The Varèse System, Hybrid Auditory Interfaces, and Satellite-Ground Control: Using Auditory Icons and Sonification in a Complex, Supervisory Control System

Michael C. Albers
Center for Human-Machine Systems Research
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
Email: malber@chmsr.isye.gatech.edu

Abstract

The basic auditory interface techniques of auditory icons, earcons, and sonification can deftly address the needs of most domains. However, there are domains that cannot be adequately addressed by any single one of these techniques. By combining the characteristics of these basic techniques, hybrid auditory interface techniques can be created to cover those domains that auditory icons, earcons, or sonification cannot. This chapter describes a methodology for creating hybrid auditory interface techniques. This methodology is demonstrated through the development of a sonification-auditory icons hybrid for use in a complex supervisory control environment. The Varèse system, which incorporates the sonification-auditory icons hybrid technique, is then developed to aid monitoring, fault detection, and fault isolation in a satellite-ground control environment.

1 Introduction

There are three main techniques for the creation of nonspeech auditory interfaces. These techniques are auditory icons, earcons, and sonification. Auditory icons are everyday sounds mapped to computer events by analogy with everyday sound-producing events [12]. Earcons are a language built from short sequences of tones and associated with actions and objects [1]. Sonification is the transformation of data by a sound generator to the classical dimensions of sound such as frequency, amplitude, and duration for monitoring and comprehension [8, 15, 18].

Each of these techniques is commonly used in a small set of application domains. Both auditory icons and earcons are generally used to represent cause-effect interactions between objects and activities, such as the user-initiated actions-on-objects in SonicFinder [11], Mercator [17], Auditory Maps [2], and Auditory-Enhanced Scrollbars [4]. Sonification is often used for interpreting complex data, such as in Parallel Program Debugging [7], the Pendulum and Smog scenarios [19], and Seismic Data [14]. The frequent use of these techniques has evolved based on attributes which make them attractive for certain situations, domains, and work environments.

However, these techniques are also being successfully employed outside these common domains. Auditory icons are used in systems such as ShareMon [5] and EAR [10] to notify people of the activities of others. Earcons are being used to give blind users access to mathematical notation [20]. McQueen [16] is using sonification techniques to help teach handwriting skills. Often, the unusual application of an auditory interface technique pushes it to the limits of its representational ability. The technique's limitations are revealed through their application in these novel domains.

From these experiences, it is often clear which techniques could be applied to a specific situation or domain. However, some domains cannot be adequately addressed by a single technique because they demand a greater information bandwidth at greater speeds than can be provided by basic auditory icon, earcon, or sonification techniques. An example of this type of domain is the monitoring and troubleshooting of complex, supervisory control systems such as power plants, some medical environments, aircraft, process control plants, and spacecraft control systems. These systems demand rapid interpretation of data that can change very quickly. So, how does one add helpful auditory cues to these demanding environments?

One option is to invent a new auditory interface technique without reinventing work that has been done previously. This approach has the benefit of being exactly applicable to the problem at hand; your solution or technique is based on a specific problem. Yet, this new approach may take enormous amounts of time and effort to develop and may not generalize well across domains.

An alternate option is to build hybrid auditory interface techniques from the existing techniques. The goal of building hybrid techniques is to integrate the existing techniques to exploit the strengths, while compensating for the weaknesses of each individual technique as the domain of interest demands. This approach has the same benefit as above: being exactly applicable to the problem at hand as the hybrid technique is based on a specific problem. Also, the hybrid technique's development cycle will likely be shorter because the hybrid techniques are developed on the foundation of previous work. Further, the hybrid techniques may generalize better than the solution described above as the domain-dependent aspects of the hybrid technique can be identified and replaced when desired or where necessary.

To illustrate this methodology's usefulness, a hybrid technique composed of the auditory icon and sonification techniques is created and applied. The Varèse system, the system in which the hybrid technique is utilized, is demonstrated in the complex supervisory control environment of satellite control. The Varèse system provides the satellite operators a time-varying, global, acoustical view of the satellite system. This auditory view of the system helps to direct the operators' visual scan of the information presented to them about the satellite. The Varèse system shows that, by using a systematic, domain-driven approach to using sound in the interface, auditory cues can effectively be incorporated into a complex, real world system.

First, a brief description of the complex supervisory control system, satellite-ground control, will be presented. Second, the hybrid technique development methodology and the creation of a sonification-auditory icons hybrid technique will be presented and discussed. Third, the Varèse system will be described and compared to similar work by Gaver, Smith and O'Shea [13] and Fitch and Kramer [6].

2 Domain of Application

Satellite-ground control is an example of a complex supervisory control domain. For each satellite, ground control is carried out by two operators who monitor, troubleshoot, and control a complex system consisting of ground facilities, data communication systems, and an Earth-orbiting scientific satellite (see Figure 1).

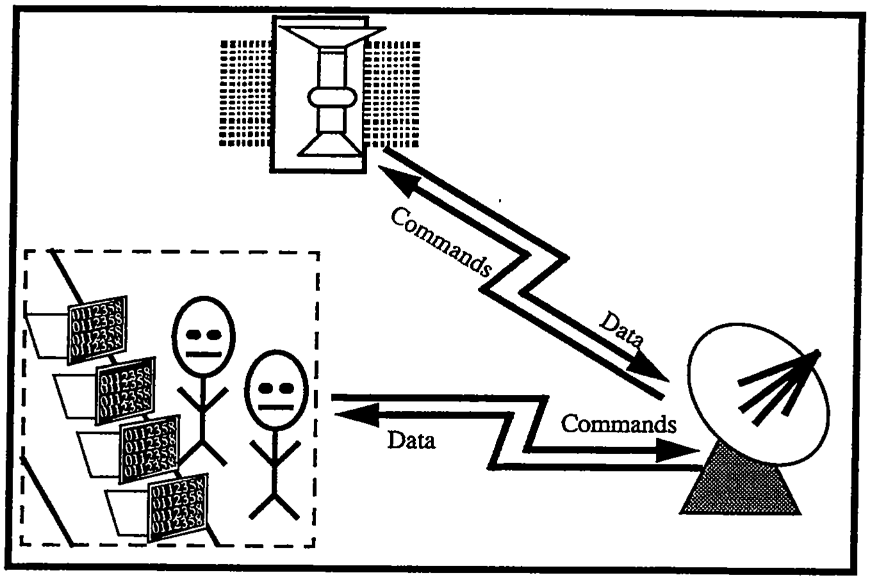

Figure 1: Satellite-ground data network and control environment.

Due to the distribution of and limited resources at the ground facilities, the operators are in communication with the satellite for only 10 minutes, four times a day. The operators have only these 10-minute long communication phases to determine the operational status of the satellite. The operational status of the six subsystems that comprise the satellite determines the operational status of the satellite. The possible operational states for the satellite subsystems are normal, warning, and critical.

Although much of the low-level control activities for the satellite are highly automated, the monitoring and troubleshooting activities are not. During the communication phases, the operators need to derive the operational states of the six satellite subsystems from over 1000 individual, time-varying "data points" which are updated once every five seconds. Each data point is a number which represents a minute aspect of the overall satellite, such as the electrical current through an auxiliary electrical bus or the temperature of a gyroscope. These data points are placed on eight virtual screens, two of which can be viewed at any one time. The operators iteratively view each screen of data points for subsystem faults—aberrant data point values which designate that a subsystem has progressed from a normal operational state to a warning or critical operational state.

3 Hybrid Auditory Interface Technique Development Methodology

This research produces a methodology to create hybrid auditory interface techniques. The hybrid auditory interface development methodology is a five step process consisting of:

1. choosing the basic auditory interface techniques to combine

2. identifying the benefits and limitations of each chosen technique

3. combining the benefits to alleviate the limitations of each technique
4. realizing where merging some aspects of each techniques is problematic
5. developing strategies to relieve the incompatible combinations

To illustrate this methodology, a hybrid sonification-auditory icons auditory interface technique will be developed alongside the methodology's description. This hybrid technique will later be used in the Varèse system.

The first step in the creation of a hybrid technique is the selection of the basic techniques to combine. The selection of the techniques could be based on the demands of the domain and/or knowledge about prior attempts to add auditory cues to this domain or similar domains.

The second step in building a hybrid auditory interface technique is to identify relevant benefits and limitations of each of the chosen, existing auditory interface techniques. In this case, sonification and auditory icons have been chosen. There are several characteristics of auditory icons and sonification which make them attractive for the situations in which they are commonly employed and detract from their being used in other domains.

The sonification technique is well-suited to representing time-varying data, multivariate data, background processes, and transient conditions [18]. To display this information, the sonification technique has evolved a strategy of using the data to drive changes in the qualities of a sound. Frequently, this is achieved by changing classical dimensions of audio signals such as frequency, amplitude, and duration [3, 18]. This strategy of data-driven changes to classical dimensions of simple musical sounds is useful for exposing small changes over a wide, possible range of data values. However, this strategy leads to the use of artificial-sounding tones without regard for any natural connection from the sounds to the data being represented [3, 12, 18].

Auditory icons are well-suited to representing cause-effect interactions between actions and objects, such as indicating user-initiated actions like button presses and item selections. Auditory icons are caricatures of naturally occurring sounds based on the way people listen to the world in their everyday lives [11]. Auditory icons are a natural connection from system events to the real world and, thus, they have repeatedly been used in systems which interactively display data to users systems where activity is dependent upon user action. The usual technique is to present a real-world sound which analogically approximates the cause-effect relationship resultant from the user's actions. Because auditory icons are based on the way people interact with the world, they are readily identifiable by users. However, this technique offers little guidance for modifying the real-world sounds to convey relevant dimensions of activities during time-varying processes.[1]

To summarize, benefits and limitations of the sonification technique are:

1. Sonification is a good technique for communicating time-varying data.
2. Sonification has a well-defined strategy for modifying sounds to convey additional information about the time-varying data.
3. Sonification often employs nonintuitive, artificial tones without regard for any natural connection from the sounds to the data being represented.

[1]While parameterizing auditory icons [5] can increase the information bandwidth of auditory icons, this method has limitations [5] which make it insufficient for this application. And while the promise of synthesized auditory icons is enticing, more research into them is required before they can be fully integrated into interfaces.

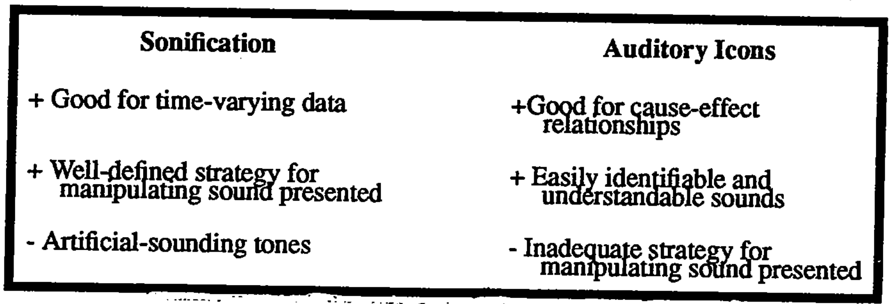

Figure 2: Hybrid interface methodology stage #2.

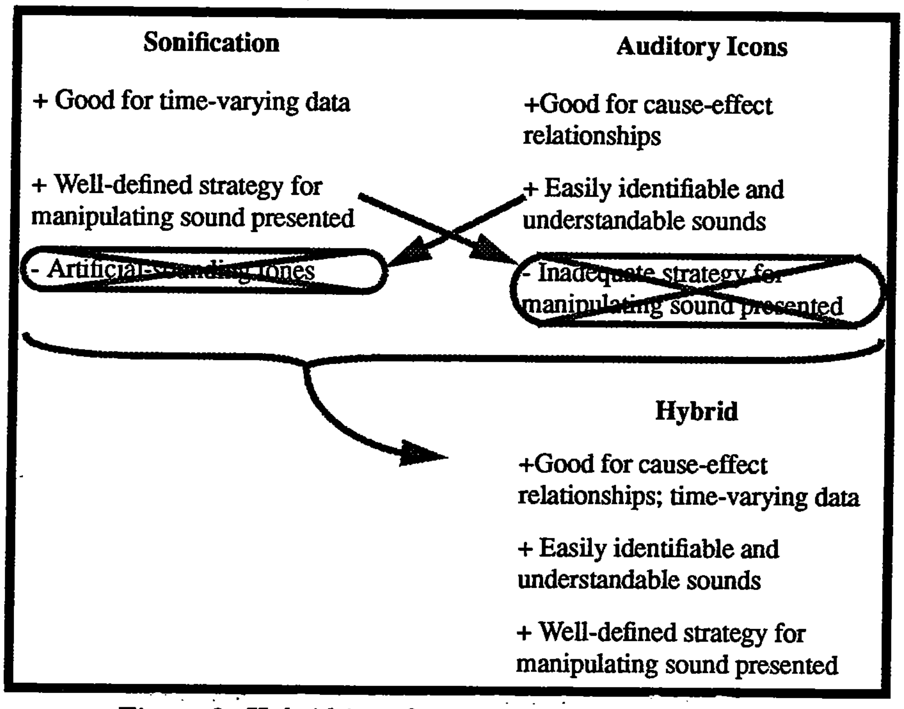

Figure 3: Hybrid interface methodology stage #3.

Benefits and limitations of the auditory icons technique are that:

1. Auditory icons are good for relating cause-effect relationships.
2. Auditory icons are sounds which are easily identifiable and understandable because they are caricatures of naturally occurring sounds.
3. Auditory icons lack a mature strategy for encoding additional information in an auditory icon by modifying it (see Figure 2).

After identifying characteristics of each technique, the benefits of one technique are identified to alleviate limitations of other techniques (see Figure 3). This is the third step in the hybrid technique development methodology. In this example, the limitation of the sonification technique, artificial tones, is countered by the auditory icons benefit of easily identifiable and understandable sounds. The limitation of the auditory icons technique, the lack of a mature strategy for auditory

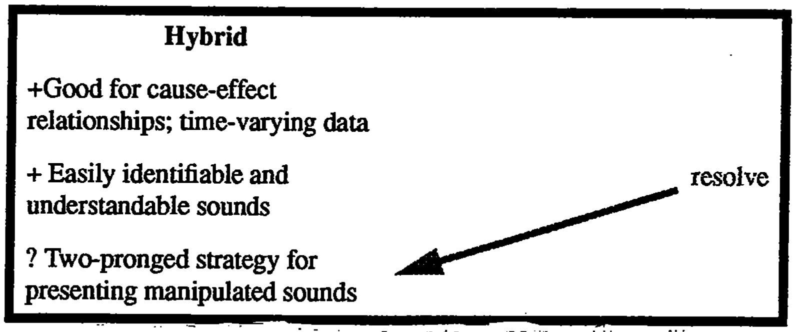

Figure 4: Hybrid interface methodology stage #4.

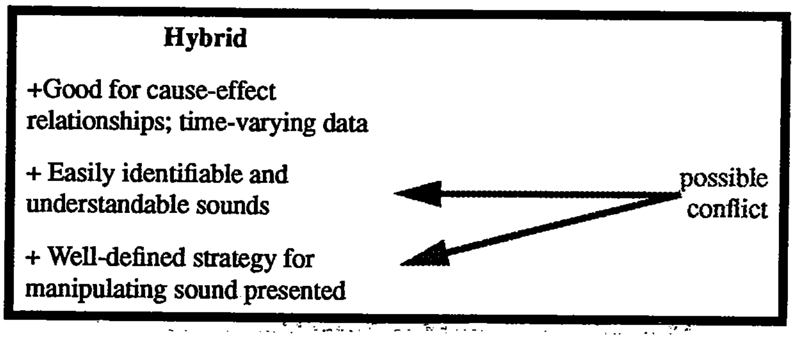

Figure 5: Hybrid interface methodology stage #5.

icon modification, is countered by the sonification benefit of a well-defined strategy for modifying sounds to convey additional information.

The straight, simple combination of the two techniques results in the first version of this hybrid technique (see Figure 3). This hybrid technique retains the benefit of being useful for cause-effect relationships in time-varying data. This first version of the hybrid technique uses the identifiable and understandable sounds from the auditory icons technique with sonification's well-defined strategy for modifying the sonic information presented.

The fourth step in the hybrid technique development methodology is to review the current state of the technique for any incompatible characteristic combinations. Upon reviewing the current aspects of this hybrid technique, a possible conflict is recognized between the auditory icons' "everyday" sounds and sonification's strategy for manipulating sounds (see Figure 4). Sonification's strategy for manipulating sounds revolves around modifying the classical dimensions of an audio signal such as frequency, amplitude, and duration [3, 18]. However, it is known that manipulating "everyday" sounds along dimensions that specify events in the world using the classical dimensions of the audio signal is difficult [9]. For example, it is difficult to sample the sound of a smoothly running engine, modify its frequencies, amplitudes, and duration, and arrive at the sound of a sputtering engine. But, lacking a mature procedure for manipulating auditory icons, some component of the sonification strategy must be employed.

The fifth step in the hybrid technique development methodology is to develop a strategy for alleviating any incompatibilities between the characteristics of the hybrid technique. In this example, the problematic combination of characteristics from sonification and auditory icons is alleviated by utilizing a two-pronged sound modification strategy that exploits aspects of the domain to guide the controlled use of sonification's sound modification approach (see Figure 5). The next section, which describes the Varèse system, will detail how aspects of the domain guide the use of the two-pronged sound modification strategy.

In conclusion, this application of the hybrid auditory interface technique development methodology produced a sonification-auditory icons technique. In the next section, this hybrid technique will be demonstrated in the complex supervisory control environment of satellite-ground control.

4 The Varèse System

The Varèse system uses the sonification-auditory icons hybrid auditory interface technique developed in the previous section for the domain of satellite-ground control. The Varèse system supports the satellite operators' monitoring, fault detection, and fault isolation tasks for the six satellite subsystems. To accomplish this, the Varèse system uses the data from the satellite to display an auditory icon at a given speed for each satellite subsystem. These six continuous sounds convey each subsystem's operational state and its proximity to the next operational state. Aspects of the data from the satellite direct the two-pronged sound modification strategy.

First, by using the existing three operational states of each subsystem (normal, warning, critical) in the satellite-ground control system, three distinct but context-related sounds are used per satellite subsystem, one per operational state. The three sounds communicate the operational state of a subsystem to the operators. For example, the power subsystem plays the sound of a smoothly running engine for the normal operational state, a sputtering engine for the warning operational state, and a choking/dying engine for the critical operational state.

Second, the data will control the speed of display of the sound to convey the subsystem's proximity to the nearest operational state. That is, as the subsystem's data approaches the threshold from normal to warning operational states, the speed of display of the auditory icon increases, conveying a sense of urgency to the operators. Because the possible data values of the operational states have upper and lower bounds, the speed modifications can be controlled, insuring that these changes will not contort the auditory icon beyond easy recognition.

For example, let us consider the attitude control subsystem which is responsible for pointing the scientific instruments and the antennas. A whooshing/gyroscope sound is for the normal operational state, spinning with friction for the warning state, and spinning with friction and clanking for the critical state. While the attitude control subsystem in the real system is described by over 60 data points, for this example, let us consider only two hypothetical data points, X and Y. For X, the lower bound is 100, the crossover to the warning state is 200, and the crossover to the critical state is 300. For Y, the lower bound is 0, the crossover to the warning state is 50, and the crossover to the critical state is 100 (see Figure 6).

Let us assume that the new, incoming value of X equals 135 and Y equals 25.[2] From these values, the Varèse system needs to decide which auditory icon to play and at what speed to play it. To decide this, the Varèse system must have some mechanism to directly compare the two values. This mechanism, the comparator scale, is used to compare the values after each data value is normalized to a lower bound of 0, a crossover to the warning state of 100, and a crossover to the critical state of 200 (see Figure 6). After normalizing X and Y to the comparator scale,

[2]Remember that each data point is updated once every five seconds.

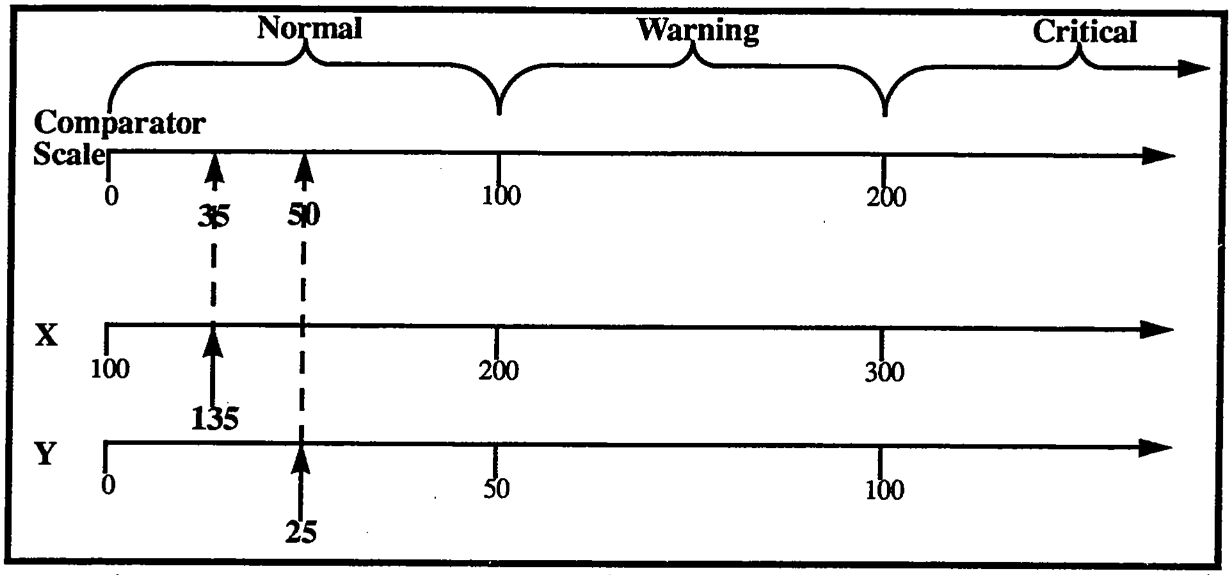

Figure 6: An example of the Varèse system.

X equals 35 and Y equals 50. The comparator scale tells the Varèse system that both X and Y fall within the normal operational state range (0–100) and that Y (50) is closer to the next operational state (warning) than X (35). Therefore, the Varèse system knows that it should play the normal operational state sound for the attitude control subsystem, the whooshing/gyroscope sound. Also, because the normalized value of Y is the closest to the next operational state, the Varèse system knows that the normalized value of Y will be used to set the speed of display for the whooshing/gyroscope sound.

The normalized value of Y, 50, is used to decide the speed of display of the auditory icons by using a property of the comparator scale. The speed of a sound corresponds to a location on the comparator scale. For the normal operational state, a normalized value of 0 equals a speed of 1 and a normalized value of 100 equals a speed of 2. For example, a two-second long sound that is played at a speed of 2 takes one second to play.[3] To derive the speed from the scale value if the value falls in the normal operational state range, let the speed equal: ((value/100) +1). Therefore, the speed of the whooshing/gyroscope sound will be 1.5 with Y's normalized value of 50. That is, if the whooshing/gyroscope sound is a one-second long sound, the actual playing time of the sound will be approximately 0.666 seconds. The auditory output of this process will be the whooshing/gyroscope sound playing at a speed of 1.5 for approximately 0.666 seconds and a short silence. This auditory cue, played at a specific speed, will be repeated until the next normalize-and-compare process. The normalize-and-compare process is repeated every five seconds when new data about X and Y is received.

In concluding discussion of the Varèse system, by employing the hybrid technique the Varèse system provides satellite control operators an auditory cue for each subsystem which conveys the subsystems' operational state and proximity to the next operational state. The operational states of the subsystems are conveyed by applying the auditory icon technique and the proximity to the next operational states are provided by the sonification technique. During a 10-minute

[3]The equation that describes this relationship is: actual playing time of sound = sound length/rate.

communication phase, the operators have a time-varying, global acoustical view of the satellite system to direct their visual scan of the data-points associated with each subsystem. That is, without viewing a particular subsystem, the operator is alerted to a fault within a subsystem by auditory cues. Further, the operator will be informed of faults that occur while compensating for other faults. The global, acoustical overview of the satellite-ground control system aids the operators in fault detection and isolation by providing state information for all subsystems.

There are two other systems that have a focus similar to that of the Varèse system. One of these systems, developed by Gaver, Smith, and O'Shea, was an ecology of auditory icons for the ARKola bottling plant simulation [13]. ARKola was a simulated soft drink factory controlled by a pair of operators. These operators were provided a shared auditory space of up to 14 auditory icons to assist collaboration and provide information about multiple, simultaneous events. The ARKola simulation and the Varèse system both present auditory icons which convey information about the state of system components. However, the ARKola simulation conveyed little inter-state information, e.g., about whether an error condition would soon occur. While the "rhythm of the sounds reflected the rate at which the machine was running," there is not necessarily a correlation between machine rate and error conditions [13]. In the Varèse system, there is a direct relationship between the speed of display of an auditory cue and its proximity to the next operational state, a pertinent characteristic of this environment.

Fitch and Kramer developed the Anesthesiologist's Workstation [6], the second system that is similar to the Varèse system. The Anesthesiologist's Workstation was a set of two parameterized auditory icons mapped to physiological variables in a simulated anesthesiologist's task. Parameterization of the two auditory icons provided information about eight simulated physiological variables. The Anesthesiologist's Workstation and the Varèse system are similar in that they both modify base auditory icons to convey further information about the system represented. However, the Anesthesiologist's Workstation differs from the Varèse system in one main way. The Anesthesiologist's Workstation interactively altered the two base auditory icons to convey information about other, related physiological systems. As an example, the pitch of the heart sound conveyed information about the systolic blood pressure of the "digital patient" [6]. Alternately, in the Varèse system, interactively altering the base auditory icons conveys further information about that particular system.

Conclusion

This chapter describes a methodology for the creation of hybrid auditory interface techniques and demonstrates this methodology through the development of a sonification-auditory icon hybrid technique. Hybrid techniques offer a method for creating auditory interfaces quickly that can be applied to situations that cannot be effectively handled by auditory icons, sonification, or earcons alone. The Varèse system shows the application of the sonification-auditory icon hybrid technique in the complex supervisory control system of satellite-ground control.

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