Sensor-Hub: A Real-Time Data Integration and Processing Nexus for Adaptive C2 Systems

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***Abstract*—The present paper introduces the Sensor-Hub, a prototype tool for augmenting the common operating picture and adaptability of distributed teams in safety-critical environments. The Sensor-Hub aims to facilitate the integration and interpretation of data collected directly from humans augmented with sensing capability involved in the situation to produce timely and relevant information on the current functional state of operators, the situation and their environment. Herein, we elaborate on the development and validation of the sensing and interpretation framework, emphasising the key adaptation capabilities that it seeks to enable. Lastly, this paper illustrates three sectors of application of the Sensor-Hub: training of safety-critical team operations, real-time error-prevention and adaptation during operations, and assessment of inter-agent and human-technology interactions.**

Keywords-Augmenting humans with technology; sensing; modeling; situation awareness; network centric operations.

I. INTRODUCTION

Sensing technologies have evolved to the point that valuable information on an evolving operation can not only be acquired with regards to observable characteristics of the environment, but also about the functional state of the team during the accomplishment of its mission [1][2][3]. Advanced human sensing tools provide the opportunity to increase decision making and situational awareness of personnel actively engaged in a task and their immediate environment. Applications exploiting such data have the potential to significantly improve individual and team situational awareness, safety, adaptability and performance – provided that the data is processed by valid and reliable assessment models.

Situational awareness is defined as the perception of information pertaining to a situation, the comprehension of its meaning, and the projection of the situation into a near-future [4][5]. It is widely posited that situational awareness is associated with operational success, as it is the basis for a Common Operating Picture (COP) within the response team. Unfortunately, the characteristics of many situations severely hinder the perception of data, its comprehension and consequently its projection into the future. This is the case, for instance, during emergency response. Emergency response is the active phase of emergency management at the occurrence of an incident. Team members involved in emergency response must coordinate their effort in order to perform effectively often in very stressful, life-threatening environments, despite the challenges of the geographically distributed nature of their work (e.g., the command center is frequently delocalized from the incident and first responders are often dispersed across the area of operations). The uncertainty and time pressure that characterise emergency response situations often severely constrains the quality of the COP, both at the tactical and operational levels. Moreover, the amount of information to consider is often considerable, pushing individuals' cognitive capacities to their limit. The state of readiness of different team members can be particularly difficult to assess in such contexts.

Despite these constraints, there is a growing effort to augment accessibility and reliability of information in these (or similar) environments [6]. The deployment of multiple sensors in these environments enables the application of a network-centric approach to operations. The concept of Network-Centric Operations (NCO) originates from the military domain and refers to linking networks of sensors, decision makers, and individual agents [7][8] to achieve information superiority. This approach strives to increase shared awareness, self-synchronization, and performance of the network as a whole [9]. Concepts pertaining to network-centric operations can also be applied to emergency response, as many similarities exist between the two domains [10]. The objective of this paper is to discuss on how the developments in human sensing can take the NCO approach to a new level by enabling adaptive solutions to Command and Control (C2) in complex, distributed environments. To serve this purpose, we use the Sensor-Hub concept as a demonstrator of potential increased capabilities in the context of C2 and emergency response.

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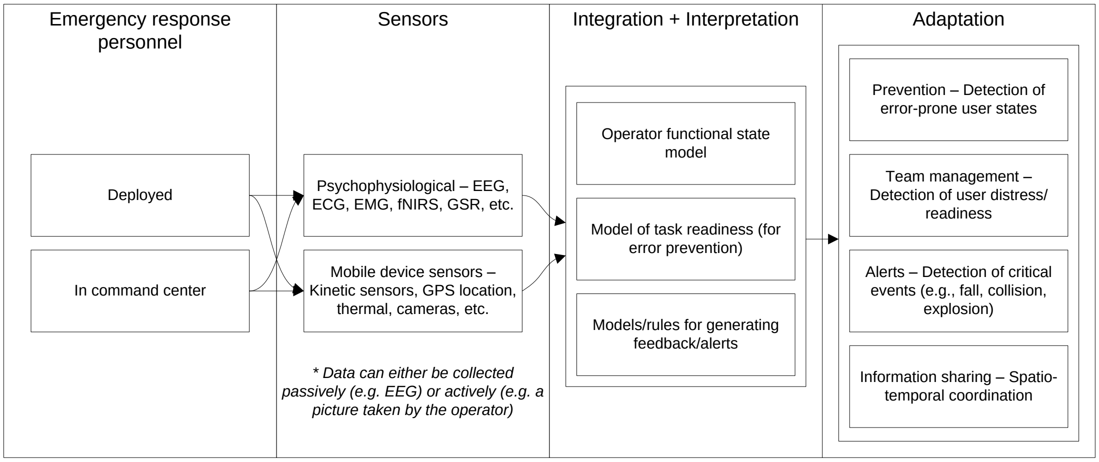

Figure 1. Sensor-Hub Framework.

This paper is divided into six sections. Section I sets the general context in which the Sensor-Hub could be deployed and implemented. Section II describes the potential sensing capabilities of the Sensor-Hub. Section III is concerned with the validation and the calibration of the higher-level models that will interpret the signals from the sensors. Section IV highlights the key features of the Sensor-Hub and discusses how these features could facilitate its implementation into different security and military contexts. Section V describes how the interpretation of sensors in the context of C2 and emergency response can trigger adaptive automation such as cognitive counter-measures. Finally, Section VI summarizes the critical components of the Sensor-Hub with regards to the concept of NCO.

II. HUMAN SENSING AND SITUATION MODELING

The Sensor-Hub aims to integrate and interpret data from multiple sensors mounted on emergency response personnel, either stationed in command centers or deployed in the field. Specifically, it integrates data from multiple sensors to derive metrics pertaining to Operators' Functional State (OFS), and passively/actively captures data about the environment. The main innovative component of the Sensor-Hub is its ability to model a series of data inputs (e.g., heart rate variability, velocity, blood pressure, positional data, temperature, etc.) and output relevant information about the functional state of the operator or the state of the operator's immediate environment. The Sensor-Hub is designed with built-in models and decision rules (to be calibrated and validated using experimental data), and allows for specifying relationships/rules as necessary to adjust to new contexts, or to different functional state concepts. The Sensor-Hub builds upon existing sensing technologies by integrating their signal and interpreting the data to derive higher level concepts. Below we describe the modeling framework (Fig. 1).

A. Sensing the Environment

Safety-critical environments are rapidly changing, dynamic and complex, which make them hard to predict. Although different situations (e.g., a toxic gas leak and a residential fire) may require different types of information, the individuals in charge of emergency response will often be well situated to provide the required information to higher level decision makers or other responders arriving on site. Providing sensors to these individuals and allowing the information of these sensors to be integrated and distributed across the response team is a key factor to augment Situation Awareness (SA) in this context and to effectively adapt to the situation. The Sensor-Hub seeks to facilitate integration and sharing of environmental information by allowing tactical operators to capture (either passively or actively) geotagged pictures, video, sounds, and measurements such as pressure and temperature. This data can be distributed across team members, both at the tactical level and command levels to support decision making and create a more capable emergency workforce. The capacity to sense the environment will help provide timely and relevant support for coordination and collaboration between tactical responders.

B. Sensing Operator Functional State (OFS)

Considerable amount of effort is put in the development of systems aiming to monitor OFS – a concept that groups together the mediators of human performance in a given context. OFS is a multidimensional concept that represents the current capacity of an individual to carry out his/her task without errors. As stated by Hockey and Robert [11], OFS is intrinsically defined in relation to the task to be carried out and its associated costs in terms of cognitive and physical efforts. For instance, in remotely operated vehicle piloting tasks, OFS involves the capacity of the pilot to re-allocate his attention between tasks, deemed critical for responding appropriately to alarms. In this context, OFS may also involve fatigue and stress as they are all related to piloting performance. Systems aiming to determine OFS are mostly, if not all, based on the assessment of the psycho and neurophysiologic state of the operator and the interpretation of this signal to derive OFS-related concepts such as fatigue, mental workload and stress. The major value in OFS assessment is the ability to anticipate human error (i.e., recognize states with high error probabilities), allowing the user or team to take preventive action. Mobile assessments of OFS are becoming increasingly feasible using wearable sensors. Furthermore, kinetic data and vital signs of deployed personnel can provide valuable information for increasing collaboration effectiveness and survivability.

C. Sensing the Situation

The OFS cannot be established solely by monitoring the operator, but requires information about the interactivity of the operator and the tasks; and on how efficient and responsive the operator is at performing his/her tasks [11]. Since there is most often a variety of tasks and sub-task to be carried out by operators in safety-critical environments, the accurate assessment of the OFS is directly related to the capacity to identify ongoing tasks and monitor modulations in performance. Determining the ongoing task remains a challenge, however, innovative techniques like dynamic cognitive task analysis [12] could be used to detect a pattern in the series of actions carried out by the operator and consequently infer the actual task being performed. Although this is not currently implemented in Sensor-Hub, having such a model capable of sensing the situation is key to augmenting the COP.

III. EXPERIMENTAL CALIBRATION/VALIDATION

The work in progress for the development of the integration and interpretation model within the Sensor-Hub involves several steps. First, an initial OFS model, based on existing literature, will be developed. This initial model will specify the filters applied to the incoming sensor data, the nature of the relationships between the different type of data generated by the sensors, and the format of the output generated. For the initial demonstration, the number of sensors used is restrained and will include heart rate monitor, global positioning system, and accelerometer. These sensors are chosen because they can provide several different metrics that were proven to be good indicators of operators' state in previous studies [11]. Heart rate variability, breathing rate, speed and acceleration will most likely be integrated within the OFS model. A hybrid architecture for the OFS model is adopted to allow for flexibility, meaning that it can easily be adapted to fit a wide variety of data with different properties. Both logical rules and the general class of regression models are implemented within the Sensor-Hub. Regression-based models have a demonstrated capacity to fit highly non linear data in similar contexts [13], whereas logical rules allow for quick implementation of disjunctive or conjunctive rules, for instance, which may be harder to model with regressions. Disjunctive rules may allow, for instance, one to differentiate between mental and physical workload based on heart rate. Second, the OFS model will be empirically calibrated through the observation of pilot participants completing an emergency response scenario. The appropriate calibration of the relationship between the data collected by the sensors and the various concepts that the Sensor-Hub aims to monitor (e.g., OFS and critical events in the environment) requires empirical testing in order to ensure good sensitivity and specificity. This involves a realistic emergency response scenario putting together multiple sub-tasks designed to be as close as possible to the real operational context. This scenario is divided into multiple phases with varying levels of mental demand, team coordination demands, physical demands, and environmental states. Given the live nature of the scenario (i.e., emphasis on realism rather than experimental control in simplified conditions), a good deal of noise in the measurement of the aforementioned concepts is to be expected. The modeling approach thus focuses on simplicity and robustness at the cost of raw accuracy. The scenarios are implemented into the SYnRGY simulation platform. As illustrated in Fig.2, the Safety-critical scenarios involving multidisciplinary teams of emergency responders are scripted and recorded (left). The responders' interface (in command centers) is composed of a geographic information system and multiple panels used for decision making, communications and displaying mission critical information (right).

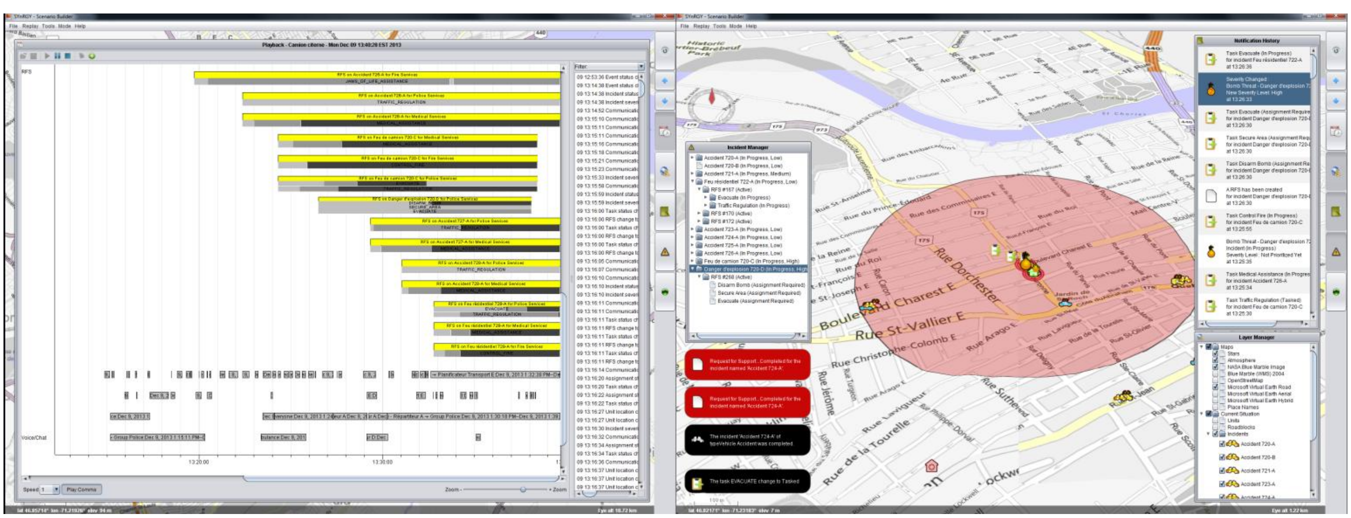

Figure 2. SYnRGY Simulation platform.

The platform allows for human in-the-loop simulations of safety-critical situations for both deployed and command center personnel [14]. These simulations allow the collection of data for model calibration in this context. Thirdly, model validity will be tested using different participants on a similar, but different emergency response scenario. The participants will be emergency management experts to improve the validity of the results. The purpose of this validation is to evaluate the predictive power of the model. Additionally, volunteers participating in the validation scenario will be asked (retrospectively) to rate the level of each of the output concepts at different moments in time. These added constraints will allow further tuning of the model. The developed scenario will enable the calibration and validation of the OFS model, which are human factors related issues, and to test for scalability and latency of the system which are technology-related issues.

IV. Toolset

A key feature of the Sensor-Hub is its toolset to facilitate (1) the integration and interpretation of new sensors and (2) visualisation of its outputs. Since OFS modeling is in its infancy, the development of each model is tedious and may represent an important obstacle, especially for non-specialists. The Sensor-Hub aims to facilitate the development of the OFS model by providing its users with pre implemented models and tuning tools. For instance, users can add or remove logical conditions to increase fit between inputs (i.e., data from sensor) and outputs (i.e., OFS). Calibration of the model is also facilitated by the availability of validated scenarios implemented within SYnRGY. These scenarios are specifically designed to vary cognitive demand, teamwork, and physical demand and consequently constitute an efficient calibrating environment. Moreover, data collected through the simulation platform constitutes an important referential database for further model development. In addition to modeling tools, the Sensor-Hub provides a component for visualizing the inputs and outputs of the model which may provide additional insight for model calibration or for decision makers in operational contexts.

V. Adaptability

Within the suggested framework, the Sensor-Hub interprets raw data to create mission-relevant information, which could serve as critical events for adaptive systems. For instance, in a safety-critical task training context, the Sensor-Hub can provide useful feedback to tactical operators during debriefings or even in real-scale exercises. Real-time assessment of cognitive load, for instance, has been shown to be insightful in the improvement of training [16]. From this point of view, what is adaptive in the system is the team of responders per se rather than the Sensor-Hub. The latter is the enabler, and so provides information required for triggering team adaptation. Adaptive systems, in general, would benefit from inputs from an assessment of the situation, OFS and of the environment that the tactical operators are facing [15]. Such adaptive systems can, for instance, offer assistance to the operators involved in safety-critical missions when detecting critical OFS levels that are likely to lead to critical failures or when detecting an environmental threat. Moreover, because environmental information can be assessed by the Sensor-Hub, the adaptive system could provide tactical operators with additional informational inputs (i.e., the information flow is bi-directional). Finally, this human-sensing and analysis capability may also be useful as an assessment tool for comprehensive assessments of human-technology interactions or team interactions in a research and development context. In the context of NCOs, and particularly emergency response, the Sensor-Hub can provide critical information on the OFS of first responders for real-time adaptation. One of our currently envisioned applications would use the high-level assessment of the functional state to suggest task re-allocation to commanders for timely team management [17]. Task re-allocation is deemed critical for highly dynamic C2 situations such as emergency response [11]. The adaptive component of the system, triggered by the OFS, is not fully automated, leaving the final decision and responsibility in the hands of the commanders.

VI. Conclusion

The current paper discussed how human sensing can support the NCO approach to C2 and emergency response by enabling adaptive solutions in dealing with the challenges of complex and dynamic distributed environments. We illustrate how the data from physiological sensors can be interpreted into higher-level concepts and trigger adaptive “support” to the commanders. The Sensor-Hub framework aims to provide an advanced human sensor integration and modeling capability to support a new and unparalleled network-centric emergency response capability. The framework is nonetheless generic and widely applicable to other domains. Three potential applications of the Sensor-Hub would provide adaptive capabilities to teams evolving in safety-critical environments: 1) Training of safety-critical team operations, 2) Real-time error-prevention and adaptation during operations, and 3) Assessment of inter-agent and human-technology interactions. Others have also developed sensor integration tools relevant to OFS measurement [1][2][18]. However, the key differentiator in the development of the Sensor-Hub is its focus on facilitating the assessment and decision making process by giving a simple yet flexible toolset for editing and calibrating the interpretation model, based on psychophysiological theory and on empirical evidence. Such an empirical evidence is also greatly facilitated by the scenarios implemented with the SYnRGY simulation platform.

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