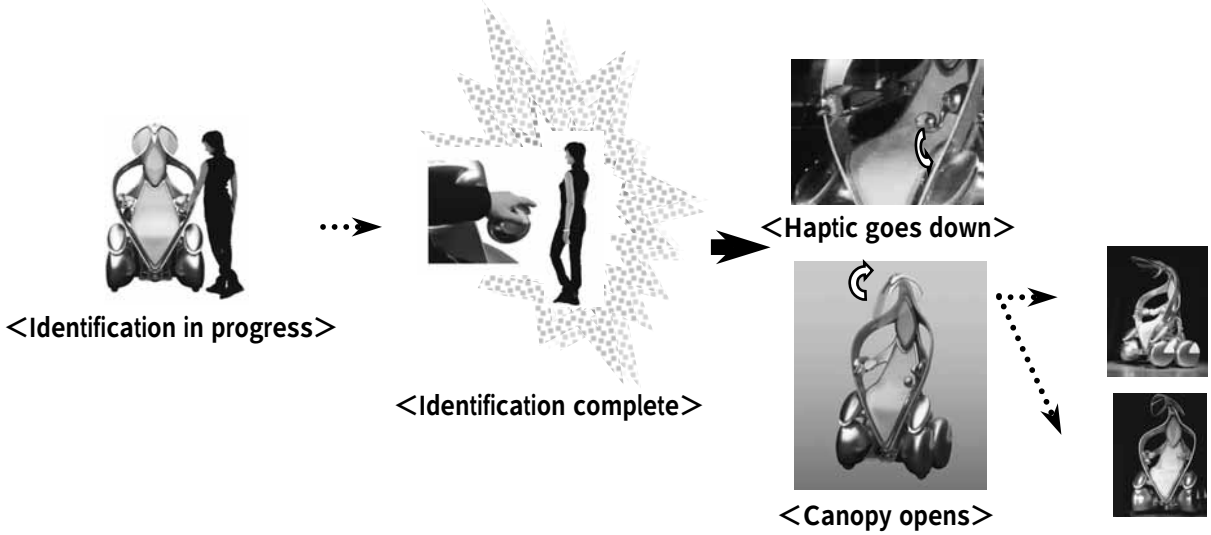

Fig.21 Procedure for individual identification

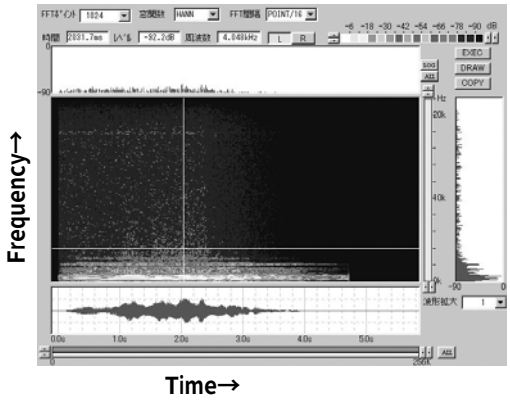

Fig.22 Sonagraph of sounds for individual identification (during identification process)

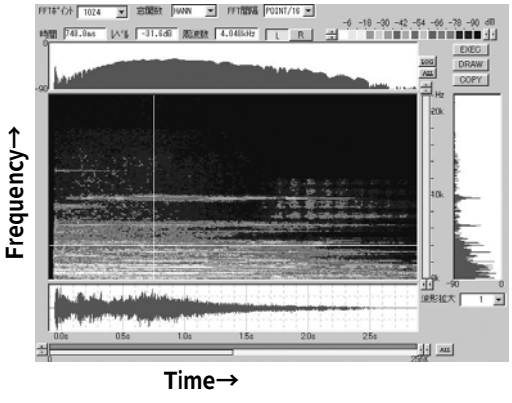

Fig.23 Sonagraph of sounds for completion of individual identification

Sound during identification

(Aim)

- Images are matched with haptic vibrations and with long-cycle haptic blinking. (spread-out sound with reduced treble-zone elements)
- Major operations cease during identification (for approx. 4 seconds), and so the driver can be relieved of stress and worry with comfortable sound.

(Outline of sound)

- Sound based on a basic frequency of 400 Hz, causing one to imagine a grass harp.
- The sound provides a sense of softness through long (approx. 1 second)
- Fade-ins and fade-outs for providing comfortable images. Amplitude modulation is performed between left and right channels, providing a sense of wideness. (cycle: approx. 5 seconds, amplitude fluctuation: approx. 3 dB)

Sound for completion of identification

(Aim)

- Making a trigger-like sound for each operation (haptic descent, canopy opening, expansion of light).
- Adding wide reverberations to fit the image of light spreading throughout the vehicle body.

(Outline of sounds)

- Expression of a trigger using a soft bell sound, based on 700Hz basic frequency.
- In the initial stage of the attack-like sound (approx. 0.7 seconds), sound is localized in the direction of the haptic (left ch), and in the reverberation stage (approx. 2 seconds) control is performed to localize sound so that it spreads to the left and right channels.

7 Conclusion

This concludes our explanation of the outline of the i-unit audio system and the audio contents. i-unit, installed with various IT functions, gives us an image of vehicles 30 years in the future. In order for the driver to easily use these functions, enhancement is being made of the human interface, which utilizes "sound", "light" and "vibration". It is believed that such improvement of a sound-adopting human interface will be ever more important for automobiles of the future.

Future audio technology for enjoying music will be

required to have "quality sound" which actively changes to respond to road environment and to the driver's psychological condition. Furthermore, for "sound" as a human interface, it will also be necessary to develop easily judged sound in the aim for improved safety, as well as sound which produces a sense of high quality luxury as an additional value.

While in this paper we have introduced one example of audio contents, we hope later on to gain feedback on user evaluation through i-unit demonstrations and exhibitions, thus moving forward with even greater audio development in the future.

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Profiles of Writers

Akira Motojima

Entered the company in 1983. Since then, has engaged in development of in-car sound systems.
Currently in the Acoustic System Department of Audio Business Division, Business Division Group.

Masanobu Maeda

Entered the company in 2002. Since then, has engaged in development of in-car sound systems and DSP algorithm.
Currently in the Acoustic System Department of Audio Business Division, Business Division Group.

Masami Ando

Entered the company in 1999. Since then, has engaged in development of in-car sound systems.
Currently in the Acoustic System Department of Audio Business Division, Business Division Group.

Yoichi Yamaguchi

Entered the company in 1980. Since then, has engaged in development of in-car audio systems (head unit).
Currently in the Acoustic Engineering Department of Audio Business Division, Business Division Group.

Tadashi Imamura

Entered the company in 1992. Since then, has engaged in development of in-car audio power amps.
Currently in the Acoustic Engineering Department of Audio Business Division, Business Division Group.

Shohei Yoshii

Entered the company in 2003. Since then, has engaged in 07 system development.
Currently in the Engineering Department 2 of Engineering Division 1, Business Division Group.

Shigeki Kato

Entered the company in 1979. Since then, has engaged in development of in-car sound systems.
Currently the Department General Manager of the Acoustic System Department of Audio Business Division, Business Division Group.