A Cognitive Architecture Framework for Critical Situation Awareness Systems

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Abstract. Goal-oriented human-machine situation-awareness systems focus on the challenges related to perception of the elements of an environment and their state, within a time-space window, the comprehension of their meaning and the estimation of their state in the future. Present computer-supported situation awareness systems provide real-time information fusion from different sources, basic data analysis and recognition, and presentation of the corresponding data using some augmented reality principles. However, a still open research challenge is to develop advanced supervisory systems, platforms and frameworks that support higher-level cognitive activities, integrate domain specific associated knowledge, learning capabilities and decision support. To address these challenges, a novel cognitive architecture framework is presented in this paper, which emphasizes the role of the Associated Reality as a new cognitive layer to improve the perception, understanding and prediction of the corresponding cognitive agent. As a proof of concept, a particular application for railways safety is shown, which uses data fusion and a semantic video infrastructure.

Keywords: Knowledge modelling · Cognitive architectures · Situation awareness · Human-machine interactive systems · Safety systems · Semantic video analysis

1 Introduction

Goal-oriented human-machine situation-awareness interactive systems are crucial in many decision-making activities and associated control processes in real-time environments, such as driving vehicles or trains, monitoring nuclear power plants, or supervising manufacturing systems, or in sectors such plant automation, intelligent transportation systems, civil construction, homeland security, cyber security or healthcare.

A common cognitive problem in these critical real time systems is the necessity of managing the corresponding environment and context information in a

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suitable way. The involved *Situation Awareness* (SA) systems focus on the challenges related to three basic cognitive layers (Endsley 1995 Model of SA) [1]: 1. Perception (observation) of the elements of a particular environment and their state, within a time-space volume (window), 2. Comprehension (understanding) of their meaning and 3. Projection (prediction-estimation) of their state in the future.

Robust computer-aided situation awareness systems, in semiautonomous or autonomous scenarios, are crucial for managing the involved critical real-time process, including surveillance, security, safety and emergency fields, command and control centres, human-machine interactive systems and alarm management frameworks.

In general, the evolving relationship between humans, technology and machines is a crucial factor pointed out by Gartner's Hype Cycle [2]. Particularly the corresponding situation-awareness cognitive systems need to tightly share knowledge and goals with the involved teams in order to be really useful for the corresponding services.

In the corresponding supervisory systems and involved cognitive architectures, the following information levels are usually considered [3,4]: 1. Reality-world 2. Perception 3. Situation comprehension 4. Future estimation 5. Decision 6. Action. Present computer-supported situation awareness systems provide real-time information fusion from different sources, basic data analysis and recognition, and presentation of the corresponding data using some augmented reality principles [5–9]. However, a still open research challenge in situation awareness and alarm management fields is to develop integrated goal-oriented supervisory systems, platforms and frameworks that support higher-level semantic cognitive activities, integrate context and historical knowledge, learning capabilities and robust decision support.

From a cognitive perspective, the main situation awareness challenges of safety, security and emergency monitoring systems lay in integrating timestamped data fusion techniques, data semantic analysis, alarms and events statistics, and expert rules knowledge. To also address context and content aware problems [10], to extract meaning and relevance, and to have a deep understanding of the systems of interest, a novel cognitive architecture framework is presented in this paper, which emphasizes the role of *associated reality as new cognitive layer* to really improve perception, understanding and prediction of the involved human-machine interactive systems.

Additionally, in this paper a particular system architecture and application developed for railway safety, which uses a semantic video framework and sensor data fusion, is also shown. The corresponding software has been implemented in C++ using OpenCV libraries, to analyse, visualize and verify the safety state, manage warnings and alarms, and generate historical and statistic records of trains. The considered approach focuses on the *interplay between humans and machines* in SA systems, and between the corresponding perception, understanding, and semantic and reasoning elements.

The paper is organized as follows. In Sect. 2, we discuss some cognitive architecture concepts applied to situation awareness systems, and introduce the associated reality cognitive layer for human-machine systems. In Sect. 3, we describe a general cognitive architecture framework for situation awareness which includes the associated reality layer. Section 4 describes a specific data fusion and semantic video architecture for situation awareness, specifically designed for railways safety applications. Section 5 summarizes a railway safety application we have developed using the previous framework. Finally, Sect. 6 discusses the conclusions and further research.

2 Associated Reality Cognitive Layer

In this paper we borrow some general concepts from systems architecture description, standard IEEE 42010 [11], to define and categorize some cognitive aspects of the situation awareness model considered. The purpose of this architectural approach is to improve the definition and abstraction levels of the corresponding cognitive elements.

A *cognitive architecture* refers to a theory about the structure of the human mind, and analogous computer cognitive layers and cognitive agents. The main purpose of a goal-oriented architecture is the understanding, and description, of the main elements of the system of interest from a particular point of view. A cognitive architecture should include data, information, knowledge and suitable techniques used to perceive, interpret, and analyse a system from the corresponding viewpoint.

A *cognitive layer* of a collaborative architecture contains information (more specifically: data, information and knowledge) and suitable processes to carry out the involved goals. When we try to develop machine cognitive layers for situation awareness, to emulate or improve human brain capabilities, usually we have to provide them with similar information and techniques to reach the corresponding goals. A cognitive layer usually incorporates different cognitive agents.

A *cognitive agent* can be considered as an active RT architect that constructs dynamic goal-oriented views of the system-of-interest and integrates these views within the general description using cognitive models and schemas, and general cognitive processes. This paper introduces the concept of Associated Reality (see Fig. 1) as an additional *cognitive layer* (architectural view) that enriches the real world with *related semantic information and data for enhancing the capabilities of a goal-oriented cognitive agent*, which can be considered as a generalization of the concept of Augmented Reality layer for HMI's [12].

A goal-oriented *Associated Reality* (AsR) cognitive layer (cognitive-copilot or expert layer), for human-machine interactive systems, *modelizes, combines and stores direct or indirect related real-time information from multiples sources, from a particular viewpoint.* This cognitive layer can include: system characteristics, state, mode and context, semantic information and historical data, models,

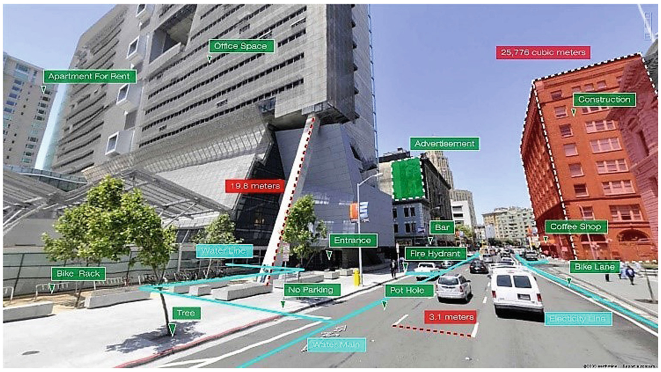

Fig. 1. Example of an Associated Reality (AsR) layer that provides a semantic goal-oriented associative layer between the world and a goal-oriented cognitive agent (Source: https://goo.gl/images/zSMTuY)

and simulation and estimation methods. Analogous knowledge associative structures are also prevalent in natural cognitive systems: especially in brain cortex of the humans and other mammals.

For developing goal-oriented AsR cognitive layers, it is also necessary to have flexible and hierarchical visualization tools to improve the corresponding processes.

The conception of the AsR cognitive layer proposed in this paper, for situation awareness system was partially inspired by Hawkin's model [13]: "*memory-prediction framework of intelligence*", which points out the strong relation among intelligence, continuous predictions and associated stored semantic knowledge. Analogous prediction ideas: "prediction is the ultimate function of the brain", were also emphasized by the neurophysiologist Llinas [14].

The AsR cognitive layer can significantly *improve the observability, controllability and situation awareness* of the system of interest. It implies a human-machine sharing of the considered goals and objectives, and a continuous vigilance and alertness for extracting relevant information and drawing inferences and conclusions. The involved cognitive agents should perceive, analyse and associate the available information about the system and its environment to improve their knowledge and make better decisions in the future.

Following Endslay's approach [1,3,4] and explicitly adding the association phase, an AsR cognitive layer for situation awareness can be decomposed into the following four basic layers (sublayers), with different feedback loops in the corresponding processes: *1. Perception of the elements and state space of a particular environment. 2. Comprehension-fusion of their meaning. 3. Association of the involved information. 4. Prediction-estimation of their state in the future.*

Using the JDL Data-Information Fusion's model [15] for situation awareness systems, cognitive layers can also be categorized into the following five levels: 0. Signal 1. Object. 2. Situation. 3. Impact. 4. Process improvement.

A goal-oriented AsR cognitive layer of an object (JDL Level 1) can includes the following timestamped attributes:

$$Table = (Time, Object - type, Object - name, (Object - attributes), (Object - related - information))$$

Example. For a particular train safety application, the corresponding historical AsR cognitive layer, and the involved timestamped database, can include the following object-attributes = (thermometer, GPS, odometer, tachometer, gyroscope, Doppler radar...) and object-related-information = (GSM-R data, GPRS-R data, command & control information, railway incidents information, and present 4G LTE external cloud information or future extended 5G connections and associated cloud services).

3 A Cognitive Architecture for Situation Awareness

Figure 2 depicts an associated reality architecture for situation awareness. Its main elements of are:

$$AsR = (\textbf{\textit{Specification, Control, Management, AsR cognitive layer, Decision, Actions}})$$

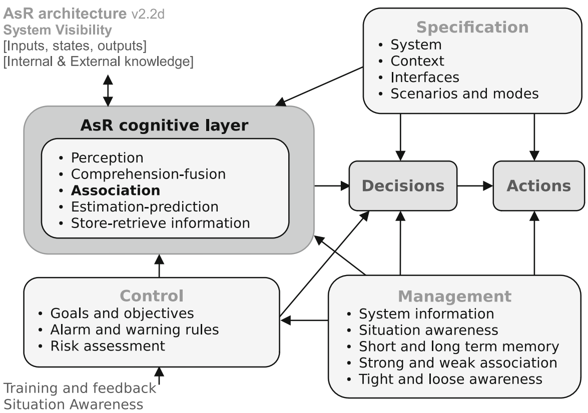

Fig. 2. AsR architecture. Situation awareness architecture with an associated reality layer.

Following the system architecture guideline IEEE 42010 [11], we include in the diagram the main elements and relations of the corresponding cognitive system. The main innovation aspect of this cognitive architecture framework is the AsR cognitive layer, which contains an active cognitive agents for situation awareness with associative knowledge. This structure basically emulates some associative properties of human brain for situation awareness activities.

The AsR cognitive layer provides the basis to perceive (capture), comprehend (analyze) and associate (relate) the corresponding semantic information, make estimations (predictions), and also store and retrieve the corresponding historical database.

4 A Situation Awareness Architecture for Railways Safety

This section presents a particular AsR cognitive architecture for critical situation awareness, specifically designed for train safety applications, which uses semantic-video and data-fusion processes (AsR.SVDF). Figure 3 depicts its main architecture components. This cognitive redundant architecture uses the associated reality layer, and it is based on a continuous vigilant semantic video, sensors, GPS, RFID balises and cloud agents. The main components of this architecture are:

$$AsR - SVDF = (I1,\ I2,\ I3,\ I4,\ FT\ SV,\ DF,\ HMI,\ HDB,\ AsR.SVDF\_Plan\ \&\ Scheduler)$$

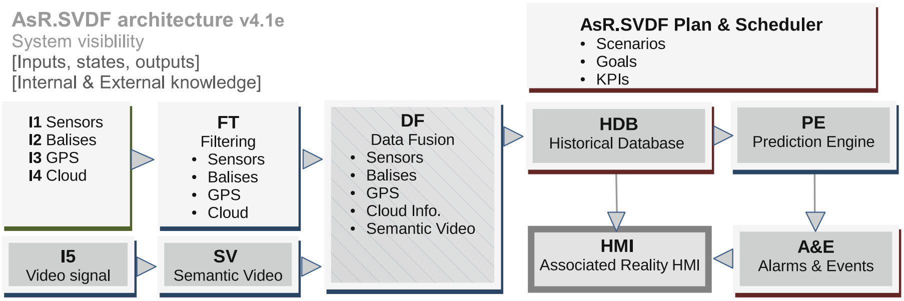

Fig. 3. AsR.SVDF model. SA system architecture for railway safety.

Main System Components

I1. System and environmental sensors: odometer, tachometer, accelerometer, gyroscope, thermometer, etc.

I2. Balises, transponders or RFID beacons placed between the rails of the railway.

I3. GPS module and antenna.

I4. External RT cloud connection with low latency. It provides additional information for the situation awareness process: context, environment and system information.

I5. Video signal input. It provides the visual perception of the environment.

FT. Filtering of sensors signals, GPS, balise and cloud information.

SV. Semantic Video. It analyzes the input video information, and detects objects and situations of interest (markerless detection).

DF. Data Fusion. It combines all available information, and stores the fusion results and complementary information in XML format.

HDB. Timestamped Historical Fusion Database of system and environment variables.

HMI. Associated reality HMI. It shows annotated and symbolic information of alarms & events, and relevant related information for the development and operations.

PE. Prediction-estimation Engine. Estimation model uses the present data and previous system state to estimate the state in the near future state. The train position estimation is basically based on a dead reckoning procedure (using previously determined position and integrating the speed over the elapsed time). GPS, balises and video information optimize the position references.

A&E. Alarms and Events Management. A&E's are triggered using A&E Rule Database, according to the detected scenario and context. A&E conditions and Rule Database can be modified by the corresponding Command & Control cloud service. The timestamp A&E's triggered are stored in the historical A&E Database.

AsR.SVDF Plan and Scheduler. It manages the complete process according to scenarios, goals, objectives, and key performance indicators (KPI's) considered.

Main Design and Operational Principles

- *Design principle:* In AsR-SVDF architecture, the associated reality layer contains HDB, A&E, PE and HMI modules.
- *Design principle:* Reliability of an AsR-SVDF situation awareness system depends on the semantic video analysis and robustness of the data fusion (redundancy).
- *Design principle:* The Quality Management and KPI's of an AsR-SVDF system depend on the monitoring of historical fusion database and historical A&E database.
- *Design principle:* The semantic video drastically reduces the necessary storage resources and the ulterior analysis computation (economy).
- *Operational principle:* Situation awareness can be improved by controlling and monitoring the trip-plan data and the statistic parameters of previous trips derived from the corresponding historical database (copilot knowledge).
- *Operational principle:* System reliability, availability and robustness depend on the maintenance plan and continuous improvement process (CIP) defined.

Example of a Record of the Historical Database

A simplified timestamped sample of the historical database is:

$$\begin{aligned} Sample = (Date : 26.05.2016; Time : 13 : 25; TrafficSign : Max90; \\ Speed : 80.4\, Km/h; TripDistance : 146.3\, Km) \end{aligned}$$

This register stores the traffic sign detected, present train speed and present trip distance derived from the redundant data fusion-association available data and prediction. The present trip distance or position of the train can be dynamically estimated from different redundant sources: GPS, radar, odometer, tachometer integration, RFID balises (marker-based references) and video specified railway objects (markerless references) that sequentially correspond to particular travelling distances of the railway. Traffic signs and others significant elements are sequentially detected with a video camera on the machine train through an intelligent video analysis (IVA). The corresponding data fusion and data association allow estimating the train position based on sensors and sources available, train state and railway conditions.

Example of a Situation Awareness Alarm Rule

A simplified register example of an Alarm & Event Rule Database for a train is:

$$Register = (Train : 00151; Rule : 8.1; Weather : normal; Begin : 143\,Km; End : 147\,Km;$$
$$Type : Alarm; Variable : Speed; Min : 0\,Km/h, Max : 90\,Km/h; AlertMessage : Reducespeed)$$

The corresponding A&E Rule Database specifies the speed constraints based on weather conditions and distance intervals. In operation, the triggered timestamp A&E's are stored in the historical A&E Database. Notice that in the associative situation awareness architecture considered, the train speed and position can be estimated in many different direct or indirect ways, which is essential for the reliability of the alarm system. This redundant structure provides much more robustness to diverse scenarios, even with a partially damaged or sensor degraded system. This way, the machine cognitive behaviour emulates the remarkable robust cognitive behaviour of many survival animals of our natural ecosystems. Next section, presents a practical demonstration of a railways situation awareness system which uses the considered AsR framework.

5 A Situation Awareness Application for Railways Safety

Severe accidents in railway systems are often based on the loss of situational awareness of engine drivers and rail traffic operators, due to different factors: distraction, fatigue, violation of procedures, etc. [16]. For example: Santiago de Compostela's derailment occurred on 24.07.2013 at 20:44 CET in Alvia Talgo high-speed train with an ASFA-ERTMS hybrid management system [17]. This accident was initially originated by a loss of situation awareness of the engine driver, with the consequences of 80 deaths and 152 injuries (Fig. 4). Further investigation of train's data recorder, revealed that the train was travelling at 179 Km/h instead the posted speed limit of 80 Km/h.

The involved tracks of the accident were equipped with Eurobalises ERTMS-ETCS Level 1 [17], which provide relevant information regarding the track ahead of the train, e.g. track conditions, maximum speed, and maximum distance allowed to travel with the corresponding balise. If the driver exceed this maximum speed, the train shall be slowed down automatically, but the corresponding Alvia trains had compatibility problems with ERTMS, and were not conveniently configured for using the Eurobalises.

To prevent this kind of railway accidents, we have developed an AsR-SVDF situation awareness demonstration platform (Fig. 5). The RT platform will be able to analyse and detect the railway traffic signs and associated data, generate an annotated reality video with the suitable information, store the time-stamped semantic video in the corresponding historical database, and compute the rule-based alarms and events module.

Fig. 4. Derailment in Alvia high-speed train (source: spanishnewstoday.com).

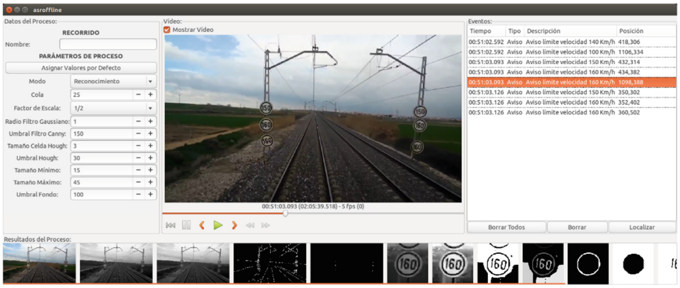

Fig. 5. Particular view of the application graphical user interface of AsR.SVDF system.

6 Conclusions

This paper has presented a general cognitive architecture framework to empower the development of novel situation awareness systems based on the *associated reality layer*. This approach emphasizes the role of this active cognitive layer *as a copilot or personal assistant for machine cognitive agents*, which contains and models related information of the system and its environment for enhancing the corresponding process. To improve real railway safety systems, a particular situation awareness architecture was defined, with redundant data fusion and a semantic video schema, to manage the corresponding A&E system. This alarm framework supports simple and flexible declarative rule style for building situation awareness systems and services. A particular demonstration prototype, to improve the railway safety, was also presented to practically show some capabilities of the approach. In the future we plan to extend the AsR cognitive layer defined and develop more applications with different scenarios and contexts.

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References

1. Endsley, M.R.: Towards a theory of situation awareness in dynamic systems. Hum. Factors **37**(1), 32–64 (1995)
2. Gartner, Inc.: Hype Cycle for Emerging Technologies (2013)
3. Endsley, M.R.: Bringing cognitive engineering to the information fusion problem: creating systems that understand situations. In: Plenary Presentation to IEEE 14th International Conference Information Fusion (2011)
4. Endsley, M.R., Jones, D.G.: Designing for Situation Awareness: An Approach to Human-Cantered Design. Taylor & Francis, Oxford (2012)
5. Nowak, C., Lambert, D.: The semantic challenge for situation assessments. In: IEEE 8th International Conference on Information Fusion, Los Alamitos, July 2005
6. Baader, F., Bauer, A., Baumgartner, P., Cregan, A., Gabaldon, A., Ji, K., Lee, K., Rajaratnam, D., Schwitter, R.: A novel architecture for situation awareness systems. In: Giese, M., Waaler, A. (eds.) TABLEAUX 2009. LNCS, vol. 5607, pp. 77–92. Springer, Heidelberg (2009). doi:10.1007/978-3-642-02716-1_7
7. Kokar, M.M., Matheus, C.J., Baclawski, K.: Ontology-based situation awareness. Inf. Fusion **10**(1), 83–98 (2009)
8. Kokar, M.M., Endsley, M.R.: Situation awareness and cognitive modelling. In: IEEE Intelligent Systems, Cyber-Physical-Social Systems, pp. 2–7, May-June 2012
9. Ulicny, B., et al.: Augmenting the analyst via situation-dependent reasoning with trust-annotated facts. In: Proceedings of 2011 IEEE International Multi-Disciplinary Conference Cognitive Methods in Situation Awareness and Decision Support, pp. 17–24. IEEE (2011)
10. Laing, C., Vickers, P.: Context informed intelligent information infrastructures for better situational awareness. In: International Conference on Cyber Situational Awareness, Data Analytics and Assessment (CyberSA), 8–9 June 2015
11. ISO/IEC/IEEE 42010: Systems and software engineering. Architecture description (2011)
12. Lukosch, S., et al.: Providing information on the spot: using augmented reality for situational awareness in the security domain. Comput. Support. Coop. Work **24**(6), 613–664 (2015)
13. Hawkins, J.: On Intelligence. St. Martin's Griffin, New York (2004)
14. Llinas, R.: I of the Vortex: From Neurons to Self. The MIT Press, Cambridge (2001)
15. Steinberg, A.N., et al.: Revisions to the JDL data fusion model. In: Proceedings of the SPIE. Sensor Fusion: Architectures, Algorithms and Applications, pp. 430–441 (1999)
16. Fischer, K.: Railway Situation Awareness Project, Swiss Federal Railways, Institute Humans in Complex Systems (2011). http://www.fhnw.ch/aps/miks
17. European Railway Agency: ERTMS. Supporting Documents (2016). http://www.era.europa.eu/Core-Activities/ERTMS/Pages/List-of-supporting-documents.aspx