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ACOUSTICAL LETTER

A steerable dummy head that tracks three-dimensional head movement: *TeleHead*

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1. Introduction

It is natural to take head and body movements into account in discussing the auditory sound localization function, because, when we hear sound, there is often some accompanying movement of the head and body. If our brain receives consistent auditory and motion-related information, we can localize virtual three-dimensional sounds fairly well, even when they are produced with non-accurate head-related transfer functions (HRTFs) [1,2]. This paper describes the design concept and architecture of a steerable dummy-head system that tracks three-dimensional human head movement in real time.

2. Human head motion mechanism

The human neck consists of superior and inferior segments. The inferior segment consists of five cervical vertebrae and performs the bending motion and rotation. As the rotation uniquely determines the lateral flexion, this segment has two degrees of freedom. On the other hand, the superior segment has three degrees of freedom. It adjusts the rough motion of the inferior segment to enable precise head motion trajectories.

A number of muscles are attached to each cervical vertebra. The scalene muscles of the prevertebral muscle group run an oblique course inferiorly and laterally. They pull each cervical vertebra aslant at various angles. When these muscles contract symmetrically, bending motion occurs. When they contract only on one side, pivot motion towards the side of the contraction occurs.

On the other hand, the majority of the posterior muscles are oblique inferiorly, medially, and posteriorly. They simultaneously produce extension, rotation, and lateral flexion towards the side of their contraction. The superficial muscles run in a counter direction to the intermediate ones. Thus, they produce extension and lateral flexion ipsilaterally, but rotation contralaterally.

The literature states that the human neck has a 130-degree range of movement for pitch motion, a 45-degree range of movement for unilateral roll motion, and an 80-degree range of movement for unilateral yaw motion [3]. We measured the maximum range of movement and the head motion speed of four subjects (two males and two females). They have 47- (standard deviation $\sigma = 8.7$ degree) and 63-degree ($\sigma = 17$ degree) ranges of movement for bending and extension motions, that is a 110-degree range of movement for pitch motion. They have 44- ($\sigma = 7.3$ degree) and 69-degree ($\sigma = 12$ degree) ranges of movement for unilateral roll and yaw motions. Their maximum head rotation speed from the front to 60 degrees right or left was 382 degree/s ($\sigma = 72$ degree/s). This maximum head rotation speed is three times quicker than that of natural head movement during sound localization.

3. Architecture

Figure 1 outlines the steerable dummy-head system we have developed. The human head posture is detected by a head tracker (Polhmus, FASTRAK) put on top of the subject's head. The posture data, i.e. the Euler angles, sampled at 120 Hz, are sent to motor drivers via a PC. They are used to control three motors, one each for yaw, pitch and roll motions of the dummy head.

A life-like dummy head was made by molding a human head shape using impression material [4]. The head surface is soft polyurethane resin. Under it is a cushioning material of 1- to 2-cm-thick formed polyurethane which surrounds a hollow skull of 0.5-mm-thick fiber reinforced plastic (FRP). The disparities between real-head and dummy-head shape were less than 7 mm, except for the pinna part. The weight of the dummy head is 1 kg.

The dummy head is mounted on a spherical joint. Two 400-W AC servomotors are positioned at both sides control pitch and roll motions. Forces of the motors are transmitted via driving wires and pulleys. A very quiet but powerful direct-drive DC servomotor (torque of 2.1 Nm at 120 rpm) controls the yaw motion. This motor is located at the bottom and rotates all of the upper structures, such as the dummy head and the two AC servomotors. The system has 54- and 26-degree ranges of movement for bending and extension motions, i.e. an 80-degree range of movement for pitch motion. It has 30- and 90-degree ranges of movement for unilateral roll and yaw motions. Because of mechanical structure constraints, these ranges are narrower than those of the human head, except for the yaw motion. There are no gears, so less mechanical noise is generated. The whole mechanical structure of the system is covered with 5-cm-thick urethane form to reduce mechanical noise radiation.

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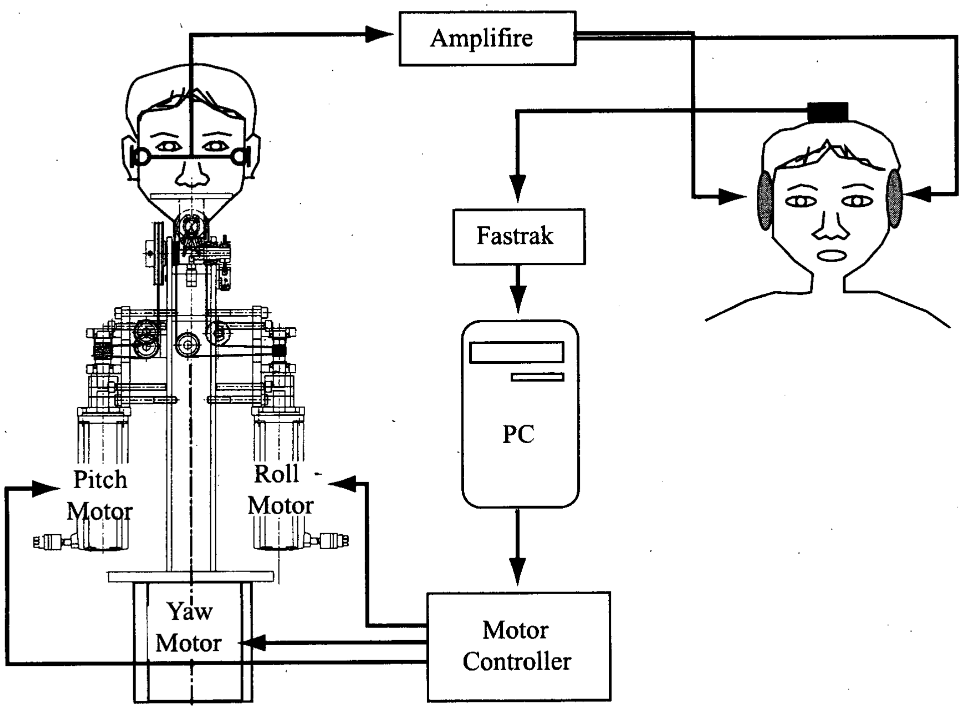

Fig. 1 Outline of the steerable dummy-head (*TeleHead*) system.

4. Mechanical responses

The mechanical response characteristics of the steerable dummy-head system are shown in Fig. 2. The upper panels show those for relatively slow head movement, i.e. when subject's maximum head rotation speed was approximately 100 to 200 degree/s. The bottom panels show those for fast head movement, i.e. when subject's maximum head rotation speed was approximately 300 to 500 degree/s. In each row, the left, middle, and right panels represent head-tracking characteristics of yaw, roll, and pitch motions, respectively. In each panel, thick and thin lines represent real- and dummy-head movements. As shown in the figure, the steerable dummy head has motion delay of 200 ms for slow real-head motions. The system, however, shows relatively good tracking characteristics for each rotation. On the other hand, there is a larger delay in a pitch and roll motions when the subject moves his head quickly. Further, the system overshoots the target trajectory by up to 70% for yaw motion. This difference

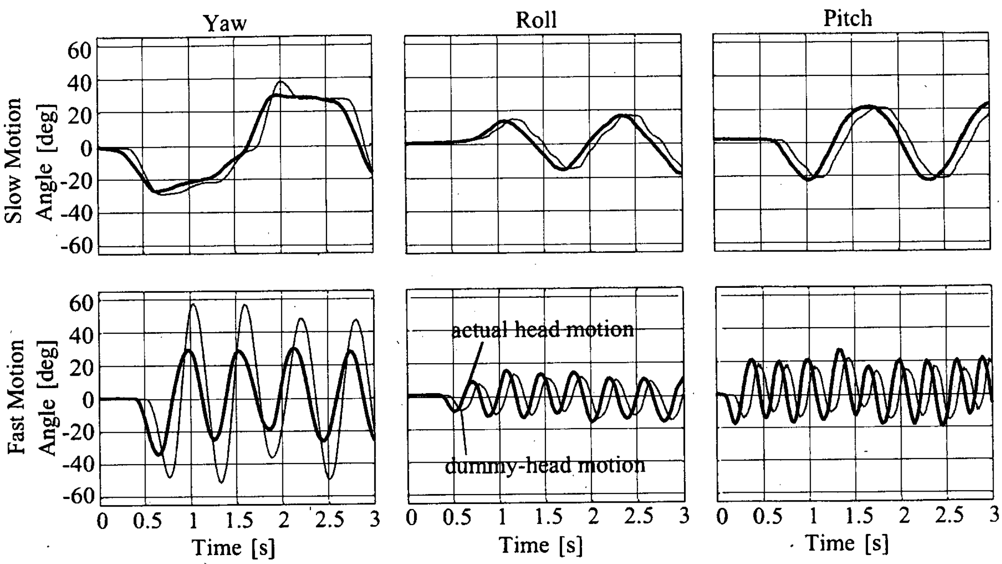

Fig. 2 Mechanical responses of the system. The upper panels show those for relatively slow (subject's maximum head rotation speed was 100 to 200 degree/s) head motion. The bottom panels show those for fast (subject's maximum head rotation speed was 300 to 500 degree/s) head motion. The left, middle, and right panels represent head-tracking characteristics of yaw, roll, and pitch. Thick and thin lines represent real- and dummy-head motions.

comes from differences in the actuators. Namely, a powerful direct-drive DC servomotors rotates the entire heavy mechanics, whereas small AC servomotors move the dummy head for pitch and roll directions. These motion delay characteristics and dynamic response characteristics are not satisfactory and should be improved.

5. Acoustical characteristics

Two small microphones (Sony, ECM77B) are placed at the entrance of the dummy head's outer ear. Sounds received by the microphones are fed to headphones, with which a user hears them remotely. Therefore, it is very important to keep the acoustical noise level of the total system low.

Figure 3 shows the noise level measured 50 cm in front of the dummy-head system. The broken line represents the noise floor of the sound-proof room in which the dummy-head system, PC, and controller system were placed. The thin line represents the noise level when all components are on but the dummy head is not in motion. The thick line represents the noise level when all components are on and the dummy head is in motion. As shown in the figure, the noise level around 1 kHz increases when the dummy head is moving. The maximum noise level, however, is 40 dB SPL, which is low enough. When the urethane body covering is removed, the noise level between 2 to 4 kHz increases 10 to 15 dB.

Another point requiring attention is the noise level in the audio line, from microphones to headphones. Figure 4 shows the audio line noise level measured as the sound pressure level of headphones (Sennheiser, HDA200) [5] put on IEC couplers. The headphone output sound pressure was calibrated with a 1-kHz tone presented in the sound-proof room. When the dummy head moves, the audio line noise between 0.3 and 2 kHz increases a lot and it reaches 60 dB SPL around 0.2 kHz. The sources of the noise are most likely mechanical vibrations of the motors and pulley rotations. These run through the metal frame and FRP skull of the dummy head and vibrate the microphones' diaphragm. Radical improvements for soundproofing are required.

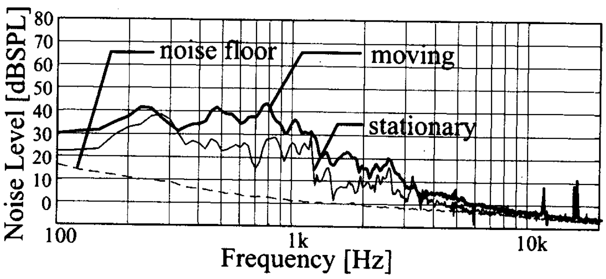

Fig. 3 Radiation noise level of the system.

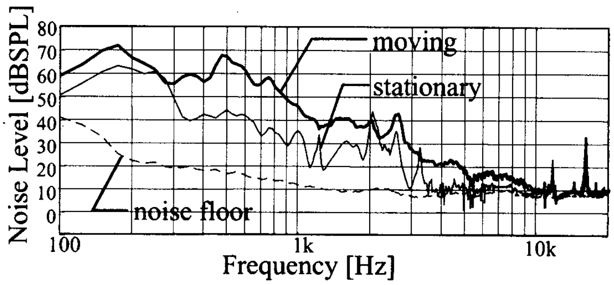

Fig. 4 Audio line noise level of the system.

6. Conclusion

This paper described the design concept and architecture of a steerable dummy-head system that tracks three-dimensional human head motion. The tracking and acoustic characteristics of the system were also described. This steerable dummy-head system used with a life-like dummy head can reproduce a real three-dimensional acoustic image over headphones. In preliminary experiments, we confirmed that sound localization becomes much easier with another's dummy head when cephalogyro motion is allowed. With this steerable dummy-head system, we can get binaural acoustic signals that include the effects of dynamic HRTF due to head motions and reproduce them at remote ears [6]. Thus, this steerable dummy-head system could lead to the development of the tele-existence system *TeleHead*, with which users can project there heads at a distance and perceive the environment where the *TeleHead* is located.

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