Army Research Laboratory

A Real-Time Audio Tele-Presence Device for Remote Acoustic Monitoring

by Michael A. Vaudrey and Sujayeendar Sachindar

ARL-CR-0502 **December 2003**

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14. ABSTRACT

This Small Business Innovation Research program sponsored by the U.S. Army Research Laboratory (ARL) addressed the issue of remote monitoring of acoustic environments with the hearing acuity a soldier is accustomed to, without placing the soldier in a potentially hostile acoustic environment. To achieve this goal, Adaptive Technologies, Inc. (ATI) employed a product-oriented design strategy to develop a wired proof-of-concept prototype using commercial-of-the-shelf components.

At the end of the Phase I effort, ATI delivered to ARL a fully functional wired binaural hearing device capable of accurately monitoring remote acoustic environments as far as 50 feet from the listener/operator. The remote head and ear system was mounted on a robotic device that permitted pan-and-tilt motion of the remote ears. The orientation of this was commanded by the local user's head location, which was measured by a head-tracking device purchased from Ascension Technologies, Inc. Finally, a customizable audio path equalization process was created to flatten the magnitude response between the remote and local ear canal locations to ensure the highest fidelity and most realistic audio reproduction possible. In addition to the customizable frequency response, ATI provided ARL with a fixed equalization filter that was fit to a small population of users tested at ATI. This generic digital filter was designed to operate at a sampling frequency of 44 kHz.

The following is a summary of the technical accomplishments at the end of the Phase I effort:

- A remotely deployable binaural hearing system was developed and delivered, which provides the ability to accurately and effectively monitor the remote acoustic environment.
- A real-time control system comprising a head tracker and a robotic head was created, which emulates head movement at the remote location, providing the ability to quickly localize any surrounding sound.
- Two equalization methods were developed that provide the user with more realistic audio reproduction. The customizable equalization and the fixed generic equalization were both delivered to ARL for testing at the end of the Phase I effort.

15. SUBJECT TERMS

acoustic monitoring; remote microphone; tele-presence

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Contents

List of Figures

1. Phase I Technical Review and Strategy

The Adaptive Technologies, Inc. (ATI) Phase I proposal clearly outlined the technical focus of the Phase I effort. In general, the resulting work of the Phase I effort closely matched the proposed tasks. This section summarizes those Phase I work tasks.

1.1 Phase I Technical Objectives and Work Plan

The primary purpose of the Phase I effort was to develop a fully functional, proof-of-concept prototype of a wired binaural microphone system to provide highly accurate remote listening capability. The design of the proposed binaural system consisted of three main components: the machine–to-soldier acoustic interface, the soldier-to-machine mechanical interface, and audio control features. The elements of the design process were as follow:

1. Generate electronic signals that accurately convey the binaural localization and discrimination capabilities of the human hearing mechanism to a remote listener so that realistic audio telepresence is achieved.
2. Develop a human-machine interface that accurately controls the orientation of the remote hearing mechanism in concert with the operator movement.
3. Investigate and implement audio control features into the binaural microphone system.

In the first month of the Phase I Small Business Innovation Research (SBIR) contract, a "kick-off" meeting was conducted at Aberdeen Proving Ground, Maryland, between ATI and U.S. Army Research Laboratory (ARL) personnel. The general form of the proposed design was agreed upon between the sponsors and ATI. The real-time head-tracking unit was received from Ascension Technologies, Inc., and was verified to be functioning within quoted specifications via the manufacturer-supplied software program. The task of designing and building the robotic armature module, along with the associated motor controllers was circumvented by the discovery of the robotic head "Biclops[1]" available for purchase from TRACLabs, a division of Metrica, Inc. The robotic head, which was developed under a separate SBIR program, was originally designed for computer vision applications intended to incorporate two cameras for stereo vision. With full pan-and-tilt capabilities, this was an ideal choice for moving forward quickly on this project.

In the second month of the Phase I SBIR, the software supplied with the Ascension Technologies head tracker device was customized by ATI. Modifications included removal of unnecessary interface code (including menus and graphical displays), inclusion of smoothing code to limit

[1] Biclops™ is a trademark of TRACLabs.

very small measurement anomalies in the normal functioning of the head tracker, and preliminary limit checking of pan-and-tilt positioning.

The robotic head or armature module (ArM) was delivered and tested with a test program provided by TRACLabs. The software supplied with the head was altered for specific position control. A prototype of the external acoustic receptor (EAR) was constructed and mounted on the Biclops. Investigation into specific filter parameters and the frequency response equalization was initiated during the course of the second month.

In the third month of the Phase I SBIR, a Windows[2]-based graphical user interface (GUI) application was developed in order to permit the 3D Bird[3] and the Biclops to function in tandem. This application uses the same functions and underlying structures for the 3D Bird and Biclops robotic head provided by the manufacturers of these commercial off-the-shelf (COTS) devices. However, an entirely new application was developed that provides only the necessary functionality for orienting the head measurements with the head tracker and homing the Biclops. Real-time communication of position information from the head tracker was relayed to the robotic head, permitting tracked movement; in the process, several performance limitations were discovered that are attributable to the position measurement. Both small and large real-time measurement errors were apparent in the 3D Bird tracking device and were translated by the robotic head as head movement.

In the fourth month of the Phase I SBIR, significant processing to the Windows-based GUI application was added in order to provide a fully functional, robust system, and improved functionality was incorporated to allow easy use. The audio path was designed and installed in the Biclops robotic head. A fully functional system was built, and preliminary tests to verify the operation of the system were conducted. Initial testing results indicated very accurate source localization capabilities with the first generation prototype system. A dynamic positional error (incorrectly interpreted as position commands by the robotic head) was caused by limited accuracy of the sensors in the low cost three-dimensional 3D Bird head tracker. A second source of position error was caused by the Biclops, wherein the digital encoder performance was being affected by electromagnetic interference (EMI) from the motor signal when it operated during high speeds. By physically separating the motor signals from the digital encoder signals, the manufacturer rectified this problem, and position errors attributable to this hardware design were eliminated.

In the fifth month of the Phase I SBIR, refining steps were made to prepare the wired binaural microphone for delivery at the end of Phase I. The Windows-based GUI application was simplified, and improved functionality was incorporated to allow easy use. A context-sensitive help window was added to assist the users in using the software program. A 50-foot serial cable

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[2] Windows™ is a trademark of Microsoft Corporation.

[3] 3D Bird®, which is a registered trademark of Ascension Technology Corporation, is a three-degree-of-freedom device that measures orientation based on the output of solid state inertial and non-inertial sensors.

was used to communicate with the robotic head, and the system was observed to function perfectly.

During the final month, a bracket designed to mount the Biclops on a camera tripod was manufactured by ATI. A head form was purchased and covered with a layer of liquid latex to provide a skin-like finish. A population average digital filter for acoustic path equalization was designed and implemented via the Analog Devices, Inc. EZ-kit portable digital signal processor (DSP) evaluation board. The wired path between the remote and local systems was extended to 50 feet. In preparation for system delivery, analog anti-alias and smoothing filters for the stereo audio paths were designed and a user manual was created (see Appendix A). The final system was retested and prepared for delivery to ARL.

The final system block diagram is shown in figure 1.

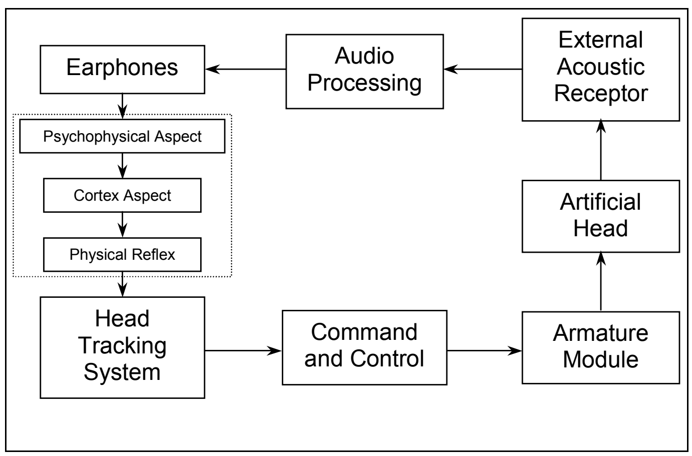

Figure 1. Wired binaural microphone system block diagram.

The dotted portion of the block diagram represents the human interaction with the system. The head tracker measures head movement and translates that to remote head movement. The external acoustic receptor delivers the remote audio signal to the user's ears through headphones after processing.

The remaining sections provide technical details for the software and hardware development of each component of the wired binaural microphone system, which consists of the head-tracking system, the remote robotic head, and the audio path.

2. Head-Tracking System

The head-tracking system measures the instantaneous position or orientation of the operators' head. This real-time information is used to command the remote robotic head in concert with the user's head to simulate real-time localization abilities. Ascension Technologies, Inc.'s 3D Bird product is used to implement the head-tracking system.

2.1 Hardware

The 3D Bird is a small (1.2 ounces), head-mountable device that communicates through the RS-232 port of a PC and provides real-time measurements at the rate of 160 times per second. The hardware unit consists of three sensors and the microprocessor that controls data acquisition and communication with the host PC. The manufacturer has provided a strain relief at the point where the sensor attaches to the cable. A minimum warm-up time of 15 minutes is required to allow the electronic circuitry time to equilibrate to temperature changes in order to achieve the highest degree of accuracy from the tracker. The sensor is sensitive to low frequency current-generating devices such as power cords, power supplies, and cathode ray tubes (CRTs). Their emanations can be detected by the sensor and converted into noise on the output orientation measurements. The sensor has been fixed to a piece of plastic and a secondary strain relief added by ATI and mounted onto the headset. The sensor cables are bundled and shielded to minimize noise and ensure accurate performance within specification.

When the hardware was connected to the communications (COM) port of the host PC and the executable test program was run, small and large errors in the real-time measurement of the orientation were observed. Based on telephonic consultation with the technical support at Ascension Technologies, Inc., it was determined that these errors were a result of the sensors being used in the hardware of the head-tracking system. Ascension Technologies produces a number of head-tracking or real-time position measurement devices, and the 3D Bird appears to be the only product that exhibits such errors, both large and small. The 3D Bird contains three sensors that are used to measure the angular orientation of the device.   Different sensors are used to measure the position in the static and dynamic modes. The dynamic mode uses a feedback algorithm that tracks angular position dynamically. However, no such algorithm is available for the static mode, and therefore, greater errors in position measurement are present when the device is stationary. In other words, even when the head tracker does not move, the measured value varies. Since this variation is passed onto the robotic head as position data, the head moves in response to the command input. This particular source of error can behave as a low magnitude, high frequency noise interfering with valid command signals or can become a higher magnitude offset in actual position measurement reaching or exceeding 20 degrees of error. The latter error is related to a Gaussian disturbance that affects the magnetic sensor. This problem was temporarily corrected with a magnetic field degausser.

A possible solution was to take advantage of the fact that different sensors are used by the tracking system in the static and dynamic mode. However, the microprocessor inside the hardware produces only orientation information; no information from the sensors could be accessed. Another potential solution involves signal processing of the head tracker signal before it is transmitted as the control signal to the robotic head. Classical DSP techniques for noise reduction such as filtering are complicated by the fact that the control system is not strictly a sampled data system executing in real time. In the Windows operating environment, non-related processes can cause interruptions in the head-tracking control code, which will effectively alter the “sample rate”. Therefore, any digital filtering could change the operation of the system in frequency and effectiveness.

As an alternative, a second product to perform head tracking was considered. Ascension Technologies produces a number of head-tracking or real-time position measurement devices, and the 3D Bird appears to be the only product that exhibits such errors, both large and small. ATI obtained the Flock of Birds[4] product and performed a comparative study of the performance between the two devices. A quantitative analysis of both devices was performed to determine their relative performance. The 3D Bird and the Flock of Birds were placed on a wooden desk, in a stationary condition, with their orientations at the origin with respect to their respective magnetic fields (earth’s magnetic field for the 3D Bird, transmitter-generated magnetic field for the Flock of Birds).

Analysis of the data streamed from both the devices provided an indication of the statistical nature of the noise in their data output. The data vectors were approximately 60,000 samples in length, corresponding to approximately 10 minutes of streamed orientation information. The standard deviation for the 3D Bird data was calculated to be 2.141 degrees, whereas for the Flock of Birds it was 0.0284 degree. A histogram plot in figure 2 indicates the distribution of the orientation information measured with both devices.

The maximum deviation with respect to the origin (the actual position) was calculated to be 4.6° for the 3D Bird and 0.13° for the Flock of Birds. Based on this statistic, ATI concluded that the Flock of Birds outperforms the less expense 3D Bird device with respect to noise in motionless measurements over time. Based on this analysis, ATI has concluded that the Flock of Birds qualifies to be used as the head-tracking device for the wireless binaural microphone implementation.

A careful cost-to-benefit performance analysis must be made during Phase II to ensure that the increased expense, complexity, and additional hardware of the Flock of Birds is warranted by the performance improvements. The Flock of Birds device is large, significantly more expensive, and requires a separate magnetic field transmitter and separate processor in addition to a PC connection.

[4] Flock of Birds® is a registered trademark of Ascension Technology Corporation.

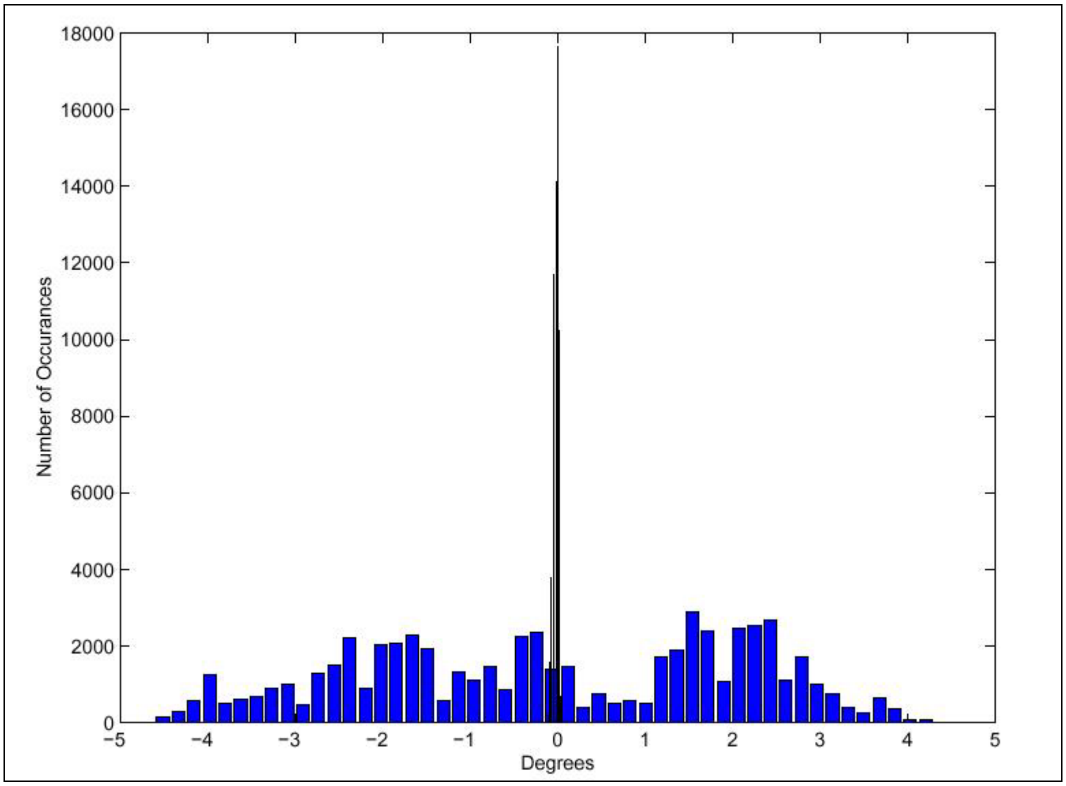

Figure 2. Quantitative analysis of the performance of 3D bird (blue) and flock of birds (black).

2.2 Software

The head-tracking unit was received by ATI along with a demonstration application. The demonstration application consists of a GUI that displays the orientation information (azimuth, elevation, and roll), both graphically and in numeric form. The menu options for this interface allow the user to choose or set the COM port that the device is connected to, the data display format, the reference angles for the three axes, the filter scale value (1 to 10) that rounds the fractional/miniscule variations in orientation data, menus to start, stop, and reset orientation of the 3D Bird, and data logging. Although nice features, many of these functions are not required for the wired binaural microphone application.

ATI modified the associated source code for this executable program to operate with a specific COM port, filtering scale, and data display format. The menu options were removed from the GUI to reflect this step. The graphic display of the azimuth, elevation, and roll axes was removed along with the data-logging facility. The corresponding source code for these was also removed. This results in a smaller and more manageable code, accomplishing only the features needed by this specific application. Although the graphical display of the head tracker orientation was removed, textual monitoring of orientation data was maintained for trouble-shooting purposes. In addition, the source was modified to indicate when the head tracker turns by more than ±165° along the pan/azimuth axis with respect to its initial orientation. This is required since the Biclops robotic head has a pan/azimuth limitation of ±165°. Likewise, a tilt or elevation that exceeds ±60° can also be detected.

A new application was created with Microsoft Visual C++[5] that establishes communication with the 3D Bird and streams the real-time data, displaying the azimuth and elevation data in edit boxes. This program allowed the user to reset the orientation of the Bird and displayed the status of the link through the COM port between the host PC and the 3D Bird. When the orientation data are streamed, the code checks for the range of the angle data and then displays the value in the edit boxes. This program, with minor modifications, would be added to the portion of the software that communicates with the Biclops armature module.

3. Armature Module

As was discussed with the contract sponsors, the customized armature module envisioned for the Phase I prototype has been replaced with a modular robotic head from TRACLabs. The Biclops was developed under a separate SBIR program and was originally designed for computer vision applications intended to incorporate two cameras for stereo vision. With full pan-and-tilt capabilities, this was an ideal choice for moving forward quickly on this project.

3.1 Hardware

The TRACLabs Biclops robotic camera-positioning mechanism is a multi-axis motion control platform for aiming single or multiple cameras. It is compact and lightweight, consumes little power, and provides excellent position observation. The pan-and-tilt axes move the camera(s) much like a standard camera tripod. All axes are under closed loop computer control, with motion commanded through a standard RS232 port. The Biclops pan/tilt (PT) mechanism is capable of handling as much as 2 kg at peak speeds exceeding 120°/second while drawing less than 20 watts of power for the motors and the controller. The controller, mounted in the base of Biclops, consists of an embedded servo-motor controller and brushed servo-amplifiers. The command interface to the controller is a straightforward packet protocol operated over a standard RS232 port. When a command packet, consisting of a command byte and command data is sent, it is immediately acknowledged by a status packet. Each axis can be polled independently for position and motion parameters as well as quality of performance indications (e.g., ability of axis to maintain commanded position).

The pan-and-tilt motions are controlled through a C++ software interface that ATI has obtained from the manufacturer. Connected through an RS-232 communication port, the commanded position and motion are a function of user-supplied velocity profiles and feedback controller

[5] Visual C++® is a registered trademark of Microsoft.

parameters. The feedback controller parameters essentially determine the position response of the system. The velocity profile for each axis consists of the velocity, acceleration and deceleration parameter values that set hardware performance limits on the velocity and acceleration for the respective motors. They are independent of the feedback controller parameters that govern the response time. If the controller parameters require motion in excess of the velocity profiles, those limits will control the motion. For the head-tracking application, no obvious velocity or acceleration limitation is induced by the load. Therefore, the velocity profiles were set at high enough values so that the feedback-controlled motion is not limited by those profiles.

The wires connecting the controller board to the motor and encoder are part of a six-wire ribbon cable. As the axis moves at full speed, it appears to induce noise on the encoder power and ground lines, causing spurious spikes on one or both of the encoder quadrature output. The control chip interpreted this as a position command, losing count of its actual position, resulting in position errors of 15° to 20° when commanded independently from errors encountered in the head-tracking hardware. The manufacturer, TRACLabs, corrected this problem by isolating the wires that connect to the motor from the encoder cable lines. ATI checked the operation of the robotic head by operating it at high speeds over extended periods of time and found no position errors after the redesign.

3.2 Software

A demonstration program developed by TRACLabs for the Biclops robotic head served as a guide in our understanding and designing the software for the prototype. A demonstration program for the Biclops robotic head contains elements needed for this application. This program performs an initialization of the robotic head by determining the hard limits on the pan-and-tilt axis and then sets itself in the (0,0) position determined on the basis of the hard limits. The program then performs an uncoordinated move, in which one of the axes reaches the commanded position before the second one can, and a coordinated move in which both the axes reach their commanded positions at the same instant. The essential set-up procedures and functions to perform the uncoordinated axis move were identified.

In the new application that was created for the 3D Bird, additional code to command and control the Biclops was added. This portion of the software establishes communication to the Biclops through COM Port 1, moves the Biclops head to the position entered by the user, and reads the position of the Biclops and displays it in an edit box. The values that the user could type to command the Biclops to move were restricted to ±165° on the pan axis and ±55° on the tilt axis to prevent the head from hitting the hard limits.

4. Command and Control Software Interface

The command and control interface that was initially developed and used to demonstrate the system to ARL is shown in figure 3.

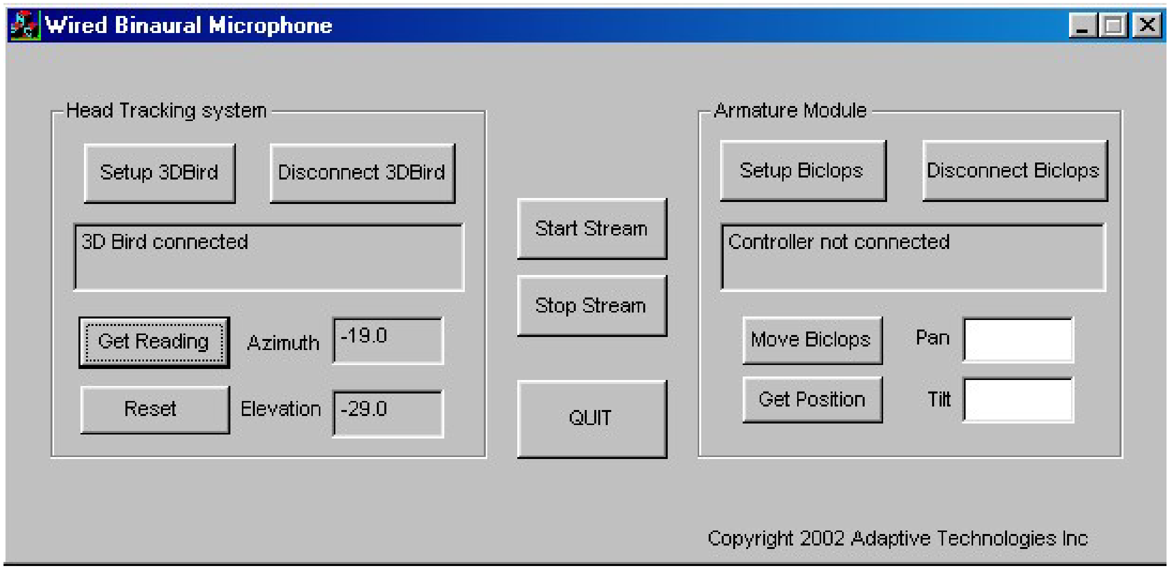

Figure 3. First generation GUI developed for the system by ATI.

This interface required the user/operator to be familiar with the sequence of steps to operate both the head tracker and the robotic head. Although this application provides the user with slightly more flexibility, it also requires the proper sequence of steps to be followed to properly configure the hardware. It was therefore determined that a more user-friendly application should be created that would require a minimum of interaction from the user to ensure that proper calibration and system setup were achieved. Therefore, the user interface was made much simpler and more user friendly with fewer buttons and controls and is shown in figure 4.

All the functionalities in the first GUI were included in the final design. When the hardware components have been connected to the COM ports and the application loads, the first step is to set up the communication between the host PC and the hardware i.e., 3D Bird and Biclops. When the "setup/init" button is clicked, the program connects the PC to the 3D Bird through COM port 2 and then to the Biclops through COM port 1. If the connection to the 3D Bird fails, either because the device is not connected to the correct COM port or because the power supply is not connected, an error message is displayed in the message box and the program quits execution. The program will not connect the Biclops unless the 3D Bird has been connected. Once the communication with the Biclops is set up, the program reconnects to the Biclops at a higher data rate (115.2 kbaud) and then performs the homing procedure. When the homing sequence executes, the user interface is locked and does not allow the operator to use the interface. This prevents the user from performing other operations before homing is complete. When homing is complete and the 3D Bird is streaming data, the "Ready to rock" message is displayed in the message window. At this point, the system is ready for use.

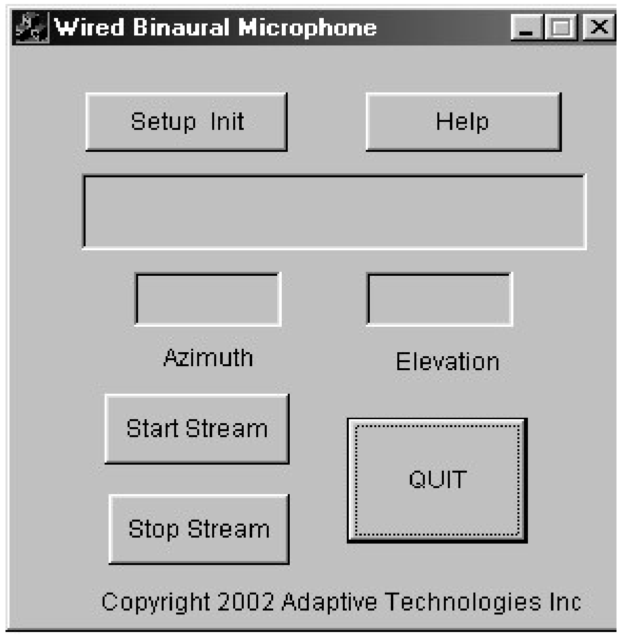

Figure 4. Simplified GUI design for the final system.

The next step is to click the "start stream" button to stream the data from the head tracker to the robotic head. The Biclops moves to its (0,0) position and a message window appears and instructs the user to look in the same general direction as that of the Biclops and level and then hit the "OK" button. The head tracker then resets its origin to its current physical orientation and begins streaming position command data to the robotic head. This manual process of coordinating remote and local orientations ensures that both heads are facing the same absolute direction during operation. The data streamed from the 3D Bird are checked for the allowable range in the pan-and-tilt axis and passed as a position command to the Biclops. The azimuth and elevation values are displayed in real time. The "stop stream" button disconnects the head tracker from the robotic head but does not disconnect the communication between the PC and the hardware. The "quit" button disconnects the head tracker and the robotic head and then closes the application. In addition to the simplifications that were made in the GUI, a context-sensitive "help" button was provided to assist the user in using the software. The help button returns to the user information based on the state of the program. Further information about the operation of the system is provided in Appendix A in the form of an operation manual.

5. Audio Path

The audio path begins with the EAR. Mounted on the armature module, the EAR uses two relatively inexpensive microphones and two artificial pinnae for acoustic shading. The remote microphones are positioned at the surface of the entrance to the artificial ear canals to avoid any acoustic filtering that could be caused by artificial ear canals. Instead, the user's actual ear canals are used to provide this acoustic filtering. The microphone signals are delivered to the digital signal processor after being appropriately amplified and filtered. The audio signals, after being processed by the DSP, are again conditioned and delivered to the stereo headphone amplifier. Finally, the headphones provide the audio signals to the user's ears at the same magnitude and sound pressure level (SPL) as if they were heard in the actual environment. figure 5 depicts this entire signal path.

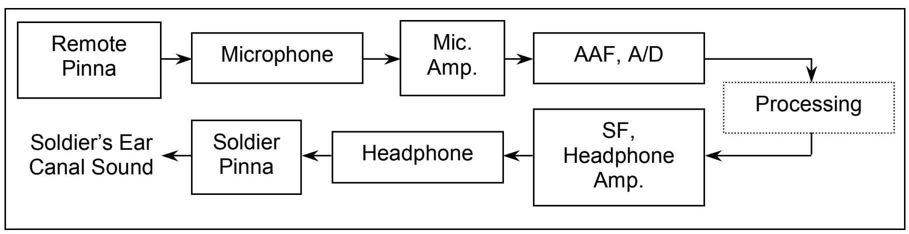

Figure 5. Audio signal path.

5.1 Input and Output Scaling

Each element of the audio system contains components that required unique design considerations. The 16-bit analog to digital (A/D) converter and 12-bit digital to analog (D/A) converter used in the customized frequency response routine must be used to their full range to maximize the audible dynamic range. The input dynamic range can be 90 dB, while the output dynamic range can only be 66 dB. Therefore, depending on the desired range of SPLs to be detected and heard, input and output hardware gains must be set, as well as internal DSP scaling. An example is presented next to illustrate these points.

Consider a desired input range of 30 dB SPL to 120 dB SPL and a desired output range of 34 dB SPL to 100 dB SPL. With a calibration tone at 94 dB and a maximum input SPL of 120 dB, we can determine that the input voltage level should be 0.5 V to maximize the dynamic range for a maximum input level of 10 V peak (V_{pk}). Likewise, if we have a desired maximum output SPL of 100 dB, we need an output voltage level of 5.0 V for 94 dB SPL. This will correspond to a scaling through the DSP of 10. These voltage levels only ensure that the dynamic range of the A/D and D/A converters are optimally used. However, input and output hardware gains must be separately set, based on the sensitivity of the microphone and headphone speakers so that when presented with a 94-dB tone, the input voltage level is correct and the output SPL at the user's ear is correct. It should be clear that when the desired input and output SPL ranges are changed, the hardware gains must also be changed in order to avoid the dynamic range limitations of the A/D and D/A converters, which could ultimately create noise in the audio system.

The generic audio equalization that is implemented via the Analog Devices DSP evaluation kit had still different input and output range requirements. The A/D input maximum is set to 3.1 V_{pk} and the output maximum is 1.1 V_{pk}. Each input and output is 16-bit and is capable of sampling at 44 kHz. The input-to-output scaling is performed automatically by the EZ-kit and does not require separate adjustment between the input and output, since their dynamic ranges are equal. A 94-dB tone presented to the A/D at 0.327 V_{pk} provides a dynamic (SPL) range of 20 dB SPL to 110 dB SPL. As discussed before, the output must be scaled differently to accommodate the sensitivity of the headphone speakers when a 94-dB SPL tone is delivered to the actual ear canal.

5.2 Headphone Wiring

An interesting phenomenon was discovered when ATI tested Sony's MDR-V900 headphone that was chosen for the Phase I prototype demonstration. This headphone was chosen on the basis of excellent reviews and specifications that indicate that the sound quality provided by this headphone was exceptional. Although the headphones are comfortable and the drivers are full range and very sensitive, it was determined through qualitative and quantitative testing that significant cross talk between the left and right channels existed. This cross talk was found to be at a signal-to-noise ratio (SNR) of approximately -30 dB—a very audible left-to-right difference. In fact, the headphone amplifier-integrated circuit selected for this prototype indicates and performs at a cross talk SNR of -70 dB.

Upon further investigation and analysis, it was determined that the source of the cross talk in the Sony headphones was attributable to the wiring of the headphones to the input audio jack. A three-wire cable is used to connect the three terminal 1/8-inch male stereo plug to the left speaker input, right speaker input, and ground line. A common ground line is connected to both speakers. The wire used in this cable is a Litz type wire approximately 6 feet long with a resistive impedance of approximately 1 ohm (Ω). Each speaker has a resistive impedance of approximately 27 Ω. Using the same ground line for both speakers generates a common mode resistance, which induces voltage in (for example) the left speaker when the right speaker is driven. The voltage divider of 1/28 corresponds approximately to the -30-dB SNR quantitatively determined in laboratory measurements. This problem was easily and very effectively solved by the use of a separate ground line for each speaker, which eliminated any significant common mode resistance present between the two speakers.

5.3 Headphone Audio Path Equalization

Figure 5 illustrates the components of the audio path from the remote microphones to the listener's ear location. At the remote location, the microphone has been placed at the surface of the entrance to the artificial pinna. Acoustically, the signal is colored by the shape of the external pinna but not by any artificial ear canals. It is thought that specific curvatures and shapes of individual pinnae contribute to localization abilities. In addition, ear canals filter the acoustic signals in a way that is unique to individual listeners. By only attempting to replicate the external features of the human ear, models are more easily created for different individuals. The features of ear canals extend all the way to the user's eardrums and would be difficult to replicate at the remote location and to eliminate at the user's location. This argument forms the reasoning behind the use of only the external ear features at the remote location.

The audio path begins with the EAR. Mounted on the armature module, the EAR uses two relatively inexpensive microphones and two artificial pinnae for acoustic shading, as well as an artificial head form for the same purpose. The remote microphones are positioned at the surface of the entrance to the artificial ear canals to avoid any acoustic filtering that could be caused by artificial ear canals. Instead, the user's actual ear canals are used to provide this acoustic filtering. A mechanism for determining listener equalization where local ear canal dynamics are not included was developed. Disposable earplugs combined with an identification microphone have been designed to fit into any user's ear to match the location of the remote microphone in the external ear canal location. This permits the user's actual ear canal dynamics to be included in the overall psycho-acoustic response, while the artificial pinna shapes the external ear response. The artificial ear microphone and identification microphone are shown in comparison in figure 6.

Figure 6. Sensing microphone in the artificial ear (left) and identification micro-phone in the human ear (right).

Although several of the components presented in figure 5 do not have substantial effect on the magnitude response of the system, several do. Therefore, this system is identified and equalized with an adaptive equalization routine. Because the magnitude response must be inverted by the equalization filter, a unique solution to an inversion of a causal, non-minimum phase system requires an acausal filter design. In practice, this is an impossible request. Since absolute phase shifts cannot be detected by human hearing, a phase delay was introduced into the equalization filter path to account for the non-minimum phase portion of the audio path. This allows the design of a causal filter to be realizable for the minimum phase portion of the audio path that can be inverted. The resulting system is a flat magnitude audio path, with some additional phase delay to compensate for the non-minimum phase dynamics during identification.

The audio path inversion is customizable to every individual by the implementation of an adaptive equalization routine. A simplified block diagram of that routine is shown in figure 7.

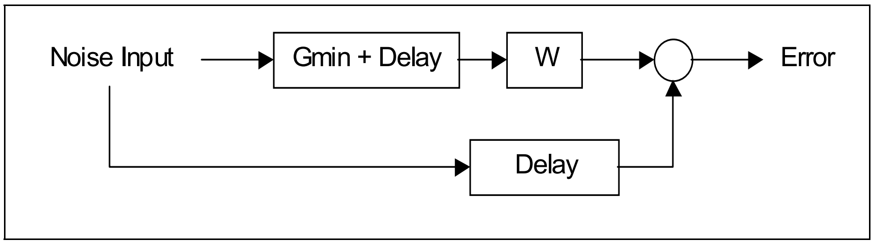

Figure 7. Equalization routine.

A delay is applied to the input signal to account for the non-minimum phase dynamics, and the adaptive filter is revised, based on reducing the mean squared error between its output and the actual system output measured by the microphone in the user's ear. Figure 8 illustrates the audio path before and after equalization for one individual.

Figure 9 illustrates the effect of the equalization filter applied to the system of figure 7, which is a combination of the converged adaptive filter and the phase delay applied to the equalization routine. This additional phase is required in both the identification and filtering stages because the vector addition of the plant signal and the filtered signal must result in proper phase alignment for the magnitude to become 0 dB.

Currently, the identification routine permits saving individual characteristics in MATLAB[6]-based .mat files for reloading into the DSP routine or analyzing in MATLAB at a later time. Customized characteristics require additional hardware and complexity as well as training. To reduce cost and complexity, another option was developed to identify a population of individuals and fit an average equalization filter to the population for use in a fixed filter system. Building a single fixed (analog or digital) filter for equalization is significantly less complex and may have acceptable (although not perfect) results.

Figure 10 presents a small group of individual transfer functions while figure 11 illustrates the equalized result of the average identification. Although these results are not as perfect as those shown in figure 8, they may represent an acceptable and low cost solution for the initial form of this product.

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[6] MATLAB® is a registered trademark of The MathWorks.

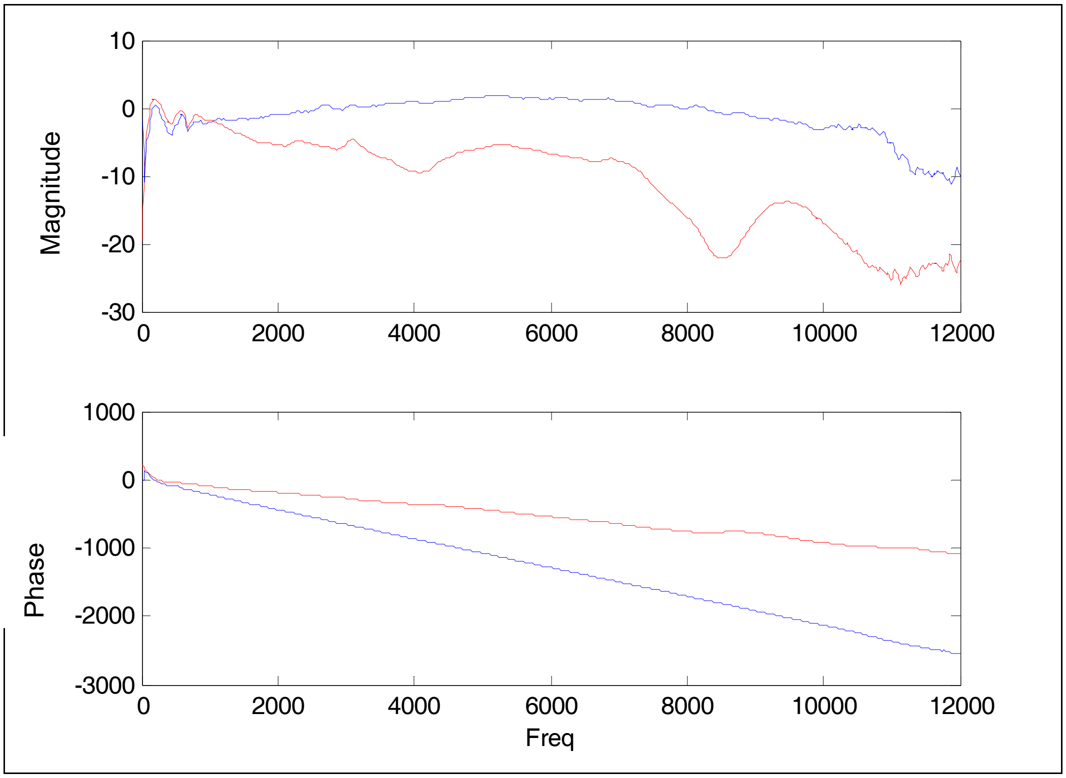

Figure 8. Frequency response before (lower curve) and after equalization (upper curve).

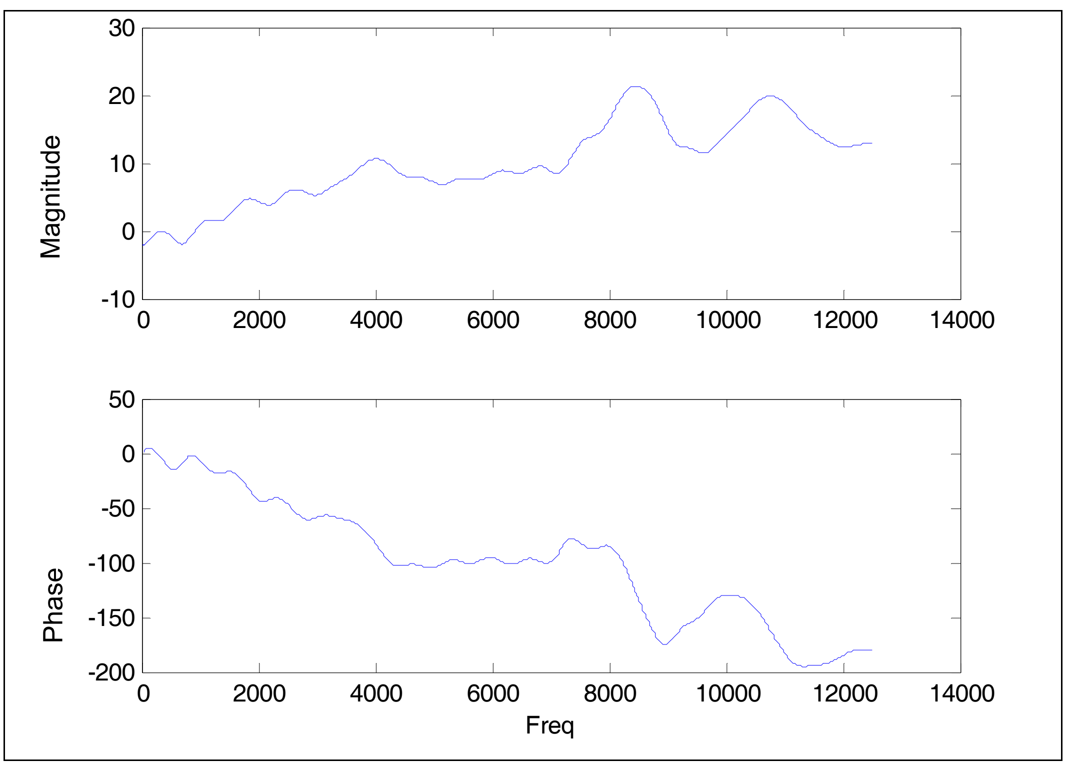

Figure 9. Equalizer filter for figure 7 system.

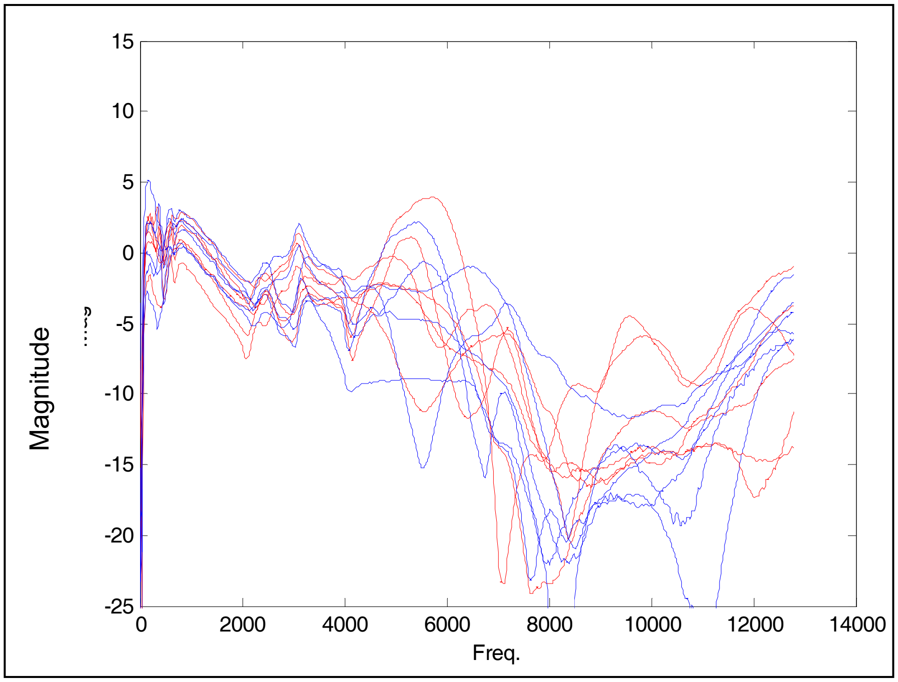

Figure 10. Small population of frequency responses.

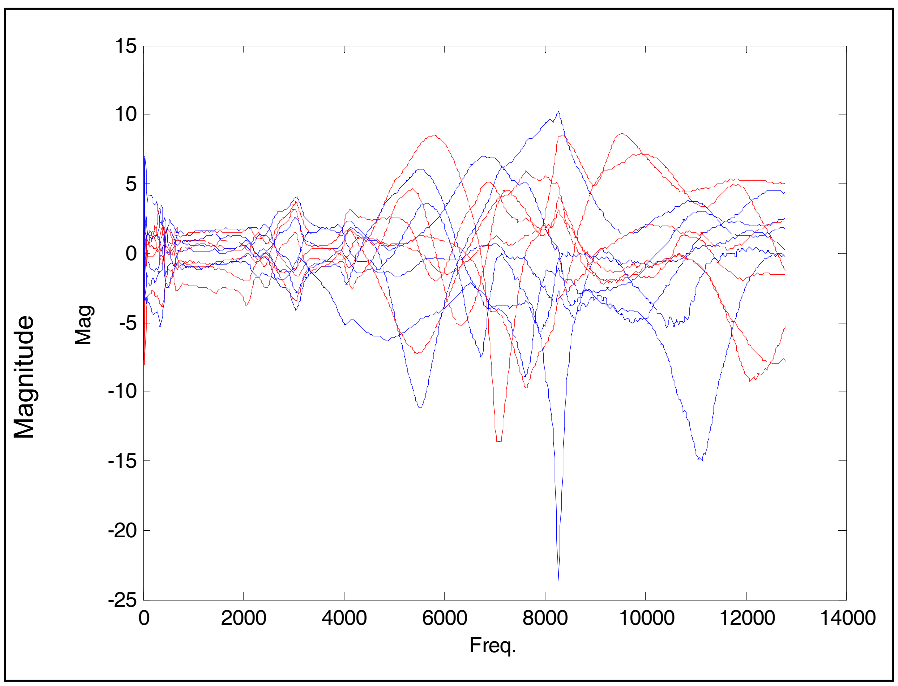

Figure 11. Population of frequency responses from figure 10, equalized with their average inverse.

The two figures represent the average equalization of a population used to illustrate this general concept to ARL. The actual implementation of the final generic filter came from another population sample that was collected through the Analog Devices' EZ-kit system that was ultimately delivered to ARL. The microphone amplifiers embedded in the EZ-kit imparted a magnitude shaping not present in the dSpace[7] population average. Therefore, the frequency responses were collected separately and a new generic filter was designed. Figure 12 illustrates the new population frequency responses.

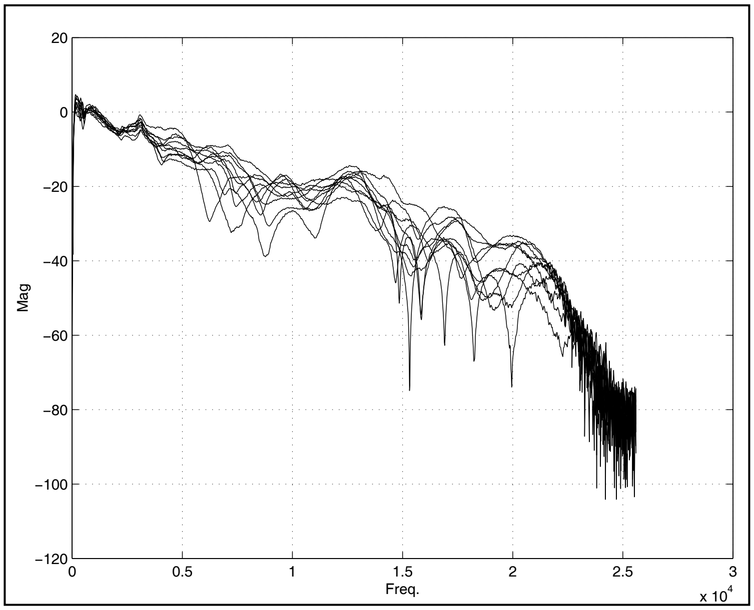

Figure 12. Population of frequency responses through EZ-kit device.

The average frequency response function (FRF) of figure 12 was created and an inverse filter was designed. This design was made with a cosine expansion, frequency sampling technique that generates a magnitude response as prescribed. The resulting filter design and the equalized FRFs are shown in figures 13 and 14, respectively.

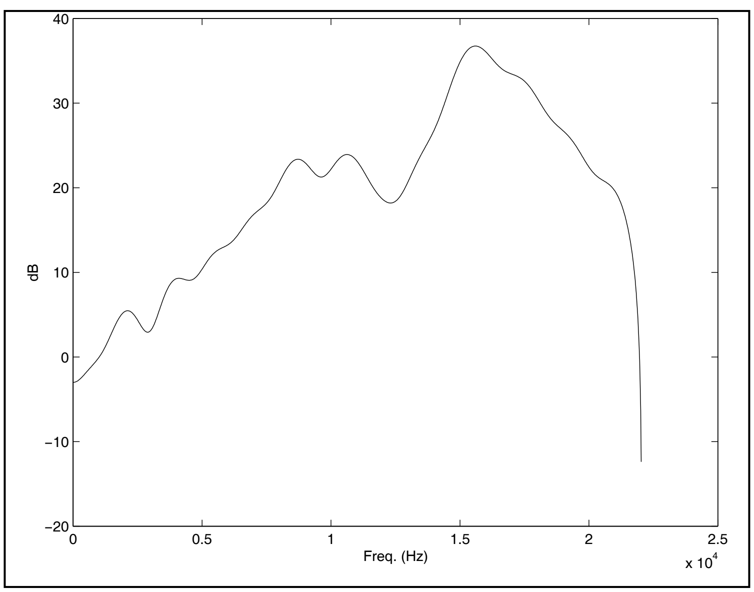

Figure 13. Equalization filter for generic solution.

[7] See appendix A, section A-2.4.

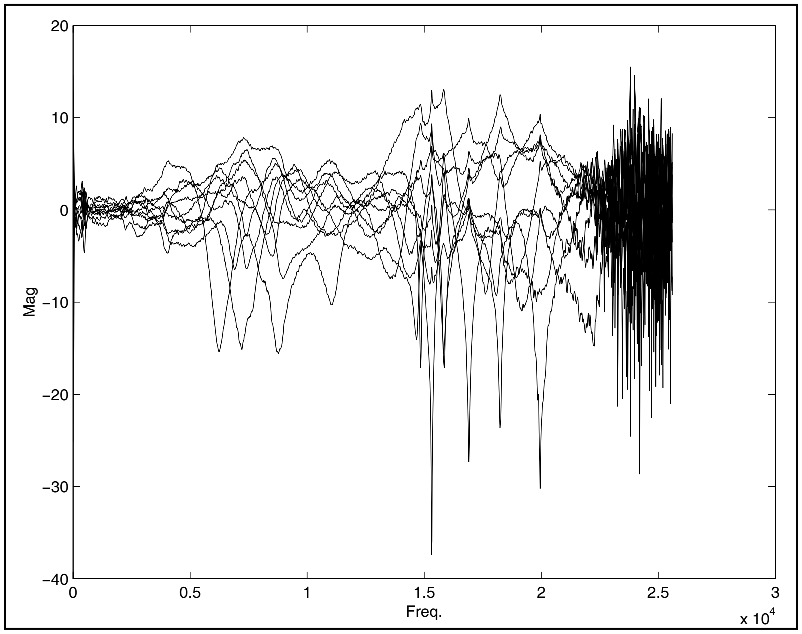

Figure 14. Generic equalized frequency responses.

6. Final System Design and Configuration

A completely customized GUI C++ software program was built by ATI to integrate the head-tracking information collected from one PC serial port with the command requirements of the remote robotic head via another serial port. Operating in real time, the remote robotic head moves simultaneously with the user's head. Several versions of this control program were designed and tested, offering the user various levels of interaction with the hardware devices. The final program incorporates an informative help section that guides the user through trouble-shooting and operation of the system. The front end interface of that program is shown in figure 15.

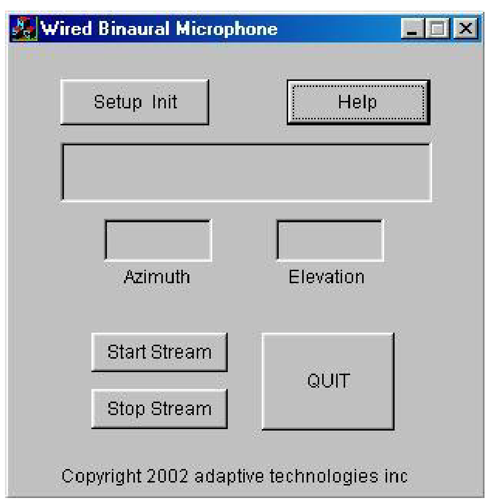

Figure 15. Command and control user interface.

Somewhat self explanatory, the user sets up the hardware by selecting the “setup init” button. A message window always displays the status of the program. In addition, the elevation and azimuth are displayed in real time once the “start stream” button is selected. Calibration of the remote and local heads is also performed immediately after the command to start stream. The help button can be selected at any time to receive troubleshooting instructions.

Operating on the same PC is the audio conditioning software previously discussed. Because real-time processing is required by the audio path, a digital signal processor is employed. A GUI was also designed by ATI to control, select, and customize the frequency response and filter the incoming signals with that response. The GUI that was designed for the audio interface is shown in figure 16.

Figure 16. Audio path user interface.

Figure 17 shows a digital photograph of the Phase I prototype system in operation, that was delivered to ARL.

Figure 17. Fully functional wired binaural microphone system.

The final remote system employs a head form that is mounted on the robotic EAR to provide acoustic shading necessary for accurate sound field measurement. A 50-foot signal and audio path was employed to allow robotic deployment from the local environment, and a fixture was designed to permit mounting on a standard camera tripod. Additional information and documentation for the operation of the system is included as an operations manual in appendix A of this report.

7. Conclusions

The primary significance of the innovations proposed in the Phase I project was the *product-oriented design strategy*, with the ultimate goal of realizing a manufacturable product at the conclusion of Phase II. By completing the proof-of-concept prototype during the Phase I effort and delivering it to the Army for further testing, ATI has virtually eliminated any technical risk of this proposed Phase II effort.

The basic problem to be solved by the Phase I effort was to allow a remotely located soldier to monitor a potentially hostile acoustic environment with localization accuracy equivalent to actually being placed in that environment. The challenges for the entire program (Phase I and Phase II) effort are to

- Employ state-of-the-art components so that remote hearing is equivalent to local hearing and may be enhanced to provide increased hearing acuity.
- Provide wireless data and audio transfer between the local and remote listening locations.
- Employ a design approach that combines the latest in technology for each component but minimizes the cost/performance ratio.
- Focus on a product-oriented design so that the end result is a robust, fieldable, manufacturable system rather than a research-based bench-top prototype.

The successful completion of the proposed Phase I effort was marked by a proof-of-concept prototype employing primarily COTS components. The Phase I prototype employed features and functionality that defined the effectiveness of the design in an actual remote acoustic environment. The Phase I option will add the remaining features envisioned for the fully functional product at the completion of Phase II. During the Phase II effort, ATI will establish original equipment manufacturer (OEM) relationships with component manufacturers to develop customized designs specific for the wireless binaural microphone. The most challenging anticipated research element of Phase II will be the inclusion of the wireless data communication between the remote location and the local listening location. The successful conclusion of the

Phase II effort will be marked by a wireless binaural microphone system ready for production, which was developed by ATI with the support of specific OEMs.

Phase I has shown that the technologies to facilitate the successful construction of a real-time audio telepresence device for remote acoustic monitoring are commercially available, cost effective, and technically sound. ATI has employed a design and construction strategy that ensures a fully manufacturable prototype will result from the Phase II effort. The successful completion of all Phase I technical objectives has guaranteed a successful conclusion to the Phase II program.

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Appendix A. Wired Binaural Microphone: User and Instruction Manual

A-1. Introduction

The ATI wired binaural microphone prototype is a real-time audio telepresence device for remote acoustic monitoring. The Phase I "alpha" prototype delivered here consists of several commercially available components including the Ascension Technologies' 3D Bird used for head tracking and TRACLabs' Biclops robotic head used for remote head and ear motion.

Delivered with this prototype are two equalization systems for the electro-acoustic signal path. One system is based on Analog Devices DSP evaluation kit. This system is non-customizable by the user. A population equalization was averaged and designed to run in real time on the evaluation kit. The second option is being offered to ARL for a period of approximately 4 weeks since it uses hardware and software currently owned by ATI. This system permits user-customizable frequency response at a slightly lower sampling rate than the non-customized solution.

The following paragraphs provide a brief overview of the hardware characteristics of the system components. Although it is advised that the user read this entire manual, Section 2.0 is not necessary if the user wishes to begin using the device immediately.

A-2. Hardware Overview

A-2.1 3D Bird

The 3D Bird is a device that measures the orientation of a small sensor in real time, allowing orientation (angular) tracking of any object to which it is attached. The 3D Bird determines orientation by measuring output from solid state inertial and non-inertial sensors. Since no signal transmitter is needed to perform measurements, the motion area of the 3D Bird is virtually unlimited. The tracker consists of a small sensor unit (sensor) that is attached to the headphones and connected to the COM port of a PC through an RS-232 cable. No intermediate electronic unit, which simplifies the system setup, is needed. The sensor unit includes all the sensors as well as the microprocessor that controls sensor data acquisition and communication between the 3D Bird and the host computer.

Figure A-1. 3D bird attached to headphones.

Specifications

Technical
Degrees of Freedom: 3 (Orientation)
Angular range: All altitude (±180°yaw, ±90°pitch, ±180°roll)
Angular Accuracy: Static Accuracy 2.5° root mean square (rms)
Dynamic Accuracy: 4.0° rms
Angular Resolution: 0.2°
Refresh Rate: As many as 160 measurements/second
Maximum No. of Sensors: 1 per serial port
Maximum Angular Speed: 1000°/second
Computer Interface: Connects to RS-232 port of host computer
Dynamic Lag: 15 milliseconds at 360°/second
Physical
Sensor Size (L x W x H): 1.41 inch x 1.08 inch x 0.92 inch
Sensor Weight: 1.0 oz.
Sensor Cable: 15 feet
Electrical
Power: 5 volts direct current (VDC) @ 100 mA
Environment
All specifications are valid at 30°C ±10° in an environment void of large metal objects and electromagnetic frequencies other than the power line.

3D Bird Product Advisory

The 3D Bird sensors, along with their attached cables/connectors, are sensitive electronic components. Most failures in the field occur because the cable attached to the sensors is mishandled. Always remember that these components are not designed to withstand severe jolting, contortions, or high impact shocks. When handling the cables, please observe the following:

- **Never flex, pull, or twist cables.** This is the most common cause of tracker failure. Note that there is a strain relief where the sensor head attaches to its cable. Its job is to protect the delicate connection between the cable conductors and the sensor assembly head. It is also the area in which sensors are attached to the object that is being tracked. Be sure you do not pull, twist, or repeatedly bend the cable.

- **Never yank the sensor off its mounting bracket or holder by grabbing the cable and pulling.**
- **Never carry, throw, or swing a sensor by its cable.**
- **Never let the sensor impact with a hard object.**
- **Never add your own extensions/connectors** to the sensor/transmitter cables. These cables are precisely bundled and shielded to minimize noise and ensure accurate performance within specification. If you add an extension, you may compromise the performance and/or negate certain regulatory certifications.

WARM-UP PERIOD
A minimum warm-up period of ***15 minutes*** is required to allow electronic circuitry time to equilibrate to temperature changes in order to achieve the highest degree of accuracy from the tracker.

A-2.2 Biclops

The TRACLabs Biclops robotic camera positioning mechanism is a multi-axis motion control platform. It is both compact and lightweight, consumes little power, and provides excellent position observation. All axes are under closed loop computer control, with motion commanded through a standard RS232 port. The Biclops PT mechanism is capable of handling as much as 2 kg and peak speeds exceed 120°/sec while drawing less than 20 watts of power for the motors and the controller. The controller, mounted in the base of Biclops, consists of an embedded servo-motor controller and brushed servo-amplifiers. The command interface to the controller is a straightforward packet protocol operated over a standard RS232 port. When a command packet, consisting of a command byte and command data, is sent, it is immediately acknowledged by an operating status packet. Each axis can be polled independently for position and motion parameters as well as quality of performance indications (e.g., ability of axis to maintain commanded position).

Figure A-2. Remote acoustic sensor shown with head form and ballast weights on biclops and tripod mount.

Specifications

Mass (without head form and weights): 1.1 Kg
Overall dimensions (without head form): 155 mm (H) x 160 mm (W) x 101 mm (D)
Mounting hole pattern: Four threaded holes (6 mm deep) 53 mm x 53 mm square pattern
Power consumption: 24 V motor power 500 mA

	Pan	**Tilt**
Range of motion	±170°	±60°
Maximum speed	120°/sec	120°/sec
Maximum acceleration	$300°/sec^2$	$300°/sec^2$
Resolution	1.8 arc-min	1.8 arc-min
(encoder ratio)	(33.33 counts/deg.)	(33.33 counts/deg.)

Biclops Product Advisory

- **Never flex, pull, or yank the power cable or the serial cable.**
- **Switch the DC supply off when trying to move/place the head form.** If the supply is on and the PT axis is stalled by hand, the motor could burn.
- **Fix the robotic head to a base while in operation.** An adapter has been designed to connect with a standard tripod mount.

A-2.3 EZ-Kit Analog Devices DSP

The portable DSP evaluation kit is used here to condition the remote acoustic sensor signals before being delivered to the user's ears. Specifically, a population average of frequency responses from the input microphone to a real-ear microphone was collected. The magnitude of this average was inverted to effectively equalize the electronic and artificial acoustic path from the remote microphone to the user's ear canal entrance. This filter was implemented with a finite impulse response filter structure with 56 weights, at a sampling frequency of 44 kHz.

Figure A-3. EZ-kit DSP evaluation board for generic population equalization.

Specifications

Technical
Two 16-bit A/D and D/A channels for stereo audio via 1/8-inch stereo jacks
User-programmable sample rate and input/output filter cutoff frequencies
User-swappable electrically erasable programmable read-only memory (EEPROM)
User programmable only with specified software (not provided)
Electrical
Power: 9 VDC @ 1200 mA

EZ-Kit Product Advisory

Handle the circuit board carefully, observing safe handling practices for electrostatic shocks. There are no serviceable parts on the board.

A-2.4 PC-Based dSpace DSP System

The dSpace system is a PC-based industry standard architecture (ISA) card coupled to an analog interface box, and user-controllable and programmable via the PC. C-code is written to run in real time on the DSP. The host computer provides control over global variables in the real-time code via a program called "Cockpit". This is a graphical environment that has already been designed for the wired binaural microphone (WBM) interface requirements. This system can be used to determine unique frequency response characteristics of specific individuals, having those responses applied to the WBM in real time, or they can be saved for later usage. Because this more complex solution was developed and implemented with hardware owned by ATI, it will only be made available to the Army for a short period of time following system delivery. This will permit ARL to analyze the utility of a customized FRF versus a more generic equalization on the EZ-kit system described.

Figure A-4. Dspace analog interface box and PC.

Specifications

Technical
Two 16-bit A/D and two 12-bit A/D channels, all ±10V input range
Four 12-bit D/A output channels, all ±10V input range
User-programmable sample rate with internal timer
User controllable via software interface "cockpit"
Texas Instruments C31 DSP processor
PC-based system

dSpace Product Advisory

- There are no serviceable parts inside the computer, so please do not open it.
- The C-code has been written specifically for the performance of this project and should not be altered in any way.

- The GUI has been designed specifically for the performance of this project and should not be altered by the user.

A-2.5 Analog Interface and Signal Conditioning

One final required element of the design is a “breadboard” containing signal conditioning for the microphones (when used with the dSpace controller) and a headphone amplifier when used with either of the two equalization options. Because of the varying dynamic ranges between the two systems, the input attenuator must be changed via a voltage divider resistor network when one is switching between the two equalization systems. The microphone amplifiers and filters are already built into the EZ-kit circuit board but are required as external components for the dSpace system to properly condition the input and output. Instructions for switching between the two systems are included in the following sections.

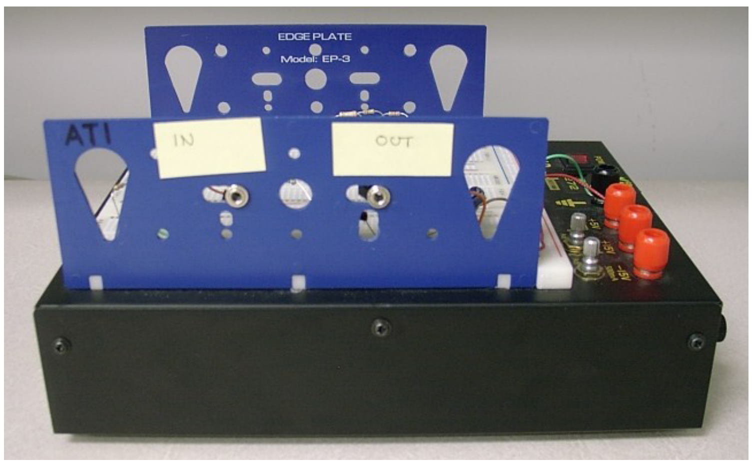

Figure A-5. Analog interface circuitry.

Specifications

Technical
Two-channel audio power amplifier for headphones with input and output 1/8-inch stereo jacks
Three-input/three-output amplified anti-alias filters at 10.5 kHz for microphone signal conditioning (left microphone, right microphone, and ID microphone) each employing three poles
Two-input/two-output smoothing filters at 10.5 kHz for DSP output, three poles each

A-2.6 List of Delivered Hardware

Hardware That ARL May Keep

- One sensor unit (3D Bird head-tracking system) mounted on a Sony head set with RS232/power cable attached
- One 100 to 240 V alternating current (AC), 1.0 A, 47- to 63-Hz regulated power supply with power cord for the 3D Bird

- One robotic head unit (Biclops) fitted with a head form, ballast weights, artificial ears, and microphones
- One 100 to 240 V AC ~50- to 60-Hz input, 24 V 1.5 A switching power supply for Biclops.
- One 50-foot serial cable (RS 232 cable for the Biclops)
- One microphone extension cable
- One EZ-kit DSP evaluation board with associate power supply (9V 1200 mA) equipped with pre-programmed EEPROM for generic equalization
- One stereo 1/8-inch male to 1/8-inch male connector cord
- One breadboard and power supply model number PP272 with headphone amplifier circuit and audio interface panel
- This user manual
- One CD containing command and control software and documentation
- Warranty information for the 3D Bird and Biclops

Hardware That ARL Must Return to ATI After 4 weeks

- Slimline PC and 17-inch monitor with mouse and keyboard containing dSpace ISA card, and associated software for customized audio path
- Connector panel for dSpace system
- Filter and amplifier semiconductors and hardware mounted on PP272 board (not including headphone amplifier)
- Associated cables and connectors that couple the dSpace connector panel with the filter modules on the PP272

Hardware That ARL Will Require After 4 Weeks

- A PC with two available COM ports

A-3 System Installation

A-3.1 3D Bird Hardware Installation

The sensor should not be situated near power cords, power supplies, or other low frequency current-generating devices. Their emanations will be detected by the sensor and converted into noise on the output orientation measurements. The sensor will detect noise when it is operated near a CRT-type display. The amount of noise will vary, depending on the operating frequency of the CRT and the amount of shielding built into the CRT.

To connect the 3D Bird to your computer, you need to do the following:

- The host PC can be switched ON/OFF.
- Attach the serial end of the 3D Bird RS232 power cable to serial port COM2 of your computer. Screw in this connector.
- Plug the power supply into the electric outlet.
- Power can then be turned on and commands sent to the 3D Bird.

A-3.2 Biclops Hardware Installation

To connect the Biclops to your computer, you need to do the following:

- The host PC can be switched ON/OFF.
- Attach the 50-foot serial cable securely to the serial interface port on the robotic head and to COM1 of the PC and screw in the connectors
- Plug in the supply for the Biclops and turn on the power on the Biclops via the small switch next to the power cord (the green light should be on)

A-3.3 Command and Control Software Installation

The package comes with a compact disc with the necessary software to run the application. The disc consists of the following files:

- WiredBinauralMic.exe
- 3DbAlg.dll
- 3DBird.dll
- Mfc42d.dll
- Mfc042d.dll
- Msvcrtd.dll

Create a working directory of your choice. Copy all these files into your working directory. Double click the WiredBinauralMic.exe file to start the application. The interface shown in figure A-6 should appear.

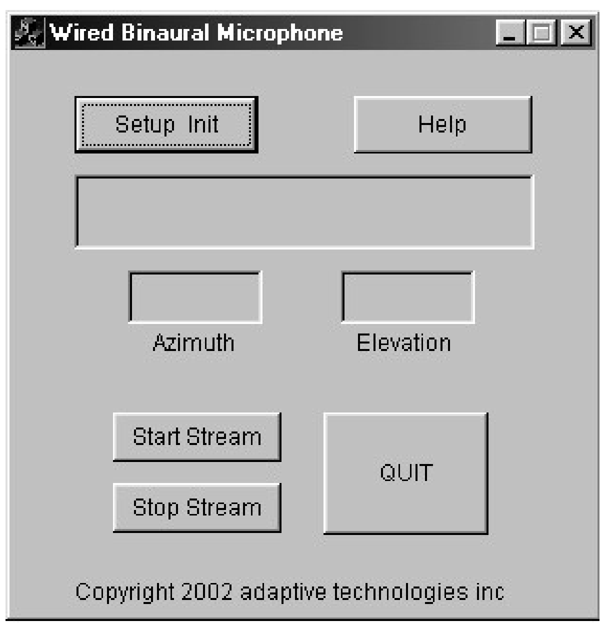

Figure A-6. Command and control graphical interface.

To test the hardware and software installation, click the "setup init" button and view the message screen and the Biclops. The Biclops will begin to move to identify its center position. If all devices are set up correctly, when the Biclops completes homing, the message "**ready to rock**" will appear in the message window. If this message does not appear, refer to the "trouble-shooting" section to identify potential problems or use the "help" feature on the GUI.

A-3.4 Generic Audio Path Hardware Installation

The generic audio path consists primarily of the EZ-kit and audio amplifier on the PP272 circuit board. The input resistor network must be modified from the dSpace settings to ensure proper calibrated SPL at the ear location. An input voltage divider is used to adjust the level coming from the D/A. Follow these steps to connect the system:

- Ensure that the input voltage divider on both the left and right inputs has a 5.6-kΩ resistor input and a 3.9-kΩ resistor to ground. Check with ATI if any confusion exists about how to accomplish this.
- Connect the 1/8-inch stereo microphone plug that is coming from the Biclops head system to the "input" stereo jack of the EZ-kit.
- Connect one end of the 1/8-inch male, 1/8-inch male extension cord to the "output" jack on the EZ-kit. Connect the other end of this cord to the input jack of the stereo headphone amplifier on the breadboard.
- Connect the headphones to the output jack of the stereo amplifier on the breadboard.
- Ensure that power is connected to both the EZ-kit with the supplied DC power supply and to the breadboard with a standard power cable.
- Switch both microphones on at the in-line pre-amplifiers near the Biclops.

You should now hear the microphone signals at normal SPL levels; you can test this by rubbing your fingers or snapping near the remote ears.

A-3.5 (temporary delivery) Customized Audio Path Hardware Installation

All the required software and hardware on the PC have been pre-installed upon delivery. The operating instructions for that software and hardware are given in the following section.

The dSpace system is not equipped with anti-alias or smoothing filters, necessary for accurate digital signal reconstruction. These filters were built by ATI on the same circuit board that holds the audio power amplifier. The proper connections between the dSpace connector panel and filter hardware must be made. The microphone signal from the Biclops is connected to the WBM input, and its output is connected to channels 1 and 2 of the dSpace connector panel. The identification microphone is connected to the middle (mono) microphone input on the circuit board, and its output is connected to channel 3 of the dSpace connector panel. Finally, outputs 1 and 2 of the dSpace connector panel are connected to the smoothing filter (stereo) input, and its output is connected to the input of the stereo headphone amplifier on the other side of the circuit board. The headphones are then connected to the output of the stereo headphone amplifier as in section 3.4.

The headphone amplifier for the dSpace customized audio path system requires a different voltage divider for the input to the stereo headphone amplifier. Ensure that this divider is in place for both left and right signal paths before operating the audio path. The appropriate voltage divider for the dSpace system consists of an input resistor of 5.6 kΩ and a 68-Ω resistor to ground.

A-3.6 (temporary delivery) Auto-Run Batch File and Custom Audio Path Equalization Software

ATI has combined ALL start-up requirements for the customized audio path into a single batch file that is situated in the center of the desktop titled "wired binaural microphone". Simply double click this icon, and several programs will be launched. First, ControlDesk will establish a host connection with the DSP, the audio code will be complied and downloaded to the DSP, cockpit will launch, MATLAB will launch, and finally, the C2 GUI for the robotic head and head-tracking hardware will be launched.

Once all windows are open, it is safe to close ControlDesk and minimize or close MATLAB, depending on desired usage. Click the "start" button on the cockpit window, and the edit mode will change to the animation mode shown in Figure A-7.

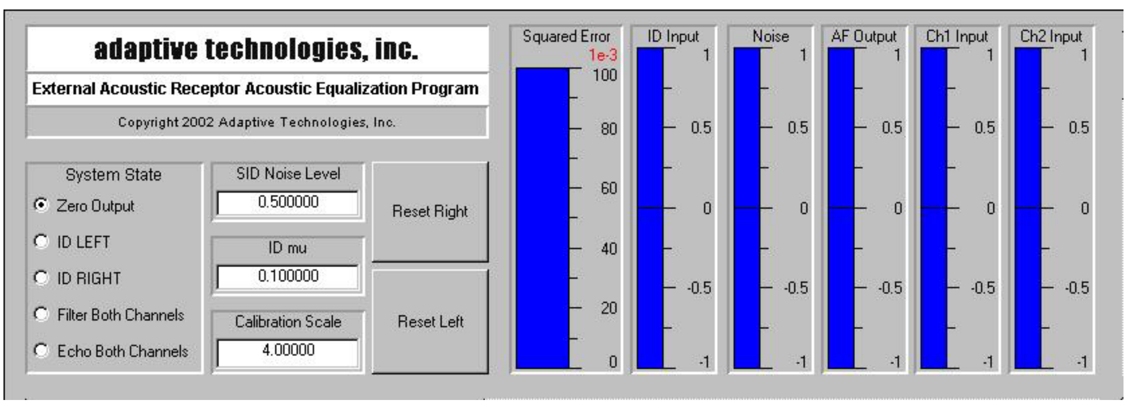

Figure A-7. Customized acoustic equalization interface.

To check the audio path, click the radio button from zero output to "echo both channels". You should then hear the remote microphones, albeit unequalized.

A-4. Operating Instructions

The head-tracking/robotic head interface and control are handled separately from the audio path hardware and control. Therefore, the two systems are discussed independently to simplify troubleshooting and setup. Because the two systems are independent, it does not matter which one is set up and initialized first. Figure A-8 shows the full system during operation.

Figure A-8. Full system during operation.

A-4.1   Head and Tracking Command and Control

The robotic head will track the user's movements in real time after the system has been properly configured.

- Ensure that power is connected and on for both the 3D Bird and the Biclops.
- Don the headset (with the Bird attached) and position it in a comfortable location on your head. Be sure that this position does not move relative to your head after it has been set.
- Double click on either the shortcut application on the desktop or the **Wired Binaural Microphone.exe** application, as described in the previous section.
- When the application loads, press the Setup/init button (see figure A-6). This will set up communication with the Bird and then to the Biclops. The Biclops will go through a homing sequence to identify the hard limits on both the pan and tilt and returns to its mechanical origin. During this time, the GUI prevents the user from controlling any aspect of the system. This robust feature ensures that the required homing procedure completes successfully.
- Once homing is complete and the 3D Bird is successfully initialized, the message **"Ready to Rock"** will be seen on the message window below the "setup init" button. At this point, hit the "start streaming" button. A message window will appear, instructing the user to look in the same direction and level as the robotic head; then hit "OK". This action manually establishes coherent directions of the robotic and human head directions and ensures that when the human looks north, the robotic head is also looking north.
- Click OK while looking in the direction of the Biclops. The Bird will reset its origin or reference to the current orientation and start streaming (orientation) 160 data records per second (azimuth and elevation, at a baud rate of 38,400) to the Biclops. The PC then interfaces through COM1 with the Biclops at a rate of 115,200 baud and conveys the orientation information. The robotic head then tracks the head movement in real time.

- If you need to stop streaming, hit "stop stream". This will cause the streaming from the head tracker to the robotic head to stop but does not disconnect the devices from the PC. This is essentially a pause feature that allows repeated use but does not require another homing procedure.
- Note that each time the "start stream" button is pressed, the user must calibrate his head location with that of the 0,0 position of the Biclops. Biclops automatically returns to 0,0 as soon as the "start stream" button is hit and before the user is required to calibrate.
- If you want to quit the application, hit "quit". This stops the streaming and disconnects the two devices from the PC and closes the application window. If the application is restarted, the homing procedure will commence.

An additional help feature is provided and is activated by the "help" button on the GUI. This feature is context sensitive and will provide instructions/help to the user, based on the current state of the application. If any problems are encountered during any step in the process, the help button can be pressed and troubleshooting assistance will appear.

Although the hard limits for the pan-and-tilt axis for the Biclops are 170° and 60°, the implementation for the wired binaural prototype has further reduced it to 165° and 55°. This has been done to ensure that the Biclops does not physically hit the hard limits when the local user moves his head toward it. In addition, when the pan/azimuth exceeds the pre-set limit of ±165°, the robotic head remains at ±165°, as may be the case, until the pan orientation data being streamed fall back within the specified limits. Similarly, on the tilt axis, the robotic head will remain at ±55°, as may be the case, until the tilt values fall within the allowed range.

A-4.2 Generic Audio Path Operation

The generic audio path has been pre-calibrated and pre-designed to generically accommodate all users. A population frequency response was collected and used to generate an average inversion filter, which was implemented on the EZ-kit device. Once power is applied, this filter is engaged on both left and right channels and does not require any user interaction to achieve calibrated and equalized audio path delivery to the user's ears. If after installation, no audio is apparent,

- Ensure that power is applied to the EZ-kit and the green light-emitting diodes (LEDs) are on.
- Ensure that all audio signal connections are correct as defined in the previous section.
- Ensure that power is applied to the circuit board and that all circuit connections have been properly made.
- If the audio sounds too low, ensure that the proper resistor network (voltage divider) is in place for the generic filter operation.

The filter cannot be changed by the user. It is possible that alternate filter designs may be used, but they must be pre-designed and burned onto an EEPROM at ATI. This capability is not provided to the end user at this time.

A-4.3 (temporary delivery) Customized Audio Path Hardware and Software Operation

The audio path can be customized for a specific individual. This involves equalizing the electronic and acoustic frequency responses between the remote and local ears. This is done by first identifying the frequency response and then filtering the incoming signals with an inverse of that response. The result is a flat magnitude response between the remote and local ears, ensuring accurate SPL delivery at all frequencies. The 1000-Hz, 0-dB gain of the audio path has been pre-set, based on a calibrated tone being delivered at the remote location and set at the local location. While this gain is adjustable on the audio path GUI (shown in figure A-7 as "calibration scale"), it does not need to be altered by the user.

After the application is loaded via the desktop icon, the user must press "start" in the cockpit window in order to control the GUI. The following steps outline the chronological operation of the customized audio path:

- Place the headphones comfortably on your head. Remember that their position also controls the head tracker information.
- The "system state" menu items govern the operation of the audio path. The default setting is zero output, which does not generate any audio at the headphones.
- In order to check the operation of the device, select "echo both channels". This sends the audio signals from the remote location to the local location, with calibrated signals at 1 kHz. No frequency response equalization is performed on these signals; it simply echoes the input to the output with appropriate gain for calibrated 1-kHz delivery.
- "Filter both channels" will filter the input with the equalization filter designed during the identification process. If no filters have been designed, no sound will be heard.
- In order to design the filters, a microphone must be placed in the user's ear that corresponds to the identification channel. The microphone is placed in a manner similar to that at the remote location (see figure A-9).

Figure A-9. The local user places the microphone facing out, using the pre-fabricated earplugs designed for holding the microphone.

- Once the microphone is in place (for example, the right ear), the headphones are placed on the user's head (ensuring that the right headphone goes to the right ear). Then the user selects "ID RIGHT" from the system state menu. The user will hear a white noise signal from the right earphone. The volume level (sound interface device noise level) is pre-set and should not need adjusting. **The user should carefully watch the "squared error" level indicator. When it reaches a very low value, the identification procedure has converged on an acceptable solution and can be paused. If during the identification procedure, the headset is moved or a large SPL is received at the ear microphone, the routine may diverge. This will be noted by a red bar occupying the "squared error" indicator. In this case, pause the routine, reset the filter by pressing "reset right," and repeat the identification, being careful to remain still.**
- Repeat the identification procedure for the left ear by placing the identification microphone in the left ear and pressing "ID LEFT".
- Once the filters have been identified, the user can select "filter both channels" to hear the equalized remote microphone signals.
- "Reset right" and "reset left" will set the filters to zero but only when the system state is in "zero output" mode.

The advanced user may also have access to the filter weights themselves by accessing the table editors to the far right of the cockpit GUI. The table editors (not shown) allow the user to load and save the identification weights from the DSP and view them in a MATLAB format file. In addition, old weights can be reloaded by the user to avoid the identification routine described.

- Scroll the GUI to the right to reveal the table editors for "11" or the left ear and "22" or the right ear.
- For each table, "manual refresh" collects the most recent weight vector from the DSP. "Save" permits the user to save the vector weights in a MATLAB format .mat file. "Load" allows the user to load a predetermined weight vector from a .mat file to the cockpit buffer, and "download" sends those weights in the buffer, to the DSP. **Warning: Only vectors originally developed in the cockpit GUI can be reloaded at a later time. Do not attempt to manually generate a filter for loading on the DSP; the format will be incorrect.**
- A MATLAB m-file called convafwts.m is provided to display the frequency response of the filter that is saved.

A-5 Troubleshooting

As before, the audio and C2 systems operate independently. Therefore, the troubleshooting and problem solving help presented here is divided into these two system components.

A-5.1 Command and Control Software and Hardware

If you are experiencing trouble with the application and you get the following on-screen messages, try the suggested steps:

Cannot communicate with bird device:

- Ensure that the power supply is plugged into the external power before the application tries to communicate to the 3D Bird (before hitting “setup/init”).
- Ensure that the 3D Bird is plugged into the **COM Port 2.**
- Ensure that you do not have multiple applications trying to use COM port 2.

Unable to read data from 3D Bird device (bad data):

- Ensure that the 3D Bird is not placed directly on top of metal during operation. Keep the Bird at least 2 inches away from metal.
- If orientation data are continuously drifting, ensure that you keep the 3D Bird still hitting the “OK” button in the pop-up window that instructs the user to look in the general direction of the Biclops. The 3D Bird performs self-calibration that takes about 0.5 second and needs to stay still during this period of time.

Cannot communicate with robotic head (Biclops) device:

- Ensure that the power supply is plugged to the external power before the application tries to communicate to the Biclops (before hitting “setup/init”).
- Ensure that the Biclops is hooked into **COM Port 1**.
- Ensure that multiple applications are not trying to use COM port 2.

Head tracker and robot head not connected:

- The power supplies to the Bird and the Biclops may not be connected.
- The Bird and the Biclops may not be connected to COM2 and COM1, respectively, or may not be connected at all.
- The toggle switch for the Biclops may not be turned on. (Check for the green LED on the back of the Biclops.)

The robotic head may move even when the user head does not move because of bad data from the head tracker. This is an anomaly of the 3D Bird device. If it becomes affected by an electromagnetic field, it can generate bad data, causing the Biclops to respond inappropriately. This is especially noticeable when the device is static. Continue moving the device, and the data may become more reasonable. If the data are scrolling continuously in either axis, the device may need to be “degaussed”. This can be done with a tape eraser available at Radio Shack[8]. This condition typically corrects itself after several minutes.

In case any of the above steps do not solve the problem, do not open the hardware (Biclops or Bird). The manufacturers’ warranties may be invalidated. There are no fuses or other user-serviceable parts in the 3D Bird sensor or Biclops.

A-5.2 Generic Audio Path Hardware

If the audio path is not working, ensure that power is on for both the circuit board and the EZ-kit. Ensure that all wired connections are made and that the proper voltage divider has been put in place.

[8] Radio Shack® is a registered trademark of the Tandy Corporation.

A-5.3 (temporary delivery) Customized Audio Path Hardware

This option will be delivered completely assembled. If the audio path does not operate properly, consider the following items:

- Batteries and power switches for the in-line microphones connected to the robotic head must be on and fully charged.
- Connect the microphone to proper input on circuit board; output of this stage goes to input 1 and 2 on dSpace interface.
- Ensure that identification microphone is plugged in, powered on, with a charged battery.
- Ensure that identification filter has been created before selecting "filter both channels".
- Ensure that correct voltage divider is put in place on audio amplifier board.

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