Real-time Cognitive-Capacity-Sensitive Multimodal Information Exchange for the Cockpit Environment

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Abstract – **Deployment of multimodal interfaces in an environment of high cognitive-load, e.g., the cockpit environment of a police helicopter or motorcyclist in-pursuit, using audio communication with the need to frequently change radio channel or mode/focus of attention under time-constraints, whilst multi-tasking, can impose an extra load on the driver in addition to that due to the complexity of vehicle manoeuvring. This can raise concerns regarding driver safety. There is a need for a multi-sensor, multimodal information exchange interface that is minimally distracting by design, with consideration for the cognitive capacity of the driver at any given point in time. This paper presents the MoveON Jacket prototype with a Cognitive Capacity Respecting Multimodal Information Exchange framework that offers a minimal-distraction interface to motorcyclists enabling access to information online in real-time while supporting enhanced compliance with road safety constraints. This project has delivered the first validated implementation of an architecture for: a) minimal-distraction, b) cognitive capacity awareness, c) multimodal communication and control, d) graceful in-line man-in-the-loop cognitive control integration, e) performance improvement context caching to support an off-line learning capability for incrementally optimised man-machine mixed-initiative taking, f) performance enhancement and personalised ambient driver's pal adaptation.**

Keywords – multimodal command and control; cognitive-load; minimal distraction; cognitive control; mixed initiative taking; man-in-the-loop; machine learning

I. INTRODUCTION

While the level of sophistication of systems on-board vehicles has steadily progressed in recent years, provision of similar functions has not relatively matured for motorcycles and other two-wheeled vehicles. The main reason underlying this lack in provision can be related to safety concerns, as the manoeuvre context of a motorcycle is more complex than that of four-wheeled vehicle. Safety of an individual moving on the road on a two-wheeled vehicle is of paramount importance. This manoeuvre complexity is further increased in the context of on-board features usage, and communication with entities external to the immediate environment of the individual, e.g., a central command and control station as in the case of police motorcyclists. Therefore, any provision of added-value system features on-board two-wheel vehicles needs to consider potential compromises on safety. Thus, a major requirement of any such development is a minimally distracting unobtrusive interface that is sensitive to, and keeps track of the cognitive load of the user at any given point in time. A multimodal, multi-sensor, minimally distracting interaction system is required for motorcyclists as at any arbitrary point of time they may not able to interact readily and safely through a visual or tactile interface. For such a system to be sensibly deployed it must be capable of gracefully receiving training on the job (in-line) without this imposing too high a cognitive load on the trainer (the user, the driver/rider in the vehicular control environment). Such an ambient Communications Command and Control assistant (C^3 Pal) will have to take experientially -based best-estimate control actions on the driver's behalf and be ready to stand corrected by the driver if mistaken and learn from the experience to get it right next time. Such man-machine mixed initiative systems require situated context caching at man-machine control handover points so as to support offline learning for enhanced adaptation to the user's requirements during man-machine team-working real-time.

In the following sections, background domain knowledge is presented in Section II. Section III details the MoveON project, whereas Section IV focuses on the cognitive capacity sensitive multimodal information exchange framework. In Section V, evaluation of the prototype is discussed, and Section VI concludes this paper.

II. MINIMISING DISTRACTION

Cognitive load is defined as the total of ongoing mental activity, at any given point in time, in the working memory – a major contributor to which is the number of attention seeking factors [10]. Cognitive load theory [11][12] states that the quality of the design of instruction is accentuated if the limitations of working memory are given careful consideration. Long term memory stores knowledge and skills while working memory performs computational tasks associated with consciousness. Information is first processed by working memory, which is very limited in terms of capacity and duration, and then may be stored in long term memory. Cognitive load theory is employed in the development of learning structures or instructional strategies to circumvent any learning impedance imposed by the limitations of working memory in conventional strategies [10]. Of the three components of the cognitive load, intrinsic load represents the inherent difficulty of the content; extraneous load may be introduced by the designer of the instructional materials; germane load represents the effort involved in the processing of content and is often associated with motivation and interest. In the context of minimising distraction for motorcyclists, cognitive load theory can inform the design of the communication interface for audio-visual and tactile information that may be relayed to the rider in real-time on the road.

Research in the measurement of cognitive load presents several constructs; for instance, the relative condition efficiency [13]. Availability of usable cognitive load measures is crucial for providing support for minimal distraction interfaces. Relatively simple subjective measures are in most frequent use; however more sophisticated methods also exist for multimodal environments to gauge the relative complexity of cognitive tasks, such as empirical approaches to cognitive load measurement, which can be divided into *i)* direct object measures, e.g., eye tracking techniques, brain activity measures, dual-task methodology; *ii)* indirect objective measures, e.g., physiological correlations (cardiovascular, EEG etc.); *iii)* direct subjective measures, e.g., self-reporting of stress level; *iv)* indirect subjective measures, e.g., self-reporting of perceived mental effort [6].

Niculescu et al. [1] studied the impact of stress and cognitive load on the perceived quality of interaction in the context of a multimodal dialogue system for crisis management, using physiological sensors and subjective measures including an evaluation questionnaire regarding the quality of system interaction, an interview, and video recordings of trials to perform behaviour analysis. Niculescu et al. report that both stress and cognitive load impact the subjects' perception of the quality of interaction with the system.

A. MoveON Project

The MoveON project [3] has developed an innovative multimodal multi-sensor system to support a distraction minimising communication control architecture using multiple modalities (tactile visual and auditory) in full duplex mode. The MoveON system can provide motorcyclists access to services and information online in real-time while attempting to protect the driver from experiencing excessive levels of cognitive load and therefore, unsafe levels of distraction arising from the perceptual-cognitive task environment including the manoeuvring of the motorcycle plus handling multiple communication channels; some in full duplex. MoveON employs a multimodal interface with the capacity for presentation of visual information via a sleeve touch screen, text-to-vibration functionality and speech recognition.

Figure 1. MoveON Jacket Interface

Information gathered by multiple sensors is used to train the Cognitive Capacity Management component that continuously assesses the user's level of distraction so as to channel information in a maximally safe and timely manner. Usability of the demonstrated prototype has been evaluated by applying a socio-technical Usability Relationship Evaluation Methodology [8].

A specialised user group of UK police motorcyclists participated in a user-centred system co-design and evaluation to assess user's distraction while interacting with the prototype system, and, identifying driving conditions in which the motorcyclist's attention is disrupted, thus, causing unsafe levels of distraction and endangering safety.

1) The MoveON Jacket

The MoveON system is fully wearable with all its components on a body area network and not on the bike. The MoveON environment comprises of a jacket interface, helmet interface and the motorcycle. The jacket is a classic motorcycle, jacket augmented with assistive electronic components. These include a microprocessor (VIA Pico-ITX housed in a Travla AnkerPC casing) affixed to the left posterior side of the jacket. A GPS device resides on the inside of the jacket near the right arm side-deltoid. This device connects to GPS satellite to obtain the geo-position of the motorcyclist.

2) Sleeve Screen

The sleeve screen (LCD touch screen) is one of the major input and output modalities of the MoveON system. Situated on the left forearm, it provides an interface between the system and the motorcyclist to call the various commands of the system or to acknowledge receipt of information from a command and control station.

The sleeve screen GUI is designed with a touch-screen smart phone / PDA interface in mind, where the user is able to interact with the system without a keypad / keyboard, using gestures (with either a stylus or finger). The buttons on the GUI are designed so that the officer can use the interface whilst wearing motorcycle gloves. The menu, as shown in Figure 2, presents various options to the user at any given time. The list of options is scrollable with either a flick gesture, whereby the list scrolls automatically with a velocity calculated from the flick gesture, or a press-down hold-and-drag gesture whereby the scrolling is controlled by the user. At any point during a flick scroll, the user may touch the screen to stop scrolling at a particular point to highlight and select an option by just tapping on it once.

The GUI is a generic container with the functionality to add/remove various listed options. This functionality is used by the Olympus dialog management system [9] to present options to the user depending on what has been selected by the user. A menu-driven command mode takes the user through three steps for device selection (e.g., radio), command selection (e.g., change channel to …) followed by parameter selection (e.g., 9).

The touch driver circuit and the main LCD display have been integrated so as to make one single module. The VGA and power supply board are fitted at the back of the jacket but housed inside the lining of the jacket so as to preserve the normal way that the jacket is worn. The main battery powers the sleeve screen as well as the CPU. The power supply cable comes from the main battery through the left arm / sleeve (inside the lining). An additional screen (dot-matrix) functions purely as a debugging facility hidden inside the jacket, attached to a micro-controller that supports the functionality of the vibration motor array.

3) Vibration Motor Array

The vibration feedback motors are asymmetric load rotary motors that give a powerful vibration output. The choice of vibration sensors was improved after the first user evaluation process whereupon it was highlighted that the vibration from the motorcycle engine muffled the vibration output from Precision 10mm shaft-less sensors i.e., submerging their vibration and making it difficult to be sensed by the rider. Two motors were attached to the driver's shoulders and the third just above the right elbow on the sleeve of the jacket. These motors provide for the MoveON text-to-vibration (ttv) functionality, controlled by an Olympus agent that supports four simple commands for the motorcyclist in a policing scenario. These commands correspond to a simple tactile vocabulary requiring only minor user-training. For this, initially, seven motors were strapped to the right arm of the motorcyclist, but user evaluation highlighted two salient issues: *a)* tactile vocabulary was too large, requiring a wider pattern of vibrations to be comfortably and reliably recognised by the motorcyclist rider under various conditions, *b)* reliable sensing of the orchestrated vibration pattern for each word was made difficult by ambient conditions such as swamping of the messaging vibration by continuous high amplitude motorcycle vibration that was also transmitted to the rider's arms through the handle bar, and other ambient detractors such as noise, wind and rain..

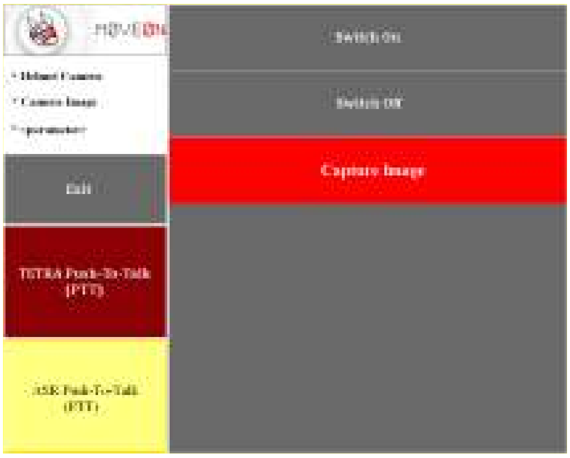

Figure 2. MoveON Sleeve Screen Interface

User evaluation informed optimisation of the physical design, vocabulary size limits, and vibration frequency for maximum user comfort.

The motors were powered by a 9V battery that was placed within the inside pocket of the jacket. A voltage regulator IC maintained the 5V required by each rotary motor. Owing to the level of power consumption of the motors, a decision to use a separate power supply for the batteries was taken. The main battery powered the CPU and other devices on the jacket. To further ensure circumvention of a single-point-of-failure, a back-up energy source was also installed in the jacket.

The jacket was connected to the helmet with a single cable that incorporated the required connection points for all devices such as a helmet camera (USB), helmet LEDs array (USB), microphones and headphones. The energy source was in the jacket so the electronic devices in the helmet were powered by the wired connection between the jacket and the helmet.

III. COGNITIVE CAPACITY SENSITIVE MULTIMODAL INFORMATION EXCHANGE

It is proposed that the user's vulnerability to stress, in a given context of stress load, affects their perceived stress levels. These, in turn, affect the perceived cognitive load and thus, the available safely 'grab-able' cognitive headroom that could be deployed to *minimally* (i.e., safely) distract but *maximally* inform an individual (*just-in-time*) whilst engaged on the move. The motorcyclist's operational context is one of the most significant determinants of the relevant situation assessment as to the relative significance and timing of various messages that the rider may have to be updated on with mission-critical timing. Typically, the police motorcyclist's residual stress level, at any instant, during a shift is expected, mainly, to have six correlations: *i)* update value of rider's baseline stress; *ii)* stress index of events already experienced during the shift; *iii)* time elapsed since the start of the shift; *iv)* the stress levels induced by instantaneous ambient conditions experienced by the rider (e.g., current task, traffic conditions, weather, road surface, communications messaging intensity and noise); *v)* stress due to unknown risks that may be waiting for the police motorcyclist en-route to an incident to which he is called (unknown risk anticipation stress); *vi)* the rider's stress vulnerability profile in the context of *i–v* above; i.e., the individual's stress management capability, which is their learned or genetic endowed ability to cope with stress. Such a context-specific stress vulnerability profile of the individual is in turn influenced by the interplay of a spectrum of associated factors, e.g., idiosyncratic, and other deterministic influences relating to the Life-Course Perspective [4] and a whole host of psycho-physiological, experiential and operational factors (historical, static, dynamic and current) spanning over time from birth to the present point in the spectral context (i.e., now, which are the day, time, place, space and point-of-decision/execution in the individual's task flow). The safely distracting informative and timely messaging of the rider has to be optimised to allow for the uncertainty in assessment of the instantaneous residual stress level and thus, the instantaneously disposable level of cognitive capacity headroom that the rider can, safely, be expected to make available for the next messaging input/output as may be optimally allowed to occur as decided by the multimodal interaction controller. The available cognitive headroom is inversely proportional to the perceived cognitive load, which is directly influenced by the perceived (residual) stress level as instantaneously experienced by the individual; which, in turn, is influenced by the individual's stress vulnerability profile. Minimising distraction can be viewed as maximising safe distraction, in an approach whereby multimodality control is based on seeking safe distraction or opportunities for grabbing safely available disposable cognitive capacity i.e., grabbing the attention of the driver for passing messages that wait in the queue to be conveyed to the driver. Paradigmatically this depends on the level of available and disposable cognitive capacity (stress levels), and requires the following constraining factors to be resolved and satisfied as part of the cognitive load resolution and optimisation.

A. Operational Context

In the context of the MoveON application domain, i.e., in the given practice context, stress level is a temporary psycho-physiological variant that can be assessed by combining the effects of

- the attention required for driving the motorcycle
- road / traffic conditions, level of activity in surroundings, GPS information indicating the present location of the driver and thus, the traffic context, e.g., approaching or passing through a junction, joining a motorway or leaving it etc.
- pre-existing communication level of the user with the MoveON system (thus, indicating the cognitive load arising from the user communication channels that are currently active).
- elapsed time on current shift (and indirectly cognitive load attendant with the Shift Envelope described as the range of experiences, from extreme to mild incidents, typically encountered on a given shift, up-to-the-decision-moment, as a variable mix of stress drivers).
- time of the day (Morning, Afternoon, Evening, Night).
- experience level and age of the driver.
- motion dynamics of the motorcycle driver (indirectly related to the motorcycle), as an indicator of the user-motorcycle neuro-motor interaction load.

In MoveON, the operational context includes, notably, the pattern of traffic conditions experienced within the particular officer's shift envelope up-to-the-moment, and critically, the present traffic conditions, and, the responsive coping capacity of the rider, their attendant stress/cognitive-headroom cost and thus, their remaining currently disposable cognitive headroom. This is because context-sensitivity in stress assessment implies consideration of the stress inducers in the task flow context. Therefore, as context-specifically identified stress inducers are the most relevant determinants of the remaining cognitive headroom, for traffic police as in the MoveON application domain, the most important stress inducers arise from the operational environment parameters; chiefly the traffic conditions. However, the cumulative amount of residual stress incurred by the driver and thus, the respective depletion of the available cognitive headroom has a highly personal pattern; itself dependent on a number of correlations of stress whose cumulative influence on the individual would be modulated by the individual's personal coping capability, which is their *stress vulnerability profile*. The correlations of stress include relatively static as well as other relatively dynamic personal and operational profile patterns. These mainly involve the psycho-physiological correlations of stress such as life-course, coping-style, cognitive-style, work/life-style as well as the operationally significant influences such as the historical and current Shift Envelope (the range of variable operational stress inducers experienced as a mix of incidents that can typically occur within a shift as time elapses. For example, Saturday night to Sunday morning as a shift having its stressors considered cumulatively up to the present instantaneous context of task challenges having to be coped with instantaneously by the rider at their current position (both geographical and task flow-specifically).

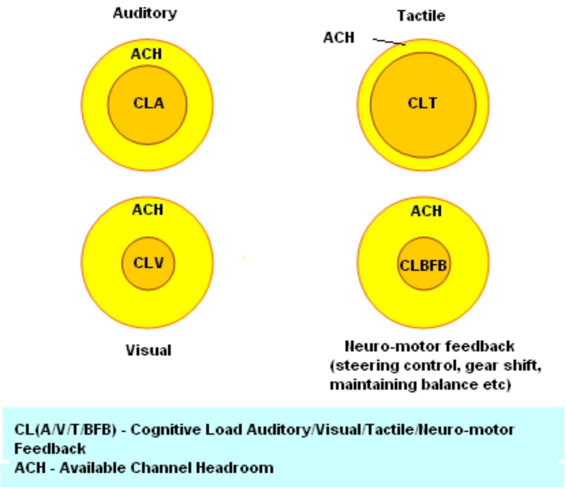

Figure 3. Attention and available cognitive headroom

B. Cognitive Load vs. Available Headroom

The visual, auditory, tactile and neuro-motor channels can be deployed, as illustrated in Figure 3. The deployed cognitive space is denoted by CL* where CL is Cognitive Load and * denotes the channel {Auditory, Visual, Tactile, Neuro-motor (bio)feedback} while the complementary area is denoted by ACH i.e., Available Channel Headroom. The available cognitive headroom perceived for a channel by an individual can be variably influenced not only by the actual cognitive load on that channel but also by cross-channel loading effects that exist in certain contexts of co-occurring neuro-motor and perceptual tasks to be discharged by the brain and such cross-channel loading effects have an irreducible person-invariant baseline plus a person-specific variation depending on a person's gender/genetic context and the task context. Essentially there are genetically variable influences as well as universally applicable influences and environmentally/ emotionally amplifying overlay influences that are associated with the extent of perceived sensory (cross)-channel loading in humans.

Within our minimal distraction C^3 paradigm, we model the above-named four sensory modality channels under the assumption of bounded cognitive headroom whereby the Available Cognitive Headroom (ACH) ranges from 0% to 100%. Incoming events from different input channels during the runtime of MoveON, affect the ACH differently for each modality in respect of a given context (e.g., the person-specific and all other relevant profiles etc as discussed previously).

As explained above, for calculating the variability of ACH per channel, we also have to take into account all possible cross-channel effects, i.e., increased levels of cognitive load when two incoming events require the simultaneous use of the same output channel or co-occurring channels and neuro-motor/bio-feedback activity as normally occurs in riding/driving; for example particularly when taking corners as a motor-cycle rider has to do in wet weather and/or poor visibility conditions when this requires more exacting orchestration of bio-feedback control mediated through coordinative structures output by the brain based on the sensory-perceptual-cognitive input.

C. Traffic Analytics

As for the rider's geographical position, the respective GPS sub-system provides information regarding the location of the officer at all times in terms of Latitude, Longitude, speed and direction with time-stamps. This information is used by the traffic analytics module in conjunction with the traffic congestion information relevant to the officer's current location as well as their stress-response profile. Such analytics are carried out to provide the requisite salient pattern discovery to help inform of the rider's currently disposable cognitive headroom level based on the de facto cumulative cognitive-load/stress-effects resulting from the interplay of a mix of idiosyncratic and deterministic influences. The analytics serve to precompile these into principal indicators of disposable cognitive headroom in so far as this is modulated by the traffic context as the main stress inducer. Thus, the rider's response to such stress inducers is influenced by the precompiled idiosyncratic personally-specific underlying factors that are thus taken into account by the analytics to inform the context-aware minimal distraction information interaction process.

This constitutes a knowledge basis that underpins the data intelligence pattern discovery for our multimodal communication dynamic optimisation architecture, including analytics, to enable the necessary predictive modelling process that can support the modality control decision engine in the context of the current situation assessment. This is to help the MoveON modality controller ultimately to derive, based on the situation assessment, the values of the currently ACH for each of the mutually cross-loading channels (auditory, visual, tactile) and hence, to decide on the channel to be the next selected in attempting to safely grab some of the user's attention within a target time window (e.g., now). This amounts effectively to deciding on the highest priority data to be transmitted, the transmission modality (the specific user's sensory channel to be the next selected conduit for conveying information), timing, place, surface and space in which to convey the data so as to safely grab some of the attention of the user. This would require the expectation values of the current perceived stress load to be estimated for the particular officer at a particular spatio-temporal point in the shift-envelope to help decide the optimal control of multimodal information input/output to best support the user in the execution of their task.

D. Predictive Learning

A Predictive Learning Model of the road traffic conditions was deployed to inform the modality control system with the congestion profile update regarding a road segment. This constituted one of the inputs to the controller to help deduce the associated stress levels to be estimated in respect of a particular rider/driver. Thus, the Predictive Traffic Learning Model exploits the static information coming from the officers' tacit knowledge as well as the historical and current dynamically evolving traffic information, e.g., from Rich Site Summary (RSS) feeds. Long-term patterns reflect the average traffic conditions within a certain area over a long time period and thus, the congestion expectation levels for a given spatio-temporal envelope. Short-term patterns contain the current traffic conditions, which are expected to point to a more accurate assessment of congestion expectation at a given time and place on the road. In cases, where short-term patterns have a traffic record for the requested position, this will take precedence over long-term patterns.

E. Biological Data

Instantaneously monitored psycho-physiological parametrics (voice pitch, heart rate, blood pressure, breathing rate, perspiration) compared to normal baselines are used as supplementary metrics, to enable the effective measurement of the overall instantaneous stress level as being proportional to the safely available disposable cognitive load or attention.

A stress vulnerability model component exists as part of the Cognitive Capacity Management in our architecture that handles measurement and evaluation of a user's biological context. After evaluation of general measurable biological data and consultation with medical personnel, a pool of biological data can be selected to adequately serve as supplementary optional knowledge to be captured to support the MoveON application domain. This includes heart rate, respiration rate, skin temperature, and blood pressure. An evaluation process has shown that each of the above parameters represents a well-established indicator for higher body activity and that all are as such directly related to psycho-physiological stress, the concomitant stress and cognition load and thus, the ACH. Heart rate, respiration rate, and blood pressure are for example likely to rise under a heavier physical load and psychological stress that manifests itself in the individual physical condition.

The evaluation process had to account for additional hardware requirements in terms of garments that can measure the identified biological data. Such garments must not disrupt or degrade a task force member's ability to perform his tasks, but must seamlessly integrate with his task performance style in strict accordance with the overall purpose of this system, which is to support officers on duty. While the vast number of suitable garments can measure heart and respiration rate, those garments able to measure skin temperature and blood pressure had to be rejected for reasons of impracticality in the context of an officer's daily routine. For this reason, skin temperature and blood pressure were discarded from the data acquisition agenda. Heart rate and respiration rate were used to estimate the measure of stress vulnerability. The fact that heart rate and respiration rate baseline patterns are highly person-specific was taken into consideration by using moving averages on available individual biological data to derive a reasonable rest-state heart rate (i.e., a personal cardiovascular baseline as an operational reference datum) and by using fuzzy parameters estimated stress factors in a given situation.

IV. EVALUATION

A prototypical user-group of UK police motorcyclists comprising a number of officers of a range of ages and ranks participated in our user-centred system co-design and evaluation process to assess the user's distraction whilst interacting with the prototype system, and identifying driving conditions in which the motorcyclist's attention is disrupted thus, potentially exposing the driver to safety risks. Additional feedback from an expert user group including Human-Computer Interaction (HCI) experts as lifelong avid motorcyclists themselves shaped the research, design and development of the minimal distraction real-time information exchange system. Biometric data on physiological factors and visual recordings collected by the officers, on-the-road in real scenarios, was used to help the quantitative and qualitative evaluation to inform our evolutionary interactive design and development of the system. Questionnaires and in-depth interviews were conducted with the user group regarding the usage of the system *i)* in a laboratory, *ii)* while on a parked motorcycle, and *iii)* whilst riding the motorcycle "in-pursuit mode" on the road. Although, ideally, further extensive tests would be needed to assess the scalability of the system fully; it is possible to confidently expect that this architecture is scalable within a range accommodating the aforementioned six variables in the context high level classification of ambient condition variations to the extent that the size of the controller optimisation search space remains below 300 nodes (decisional state space) consistent with real-time performance and controller in-line responsive mode. For offline learning mode, there will be no such limitation to scalability as long as the context caching parametric space is adjusted to include any additional variables of interest. However such scalability boundary condition as might be considered are in any case significantly mitigated by this architecture through *a)* a more conservative incremental approach to disposable cognitive load recruitment, *b)* risk-minimising instantaneous and graceful handover of control to the rider through rider simply signalling an "over-ride" command, *c)* hardware acceleration, *d)* context-caching all decision instances for offline training, thus, enhancing the learning case base of the system so as to continuously evolve a more efficient and reliable and safe multimodal C^3 assistance capability for all mobile task forces and their field commanders and the Central Taskforce Command.

V. CONCLUSION

This paper has set out the relevant state-of-the-art and thus motivated, as well as described, the architecture of the system arising from our user-centred design and development of a real-time multimodal communications controller interface system for (hostile) high cognitive-load environments as exemplified by our police motorcyclist test-case. The resulting system has been evaluated and shown to support the key objective of maximising real-time and time-critical mission information exchange between each taskforce member and other command and control units whilst minimising driver distraction that may become unsafe. The overall architecture of the MoveON Jacket prototype has been described. This has been shown, under real-road traffic conditions, to enable motorcyclists to carry out various technologically assisted functions. A detailed description of the minimal distraction design concepts has been presented with reference to cognitive-load and perceived stress levels considering physiological factors, manoeuvre-context of the vehicle, and the interaction between the user and the system on the road. This architecture as powerfully supported by the Cognitive Capacity Management paradigm represents a pioneering dynamic taskforce stress load management architecture that has delivered the first validated implementation of a mobile taskforce multimodal C^3 optimisation architecture Ambient Assistive Partner capable of graceful in-line man-in-the-loop cognitive control supported by man-machine mixed-initiative taking and messaging prioritisation focused on timing critical mission situation assessment updates in full duplex.

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