Towards Tactile Alarms Systems for Increased Awareness in Smart Environments

Girts Strazdins
Maritime Human Factors Lab
Aalesund University College, Norway
gist@hials.no

Sashidharan Komandur
Maritime Human Factors Lab
Aalesund University College, Norway
sash.kom@hials.no

Frøy Birte Bjørneseth
Rolls Royce Marine AS
Aalesund, Norway
froy.bjorneseth@rolls-royce.com

Abstract—**Alarms are an important part of automation systems that raise user awareness in emergency situations. However, research shows that existing audible and visual alarms are ineffective. Failure to deliver alarm signals leads to lack of awareness that results in accidents. This paper presents a work in progress on a wearable tactile device application for smart alarm systems. We describe our hypotheses that tactile alarms can decrease user resistance and deliver more focused awareness with directional hints. In this paper, the prototype of a wearable tactile belt is described and its future improvements are analysed.**

Keywords–tactile; belt; alarms; wearable computing; wireless sensor networks.

I. INTRODUCTION

In many complex environments, the outcomes of critical situations depend on user awareness. If necessary emergency information is delivered on time, many accidents can be avoided. Our research focuses mainly on the maritime domain: offshore operations and ships in general. Offshore operations and navigation involve multiple complex tasks and cooperative work between people located in different physical locations. In addition, ships are also complex systems consisting of numerous subsystems. Ship accident reports show that many accidents happen due to lack of timely awareness of dangerous system states. Operators either do not perceive existing alarms [1], misinterpret them [2], or have turned them off due to inefficient and too frequent distractions [3].

In addition to maritime operations, we identify other environments in which smart systems with increased awareness are important. This might include control rooms of other complex systems such as oil rigs, and nuclear reactors that require constant monitoring. It can also be relevant for property night watch officers who monitor possible break-ins, as well as-for other alarm systems in general. All of the above scenarios involve human operators in protracted routine tasks where highly active periods are rare. This can lead to high risk situations for operators where fatigue plays a significant role and the operator can fall asleep. Effective alarm systems are necessary that can wake up sleeping watch officers.

Traditional alarm systems consist of two parts. User attention is attracted by audible alarms that are able to deliver signals to users regardless of their position and orientation of their head. A detailed explanation of the alarm source and type is presented as visual information: light indicators with different color codes in simpler cases and textual displays in more complex systems. However, accident reports [1][2][3] show that existing alarm systems are not efficient, and identify the need for improved alarm systems that:

- Deliver alarms on time and in an easily perceivable manner.
- Minimize distractions during insignificant errors.
- Deliver alarms focused on the responsible persons, and not directed to the general population.

In this paper, we present a novel alarm system based on wearable sensor and actuator networks that delivers tactile stimuli. We propose an approach, system architecture, and its advantages in Section III. We have built a prototype of a wearable tactile belt, described in Section IV. Its preliminary evaluation and need for optimization is described in Section V. Substantiation of our hypotheses require significant future work that we discuss in Section VI.

II. RELATED WORK

Improved emergency detection has been proposed previously [4]. We focus on alarm delivery in this paper, rather than detection. Tactile cues have been explored previously. Recognition ability has been proved for tactile cues [5]. Multiple tactile wearable devices have been proposed, including belts [6], vests [7] and wristbands [5]. Measurements show that resolution of tactile stimuli is around 24mm [8]. We utilize existing knowledge, but apply it to a different application: dissemination of alarms. Conclusions will be reached only after extensive field studies. Nevertheless, description of the system design process is an important step for both engineers and researchers.

III. TACTILE ALARM SYSTEM ARCHITECTURE

We envision a smart alarm system that extends beyond audible and visual stimulation. We want to challenge the notion of traditional alarms that are obtrusive and render users resistant to technology. Wearable tactile devices provide a novel approach to solve traditional alarm system inefficiency. This paper describes a work in progress with the following hypotheses on the advantages of tactile alarm system:

- Tactile devices can better raise awareness of tired and sleeping users regardless of their location and position.
- User resistance (and system turn-off probability) can be mitigated by providing different levels of alarms and deliver them in a more focused manner.
- Tactile (compared to audible) cues can be more efficient in directing user's attention to the desired location and providing hints on the type and source of error.

We set the following design rules for tactile alarm system development:

1) **Simplicity**. The system should be easy and fast to don.

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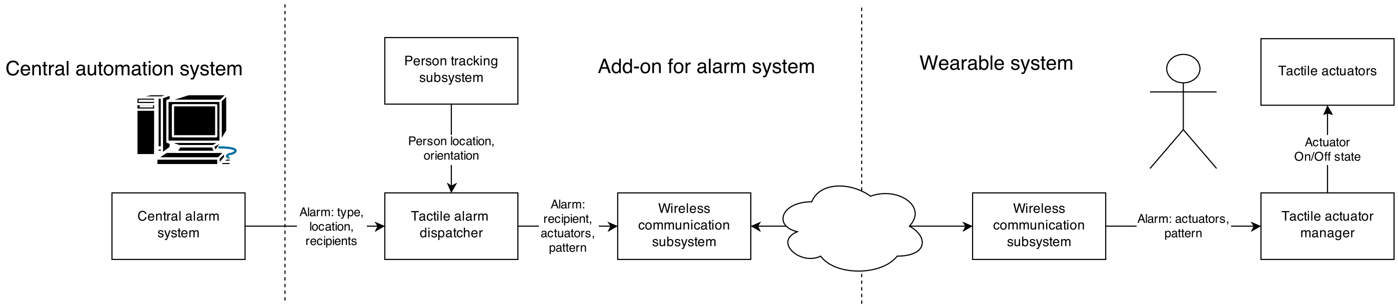

Figure 1. Proposed system architecture. Central automation system disseminates alarms that are translated to tactile cues by the wearable device. Wireless communication exists between the two parts of the system.

2) **Adaptability**. The system should be interchangeable and adaptable for persons with different bodily structure and age.
3) **Comfort.** The system should be lightweight, small, and not disturb the performance of daily activities and maritime operations.
4) **Robustness**. The system should be waterproof, and withstand high pressure and temperature changes that might occur during maritime operations. In addition to tasks on the ship bridge, operators should be able to move to the deck. It should not expose fragile parts, including wires and sensors.
5) **Accuracy**. The system should be able to deliver all required signals with acceptable latency while also not generating false alarms.
6) **Longevity**. The system should be able to operate without changing batteries for at least 24 hours. In the ideal case the system should be able to operate for 7 days (168 hours).

The proposed system architecture is depicted in Figure 1. The system consists of three parts. First, a central automation and alarm generation system is considered. This paper focuses only on alarm delivery, not detection or generation. Therefore, it is assumed that this part is already provided. The second part represents an add-on for the central automation system that is responsible for monitoring of the whole environment and raising alarm events accordingly. This component translates system conditions into tactile alarms that incorporate actual scene and user information. This sub-system is domain-specific and must be specified per application. The third part consists of a wearable sensor and actuator device that tracks users and delivers physical tactile stimuli to them, according to commands from the central system. The wireless sensor network approach is used for communication between the two parts of the system. Both parts of the system are independent and interchangeable as long as common communication standards and protocols are used, such as Bluetooth or 802.15.4.

In addition to attraction of user's attention, tactile systems can also deliver directional cues and focused alarms. Pointers and hints of focus can be given to specific users who can react on a particular event. Human location, pose and orientation tracking must be used to keep the system informed of the actual user state. Although localization techniques depend heavily on the environmental constraints and no generic technique can be provided, existing knowledge of indoor localization can be used to develop custom solutions.

The main advantage of the proposed approach is the interoperability of the components that are interchangeable. The wearable system can be seen as another user interface peripheral device, much like a remote headset or wireless keyboard. It can even be implemented as an external speaker that is able to translate specific sound patterns into tactile cues.

IV. SYSTEM PROTOTYPE

There are several options for device types to be used for our proposed system. The authors of this paper selected a tactile belt as the most appropriate. Ideally, this would be a smart belt that humans wear as usual during their daily activities. But in these first iterations this device will consist of a stretchable add-on-type belt. It can be worn over the regular belt or situated individually around the abdominal region. Its main advantages: close contact with the user, naturalness (immersiveness) that leads to low human resistance, ability to follow the user 24 hours a day (during service hours), and ability to provide accurate directions.

The tactile alarm system presented here is a sensor-actuator network, although the first implementations might seem otherwise. Although the main focus of the system is actuation, not sensing, in further, more advanced revisions, the system would contain sensor modality, such as position and pose estimation with inertial sensors, in combination with external vision-based user tracking. In this experimental phase, the authors have assembled only one prototype belt, yet for deployment at least two belts are required for cooperative operators, such as dynamic positioning and anchor handling operators on offshore vessels. In general, offshore vessels would require one belt for the captain and optional belts for other crew members. Continuous connectivity would require a wireless base station and router infrastructure that is able to provide two-way communication with the mobile, wearable devices in the environment that might be harsh in terms of interference and signal attenuation.

As can be seen in Figure 1, the device consists of three components: tactile actuators, actuator manager, and wireless communication. All of these components are independent and can have different implementations, as long as the interaction protocol is followed. For example, wireless communication can be implemented using WiFi, BlueTooth, ZigBee or other standards; AVR, MSP430 or other microcontrollers can be used as actuator managers; and different vibrating motors are supported.

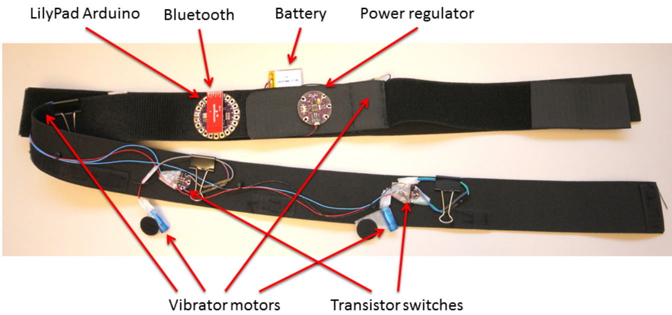

Figure 2. Tactile belt prototype.

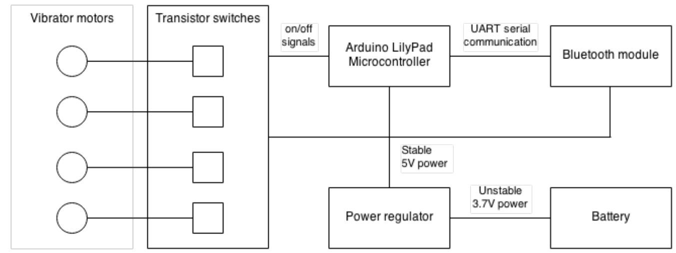

Figure 3. Tactile belt architecture.

We have created a hardware prototype, shown in Figure 2. Its structural diagram is shown in Figure 3.

A. Hardware components

The belt consists of the following components:

- Bluetooth radio module acting as a wireless bridge between the belt and external alarm system. Bluetooth Mate silver is used for the prototype, consisting of a Roving Networks RN-42 Bluetooth Class 2 module.
- 4 vibrating motors generating tactile cues. These are situated across the abdominal region of the user: one motor in the front, one in back, one on the left side and one on the right side. Literature studies show that users can distinguish between 8 evenly spaced locations on a tactile belt [9], yet we assume that four will be sufficient at this early investigative stage. The architecture is flexible: additional motors can be added later if necessary. A switch circuit with a transistor is added for each motor so that it can be controlled by a microcontroller. Precision Microdrives 307-100 Pico Vibe 0mm-25mm vibrating motors are used in the prototype with switch circuits consisting of BC368 NPN transistor, 1N4148 diode, and a resistor mounted on a LilyPad Small Protoboard.
- An Arduino LilyPad microcontroller acting as the manager: parses wirelessly received messages and sends commands to motors.
- A Lithium Polymer (LiPo) battery powering the whole belt. A 400mAh battery weighting 9 grams (0.32 oz) is sufficient to supply the system for about 8 hours. A 2000mAh battery (36 grams or 1.27 oz) would last about 40 hours.
- A power regulator module transforming unstable 3.7V battery voltage to a stable 5V power source.

The choice of components was motivated by requirements of rapid prototyping. Therefore, most of the components are simple and available off-the-shelf modules, not necessarily the best choices in terms of energy efficiency and performance.

B. Software components

The software is designed as a master-slave (or client-server) system where tactile devices act as slaves/clients receiving commands from a central computer. In deployment, the central computer is represented as a module in the central alarm system, while in test scenarios this can be any personal computer or any other device capable of connecting to the tactile device wireless network. Wireless communication involves reliability issues potentially causing the alarm signals not to reach their target. However, this is out of the scope of this paper and will be researched further at a later stage in this project.

Client devices are programmed using the Arduino Integrated Development Environment (IDE) [10]. The server application was developed in Java, using the RXTX serial communication library.

The motors are activated by sending a `MotorCommand` message from the server to the client. The client responds with an `Acknowledgement` message. If the server receives no `Acknowledgement` within a certain period of time after sending a `MotorCommand`, it should resend the `MotorCommand` message. Timeouts and number of retries are system-specific and are not defined here.

V. Optimizations

The following problems have been identified for the prototype implementation:

- **Short network lifetime**. The devices are not able to operate autonomously for the desired period of 7 days. There are multiple reasons for this, including energy-inefficient hardware and task scheduling.
- **No multi-hop communication support**. While single-hop communication is reasonable for tactile alarm dissemination in a single room, it prohibits the implementation of alarm forwarding to watch officers in other facilities.
- **No multitasking**. One can implement all required processes (motor control, data reception, data transmission, and sensor sampling) in a single thread, yet this would involve the creation of a state machine with inefficient and error-prone polling strategies.

These drawbacks can be mitigated by following the wireless sensor network design rules proposed by Strazdins [11].

A. Network lifetime extension

The majority of energy is spent in radio listening mode. Customized MAC protocols that allow changing the radio duty cycle can help to reduce energy consumption significantly. For example, if the radio transmission is activated every 5 seconds for a 250ms period (it takes around 100ms to send a 46-byte packet [12]; 250ms is enough for two-way communication), this results in a 20% duty cycle.

The current Bluetooth module does not allow control of MAC protocols. Therefore, a more efficient radio module must be selected. In addition, the Arduino board with AVR ATMega328 microcontroller is also not the best option in terms of energy efficiency: it consumes around 25mA in active mode, and additional 25mA for Bluetooth radio, the total consumption of the platform is more than 50mA, or less than 8 hours of operation from a 400mAh battery.

Vibrator motor energy consumption cannot be accurately predicted in the absence of a particular scenario. However, the motor energy consumption in a realistic scenario is insignificant, compared to consumption of the rest of the system.

Selection of an energy-efficient wearable sensor-actuator node increases the lifetime dramatically. Let us take a TelosB-compatible platform with MSP430F1611 microcontroller and CC2420 radio, such as TMote Sky, as an example. The whole platform consumes 20-23mA during active radio transmission or reception. With a 20% duty-cycle this would result in less than 5mA average consumption. This is a tenfold increase in energy efficiency, compared to the existing implementation. Mercury is an example of a low-power wearable wireless sensor network with average consumption below 5mA including accelerometer and gyroscope sensors, and wireless communication [13]. To conclude, a solution that supports custom MAC protocols, TelosB-compatible platform, and low duty-cycle, would lead to significant lifetime extension of the device.

B. Multi-hop communication

To implement a deployable system, alarm dissemination is also required outside a single room, and 24-hour stable operation is required. Multi-hop communication between the alarm generation system and tactile wearable devices is an essential part of this requirement. The solution can be implemented in multiple different ways: either the conventional automation system's network (TCP/IP or other) is used to create a backbone network and connect tactile devices using gateway nodes attached to each backbone network router, or a mesh network of wearable devices and corresponding sensor network routers (802.15.4) can be installed in the environment and connected to the automation system's network using a single (or multiple redundant) gateway nodes.

C. Multitasking support

There are multiple logical tasks running concurrently on the wearable device: motor control, data reception, data transmission, and sensor sampling (no sensors attached at the moment, but these could be required in future deployments). Support of multi-tasking by providing API for separate thread creation is necessary for different reasons. First, it is correct to separate and encapsulate threads with different responsibilities and resources. It is logically more correct and makes the code easier to maintain and expand. Second, correct multi-tasking can improve the efficiency of the application in terms of time-sharing: threads wait when they have no operation to perform and start running whenever the expected event has occurred. An operating system such as Contiki OS [14], permitting multitasking, is essential part of maintenance improvement for wearable systems.

VI. Conclusion and Future Work

This paper presents a work-in-progress research study on tactile device evaluation for alarm systems. We present an architecture and a prototype device, and we analyse its drawbacks and optimizations. Several further activities are planned as future work to finish this research study. A field study must be executed to collect both qualitative user feedback and quantitative data on reaction time and accuracy of directional cues. Two challenges are identified. First, it is difficult to simulate real emergency situations, because long idle periods are involved in such scenarios. Second, a trade-off between unobtrusiveness and alarm redundancy must be maintained. Studies in maritime operation simulators (an environment similar to one used in [15]) are planned using the tactile belt as an alarm delivery mechanism to attract user attention to particular areas of the ship bridge. In synergy with other local research activities [16], eye trackers will be used as quantitative tools for reaction accuracy and latency measurement. In the case of positive results, this research study can serve as an important milestone for discussion involving industry, academia, and standardization institutions.

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