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NOTICES

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14. ABSTRACT
We present a novel system for a distributed Value of Information-based approach for collecting, disseminating, mediating, and tailoring information to and from Warfighters at the tactical edge and the tactical operations center or forward operating base. By modelling user, mission, environmental, and communications context, we postulate we can provide the Warfighter with equal or better situation awareness (SA) at a much reduced network transmission cost. By monitoring and adapting to user, mission, environmental, and network context and exploiting multiple presentation modalities, we can reduce the cognitive workload and improve SA by identifying, prioritizing, filtering, shaping, and tailoring information most relevant to the Warfighter or intelligence analyst given the current context.

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1. Introduction

This report describes a distributed Value of Information (VoI)-based approach for collecting, disseminating, mediating, and tailoring information to and from Warfighters at the tactical edge and the tactical operations center or forward operating base. By modelling user context (physiological and cognitive state, current activity and workload, available presentation modalities, information needs, etc.), mission context (commander's intent, operational orders, commander's critical information requirements, friendly and enemy intelligence, etc.), environmental context (location, temperature, humidity, ambient light, wind speed, soil type, etc.), and communications context (bandwidth, capacity, throughput, connectivity, latency, etc.), we postulate we can provide the Warfighter with equal or better situation awareness (SA) at a much reduced network transmissions cost than, for example, sending all available information to every Warfighter constantly and independent of context. By monitoring and adapting to user, mission, environmental, and network context and exploiting multiple presentation modalities, we can reduce the cognitive workload and improve SA by identifying, prioritizing, filtering, shaping, and tailoring information most relevant to the Warfighter or intelligence analyst given the current context. In this report we describe a prototype system that begins to realize a mission-adaptive context-aware framework necessary for the testing and evaluation of our premise.

This report is organized as follows: In Section 2 we provide our definitions of Quality of Information (QoI) and VoI in the context of the approach we took in designing the system. Section 3 describes the overall architecture of such a system and the specific devices used in our system. Section 4 discusses each variety of context considered—which include user, mission, environmental, and network oriented context—and identifies current limitations that need to be addressed to work with each in-parallel. Section 5 then transitions into strategies and challenges for aggregating heterogeneous context information. Section 6 identifies related work, Section 7 discusses future work, and Section 8 concludes the report.

2. Background

Following early work by Howard based on information theory,[1] many domains have explored the use of VoI and QoI, ranging from economics[2] to health care[3] to sensor management.[4] Because of the diversity of these domains, much debate exists on precise definitions for VoI and QoI and whether they should even be formally distinguished.

An early attempt to define data quality emerged from work on assessment of industrial processes by Juran,[5] where quality is defined as “fitness for use for a particular operation or task”. Follow-on research by Wang and Strong defined a data management framework that considered both intrinsic and contextual quality,[6] which can be viewed as an early effort to explicitly distinguish VoI and QoI as attributes of data.

For our purposes, we define QoI as parameters or features intrinsic to the data itself independent of context. Examples include features intrinsic to data products such as images or videos (e.g., resolution, modality, time of collection, frame rate, location), to physiological measures (e.g., heartrate, blood pressure, temperature, O_2 levels, dehydration levels), and to network measures (e.g., bandwidth, capacity, throughput, latency, connectivity). We define VoI as a function of the QoI parameters in terms of the current state of user, mission, environmental and network contexts. In other words, the value of information is a function of the data and their quality in a particular context.

When considering Warfighters as information consumers, potentially relevant data based on current mission context (e.g., location of unusual or potentially dangerous situations or activities) should be pushed to them as needed. Equally important is filtering irrelevant data so as to not overburden either the Warfighter or supporting network infrastructure. The VoI estimation should also consider the Warfighter’s current activity, cognitive workload, and physiological state, which could be anything from resting to engaged in high operating tempo activities such as combat. Our goal is to apply available varieties of Warfighter context toward information filtering, dissemination, and presentation. Initially, information would be filtered based on calculated relevance to the mission context. In turn, the network context would be used to decide how to deliver the information most efficiently. Finally, both the user and environmental context would aid in deciding how to present the information to the Warfighter. The prototype system currently uses readily available visual, auditory, and tactile technologies as exemplars to determine the best possible modality given a particular type of information and Warfighter activity.

3. System Architecture

A VoI platform is a host for a suite of sensors and VoI components and algorithms. A VoI host may be a computer or a human carrying wearable sensors and a computer (typically a smart phone). Figure 1 illustrates the architectural diagram for a single VoI platform. The entire system consists of one or more instances of a VoI platform.

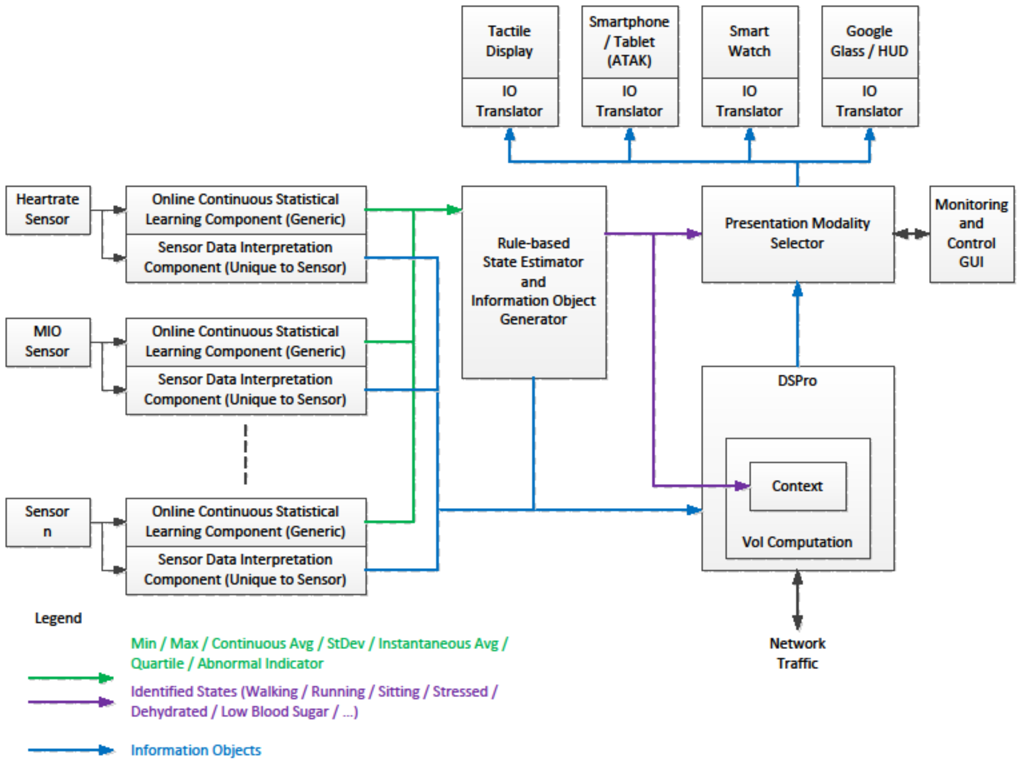

Fig. 1 VoI platform system diagram

3.1 Sensors

A variety of sensors provide raw data to the system. These data may be in the form of streams, discrete events, or both. For sensing the human user state, the platform can select from a variety of available physiological sensors: heart rate, galvanic skin response, eye tracking, temperature, etc., and easily derive information such as heart rate variability (HRV) and visual gaze, to classify and estimate different dimensions of a Warfighter's cognitive state from the physiologic data. Body-worn accelerometers, global positioning system, and rate sensors can provide user-specific context to disambiguate physiologic data. The consumer "quantified self" market has driven the development of miniaturized, low-power, wearable sensors; however, careful selection based on signal quality will support reliable classification. We also employ a forearm-worn electromyography device (Myo, Thalmic Labs, Inc., Ontario, Canada) for recognizing gestures (i.e., tactical hand signals) to infer a squad leader's commands. For a sensor gateway platform the environmental sensors will generally consist of unattended ground sensors with a variety of different modalities: acoustic, seismic, visible and infrared (IR) cameras, trip wires, radio-frequency identification, etc.

3.2 Sensor Data Interpretation Component

The role of the Sensor Data Interpretation Component is to convert the raw sensor data into information objects (IOs) as appropriate. This could involve data compression, reduction, or discretization of the raw data to accommodate low bandwidth network connections. The IOs are sent to DSPro where they are evaluated against contexts of other platforms to determine if and where the IO should be sent.

3.3 Online Continuous Statistical Learning Component

The Online Continuous Statistical Learning Component computes a variety of statistics and/or classifications of the raw data, including the following: min/max, continuous average, instantaneous average, quartile, and anomaly detection. These statistics/classifications are used by the Rule-Based State Estimator to estimate various states.

3.4 Rule-Based State Estimator and IO Generator

The role of the Rule-Based State Estimator and IO Generator is 2-fold. First, it combines the outputs of the various Online Continuous Statistical Learning Components to deduce or infer states such as walking, running, sitting, dehydration, low blood sugar, and high stress. These states are used to inform the various local contexts and by the Presentation Modality Selector to determine in which modality to present the information: video, image, audio, text, tactile, etc. Second, during this process additional IO artifacts may be produced. These IOs are sent to DSPro where they are evaluated against other platform contexts to determine if and where the IO should be sent.

3.5 Presentation Modality Selector

The Presentation Modality Selector considers the user context and available display devices to determine which mode of presentation is appropriate at that time for that user and when to present the content. The IO translators associated with each display device are used to inform the Presentation Modality Selector which modalities each device supports.

3.6 Monitoring and Control Graphical User Interface (GUI) and DSPro

The Monitoring and Control GUI is used to monitor the Presentation Modality Selector and dynamically reconfigure it as necessary. DSPro is a software component that supports the dissemination of IOs to and from the tactical edge. In this capacity, it replaces the traditional role played by a transport protocol such as transmission control protocol (TCP), which might have been used in a more traditional client-server setting. DSPro differs from a simple TCP-like transport protocol in many ways, such as supporting peer-to-peer information exchange, multipoint information exchange, and advanced features for prioritization and filtering of information. IOs may be as simple as a commander's signal, location data of a friendly or enemy unit, a graphic such as a map, a picture, a document such as an intelligence report, or a full motion video clip. For this application, DSPro has been integrated with the DisService middleware. DisService, is a peer-to-peer, publish-subscribe, store-carry-and-forward middleware that was designed to support efficient information dissemination and group communication in challenged networks.[7] DSPro implements a proactive information dissemination algorithm that attempts to predict which IOs will be of relevance or of value to the end user and sends these IOs to the end user before they are requested. Hence, it calculates the VoI of each IO for each end user. In a military context, information may be deemed to be of value if it increases the SA of the Soldier or analyst and/or causes them to alter their course of action for a better outcome. This capability can reduce bandwidth, reduce latency and reduce the workload of the end user/receiver/analyst/Soldier due to its ability to prioritize the IOs, which are being sent to the end user (based on the users' predefined or mission requirements and the value and quality of the IOs). Integrating the physiological sensing and wearable computing adds 3 new capabilities to the overall system. First, the physiological state may be used to change the algorithm that determines the VoI for an IO. Second, the physiological state may trigger new IOs (for example, a warning about over exertion or dehydration) that can be propagated to other team members (since such information would be of value to them). Third, the wearable computing capabilities provide new presentation modalities for the IOs, and the system can select the best modality(ies) based on the sensed physiological state.

Calculating the actual VoI of an IO for a particular end user is challenging, as it requires the system to model each end user in terms of their existing knowledge, their objectives, their information needs, and their decision-making strategy. DSPro realizes VoI-based filtering for a small set of critically important IO types in tactical environments, such as tracks, sensor reports, and other documents with metadata that supports such evaluation. For this application DSPro has been expanded to calculate the VoI threshold for dissemination based on sensor data that tries to evaluate the physical and cognitive state of the end user as well.

The DSPro prediction algorithm is based on a set of policies that match the parameters in the metadata associated with each IO published in DSPro against the context of the users that are currently reachable and compute a predicted VoI of each IO for each user. The metadata of the IO contains a set of pre-defined attributes, which includes the geographical relevance of the IO, the mission relevance, the commander's intent, the creation time, and the pedigree. The user context contains the planned path that the user is expected to follow, the current position, the mission he or she is performing, and his or her role. Along with these properties, the user context also includes parameters to tune the behavior of the matchmaking algorithm. Users can specify the size of the region around the route for which they are interested in receiving IOs, along with a relevance threshold under which they are not interested in receiving IOs. All IOs that have been published to the end user are tracked in a history store, so that they will not be considered again in the future unless the context of the end user changes. In this case, the IOs in the data store that were not already transmitted are examined to see if any of them would now be relevant to the consumer given the updated user context. If so, those new matching IOs are transmitted to the consumer and tracked in the history store.

In addition to these parameters, for this application in particular, the prediction mechanism takes into consideration VoI based on the perceived physiological and cognitive state of the end user, based on measures such as heart rate, breathing rate, and body temperature. If it is perceived that the end user is in state of stress or in active combat, only the absolutely critical IOs will be sent. For this to occur, the sensor data used to assess the physical and cognitive state of the end user will be used to modify or adjust their context profile.

An individual sensor providing the IO can also be given a priority parameter that can be adjusted according to the type or importance of information it provides. For a particular Warfighter, information from a poisonous gas sensor in their immediate vicinity could automatically be assigned a high VoI. Additionally, signals from a commander's Myo armband may also be prioritized at a higher level to ensure that Warfighters receive them prior to less important/relevant IOs.

The metadata of IOs that are matched for a specific end user are ranked by the predicted VoI and queued for dissemination. Upon reception of the metadata, the receiving node can decide whether or not to retrieve the entire message. If at any given time before the IO is disseminated, the context of a user changes, the matchmaking is performed again, and the IOs that are no longer relevant will be de-queued and will not be disseminated.

3.7 Physiological Sensing Component

Three factors require primary consideration for the physiologic sensing component: size, power and signal quality. Many laboratory-based sensor devices exist that provide clinical quality data to support physiologic and cognitive state detections and tracking, however, these have little relevance in the field and in particular in the dismounted Warfighter environment. The physical volume of the device must not interfere with operations and the power requirements must not increase the number of batteries a Soldier must carry. Commercial-off-the-shelf devices such as wearable fitness trackers (e.g., Fitbit, Fitbit, Inc., San Francisco, CA; UP3 Jawbone, Inc., San Francisco, CA), provide limited on device information but offload computational activities to the user's home computer or the vendor's cloud servers. A similar approach (with appropriate security and policy controls) will allow the use of simple, low-power, wireless physiologic sensors by processing raw data either on a central, body-worn computer or on remote assets when available. Because of the orders of magnitude of processing power available to cloud computing versus wearable computers, the QoI for the physiologic sensing will vary in granularity as the available bandwidth changes. The overall architecture will place sensors on the body in locations that either have the optimal location for the signal source, such as placing electrocardiograph sensors near the chest wall, or that can acquire reliable data when integrated into existing devices (e.g., sensing heart rate through a sensor embedded in a smart watch). The sensors will use a personal area network to link to a body-worn processing node. This node will manage local data reduction and large granularity IO extraction. When sufficient bandwidth opens, then the node will offload processing to remote or meshed processing assets to increase IO granularity and improve QoI. By combining both physiologic and environmental sensors in the architecture, the processing elements will acquire the context necessary to discern changes due to physical or mental activity to provide VoI.

4. Context Factors for Wearable Computing

4.1 Utility of Context Types

Context modeling, particularly within military applications, remains an open research area. Therefore, a key focus of this research is to lay down an initial set of factors, and a means to seamlessly integrate and use them to make content selection decisions. As of now, this work considers the following classes of contextual factors:

- **User Oriented:** Intended to capture aspects of a Soldier's cognitive and physiological states.
- **Environment Oriented:** Factors deriving from information about an area of operations. These can be obtained from deployed sensor networks and include environmental readings and sightings of enemy activities.
- **Mission Oriented:** Deriving from descriptions of a Soldier's mission, which can include descriptions of corresponding tasks and goals.
- **Network Oriented:** Deriving from properties of the network being used for content dissemination (e.g., topology).

Overviews for each of these classes will be provided, followed by a discussion of technologies for seamless integration of context factors.

4.2 User Context

For purposes of this work, user context is intended to correspond to physiological data for inferring cognitive processes. Psychophysiological metrics have been previously investigated for usage in adaptive systems[8] as a means of inferring user state beyond conventional input modalities.[9]

A goal of psychophysiological research has been identifying cognitive states through metrics such as HRV[10] and electroencephalogram readings. States such as mental fatigue, drowsiness,[11] level of task engagement, and emotional state[12] have each been measured through experimentation in laboratory settings. Commonly, tasks conducted during these experiments have been simulations covering air-traffic control,[13,14] car and aircraft operation,[11] and dismounted Soldier applications.[15]

Common applications involving psychophysiological metrics involve regulating automation of complex systems, such as aircraft.[12] Additionally, adaptive management of content in user interfaces has also been considered in the context of lesson plans for tutoring systems[16] and for the design of computer games.[12] However, limited prior work appears to exist on real-time, adaptive content streaming based on psychophysiological readings.

4.3 Environment Oriented

For military applications, environmental monitoring consists not only of tracking natural phenomena (e.g., reading temperature, humidity, and wind speed) but also activities taken by both friendly and enemy forces. With respect to forces monitoring, sensor networks have commonly been applied toward enemy combatant detection in remote areas,[17,18] and protection of secured areas.[17]

4.4 Mission Oriented

For purposes of this work, we consider mission context as a specification of mission activities sufficiently detailed to be able to infer Warfighter information requirements. A significant portion of research on mission context concerns pairing of materiel to mission tasks, which in-turn can be paired to greater mission objectives. The Military Mission and Means Framework (MMF)[19] represents an effort to define mission specifications around descriptions of tasks, capability requirements, materiel, and interactions between opposing forces. Following its definition, MMF has been applied toward defining computational pairings of tasks to materiel.[20,21] Prior efforts in computer-driven task-materiel pairing appear to show promise for integration into greater models of Warfighter context, and research on their extension is ongoing.

4.5 Network Oriented

The network context in a tactical communications environment consists of the following:

- Network node context, which includes parameters of a radio node, such as frequency range, bandwidth range, transmit power, forward error correction, transmitter and receiver antenna configuration, aggregate received bandwidth, aggregate transmit bandwidth, battery status, power consumption, and mobility patterns.
- Network link context, which includes received signal strength, path loss, received bandwidth, transmit bandwidth, bit error rate, packet loss, latency, and jitter on a per link basis
- Network structure context, including topology, churn rate, density, stability, and link diversity.

The network context provides data to higher-level applications to dynamically develop informed strategies to meet the dissemination demands of potentially competing IOs.

5. Strategies and Challenges for Aggregating Heterogeneous Context Information

A core research goal of this work involves prioritization and dissemination of IOs relevant to a consumer's context. Several forms of Warfighter context are now being considered—physiological, mission, environment, and network-based—which, dependent on mission requirements, may need to be applied toward several varieties of IOs. Regardless of the prioritization strategy applied, we envision 2 high-level development steps being needed: 1) comparing attributes of IOs against different context factors, producing a set of rankings for individual VoI factors and 2) generation of a single aggregate VoI ranking to determine what order to send content out. Following a discussion of research challenges affecting this 2-step process, we will provide a discussion of ranking techniques.

5.1 Challenges in Research

Currently, we have identified 2 research challenges for IO ranking: (I) design of techniques for VoI factor assessment, based on evaluation of IOs against a Warfighter's context and (II) selection of weightings for each VoI factor chosen.

For category (I), 2 methods have been identified for Context-IO comparisons. The first, known as "function-based comparison", applies one or more mathematical functions toward comparing a Warfighter's context with properties of an IO. Examples of function-based comparison can include comparing the location of an IO to a Warfighter's location via a distance calculation, and comparing its timestamp to the present time. The second category, termed "knowledge-based comparison", relies upon comparison of encoded information about Warfighter context (e.g., mission and environmental conditions) to corresponding IO requirements. As an example, imaging data corresponding to IR sensors, as opposed to visible light sensors, may be chosen based both on encoded knowledge of environmental conditions and appropriate environment-sensor pairings. Here, we see knowledge-based comparison as having a particularly rich set of research challenges, primarily centered on development and validation of appropriate knowledge base content.

Building on category (I), category (II) requires mechanisms to ensure VoI weightings are appropriate to a particular Warfighter's needs. VoI weightings may be determined through multiple approaches, which may either be automated or driven through Warfighter feedback. In cases where such feedback is applied, mechanisms should be available to enable Warfighters to easily modify their weightings based on changing content requirements.

5.2 Ranking Techniques

Given the variety of VoI factors relevant to Warfighters—each consisting of different forms of Context-IO comparisons—many possibilities may exist for the design of ranking functions. Furthermore, many VoI factor types (e.g., mission relevance) presently lack established ranking methods. Therefore, it becomes necessary to consider VoI rankings at different stages of development and consensus by subject matter experts (SMEs). Accordingly, 2 classes of IO ranking are being considered: (I) production-ready rankings, which may be implemented using whatever method determined appropriate and (II) development-oriented rankings, which rely upon an implementation-agnostic ranking approach based on the Analytic Hierarchy Process (AHP).

5.3 When to Use Each

Classes (I) and (II) are both applicable toward IO selection and prioritization. However, each technique is intended to represent a different level of VoI ranking development. Here, class (I) rankings can be viewed as "production-level" implementations, in which specific details of the ranking approach may be hidden from consumers (e.g., Warfighters, SMEs). Likewise, class (II) is intended to serve as a "development" method for SMEs to create and experiment with new ranking approaches.

By design, AHP is intended to enable aggregation of feedback from multiple SMEs, which can be a starting point in reconciling conflicting opinions.[21] Additionally, since AHP can facilitate traceability of decision outcomes to specific criteria, incremental refinement of ranking approaches can be facilitated. Ultimately, as rankings developed using the class (II) technique are refined and agreed upon by SMEs, they may be implemented through alternate methods as needed.

5.4 Ranking Method 1: Production-Ready

Several production-ready ranking techniques, based on established Context-IO comparisons, are presently implemented in the DSPro framework. DSPro defines a collection of functions for IO ranking based on spatiotemporal properties, designed to rank objects with respect to a Warfighter's context. Each VoI factor considered is then weighted by importance to a consumer, resulting in a single aggregate rank value for each IO.

The current implementation of the DSPro ranking function considers the following 7 attributes while evaluating the VoI of an IO:

1) Geographical Relevance (also called the Coordinate Rank), which measures the distance between the current position, area of interest, and/or planned route of a consumer and the geographical extents, if any, for the IO

2) Time Relevance, which determines how soon the information is likely to be relevant (of use) to the consumer

3) Expiration, which is used to determine the age of the information

4) Importance, which is a user-defined assessment of the importance of the information, independent of the receiver

5) Target, which is a user-defined list of missions or individual consumers who would find this information of use

6) Information Content, which is a user-defined measure of the significance of the information, again independent of the receiver

7) Source Reliability, which is a user-defined measure of the reliability of the source/provider of the information

DSPro uses a weighted ranking function that first computes the values for each of the previously listed components and then combines them into a single value based on user-configured weights for each component. The formula is as follows:

$$VoI = (d \cdot w_d) + (t \cdot w_t) + (e \cdot w_e) + (i \cdot w_i) + (tgt \cdot w_{tgt}) + (ic \cdot w_{ic}) + (sr \cdot w_{sr}) + (l \cdot w_l) \quad (1)$$

Where *d* is the distance (geographical relevance), *t* is the expected time of use, *e* is the expiration, *i* is the importance, *tgt* is the target, *ic* is the information content, and *sr* is the source reliability.

The last component, *l*, is the learned preference, a feedback-based learning mechanism that is also integrated into DSPro.

5.5 Ranking Strategy 2: Development-Based, Using the Analytic Hierarchy Process

AHP is a technique established for organizing group decision-making exercises, based on defined hierarchies of selection criteria.[22] Prior efforts to ours, which serve as a starting point for our research on AHP, have applied the technique toward gauging QoI.[4]

In AHP, methods for selecting or ranking IOs—also referred to as "alternatives"—are driven by evaluation of selected criteria, which may be organized into a hierarchy according to criteria/sub-criteria relationships. Figure 2 gives an example of AHP hierarchy, involving the ranking of 5 image files to assess what order they should be sent to a Warfighter. To determine a ranking, 3 factors are considered by SMEs:

- The type of imaging sensor used to capture the image.
- The resolution of the imaging sensor.
- The distance of the sensor from a consumer.

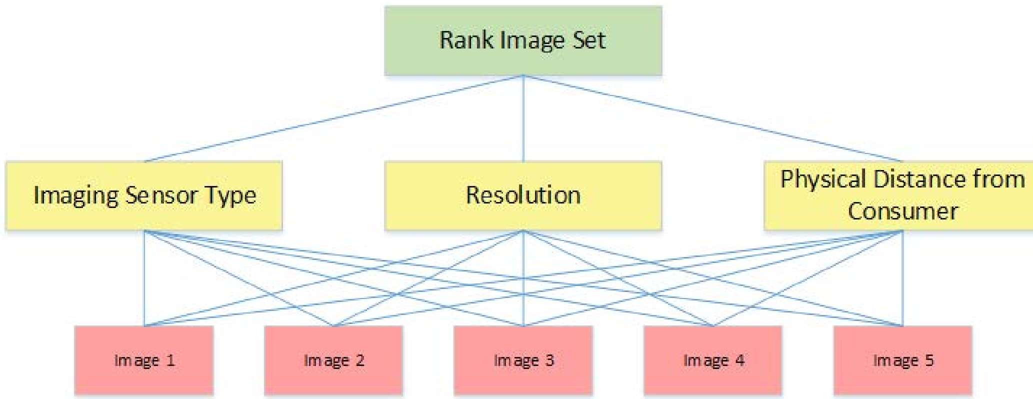

Fig. 2 Example AHP hierarchy for image ranking task

To produce a complete ranking, 2 steps must be completed: 1) pairwise comparison for each of the 5 images must be done over all 3 factors and 2) pairwise comparison of the 3 factors to gauge their relative importance. In AHP, pairwise comparisons are given by SMEs on a scale of 1– 9 (Table 1), representing varying levels of difference between a pair of alternatives.

Table 1 Levels of difference between a pair of alternatives

Value	Difference between A and B
1	Equally valued
3	Moderate difference
5	Strong difference
7	Very strong difference
9	Extreme difference
2,4,6,8	Intermediate values

In this example, evaluation of the criteria require assessment of each image (its metadata and content) and the consumer's context. For the criteria "Imaging Sensor Type", existing knowledge of lighting conditions could lead to the following SME assessment: images taken using an IR imaging sensor will be 4 times as desirable as ones from a visible light sensor. Assuming that images 2 and 3 were IR-based, while 1, 4, and 5 were taken with a visible light sensor, Table 2 gives a pairwise comparison for the Imaging Sensor Type criteria[5]:

Table 2 Pairwise comparison for "imaging sensor type"

Sample	Image 1	Image 2	Image 3	Image 4	Image 5	Priority
Image 1	1	1/4	1/4	1	1	0.09091
Image 2	4	1	1	4	4	0.36364
Image 3	4	1	1	4	4	0.36364
Image 4	1	1/4	1/4	1	1	0.09091
Image 5	1	1/4	1/4	1	1	0.09091

Next, for the criteria "Resolution", assume images 1 and 2 have a resolution of 640 × 480 pixels, images 4 and 5 have a resolution of 800 × 600, and image 3 has a resolution of 1,600 × 1,200. Based on SME review, the following assessments could be made: 1) 800 × 600 images are 2 times as desirable as 640 × 480, 2) 1,600 × 1,200 images are 5 times as desirable as 640 × 480 and 3) 1,600 × 1,200 images are 3 times as desirable as 800 × 600. Table 3 gives a corresponding comparison over the Image Resolution criteria.

Table 3 Pairwise comparison for "resolution"

Sample	Image 1	Image 2	Image 3	Image 4	Image 5	Priority
Image 1	1	1	1/5	1/2	1/2	0.08905
Image 2	1	1	1/5	1/2	1/2	0.08905
Image 3	5	5	1	3	3	0.47859
Image 4	2	2	1/3	1	1	0.17165
Image 5	2	2	1/3	1	1	0.17165

Then, for the criteria "Distance from Consumer", assume that each image was captured by a sensor some distance from the target consumer. In this case, assume the following image distances: 1) Image 1 is 15 m away, 2) Image 2 is 45 m away, 3) Image 3 is 5 m away, 4) Image 4 is 25 m away, and 5) Image 5 is 35 m away. Using these distances, SMEs could define a function for pairwise comparison as a function of distance, giving closer images a higher priority. Table 4 gives the resulting comparison.

Table 4 Pairwise comparison for "distance from consumer"

Sample	Image 1	Image 2	Image 3	Image 4	Image 5	Priority
Image 1	1	3	1/3	5/3	7/3	0.18596
Image 2	1/3	1	1/9	4/9	7/9	0.09677
Image 3	3	9	1	5	7	0.55788
Image 4	3/5	9/4	1/5	1	7/5	0.11702
Image 5	3/7	9/7	1/7	5/7	1	0.07970

Once all criteria are individually evaluated, a pairwise comparison of the selected criteria must be conducted as well. Table 5 provides a comparison that favors the Imaging Sensor Type criteria.

Table 5 Pairwise comparison of the 3 criteria

Criteria	Sensor type	Resolution	Distance	Priority
Sensor type	1	9	6	0.76437
Resolution	1/9	1	1/3	0.06978
Distance	1/6	3	1	0.16586

Finally, Table 6 gives a ranking of the 5 images, based on the pairwise comparisons completed by the SMEs. In this case, the image ordering obtained is 3, 2, 4, 1, and 5.

Table 6 Priority calculation for the 5 images

Sample	Category 1 priority * weight	Category 2 priority * weight	Category 3 priority * weight	Priority (image rank)
Image 1	(0.09091) * (0.76437) = 0.06949	(0.08905) * (0.06978) = 0.00621	(0.18596) * (0.16586) = 0.03084	0.10033 (4th)
Image 2	(0.36364) * (0.76437) = 0.27796	(0.08905) * (0.06978) = 0.00621	(0.09677) * (0.16586) = 0.01605	0.30022 (2nd)
Image 3	(0.36364) * (0.76437) = 0.27796	(0.47859) * (0.06978) = 0.03340	(0.55788) * (0.16586) = 0.09253	0.40389 (1st)
Image 4	(0.09091) * (0.76437) = 0.06949	(0.17165) * (0.06978) = 0.01198	(0.11702) * (0.16586) = 0.01941	0.10088 (3rd)
Image 5	(0.09091) * (0.76437) = 0.06949	(0.17165) * (0.06978) = 0.01198	(0.07970) * (0.16586) = 0.01322	0.09469 (5th)

In this example, knowledge of relevant Warfighter context was applied by SMEs toward assessment of the image set, based on 3 available data properties: the sensor type used, the resolution, and the distance from a target consumer. Based on the results of this ranking, SMEs may either determine the ranking strategy appropriate for mission needs or refine it further to reorder the images. Once consensus on the ranking is achieved, the knowledge elicited from SMEs in the AHP method may then be transferred to alternate implementations (i.e., production-level rankings).

6. Related Work

QoI and VoI are relatively novel concepts, which have been recently proposed and investigated by the wireless sensor network research community. These concepts arise from the seminal work by Howard[1] that attempted to extend Shannon's information theory to consider both "the probabilistic nature of the uncertainties that surround us, but also with the economic impact that these uncertainties will have on us". The investigation of the "utility that an IO provides to its consumer" —that is, of its ability to support the consumer in more effective decision making— has been a major research topic in economic and decision theories for the last 50 years and is still receiving a considerable amount of attention.[2,23]

Research in wireless sensor networks, where strict constraints on computation, energy, and channel access make communications particularly expensive, has investigated those concepts by developing system-wide (i.e., nonconsumer specific) and time-invariant QoI- and VoI-based data reduction solutions leveraging multiple-criteria decision making techniques such as the Analytic Hierarchy Process[4] and Von Neumann-Morgenstern utility functions.[24] Those earlier works mostly focused on developing methodologies and tools to calculate a static VoI value for each IO exchanged, and to leverage those values for information filtering from a congestion control perspective.

Other proposals devised more sophisticated schemes to capture the dynamic nature of VoI values that change according to many factors, such as a consumer's needs and information availability (the same IO may have different VoI values for different consumers and that an IO may have a very high QoI, but it may have a very low VoI for a particular consumer, for whom it represents irrelevant information). Those proposals consider time-varying properties in VoI metrics to optimize the scheduling of message transmissions[25] or the traveling path of unmanned data harvesters[26] in underwater wireless sensor networks. To the best of the authors' knowledge, the investigation of time-varying and consumer-specific VoI metrics for dynamic information filtering and prioritization in tactical networks has only been recently addressed in Suri et al.'s work.[27]

The fog computing and mobile-edge computing research areas also focus on the deployment and exploitation of computational resources at the edge of the network in proximity to the data sources and to the service consumers.[28,29] While they represent very promising research areas, fog computing and mobile-edge computing appear to be focused on the architectural level and on the mechanisms to realize dynamic allocation of virtual resources. They do not place significant attention on defining and supporting new paradigms for Internet of Things application realization and are more interested in extending traditional cloud concepts so that they could be used to perform computation at the edge of the network.

7. Future Work

We postulated in Section 1 that by modelling and adapting to user context, mission context, environmental context, and communications context we can provide the Warfighter with equal or better SA at a much reduced transmission cost. In addition to continuing to further develop and refine the various components of our system and pursue the research challenges identified in Section 2, we have sufficient infrastructure to conduct human subject experiments to initially test this hypothesis. We are designing protocols for these experiments.

8. Conclusion

In this report we described a novel VoI-based system for realizing a mission-adaptive context-aware framework necessary for the testing and evaluation of our premise that by modelling, manipulating, and adapting contextual information we can increase the Warfighters' SA at a greatly reduced transmission cost. We have identified various ways of combining and comparing attributes of varying types of IOs and different contexts and identified research challenges. We have also discussed ways to model the Warfighter profile, which describes which IOs and how much information is received, based on the Soldier's mission and his/her cognitive and physiological states. Automated modifications to the Soldier profile for VoI or semi-automated modifications to the Soldier's mission can also be achieved by using the cognitive and physiological information obtained about the Soldier from the wearable devices. With the addition of this sensor information the Soldier's SA, physical well-being and mission accomplishments can be improved.

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List of Symbols, Abbreviations, and Acronyms

AHP	Analytic Hierarchy Process
GUI	graphical unit interface
HRV	heart rate variability
IO	information object
IR	infrared
MMF	Military Mission and Means Framework
SA	situation awareness
SME	subject matter expert
TCP	transmission control protocol
QoI	Quality of Information
VoI	Value of Information

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