Wearable Stress Monitoring During Live Training

James A Pharmer, Ph.D.,
Richard Plumlee
Naval Air Warfare Center
Training Systems Division Orlando, FL

James.Pharmer@navy.mil
Richard.Plumlee@navy.mil

Kelly Hale, Ph.D.,
Zach Huber
Design Interactive, Orlando, FL

Kelly@designinteractive.net
Zach.Huber@designinteractive.net

ABSTRACT

One of the most critical domains sailors must learn is shipboard firefighting. Firefighting exposes individuals to heat stress and fluid loss, which may be capable of causing sudden cardiac events (Holsworth, Cho, & Weidman, 2013) and to physical danger, physical overexertion, and mental stress, which can reduce performance (Gomes Moreira, Loda, Nosaka, & Couts, 2013). It is critical to ensure sailors are trained to fight fires under realistic, stressful conditions to prepare them for shipboard firefighting. At the Surface Warfare Officer School (SWOS) Learning Site Firefighting School at Naval Station Mayport, the goal is to develop Warfighter readiness and effectiveness in firefighting onboard ship within a controlled, realistic environment. This includes incorporating physical and psychological stressors (e.g., physical ship layout challenges; multiple, active fires to control) into training. Quantifying the occurrence of stress experienced by trainees for this facility, and the majority of live training exercises is currently limited to subjective accounts during hotwashes. The integration of physiological stress levels tied directly to scenario events can potentially allow instructors to enrich the training through adaptation of physiological stressors to individual trainee response and performance.

This paper will demonstrate an innovative approach to objectively evaluating stress within the SWOS Mayport Firefighting school training scenarios using wearable technology, which monitors physiological and physical state of trainees. Trainee stress state within scenario context can be monitored throughout a scenario in real-time via an instructor-based interface to alert instructors of potential stress issues before they become emergencies. The paper will discuss end user feedback based on the stress monitoring closed loop system and outlines strengths and opportunities for improvement in enhancing awareness of scenario stress and training effectiveness.

ABOUT THE AUTHORS

Dr. Jim Pharmer is a Naval Aviation Systems Command Fellow and the Principal Scientist for the Human Systems Department at the Naval Air Warfare Center Training Systems Division. His research interests are in applying Human Systems Integration (HSI) principles to the systems engineering and acquisition processes. He holds a Ph.D. in Applied Experimental and Human Factors Psychology from the University of Central Florida and an M.S. in Engineering Psychology from the Florida Institute of Technology

Dr. Kelly Hale Senior Vice President of Applied Research at Design Interactive, Inc., a woman-owned small business focused on human-systems integration. She has over 15 years of experience in human systems integration research and development across areas of augmented cognition, multimodal interaction, training sciences, and virtual and augmented reality environments. She received her BSc in Kinesiology/Ergonomics Option from the University of Waterloo in Ontario, Canada, and her Masters and Ph.D. in Industrial Engineering, with a focus on Human Factors Engineering, from the University of Central Florida.

Mr. Richard Plumlee is a Training Specialist at the Naval Air Warfare Center Training Systems Division, where he provides subject matter expertise in applied training research. He has over 40 years of military and Federal Civil Service experience. His expertise includes Navy aircraft acceptance evaluation, training effectiveness evaluations, adaptive training research, and instructional development. He has a Bachelor of Science in Business Administration from the University of Nebraska.

Zach Huber is a Senior Research Associate on the Biosignature Analytics team at Design Interactive, Inc., focusing on research involving classification of human state. Zach has worked with data collection tools, augmented/mixed reality, and has led projects in developing and utilizing real-time stress classification. He has also worked on projects creating estimates of mental acuity from sleep inputs and developing training and assessment tools for children with Cerebral Palsy. Prior to joining Design Interactive, Inc., Zach was at the Spine Research Institute at the Ohio State University where his work focused on modeling the spine

----

Wearable Stress Monitoring during Live Training

James A. Pharmer, Richard Plumlee
Naval Air Warfare Center Training Systems Division
Orlando, FL
James.Pharmer@navy.mil; Richard.Plumlee@navy.mil

Kelly Hale, Zach Huber
Design Interactive, Inc.
Orlando, FL
Kelly@designinteractive.net; Zach.Huber@designinteractive.net

INTRODUCTION

According to Arkin and Handler (1989, p. 2), "fires are by far the most prevalent cause of ship damage". Between 1973 and 1983, it is reported that an average of 148 fires per year occurred onboard ships or at shore bases (Arkin & Handler, 1989). Thus, one of the most critical aspects to ship Damage Control (Varelas, 2011) is shipboard firefighting, and every Sailor is required to be trained in basic firefighting skills. In addition, specialized and advanced training is provided to select crewmembers to ensure the safety of each ship. The Navy has designed and developed specialized training facilities to support shipboard firefighting training, where students are exposed to live fires in a controlled environment under instructor supervision. At the Surface Warfare Officer School (SWOS) Learning Site Firefighting School at Naval Station Mayport, the goal is to develop Warfighter readiness and effectiveness in firefighting onboard ship within a controlled, realistic environment. This includes incorporating physical and psychological stressors (e.g., physical ship layout challenges; multiple, active fires to control) into training.

While the training facility at Mayport, FL provides exposure to firefighting equipment and live fire within the Naval context, SWOS leadership and instructors are continuing to seek more objective indicators of how such exposure impacts the trainees from the first scenario to the last scenario. In particular, SWOS leadership, curriculum developers, and instructors are providing support for a project to a) ensure that the high fidelity firefighting training is commensurate with stress experienced in the live firefighting environment so that trainee state is as consistent between as possible the training environment and the real world, and b) better understand what specific aspects of the training are associated with high stress levels experienced by trainees.

The actual shipboard firefighting environment can expose damage control personnel to air temperatures as high as 1200° F near the fire. In an investigation of heat strain experienced by damage control personnel combating fires aboard a Navy damage control research/firefighting ship, Bennett, Hagan, Banta, and Williams (1993) found high body temperatures exceeding 102° F and peak heart rates averaging 186 ± 13 beats per minute, attributable to both extreme heat and high physical workload. Moreover, firefighting exposes individuals to heat stress and fluid loss, which may cause sudden cardiac events (Holsworth et al., 2013) and to physical danger, physical overexertion, and mental stress, which can reduce performance (Gomes et al., 2013). Given the highly stressful nature of this training, both physical and psychological, stakeholders affiliated with such firefighting training facilities are interested in quantifying trainee stress throughout scenario-based training to (1) ensure safety and identify those that need a 'tactical time out' earlier, and (2) objectively see what aspects of training (e.g., specific roles, types of fires, number of fires) correlate with high stress, which can then be used to adapt scenarios for optimal training.

This paper outlines a user-centered design approach for developing objective physiological based indicators of trainee stress during simulated firefighting training within the Advanced Firefighting course at SWOS Mayport, providing instructors with a real-time indicator of trainee stress throughout a scenario such that they can better ensure the safety of trainees, and provide insight into trainees that may need additional experience in specific roles to further train their skills under stress.

BACKGROUND

Surface Warfare Officer School Firefighting Training

The Advanced Firefighting Course (J-495-0419) is designed to train supervisory fire-party personnel with advanced firefighting techniques and effective management of on-scene personnel in a shipboard environment. The course includes both classroom instruction and hands-on scenario-based training in various roles such as Repair Locker

Leader, On-Scene Leader, Investigator, Team Leader, Nozzleman, Hoseman, Plugman, and Plotter. Students combat different classes of fires under varied scenarios using different methods and equipment. Throughout the 4-day course, students participate in in multiple scenarios, taking on various roles.

While the Advanced Shipboard Firefighting course is offered in multiple locations around the world, the current effort is taking place at the Mayport, FL training site in the facility shown in Figure 1. The training facility is a 4-story, concrete building that houses different spaces used to mimic surface ship compartments. The Advanced course typically trains on main deck, and decks 1 and 2 of this facility. Damage Control Central/Instructor Operating Station is located on the main deck. This space is where the lead instructor monitors the scenarios and can monitor the progress of firefighting and radio communications throughout the scenario (access door remains open during scenarios to allow radio communications to be received. As in the shipboard firefighting environment, transmission of data (radio communications or data signals in general) is challenging in this facility, as the concrete and steel walls block signal transmission between floors.

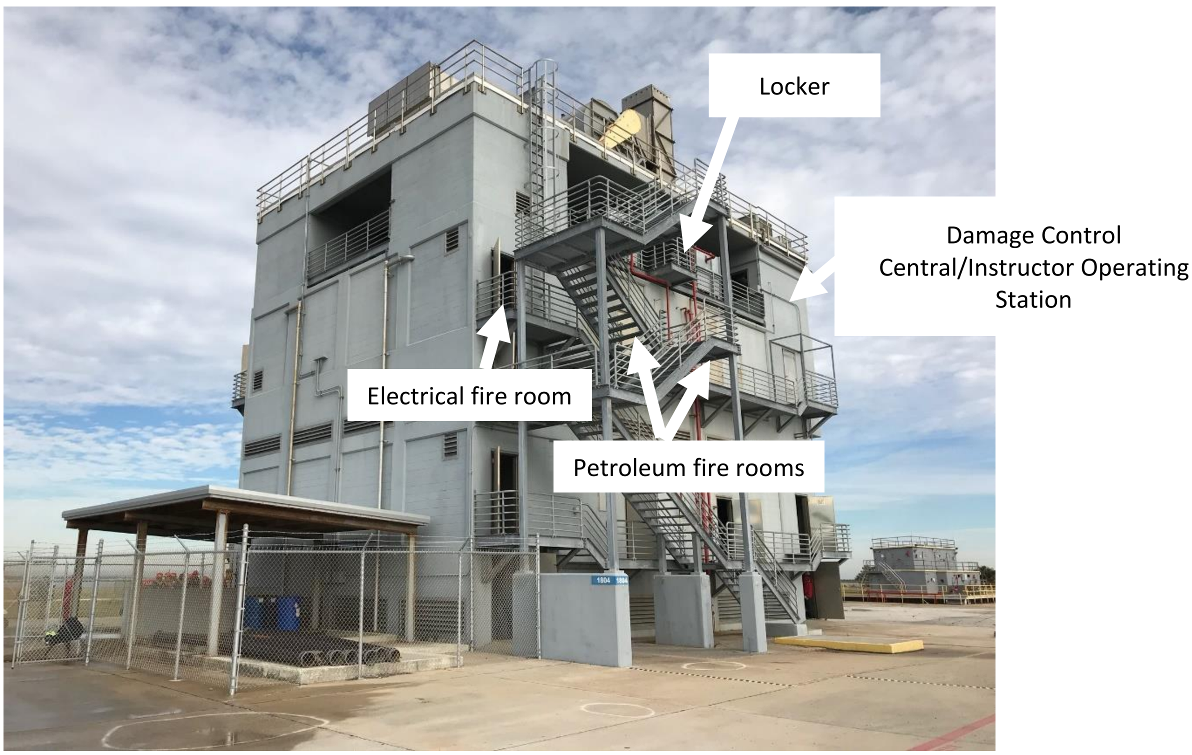

Figure 1: Fire Trainer Facility at SWOS Mayport, FL

Also located on the main deck is the Lockers, where the Repair Party stage prior to the start of a scenario. The Locker is where firefighting equipment is stored on a ship, and the training facility mimics this. The Repair Locker is a 'control space' – Damage Control (DC) plates of the ship are on the bulkhead and are used to chart /damage as information is passed through team radio communications. Decks 1 and 2 house the fire rooms. There are ladders between each deck that mimic those found onboard ship, and these are typically used by students to descend to the fire location after getting equipment as needed from the locker. During firefighting, rooms can reach temperatures of 180°F in the engine fire room, and student body temperatures can increase by up to 3°F.

TRAINING NEEDS ANALYSIS

Building on a previous effort (Huber, 2018) investigating the feasibility of real time physiological data capture in the extreme environment of the SWOS firefighting trainer, a detailed training needs analysis of scenario-based training was completed during the Advanced Firefighting Course (J-495-0419). Initially, training relevant documentation was reviewed, which included the Training Course Summary and Training Curriculum Presentation Slides provided by instructors. From this, designers were able to identify high-level training objectives and tasks that could be implemented within the training scenarios. This documentation review was followed up with task observations and instructor interviews. Observations included seven scenario-based training sessions across three days, as well as a walk-through of the facility when no training was occurring. This walk-through allowed designers to get a full understanding of the space layout and fire types/locations within the facility that could be implemented during a scenario.

Outcomes

The Advanced Firefighting course has three main objectives: (1) train advanced firefighting techniques; (2) train effective management of on-scene personnel in a shipboard environment; and (3) provide practical experience with various damage control and firefighting equipment. Scenario-based training is used to provide hands-on practical training in a number of roles, and trainees are required to identify and combat different classes of fires under varied scenarios using different methods and equipment. This effort focused on Objective 3 (scenario-based training) and identified opportunities to monitor physiological indicators of psychological stress in real-time during active scenarios, and provide instructors with insights to all students' states while participating in the scenarios.

Each training class can host up to 30 students that assume specific roles during any given scenario. Instructors assign the roles such that each trainee experiences as many roles as possible throughout the course. Trainees are assigned a Billet Number that is used throughout the course – the numbers are visible on their equipment to support instructors monitoring the scenarios. Figure 2 shows the available trainee roles (note: the number of fire teams may be adjusted to match student class size). Instructors are assigned to each smaller group (i.e., Investigators, Electrician, and each Fire Team) throughout a scenario, and observe each group's behaviors. Instructors are authorized to remove any trainee from the facility for safety reasons and are in constant radio contact with the Lead Instructor stationed in the Instructor Operator Station (IOS). The Lead Instructor can oversee the operations via the main control display situated in the IOS and is monitoring radio communications from other instructors.

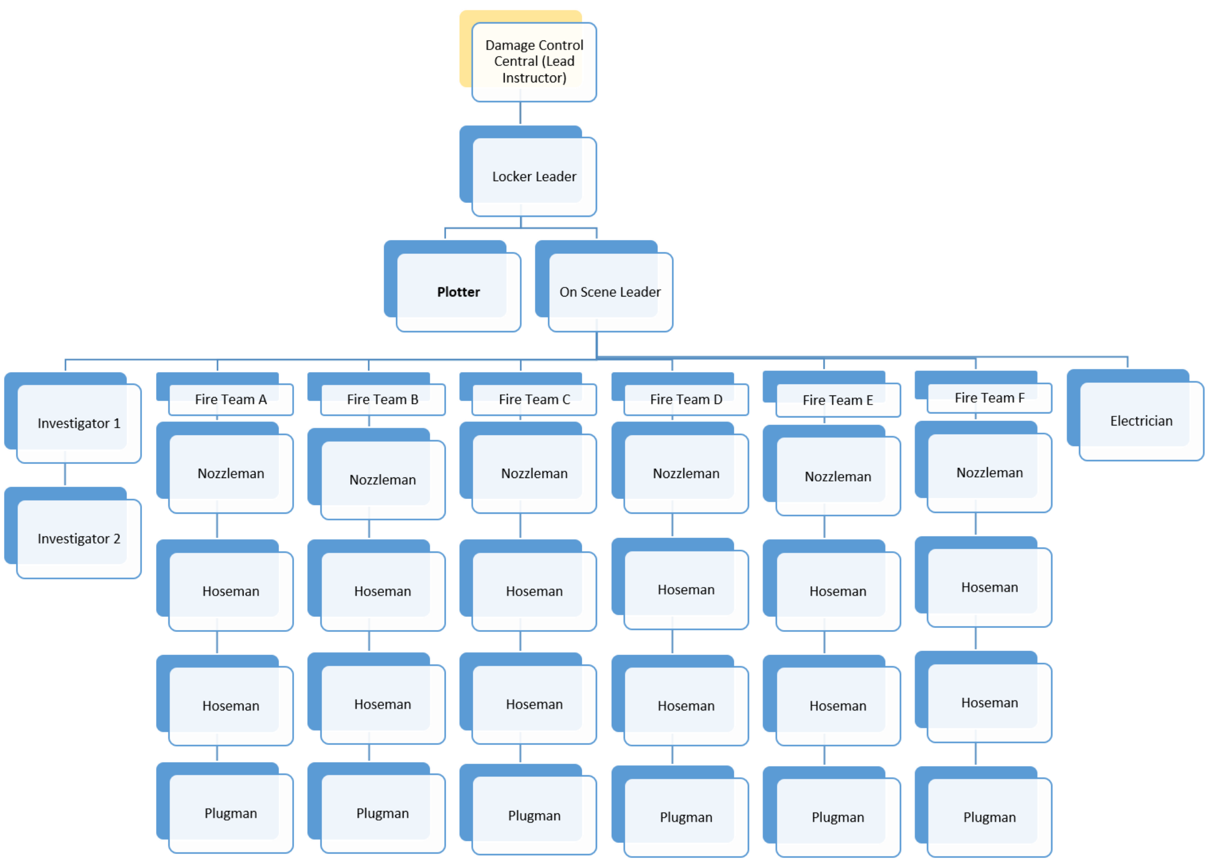

Figure 2: Trainee Roles during SWOS Advanced Firefighting Course Scenario-based Training

Throughout Training Days 2-4, trainees participate in one to three scenarios. Roles may or may not change on a given day, but regularly change across training days to provide experience in multiple firefighting roles. Instructors report that scenario difficulty/complexity increases throughout the course, with initial scenarios including a single fire at a time that are Class A (ordinary combustibles) or Class B (fire in flammable liquids or flammable gases, petroleum greases, tars, oils, oil-based paints, solvents, lacquers, or alcohols). Instructors provide verbal instructions and support to trainees during these initial scenarios to guide them through the tasks. Additional complexity of scenarios is added over time (e.g., different Fire Classes, back to back fires), leading up to the final scenario which incorporates more chaotic components, with multiple fire alarms going off in succession, requiring multiple fire teams to be moving throughout the facility at the same time. In addition, instructors increase pressure on trainees to move quickly and respond appropriately through hurried, loud speech.

Each scenario initiates with a safety briefing once students are dressed out, where roles are assigned for the upcoming scenario and instructions regarding safety are reviewed. This typically occurs prior to students entering the training facility itself, whether it be outside the Muster area (building approximately 100 ft. from the training facility) or on nearby bleachers. Students then walk up to the Main Deck of the Training Facility and assume their roles. An initial fire alarm typically indicates the start of a scenario. Each scenario runs typically between 30 and 90 minutes, and is ended by the Lead Instructor. After each scenario, a hot wash is conducted, with instructors providing feedback to trainees on their overall mission performance.

STRESS MONITORING TOOL SYSTEM DESIGN REQUIREMENTS

During scenario-based training at this facility, each of the trainee roles is exposed to various physical and psychological stressors. This effort was designed to investigate how best to access physiological indicators of stress and how having these indicators can potentially aid instructors in adjusting stressors within a scenario (e.g., size/scope of fire damage, duration of scenario, number of fire events), and how monitoring trainee stress real-time during a scenario can support effective training and safety of operations. To accomplish this goal, a closed-loop system is required that (1) captures physiological data from students in real-time, (2) transmits that data to a centralized access point that can then feed data to an instructor, (3) algorithms to transform the raw physiological signals into a stress classifier, and (4) an instructor interface for stress presentation that is intuitive to gain insight to student state within a glance. From the task analysis, a number of design requirements and constraints were identified, which informed the overall system design to best meet the needs of instructors and students at the SWOS facility. Table 2 summarizes the high-level requirements that drove the user-centered design approach.

Table 1: Design Requirements

	Requirement
Physiological Monitoring Sensors	Minimally intrusive to students; cannot interfere with hands. Must capture data in near real-time from multiple floors of the facility and feed forward to instructor interface.
Instructor Feedback Display	Intuitive design that shows each trainee's physiological stress level throughout a scenario. Setup in 5 minutes or less for entire class (assigning sensors to specific students for a given scenario). Portable instructor interface that allows instructors to conduct baselines and/or access student data inside as well as outside of the Instructor Operator Station.
Network Requirements	Develop a closed network that allows for sensor data communication within the facility in near real-time.

To classify stress, the Operational Stress Index (OSI) (Winslow, Chadderon, Dechmerowski, Jones, Kalkstein, Greene, & Gehrman, 2016) was selected, as it provides an objective, near real-time indicator of stress based on physiological data from individual trainees. The OSI is normalized for each student using an individual baseline procedure to provide a scaled output of physiological stress ranging from 0 (no stress) to 10 (extreme stress). Ranges of low (1-3), mid (4-

6), and high (7-10) are used to color code stress indicators throughout a training event. During a previous effort (Huber, 2018, the OSI algorithm was optimized to function in the extreme environments to which firefighters are routinely exposed. This optimization incorporated electrocardiography (ECG) signals (alternative to the original photoplethysmography [PPG] data) and associated bandpass path length, and burst filtering techniques to remove signal noise, and reduced the data moving window to 30seconds from 60 seconds – allowing for higher sensitivity in detecting stress changes.

A key requirement to this effort was a networked solution that could capture data from students at different locations within the concrete facility. This meant that the sensor solution investigated in the earlier feasibility investigation (Equivital EQ02) that provided both ECG and electrodermal activity [EDA] data signals for physiological assessment of stress) was no longer applicable, as it required a portable storage device (e.g., mobile phone) and Bluetooth communications for sharing data. Instead, a solution that incorporated data nodes that supported real-time transfer of signal from multiple locations was needed. The Zephyr Bioharness ™ 3.0 (MedTronics, Inc.; Figure 3), a chest-worn wireless sensor that includes a sensor suite and chest strap was identified as a potential solution. The Bioharness ™ 3.0 provides access to streams of raw physiological data (ECG only) via IEEE 802.15.4 connections in near real-time. ECG data are streamed as packets at a frequency of 250 Hz for cardiovascular data, and 100 Hz for accelerometer data. The strap is machine washable, waterproof to 1 meter, has a transmission range up to 1000ft, and can hold a charge for more than 24 hours. There is an optional five-bay charging station that supports charging all BioModules in a single device.

Figure 3: Zephyr™ Bioharness™ 3

Further, MedTronics, Inc. has developed their own radio communication networking capability that supports real-time data sharing from multiple BioHarness 3.0™ systems. This ECHO system is made up of several Zephyr™ components including the BioHarness™ 3.0, the ECHO gateway and auxiliary field repeater units that can be added to extend the range. These components communicate with each other via IEEE 802.15.4 radio communication protocol, and can track BioHarness sensor units as they move between available field repeaters, seamlessly providing a continuous data stream for evaluation.

Validation of Cardiovascular-based OSI

The original development of the OSI utilized both heart rate (HR) calculated from ECG and electrodermal activity (EDA), but was developed in such a way that it could utilize HR or EDA alone in the absence of another sensor. While using a single data stream (HR or EDA) does impact classifier accuracy (94% with both vs. 87% with HR only based on laboratory studies (Winslow, 2016), it allows different sensors systems to be utilized. Given that the Zephyr™ BioHarness 3.0™ provides cardiovascular inputs, but does not provide electrodermal information, the HR-only version was used with this sensor solution. In order to evaluate the Zephyr Bioharness™ data and the impact to stress classification outcomes, the data HR-only algorithm was compared to the combined data algorithm using data captured from students during firefighting scenarios. Based on the data collected under Phase I of this effort, the filtering on the ECG was significantly improved to target high-motion environments, which improves the accuracy of the ECG-only classifier. It is anticipated that these changes will allow for the ECG-only algorithm to be close in accuracy to the ECG+EDA classifier.

Data that were previously collected on 10 trainees going through the SWOS Advanced Training course was evaluated to compare the difference between the two OSI classifier algorithms. Overall, while the OSI value (0-10) were not always exactly the same, the 2 different algorithms reported students in the same stress bracket (green, yellow, red) with high consistency. Figure 4 shows data visualizations of the two classifiers from 5 different students who were members of a fire team during a training scenario (note: all students shown did not necessarily participate in the same scenario). Note that the fifth participant shown has a longer duration, as their data were captured over multiple scenarios on the same day. The red circles denote brief periods where the classifiers differed – these occurred in the second half of scenarios often, and usually showed the EDA + HR classifier maintained a higher stress score for a brief time. This may be attributed to delayed responses in EDA signal behavior compared to HR (where EDA has a typical physiological response window of ~6s; Boucsein et al. 2012). Overall, the average OSI difference between the two classifiers was between 0.25 and 1.0 OSI score when compared within participants.

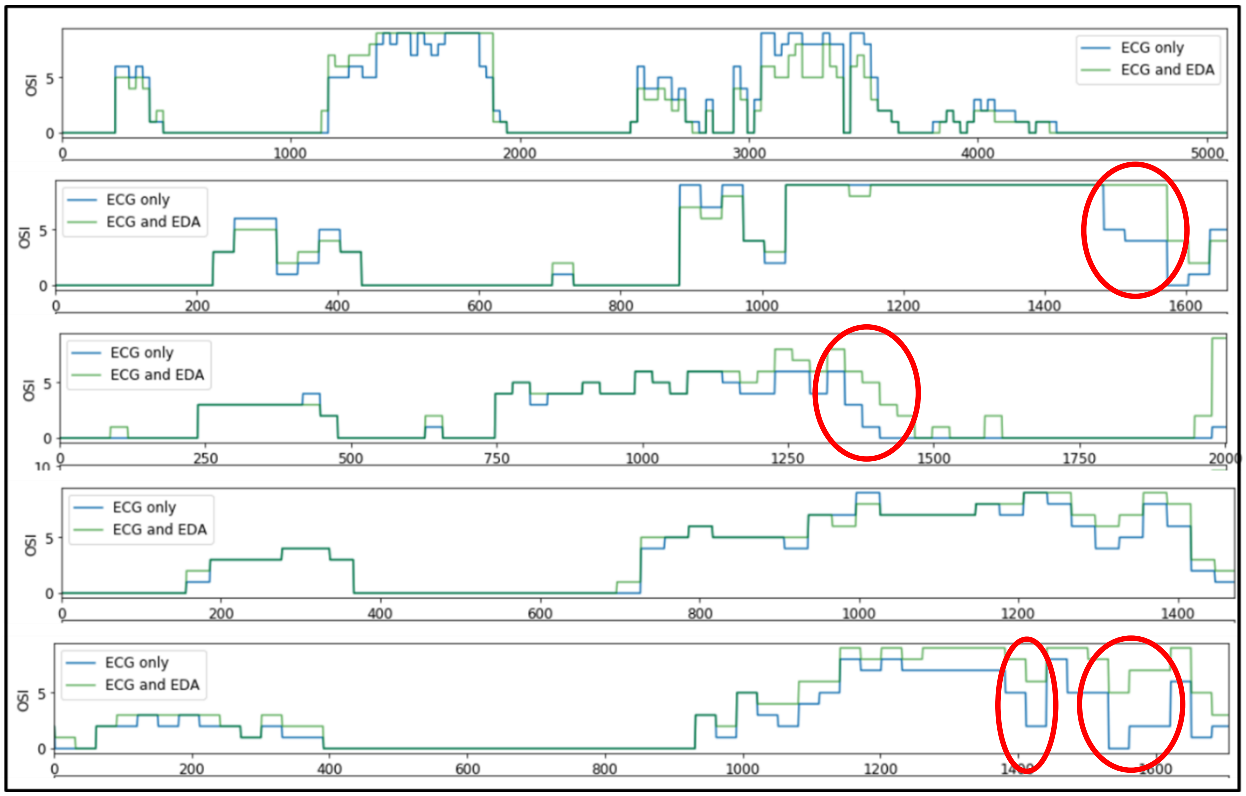

Figure 4: Data from 5 participants through a single training scenario within the Advanced Firefighting Course showing the comparison of the ECG only and ECG and EDA stress classifier algorithms.

STRESS MONITORING TOOL SYSTEM DESIGN

The proposed network solution (Figure 5) uses the Zephyr BioHarness™ 3.0 and ECHO/Gateway components to support data communication. The Gateway is connected to a Next Unit of Computer (NUC; small form-factor computer) on the main deck – mounted on the ceiling for best coverage. A weatherproof case is required to ensure these components are protected from the elements. The NUC communicates directly with the Gateway to pull sensor data from students, and wirelessly sends data to a Windows-based tablet with which instructors will interact. The field repeater units are powered by an integrated rechargeable battery source and are used to extend absolute range of the system and provide better coverage of an area. Field repeaters transmit directly to the base ECHO gateway, which has a coverage range of up to 300 yards. A total of four field repeater units will be placed within the recessed cavities on the wall of each targeted deck – Deck 1 will have one in each stairwell, Deck 2 will have one in the South stairwell, and a forth repeater placed in the North side of Deck 2 to support capture of baseline data while students are at the Muster station. This communication network has been tested at the SWOS Mayport facility with success.

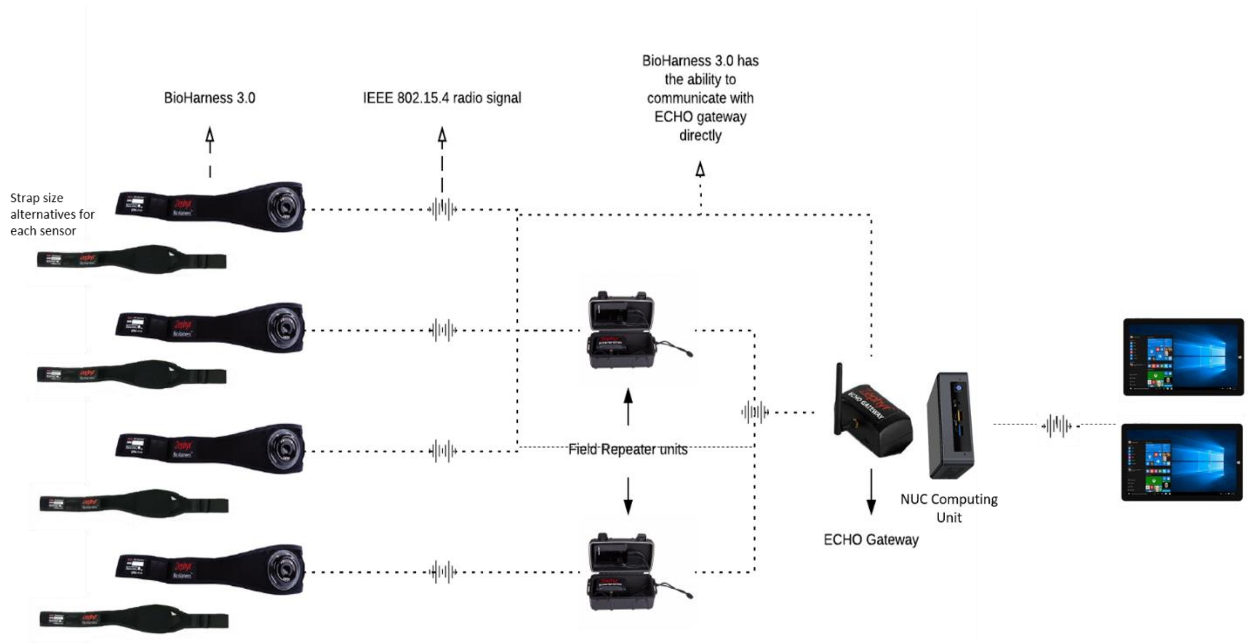

Figure 5: Hardware Network Diagram

The instructor interface was designed to be a quick and easy access tool for the lead instructor to monitor stress across students throughout a scenario. Billet numbers are used to identify students in the software, and students are grouped by Role (see Figure 6). During a scenario, instructors are shown a color-coded stress block for each Billet number, providing a quick glance status of student state.

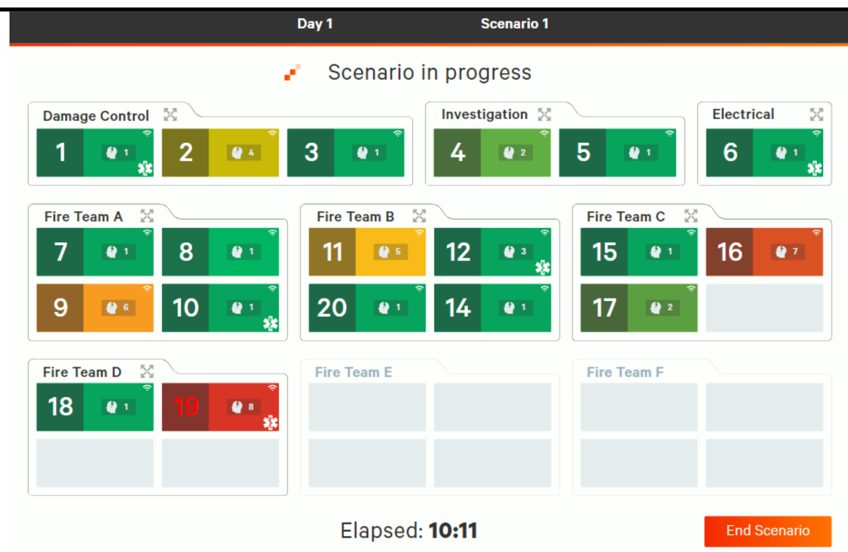

Figure 6: Instructor interface providing quick glance status of student stress

CONCLUSIONS

Providing real-time stress monitoring of students during SWOS' Advanced Firefighting Course gives instructors and SWOS leadership an opportunity for enhanced student safety – identifying potential stress-related issues before overt behavioral responses would indicate trouble. Further, such data provides insights to evaluate scenario design and execution – identifying components of scenarios that are related to high stress and/or where scenarios sustain high stress for substantial duration, where learning may be negatively impacted. Having objective measures of stress across multiple classes can be used to refine training scenarios to maximize learning opportunities and build Sailor resilience to the high-stress firefighting environment.

This effort identified a networked solution that is suitable for installation within the firefighting training facility, meeting requirements for stress monitoring and real-time data sharing within facility constraints. While the identified sensor technology is limited to providing ECG data output, analysis of data from the environment indicated that this is sufficient to meet the needs of stress classification of students. Implementation of the designed solution is currently ongoing, with full installation expected in Fall 2019.

FUTURE RESEARCH

Ultimately, in addition to enhancing the safety of training, a goal of this effort is to better understand how to apply physiological stress measures to the training curriculum to support more effective firefighting training. The ability to use physiological measures to adapt scenario based firefighting training at an individual and team level either real time or across scenarios has potential to improve training efficiency by tailoring the training to trainee responses rather than to rigid constrained scenarios. Even if scenario physiological measure based scenario adaptations may be limited in their contribution to overall training, aggregating these measures with trainee performance measures and other individual and team characteristics may provide instructors with more flexibility in tailoring training to individual and team performance. This would represent a first step toward the development of adaptive training algorithms, measures, and strategies for more effective firefighting training.

REFERENCES

Arkin, W.M., & Handler, J. (1989). Nepture Paper No. 3: Naval Accidents 1945-1988. *Greenpeace/Institute for Policy Studies Report*. Available online at: https://fas.org/wp-content/uploads/2014/05/NavalAccidents1945-1988.pdf. Viewed May 8, 2019.

Bennett, B. L., Hagan, R. D., Banta, G., & Williams, F. (1993). *Physiological responses during shipboard firefighting* (No. NHRC-93-9). NAVAL HEALTH RESEARCH CENTER SAN DIEGO CA.

Boucsein, W., Fowles, D.C., Grimnes, S., Ben-Shakhar, G., Roth, W.T., Dawson, M.E., & Filion, D.L (2012). Publication recommendations for electrodermal measurements. *Psychophysiology, 49,* 1017-1034.

Gomes, R. V., Moreira, A., Lodo, L., Nosaka, K., Coutts, A. J., & Aoki, M. S. (2013). Monitoring training loads, stress, immune-endocrine responses and performance in tennis players. *Biology of sport, 30(3),* 173.

Holsworth Jr, R. E., Cho, Y. I., & Weidman, J. (2013). Effect of hydration on whole blood viscosity in firefighters. *Altern Ther Health Med, 19(4),* 44-9.

Huber Z., Winslow, B, Chiang, J, Ajmal Aziz, A., & Drania, M. (2018). Objective stress monitoring for live training exercises. Paper presented at the 2019 Interservice Industry Training Simulation and Education Conference (I/ITSEC), Orlando, FL.

Varelas, G. (2011). Evaluation of Modern Navies' Damage Control and Firefighting Training using Simulator Platforms. Thesis submitted to Naval Postgraduate School. Available online at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a551925.pdf. Viewed May 9, 2019.

Winslow, B., Chadderdon, G., Dechmerowski, S., Jones, D., Kalkstein, S., Greene, J., Gehrman, P. Development and Clinical Evaluation of a Health Application for Stress Management. *Frontiers in Psychiatry,* July 2016.