An Approach to Model Checking the Perceptual Interactions of Medical Alarms

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The perceptibiliy of auditory medical alarms is critical to patient health and safety. Unfortunately concurrently sounding alarms can interact in ways that can mask one or more of them: render them imperceptible. Masking may only occur in extremely specific and/or rare situations. Thus, experimentation is insufficient for detecting it in all of the potential alarm configurations used in medicine. Therefore, there is a real need for computational methods capable of determining if masking exists in medical alarm configurations. In this work, we present such a method. Using a combination of formal modeling, psychoacoustic modeling, temporal logic specification, and model checking, our method is able to prove whether a configuration of alarms can interact in a way that produces masking. This paper motivates and presents this method, describes its implementation, demonstrates its power with an application, and outlines future developments.

INTRODUCTION

Medical alarms (which are usually auditory) are used by automation to notify humans that monitored patient health measures have passed a threshold, indicating a potentially unsafe condition that requires immediate attention. Clearly, the ability of the humans to perceive, understand, and respond to alarms is critical to patient safety.

There are many limitation of auditory medical alarms (Edworthy, 2013). Significant numbers of false alarms can desensitize humans to them; they can be poorly designed, reducing their effectiveness (Edworthy, 2013); and concurrently sounding alarms can perceptually interact in ways that make them difficult to identify (Lacherez, Seah, & Sanderson, 2007) or mask each other (make one or more of them imperceptible) (Fastl & Zwicker, 2006). Unfortunately, problems caused by the masking of concurrently sounding alarms can be very difficult to identify because they may occur under rare or unusual conditions or through the interaction of alarms within or between systems. Thus, while auditory masking has been experimentally detected in clinical settings (Momtahan, Hetu, & Tansley, 1993; Toor, Ryan, & Richard, 2008), the vast majority of the work on alarms has focused on other problems. However, as the number of medical alarms increases and alarms from different systems interact, the presence of masking will significantly increase (Edworthy, 1994). Thus, there is a real need for methods capable of identifying if masking is present in medical alarm configurations before they are used.

In this work, we describe a method we developed capable of doing such analyses that uses model checking and psychoacoustic modeling. Model checking is an analysis tool designed to find concurrency problems in computer systems using a form of automated theorem proving (Clarke, Grumberg, & Peled, 1999). Psychoacoustic models are capable of indicating if concurrently sounding alarms interact in ways that can produce masking (Bosi & Goldberg, 2003; Fastl & Zwicker, 2006). When used together in our method, an analysts can computationally determine if masking exists in a configuration of alarms. With such a detection capability, health care providers should be able to deploy systems guaranteed to avoid masking, ensuring that sounding alarms are perceivable, enabling the proper human response, and potentially saving patient lives.

This paper describes this method. We first survey the relevant literature on masking in medical alarms, psychoacoustic models of masking, and model checking. We then describe our method: its conceptualization, design, and implementation. To illustrate its utility, we use the method to evaluate a realistic configuration of medical alarms. We ultimately discuss our results and future avenues of research.

REVIEW OF THE RELEVANT LITERATURE

Concurrently Sounding Medical Alarms

Auditory medical alarms have a number of problems, making them one of the most significant hazards to patient safety for over a decade (ECRI Institute, 2012). An event alert issued by the Joint Commission (April 8, 2013) reported 98 events related to alarms from January 2009 to June 2012: 80 resulted in patient death, 13 produced "permanent loss of function", and 5 extended patient hospital stays.

There are many perceptual problems that can arise with medical alarms (see Edworthy 2013). For this paper, we are primarily concerned with the perceptibility of concurrently sounding alarms. Specifically, alarms that sound in close temporal proximity may produce auditory masking (Fastl & Zwicker, 2006), a condition where multiple sounds interact in a way that prevents a human from perceiving one of or more of them.

Different sounds can be used for auditory alarms. However, most alarms are represented as a sequence of sounds each with a distinct tone or center frequency (Edworthy, 2013; IEC 60601-1-8, 2003). Unfortunately, these types of sounds are particularly susceptible to masking in the presence of other alarms. Although many medical alarm experts have acknowledged auditory masking between concurrent medical alarms as a hazard (Konkani, Oakley, & Bauld, 2012; Patterson, Mayfield, Patterson, & Mayfield, 1990), it has been given very little research attention. Only Momtahan et al. (1993) and Toor et al. (2008) have experimentally explored the subject, where both detected masking of alarms in different hospital locations.

While there are many ways that auditory masking can occur (Fastl & Zwicker, 2006), for tonal alarms, the most important is simultaneous masking. Simultaneous masking describes particular relationships between frequencies and volumes (determined by the human perceptual system) that can result in sounds being undetectable. Psychoacoustic models exist that are capable of detecting if simultaneous masking will occur.

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Psychoacoustic Models of Simultaneous Masking

While multiple models exist for predicting auditory masking (Moore, 1996), psychoacoustic models of masking are the most appropriate to this work because they mathematically relate a sound's physical characteristics (its center frequency and volume) to the masking effect the sound has on human perception. The most successful of these use heuristics based on the expected excitation patterns of the human ear's basilar membrane (the physical structure largely responsible for allowing humans to distinguish between different sounds) to predict simultaneous masking (Bosi & Goldberg, 2003).

These psychoacoustic models represent a sound's masking threshold for different frequencies of concurrent sounds (its masking curve) as a function of the sound's volume in decibels (dB) and frequency in Barks. The Bark scale is psychoacoustic in that it represents a sound's frequency from 1 to 24 (Zwicker & Terhardt, 1980), indicating which of the 24 critical bands of hearing the sound falls in (the frequency bandwidth of the filters produced by the ear's basilar membrane). For a given sound (*sound*) with a frequency (f_{sound}) in Hz, the frequency in Barks is computed as

$$\begin{aligned} z_{sound} &= 13 \cdot \arctan(0.00076 \cdot f_{sound}) \\ &+ 3.5 \cdot \arctan\left((f_{sound}/7500)^2\right). \end{aligned} \quad (1)$$

The masking curve for a given sound (a *masker*) is generally formulated as a function of both the sound and the frequencies distance of another, potentially masked, sound (a *maskee*) on the Bark scale. This difference, dz is represented as

$$\delta z = z_{maskee} - z_{masker}. \quad (2)$$

Then, the masker's masking curve is represented as

$$\begin{aligned} \text{curve}_{\text{masker}}(v_{masker}, \delta z) &= \text{spread}_{\text{masker}}(v_{masker}, \delta z) \\ &+ v_{masker} - \Delta \end{aligned} \quad (3)$$

where v_{masker} is the volume of the masker in dB, spread is a function that defines how the volume changes as δz moves away from zero, and Δ represents the minimum difference between a masker's and maskee's volume under which masking can occur.

There are a variety of psychoacoustic spreading functions. Each makes tradeoffs between misses and false alarms in the detection of masking (Bosi & Goldberg, 2003) and have been tuned to different applications. For example, many of these spreading functions were developed to compute the masking functions that are used in lossy audio compression formats like MPEG 2 and MP3 (Bosi & Goldberg, 2003), where masked audio data is removed to reduce file size.

For example, the spreading function used as the basis for the MPEG2 audio codec (Schroeder, Atal, & Hall, 1979) is

$$\begin{aligned} \text{spread}_{\text{masker}}(\delta z) &= 15.81 + 7.5 \cdot (\delta z + 0.474) \\ &- 17.5 \cdot \sqrt{1 + (\delta z + 0.474)^2}. \end{aligned} \quad (4)$$

This spreading function is tuned to normal human hearing. It also has only one independent variable (δz). Other spreading functions can also take volume (v_{masker}) as an argument.

There can also be different formulations of Δ depending on the nature of the sound. For tonal maskers (Jayant, Johnston, & Safranek, 1993), Δ (in dB) is formulated as

$$\Delta = 14.5 + z_{masker}. \quad (5)$$

For a given masking curve, we know that the masker (with volume v_{masker} and Bark frequency z_{masker}) is masking the maskee (with volume v_{maskee} and frequency z_{maskee}) if

$$\text{curve}_{\text{masker}}(v_{masker}, z_{maskee} - z_{masker}) \geq v_{maskee}. \quad (6)$$

Formal Verification with Model Checking

Model checking is an analysis technique that falls in the broader category of formal methods. Formal methods are mathematical languages and techniques for the specification, modeling, and verification of systems (Wing, 1990). Specifications are formulated to describe desirable system properties in rigorous, unambiguous notations. Systems are modeled using mathematically based languages (such as finite state automata). The verification process mathematically proves whether or not the model satisfies the specification. Model checking is an automated approach to verification (Clarke et al., 1999). In it, the statespace of the formal model is exhaustively searched to see if it satisfies a temporal logic specification (Emerson, 1990). If it does, the model checker returns a confirmation. If there is a violation, an execution trace called a counterexample is produced. This counterexample depicts a trace of mode states that led to the violation. Because of its approach, model checking is particularly good at finding problems in systems with concurrency, where independent system elements can interact in ways unanticipated by designers.

Most formal verification analyses are concerned with discrete systems. However, hybrid modeling and analysis techniques can allow formal verification to be used with models that contain continuous quantities. For example, timed automata can be used to include real number time in a formal model (Alur & Dill, 1994; Dutertre & Sorea, 2004).

Researchers have used formal verification to evaluate issues related to human-automation interaction (see Bolton, Bass, and Siminiceanu 2013 for a review). These techniques focus on abstract models from the human factors literature that can be represented with discrete mathematical models and used in analyses of a scope such that specific human factors problems can be discovered. Collectively, these studies have shown that formal verification can be very useful for finding problems related to human factors in automated systems. However, none of them have explored how human perception and problems associated with it can be included in these formal analyses.

OBJECTIVE

Because of its ability to detect problems in complex, concurrent systems, formal verification should be capable of detecting if masking can manifest in a particular configuration of medical alarms. The work presented here strived to show this. To this end, we developed a method that allows an analyst to specify a configuration of alarms and use formal verification to detect if there are any situations where each alarm would

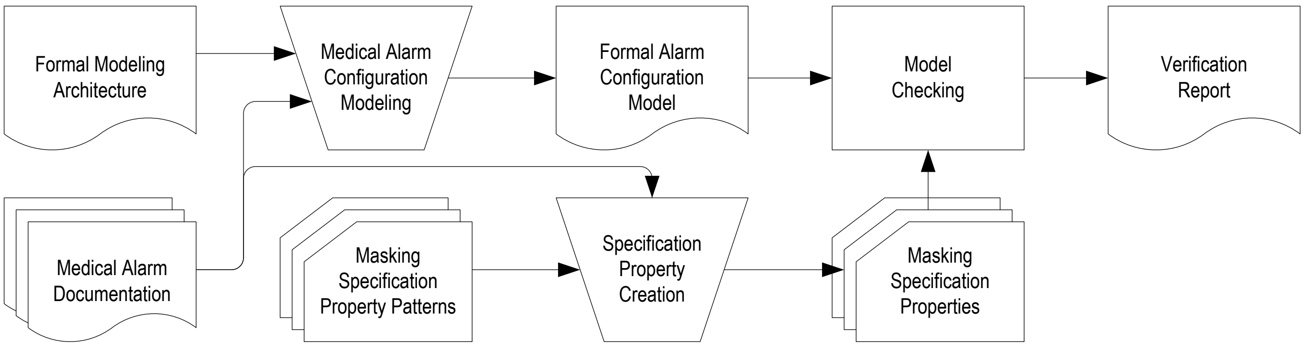

Figure 1. Method for using formal verification to detect auditory masking in medical alarm configurations.

be masked for a person with normal hearing. This method is built around a formal modeling architecture that allows for the sounding behavior of medical alarms to be represented formally. Our framework includes psychoacoustic functions capable of indicating when masking can occur and temporal logic specification property patterns for asserting the absence of masking conditions. In what follows, we describe our method, its associated architecture, its implementation, and an application which illustrates its power.

METHODS

In the method we have developed (Figure 1), an analyst models the behavior of a set of alarms using a formal modeling architecture. The analyst must also specify the absence of masking using specification property patterns. Finally, he or she uses model checking to determine if the specification properties hold. If no masking exists, the model checker will return a confirmation. Otherwise, a counterexample will be produced showing how masking can occur.

Timing of concurrently sounding alarms can have a profound impact on whether alarms are masked or not, thus we need to evaluate all of the different ways alarms can temporally overlap. Therefore, we have designed our formal modeling architecture (Figure 2) to be based on timed automata. Timed automata (Dutertre & Sorea, 2004) provide a means of modeling time as a real-valued continuous quantity in a formal model. This architecture has multiple sub-models that are synchronously composed together: a clock (a timed automata) that keeps and advances time, models of the behavior of the alarms in a given configuration, and a model that computes whether masking is occurring for each alarm and determines the maximum advance of the clock. We describe each in detail below.

Clock

The clock sub-model represents time as a real number. It is responsible for advancing time and communicating the current time (*GlobalTime*) to other model elements. *GlobalTime* is initially 0. For every subsequent step through the model, it is advanced to a new time that is always greater than the current *GlobalTime* and less than or equal to *MaxNextTime*.

Alarms

The behavior of each alarm (which is assumed to be a pattern of tones) is described in a separate model that all follow a similar implementation pattern. Specifically, each alarm

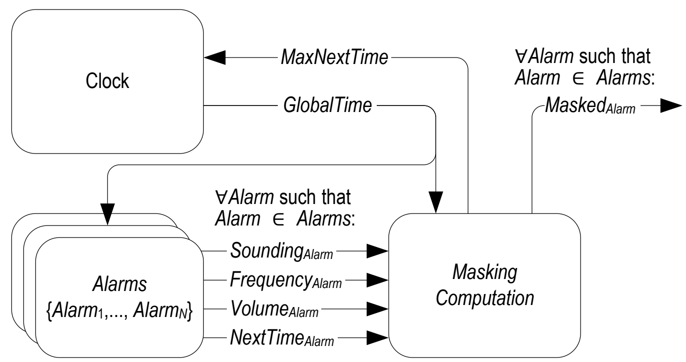

Figure 2. Architecture for formally modeling a configuration of auditory medical alarms. Boxes represent sub-models of the larger system model and arrows represent variables with input-output relationships. Arrows with no target indicate outputs.

model keeps track of whether it is sounding or not (the alarm is sounding if $Sounding_{Alarm} \Leftrightarrow StartTime > 0$) and to change the alarm's output at set times relative to its *StartTime*. If the alarm is not sounding, at any *GlobalTime* > 0 the alarm can start by assigning the *GlobalTime* to the *StartTime*. Each alarm has a constant *CycleTime* relating to the amount of time it takes an alarm to play a full melody cycle (this includes any gaps that occur between notes). Once started, an alarm will sound for one cycle and stop (set the *StartTime* to zero). The alarm can sound again in the future. Each alarm model must compute the amount of time the alarm has been sounding (*TimeInCycle = GlobalTime - StartTime*) and adjust the model's outputs ($Frequency_{Alarm}$, $Volume_{Alarm}$, $NextTime_{Alarm}$) accordingly. Note that $NextTime_{Alarm}$ represents the next time that either the alarm frequency or volume will change its value.

Figure 3 shows how the state/value of output variables (in this case frequency) can change in response to *TimeInCycle*. The output starts at a default value and, if the alarm is sounding (*StartTime* > 0) and the *TimeInCycle* exceeds a certain specific threshold, this is incrementally changed. Once a cycle is completed, the *StartTime* will be set to zero and the output will return to its default. Both $Frequency_{Alarm}$ and $Volume_{Alarm}$ can use a pattern like the one in Figure 3: they have an initial value of zero, and the values changes at different set times. However, $NextTime_{Alarm}$ is different in that its initial value (when the alarm is not sounding) is some arbitrarily large value *BigMax*, and the values that it can assume must represent the global times corresponding to the event times the other outputs change at

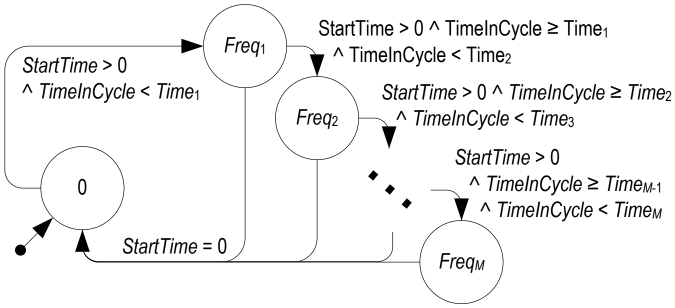

Figure 3. Finite state representation showing how a modeled alarm's frequency ($Frequency_{Alarm}$) changes in response to the alarm's calculated *TimeInCycle*. Frequency values ($Freq_1$–$Freq_M$) are states (circles). Arrows labeled with logical conditions are transitions. An arrow starting with a dot points to the initial state. Specific values of *TimeInCycle* ($Time_1$ – $Time_M$) help control when transitions occur. Similar patterns are used to define the behavior of $Volume_{Alarm}$ and $NextTime_{Alarm}$.

(i.e., $Time_1$ – $Time_M$, in Figure 3). For example, if the alarm is sounding and $TimeInCycle < Time_1$, *NextTime* should equal $StartTime + Time_1$.

Masking Computation. The masking computation model has two roles. Firstly, it finds the minimum value of all of the next time variables ($NextTime_{Alarm}$) from all of the alarms and communicates it to the clock as *MaxNextTime*. Secondly, it looks at the frequency and volume of each alarm and computes whether it is being masked by the other sounding alarms using (6) with the equations in (1)–(5). These computations are synthesized into a single boolean variable for each alarm that indicates if that alarm is being masked ($Masked_{Alarm}$).

Specification

To model check whether or not masking is present in a model, specifications must assert its absence. Our method uses property patterns to do this, where an analyst must instantiate the specification pattern for each alarm in a configuration. We are most interested in determining if there is a situation where each alarm is completely imperceptible: that it is totally masked. For a given alarm (*Alarm*), this is represented as

$$\mathbf{G}\neg\left(\begin{array}{l}\neg Sounding_{Alarm}\\ \wedge\mathbf{X}\left(\begin{array}{l}Sounding_{Alarm}\wedge Masked_{Alarm}\\ \wedge\left(\left(\begin{array}{l}Sounding_{Alarm}\\ \wedge Masked_{Alarm}\end{array}\right)\mathbf{U}\left(\neg Sounding_{Alarm}\right)\right)\end{array}\right)\end{array}\right) \quad (7)$$

using linear temporal logic (Emerson, 1990). This can be interpreted as: through all (**G**) paths through the model, we never want it to be true that the alarm goes from not sound to sounding and masked in the next (**X**) state such that, from then on, the alarm is sounding and masked until (**U**) it is no longer sounding.

APPLICATION

We have implemented this method in the Symbolic Analysis Laboratory (De Moura et al., 2004). We then used this to create and evaluate a simple model of a medical alarm configuration to demonstrate the method's power.

In the target configuration there are three alarms. In a given cycle, each alarm plays a two tone melody with a pause in between (see Table 1). These alarms were modeled using our implementation of the method and specifications were created using (7) to assert that each alarm should never be totally masked (see http://fhsl.eng.buffalo.edu/resources/ for a full model listing). The model was then evaluated using SAL's infinite bounded model checker (De Moura et al., 2004) (with search depth 12) on a Linux workstation with a 3.3 gigahertz Intel Xeon Processor and 64 gigabytes of RAM. The specifications for Alarm 1 and Alarm 3 verified to true in 906 and 1,327 seconds respectively. However, the specification for Alarm 2 returned a counterexample after 2,248 seconds. This showed that it was possible for Alarm 2 to be completely masked by Alarm 1 and Alarm 3 (see Figure 4 for an explanation).

Table 1. *Alarm Configuration Profiles*

Alarm	Tone 1 Freq. (Hz)	Tone 1 Vol. (dB)	Tone 1 Time (s)	Pause Time (s)	Tone 2 Freq. (Hz)	Tone 2 Vol. (dB)	Tone 2 Time (s)
Alarm 1	261	80	0.25	0.100	370	80	0.25
Alarm 2	277	60	0.15	0.050	277	60	0.15
Alarm 3	524	85	0.20	0.075	294	85	0.20

Note. Each of the frequencies used represent a note commonly used in tonal alarms. Durations, and volumes are also consistent with IEC 60601-1-8 (2003).

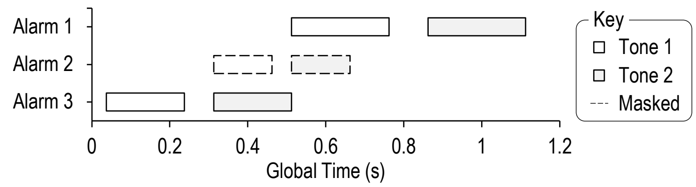

Figure 4. Illustration of the counterexample returned when the model checker failed to prove that Alarm 2 would not be completely masked. The second tone of Alarm 3 masks the first tone of Alarm 2. Then, when Alarm 2's second tone began sounding, it was masked by the first tone of Alarm 1.

Even in this simple example, alarms can concurrently interact in ways that makes one or more of them imperceptible. Clearly more complex medical alarm configurations could potentially have more subtle manifestations of this problem.

DISCUSSION

This work has introduced a novel method for identifying masking in configurations of medical alarms. This method uses a formal modeling architecture, psychoacoustic models of masking, specification property patterns, and formal verification with model checking to prove whether or not each alarm in a configuration will be perceptible with normal hearing. We have implemented a version of this method in the symbolic analysis laboratory using timed automata. To demonstrate the method's power, we presented a specific medical alarm configuration and showed how our method could be used to find masking conditions. Thus, the presented method could be used by hospital personnel to evaluate the safety of different medical alarm configurations. However, despite its success, this method has some limitations which will be addressed in future work.

Additional Masking Considerations

The method currently only supports the detection of total masking. However, partial masking could also make alarms difficult to identify. Future work should incorporate partial masking detection into our method. Further, while this work addresses simultaneous masking, there are other ways that masking can occur. For example, additive masking describes a condition where two simultaneous sounds can produce masking greater than the sum of their respective masking curves (Bosi & Goldberg, 2003). This can be particularly problematic in configurations where alarms contain multiple auditory harmonics or when multiple alarms sound concurrently. Future work should investigate how additive masking could be incorporated into our method. Additionally, temporal masking can also occur (Fastl & Zwicker, 2006), where sounds can mask sounds not concurrently sounding. Future work should investigate the possibility of including temporal masking detection in our method. It is also uncommon for alarms to be operating in a completely quite environment. Thus alarms may interact with environmental noises that could exacerbate masking conditions. Future work should investigate how other environmental sounds could be incorporated into our method.

Experimental Validation

Our method is based on established psychological principals and is thus expected to give accurate predictions. However, it would be good to validate our methods predictions against actual human subject experimental results in realistic operational environments. Future work should pursue this.

Use in Design and Additional Applications

While the presented application illustrates the method's utility, there are many medical alarm configurations (Boyd, 2010) and standards (IEC 60601-1-8, 2003) that could be evaluated. Future work will investigate this. To date, the method has only been used to detect masking, not prevent it. However, iterative modeling and verification with the method could enable analysts to find alarm configurations that would avoid masking. In use, it is also conceivable that an analyst will encounter situations where an alarm configuration must produces masking. Even in this situation, the method should have utility as it would allow the analyst to identify interventions (such as alarm positioning to encourage localization) that could improve the chances of perceptibility. Future work should investigate how the method could be used in alarm configuration design.

Additionally, alarms are critical to safety in domains beyond medicine including automotives, aviation, and industrial settings. Future work should explore how our method could be used to detect masking in these environments.

Scalability

All formal verifications scale poorly: model size grows exponentially as concurrent elements are included leading to models that are too big or take too long to verify (Clarke et al., 1999). Future work should evaluate how our method scales.

Tool Usability

Finally, the current method requires analysts to manually perform formal modeling. Thus, it will be cumbersome for individuals with no formal modeling experience to use. Future work should investigate how to developed modeling tools that will allow non-formal modeling experts to employ the method.

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