The Orchestra: A conceptual model for function allocation and scenario-based engineering in multi-agent safety-critical systems

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ABSTRACT

Function allocation in safety-critical systems is not a new research topic. However, there is a need for unifying what is separately done in engineering, human factors and organization science. In aviation for example, functions have been allocated on the flight deck and on the ground control stations, but very little has been done in between flight decks and ground stations. As we go forward, a multitude of machine agents grows and intertwined information flows become more important to understand information management by both individuals and organizations. This paper proposes a new approach to function allocation among human and machine agents based on the orchestra metaphor, where agents are considered as musicians. This kind of model requires a common frame of reference (the music theory), contracts (scores) must be appropriately initially and formally coordinated (the role of the composer), real-time coordination (the role of the conductor), and specific abilities to perform according to contracts (role and proficiency of the musicians). Contracts are seen as scenarios or storyboards, with an additional responsibility dimension. More generally, authority has become the central driving force of the model, where authority encapsulates both control and accountability. The understanding, which we commonly have of an orchestra, is extended by including authority trading that is based on negotiation among agents, as musicians. Examples are taken from the air traffic management domain currently under investigation worldwide. The Orchestra model is compared to previous related theoretical models of socio-technical systems.

Keywords


ACM Classification Keywords


1. INTRODUCTION

Technology is now almost always equipped with layers of software that enable machines to interact like humans do, at least in very limited contexts. We commonly talk about human and machine agents (HMA). Human-computer interaction was traditionally thought as a person facing a computer as a one-to-one relation. Today, there are HMA societies in the sense of Minsky (1985), i.e., an agent being a society of agents. Human modeling, often commonly thought as information processing (Newell & Simon, 1972; Wickens, 1992), progressively migrated towards multi-agent organization modeling (Hutchins, 1995; Boy, 1998). The cognitive function concept emerged as a useful representation to support such modeling of both individuals (i.e., an individual as a organized structure of cognitive functions) and organizations (i.e., a set of cognitive functions distributed among a set of agents). The multi-agent approach is a fundamental approach to modeling contemporary human-machine systems. This paper proposes a new multi-function conceptual model that encapsulates basic organizational and cognitive processes that support the identification of emergent cognitive functions in HMA societies. It is based on previous work on cognitive function analysis (Boy, 1998) and function allocation work (Grote et al., 2000). This model was motivated by the introduction of new concepts of operations in air traffic management (ATM), such as task delegation from ground controllers to flight crews. This kind of transfer of authority will inevitably induce the emergence of new cognitive functions among the various ATM agents whether they are humans or automation. More specifically, the current hierarchical model of air traffic control (ATC), where authority is centralized on the ground, is evolving toward a distributed model of authorities that need to be coordinated among agents that are also evolving. This paper proposes the Orchestra model that suits well this kind of evolution where agents require a common frame of reference (a music theory analog), contracts (such as scores), and coordination (i.e., the role of the conductor). In addition, dynamic negotiation needs to be taken into account. Consequently, the paper proposes a methodology for the rationalization of cognitive functions during the life cycle of a multi-agent safety critical system.

2. FUNCTION ALLOCATION

Paul M. Fitts edited a famous report on human engineering for an effective air-navigation and traffic-control system in 1951, where he and his colleagues drafted possible roles of the human operator in future air-traffic control and navigation systems. They developed principles and criteria to design and assess the division of responsibility between human operators and machines, as well as among human operators themselves. They anticipated issues in decision-making, the nature of information, the form that information may take (i.e., encoding), the rate of flow of information, its storage, perturbation, redundancy, and related research problems. They mostly focused on visual and voice communication problems. Among other things, this report provided what is now known as the Fitt’s list of where humans appear to surpass machines and conversely. This preliminary work led to several lists of strengths and weaknesses of human
operators and automated machines (Chapanis, 1965; Swain & Guttmann, 1980; Sheridan, 1987). They were called MABA MABA, i.e., “Men Are Better At – Machines Are Better At”. This was an easy but very limited way to provide guidelines for automation design (Parasuraman, Sheridan & Wickens, 2000). Later on, Hollnagel and Woods (2005) based their approach on the fact that joint cognitive systems (humans and machines) are dynamic and therefore complex, and need to cope with this kind of complexity at both individual and organizational levels. This approach is descriptive and requires operational developments.

Function allocation cannot be only addressed from a static point of view; it can also be highly dynamic. It can be dynamic because underlying processes are dynamic; it would be better to talk about real-time function adaptation, even if this is often referred to as dynamic function allocation (Corso & Maloney, 1996; Hildebrand & Harrison, 2003). It can also be dynamic because cognition is distributed (Hutchins, 1995; Wright, Fields & Harrison, 2000).

It is interesting to notice that the next generation of ATM systems will have to be designed taking into account principles and criteria for both static and dynamic function allocation. What drastically changes today is the magnitude of the air capacity, i.e., the number of aircraft is tremendously more important than in 1951. Consequently, the conceptual model shifts from a single agent approach to a multi-agent approach. It is no longer possible to analyze each agent in the system individually because the interrelations are far more important than before. Technology is information intensive and organizational setups need to be revisited. Furthermore, agents are no longer only human operators, but also automation in the form of various kinds of software agents dedicated to specific tasks. For that matter, function allocation cannot be thought as an a priori process, but as an evolutionary process. The separability of human-automation sub-systems has become a real issue. The overall ATM system is becoming like a multi-agent biological entity where complexity is as much in the links between agents as in agents themselves. This is why function allocation among a set of interconnected agents is a difficult problem.

In complex dynamic human-machine systems, it is crucial to know which agent does what and when. In addition, each agent should have the capacity to execute the task he/she/it has to perform, i.e., an appropriate cognitive function should be allocated to this agent. Each function allocation has a cost that should be carefully understood and eventually measured. Finally, each function allocation induces a level of confidence and trust in the agent (Campbell et al., 1997). When the agent is a human, this is characterized in terms of level of training and experience. When the agent is an automated system, trust can be characterized by several metrics such as reliability, flexibility and cognitive stability, i.e., the ability to recover from human errors or system failure (Boy, 2007).

The cognitive function paradigm was chosen to support the multi-agent approach of the next generation of ATM systems in the French national PAUSA project (Boy et al., 2008). A cognitive function is defined by three kinds of attributes that are its role in the organization where it is involved, its context of use, and its resources that are required to implement it. A cognitive function could be defined recursively by a network of cognitive functions that may be distributed among various agents in the organization, and across various meaningful contexts of use, whether nominal or off-nominal. Anytime a new cognitive function is defined or moved from an agent to another, it is crucial to look for new cognitive functions that emerge from the various interactions in the related agent network. Technology-centered automation is often defined as the transfer of a cognitive function from a human agent to a machine agent. When this process is extended to the search for emergent cognitive functions, it can be called human-centered automation (HCA). For that matter, HCA is an incremental process where design, test, practice and discovery of the emergent cognitive functions are intertwined. This approach to automation is strongly based on operational expertise, development of scenarios, human-in-the-loop simulations (HITLS) and formative evaluations.

3. SCENARIO-BASED ENGINEERING

Scenario-based design (SBD) is not new. SBD changes the focus of design work from defining system operations, i.e., functional specifications, to describing how people will use a system to accomplish work tasks and other activities (Carroll, 1995, 2009). SBD elaborates a traditional principle in human factors and ergonomics, i.e., human attributes and requirements should be taken into account in design and development. SBD consists in describing usage situations as design objects. It starts with the involvement of appropriate domain experts. In our case, pilots and ATC personnel are the domain experts. During the early phases of design, envisioned scenarios are developed from expert knowledge and knowhow. Such scenarios are usually built as extensions of current observed scenarios in the real world. They may be designed as analogs of similar configurations and chronologies observed in other domains. Scenarios are constantly readapted to support human-centered design appropriately.

In the context of function allocation for multi-agent safety-critical systems, such as the construction of commercial airplanes, the need for scenarios takes another dimension. Even if it is clear that scenarios are needed from the early beginning of the design process, they are also needed along the whole life cycle of the product. They are not only storyboard guides in human-centered design and development; they also provide an excellent framework for the rationalization of evaluation-test results, which in turn are used for re-engineering the product and improve its safety, usefulness and usability. For that matter, we move from SBD to scenario-based engineering as a support to function allocation during the whole life cycle of a socio-technical system.

A distinction is made between declarative and procedural scenarios (Boy et al., 2008; Straussberger et al., 2008). First, we deliberately choose the multi-agent model to support the development of scenarios. Scenarios are thought of in the same way as movie scenarios. Declarative scenarios describe the necessary objects and agents involved in the final product. These objects and agents are presented in the form of structure and function. Such descriptions necessarily lead to the way objects and agents interact among each other, and consequently to application use cases. Procedural scenarios describe chronologies of events and interactions among objects and agents. Such descriptions are stories and episodes that lead to appropriate definitions of such objects and agents. Declarative and procedural scenarios may be initially developed by different groups of people in isolation. These two types of scenarios are developed concurrently to improve completeness of both objects/agents and their possible interactions. They are incrementally merged into synthesized generic scenarios.

Technical systems should never be looked at in isolation, but always as part of a bigger socio-technical system, which includes humans operating the system as well as formal and informal structures and processes within which they work. This is why scenarios are so important because they support the
rationalization of the meaningful interactions in the socio-technical system. There are situations that are very difficult and even impossible to predict before they actually happen. These situations are usually called surprises. For example, the 2002 mid-air collision accident at Überlingen, Switzerland, which has been extensively analyzed (Weyer, 2006), has shown the effect of the introduction of the Traffic alert and Collision Avoidance Systems (TCAS) as a deconstruction of order or even a regime change, which may be a gradual shift from central control to decentralized self-organization. Some accidents such as the Überlingen one highlight such evolution, and sometimes revolution, in the overall socio-technical system where coordination has become one of the major issues. This is why we deliberately choose a multi-agent approach, instead of a single-agent approach (e.g., the pilot facing a screen), to express function allocation. To do this, we need to develop a common frame of reference, task delegation, and information flows among agents. The evolution of ATM is seen as a shift from army to orchestra from recent experience-based investigations (Boy & Grote, 2009; Boy, 2009). This metaphor and its possible extensions support very well the ongoing evolution of the airspace multi-agent system. In this way, we expect that we will be moving from the design-and-surprise approach to a principled approach of design based on scenario-based engineering toward the development of more robust and resilient socio-technical systems. We argue that such a principled approach to design could have avoided the Uberlingen accident, by recognizing that a connection between TCAS and ground-based STCA (Short-Term Conflict Alert) systems could have facilitated the controller’s situation awareness.

During the last decades, human factors researchers tended to blame the fact that engineering waited surprises to correct ergonomics of products, i.e., structures and functions of products. There will always be surprises unfortunately. The main issue is to try to anticipate them as much as possible. It is difficult to imagine other ways than constantly developing deeper knowledge and knowhow from positive and negative experience using the product. Our technological society is developing very fast, tremendously faster than before. We do not take enough time to analyze our mistakes and generate syntheses, in the form of “golden rules” for example. Scenarios are good tools to pose questions such as Who, What, When, Where, Why, How and How much (5W2H): Who and What are the agents and objects and relationships among them along relevant dimensions such as time (chronology), functional and structural dependencies, topological organizations and so on; Why do they exist in terms of role, context and resources (i.e., cognitive functions); When and Where they are useful, active or potentially related to one another; How do they work or how can people work with them or use them; How much load is involved in user’s activity, in terms of workload, appropriate cost of any kind and so on. This is why maturity has become a field of research that is far from being mastered and “mature”.

Scenario-based engineering should then look for maturity. The issue of maturity has been analyzed before (Boy, 2005). We know that we must focus on product maturity and practice maturity, i.e., what the product is for and how it is really used. Product maturity is strongly based on the quality of high-level requirements and on their constant adjustments to the real world during the whole life cycle of the product. Of course, if high-level requirements are not right or strong enough in the first place, chances are that designers and engineers will have to re-engineer the product many times in the future, and sometimes get rid of the product unfortunately. This is why starting right is the best advice that we could give to a design team. But what does it mean to start right? It means starting with the appropriate scenarios. In addition, it means that the product should be thought as a global entity and not a juxtaposition of pieces that will eventually be assembled later. This is another reason why human-in-the-loop simulations are crucial as early as possible during the design/development process. Finally, teamwork must be cohesive from the beginning of design to operations and obsolescence of the product. Following up on this analysis, there is a need for a conceptual model that could support function allocation, scenario-based engineering and maturity reaching; this model is presented in the next section.

4. THE ORCHESTRA MODEL

The Orchestra model requires the definition of the authority concept. It was designed over the years (Boy, 1991) and finally refined during a study carried out from 2006 to 2008 on authority sharing in the aeronautical system, the already mentioned PAUSA project. Authority is defined from two main perspectives, i.e., control in the engineering sense (i.e., who is in charge and competent for a given task and function), and accountability in the legal sense (i.e., we are always accountable to someone else, and accountability includes responsibility).

Results were based on the definition of a scenario-based approach that supports the design of such HMA systems. We used the distinction between declarative and procedural scenarios. The main problem was to obtain meaningful and generic scenarios that would be the source of emergent cognitive functions during further HITLs, which range from very simple paper and pencil narrative simulations to the use of interconnected very sophisticated realistic simulators. Both involve domain experts.

In the beginning of a project of this kind, strong expertise and experience from operational practitioners is required to develop useful scenarios. In ATM, these practitioners are both pilots and ATC controllers (ATCOs), and also aerospace designers and certifiers. It is of course also important to motivate and carefully filter their inputs through creative designs in a reflexive way. However, testing will always remain the mandatory (long) step on which design and development processes will have to comply.

No simulation can be purposefully and efficiently carried out without a conceptual model. In this scenario-based engineering approach to function allocation, the Orchestra model is an alternative to the traditional army-type model that supports a hierarchical decomposition of functions. Four categories of entities must be defined.

- First, the music theory that supports the various information-flows and provides a common frame of reference for all agents in the environment.
- Second, the scores that agents are required to use in order to support their assigned functions during operations. Composers typically develop scores and articulate them among each other. These composers still remain to be identified correctly in the ATM case.
- Third, conductors who provide the operational timing patterns, and consequently will be responsible for the effective information flows, i.e., the overall symphony performance to take the orchestra metaphor.
- Fourth, musicians themselves who are required not only to perform what their scores say, but also to articulate their own plays with the others'.
In an HMA organization such as an orchestra, agents are interrelated with respect to three kinds of interaction models (Boy, 2002). These models are distinguished with respect to the level of knowledge each agent has of the others in the organization.

1. When agents do not know each other, the best way to interact safely, efficiently and comfortably is to be supervised. Supervision is the first interaction model. None of the supervised agents has the authority to decide what to do; a supervisor does it for them.

2. Mediation is the second interaction model. Agents have a common frame of reference (CFR) through which they are able to interact. They still do not know each other deeply, but they know that they can interact between each other through the CFR. In addition to the CFR, there are mediating agents who facilitate interactions. In WYSIWYG user interfaces in addition to desktop metaphors, there are mouse-sensitive help lines that pops-up on demand for example. In this model, the authority is distributed among the agents.

3. The third interaction model is cooperation by mutual understanding. This is what people usually do when they interact with each other. This model assumes that agents are able to construct a mental model of the others in order to perform better in future interactions. Very simple instances of such a model have been developed and used so far on computers. For example, some pieces of software are able to learn user’s habits and are able to incrementally provide smart options or suggestions. This is the case of Microsoft Word that is able to learn user’s specific lexicon from frequent uses of words. Web browsers remember frequent URL, etc. In this model, authority is traded between the agents. In human-human interaction via machine agents, related technology should provide appropriate situation awareness means to enable sustainable and symbiotic communication.

![Figure 1. Interaction models from no-autonomy to full-autonomy of agents.](image)

To summarize, there is a continuum from the supervision model of interaction where authority follows a top-down army-type model, to the mediation model of interaction where authority follows a transversal orchestra-type model, to the cooperation by mutual understanding model of interaction where authority follows a more-chaotic trade model (Figure 1). These interaction models are very useful to support the way cognitive functions are implemented in complex software not only from a human-computer interaction point of view, but also from an internal subsystem-to-subsystem point of view. In particular, they also provide an articulated way to validate large object-oriented software.

5. AN AERONAUTICAL APPLICATION

Authority sharing is one of the major themes of the next generation of air traffic management (ATM) system, flight deck automation in particular. The fact that we will have more aircraft in the sky (i.e., air traffic capacity increase), and we want to enhance safety, requires deepest research on the way various functions are being reallocated among the various agents. We need to better identify pilots’ information requirements and communication needs to perform tasks currently managed by air traffic control (ATC), which will greatly increase the needs for pilot’s awareness of the surrounding airspace, (human and system) failure identification and recovery, and unexpected-event handling in this dynamic and complex multi-agent infrastructure.

Therefore, we need to co-design and co-adapt both technological and organizational support. Avionics software is now highly sophisticated, enabling many machines to be considered as agents, i.e., having cognitive functions as humans have. Human and machine agents are more interconnected in the air space than before, and their inter-relationships are often crucial to understand, master and support. This evolving ATM multi-agent world is highly situated and context identification is a primary concern. In particular, flight deck automation will have to be designed taking into account that pilots will gain autonomy thus changing the coordination requirements.

Consequently, function allocation needs to be addressed during the whole life cycle of all ATM systems. Cognitive function analysis is typically used to support the analysis, design and evaluation of such function allocation. More specifically, cognitive processes, such as authority sharing, distribution, delegation and trading, must be addressed. While there are human cognitive functions that can be predicted during design, there are some that will only emerge from use. This is why scenarios should be extensively developed and HITLS carried out.

We are currently working on the difficult problem of spacing and merging (S&M) in dense traffic to improve the sequencing of arrival flows through a new allocation of spacing tasks between air and ground. Today, ATCOs solely manage aircraft S&M in busy airspaces. They control both the sequencing decisions and manage the merging routes, airspeeds and altitudes, guiding each aircraft. Controllers are aided by today’s tools, which range from simple Letters of Agreement (LOA) and standard navigation aids, to more advanced systems like today’s GPS approaches and integrated Flight Management Systems (FMS). The new Required Navigation Performance (RNP) procedures are the latest improvement down the traditional path of providing the pilot with standard procedures and a more accurate way to follow them. While this approach is an important one, it alone will not solve the future problems of airspace congestion because it addresses only execution and does not address the major issue, which is coordination. Today, ATC is a centralized army-type decision point, i.e., all decisions must pass through this point and be distributed in a serial manner to all pilots within the managed airspace. This is a clear bottleneck that is highly dependent on the skill of the controller to analyze the situation, make decisions, and then communicate the required information to each aircraft as necessary.

Pilots under instrument meteorological conditions (IMC) have traditionally been “flying blind” with respect to other aircraft around them. Good pilots will build a mental map by listening
to the radios (party-line) and piecing the scene together. Recently, TCAS and Automatic Dependent Surveillance-Broadcast (ADS-B) have started providing pilots with a little more awareness of their immediate environment. These technologies provide the pilot with a “second set of eyes” besides the controllers. This information allows pilots to make decisions of their own, but unfortunately it is not coordinated with ATC, which has resulted in unfortunate accidents, again highlighting the importance of coordination.

Future ATM systems will enable pilots to be more autonomous and consequently will require more coordination among agents. They will have contracts like musicians have scores. Consequently, these contracts will have to be coordinated by some kinds of planners, like the composers do. From this point of view, the main difference between ATM and a symphony is that contracts may change during performance, like the play of a Jazz orchestra. Authority trading will be a major issue. Situation awareness of each agent remains a central emergent cognitive function to investigate and identify during design and development. In fact, agent’s authority and situation awareness are intimately coupled, and their identification determines the type of interaction model the agent will have with the other agents that are relevant in the operational context. Sometimes, supervision is the only interaction model that is possible, and agents will need to refer to a conductor. In other situations, they will be able to interact via contracts (scores) and trust this mediating means. Finally, it will happen that they will perfectly understand what the others are doing, and therefore will communicate directly.

Off-nominal situations are infrequent, but have a tremendous impact when they do occur. They typically induce dynamic function allocation, i.e., appropriate agents will have to be aware of the situation change (resulting in a different common frame of reference), contracts will have to be redefined and coordinated (composer role), and consequent operations will have to be coordinated (conductor role). For example, it may happen that an aircrew would not be able to make it off the runway at the high-speed exit and take a full-length landing. In a congested terminal area, the following aircraft will have to perform a go-around maneuver. First, the aircrew must realize they are not going to make the exit (situation awareness cognitive function), they must manage the landing (safety-assurance and action-taking cognitive functions), and find time to let the controller know (coordination cognitive function). Consequently, the ATCO must inform the trailing aircraft and potentially all other aircraft sequenced on the approach (coordination cognitive function). All these cognitive functions must be implemented at the right time, which might not be the case taking the extra workload during this kind of operations. Information flows are highly dynamic and can only be managed by well aware and knowledgeable agents, possibly new technology. For example, the ATCO re-sequencing traffic may also find out that there is an aircraft that is low on fuel and requires an emergency landing. Creative decision-making is consequently the appropriate cognitive function that is at stake for the ATCO. On this very simple example, we see that authority must be timely shared among appropriate agents.

One way of managing this coordination problem is to develop appropriate automation. Automation can be used to detect when an aircraft will not make the exit and automatically signal the controller, elevating this burden from the pilot who is likely under high workload already. That same signal could automatically be sent to all the trailing aircraft. This kind of additional agent is expected to create more situation awareness among involved agents and therefore increase their common understanding of the situation (thus promoting the third interaction model). In addition, the ATCO, as a conductor, could make a single call confirming the situation and requesting reduced speeds. Each aircraft could acknowledge through their flight displays instead of using radio communications and ATCOs would see each response on their own screens. If this kind of solution seems to simplify the job of the various agents, it is mandatory to make sure that they are properly trained or fine-tuned, and use the right cognitive functions.

In these examples, we can see that cognitive function analysis using the Orchestra model enables the investigation of the various relationships among agents and the emergence of new cognitive functions, such as appropriate automation. Of course, any solution needs to be tested and further validated in HITL or in the real world.

6. DISCUSSION

Systems such as air-air surveillance capabilities (ADS-B) and cockpit automation (ASAS) are being designed to enhance authority sharing between the flight deck and the ground. The evolution between what is currently done and the next generation of air-ground environments requires carefully studying function allocation and keeping automation as simple as possible, in terms of flexibility for the actors. Aircraft S&M technology remains immature and requires further investigation and development. In terminal areas, S&M currently relies on air traffic controllers’ skills and experience and is affected by weather conditions, rates of runway use, ground congestion and other factors. In the perspective of authority delegation to the flight deck, new approaches to S&M need to be invented, especially in high-density traffic situations. They will rely on new kinds of automated technology and procedures. Obviously, whenever S&M can be anticipated en route, it would be a great gain of time and workload in terminal areas. It is now important to identify required functional evolutions and cognitive functions that emerge from this evolution, taking into account a representative environment with very high traffic. Referring to the Orchestra model, new approach procedures and terminal area patterns are part of the common frame of reference, i.e., a music theory analog. Generic contracts, as scores, needs to be defined according to cognitive functions that will emerge from both new automation and organizational rules, mainly coordination rules. Contract coordination should be both anticipated (composer role) and managed (conductor role). Finally, function allocation should be thought in terms of authority sharing in the sense that several agents share responsibility and control in context. It could be a priori defined, i.e., each function represented by a contract is allocated to an appropriate agent. It should also be dynamically defined, i.e., cognitive function may be allocated with respect to the ongoing situation. As already seen, dynamic function allocation requires appropriate situation awareness, i.e., there is a constant need to look for potential hazards and understand the perception and cognitive limits of the various agents in order to compensate with additional cognitive functions and maintain an appropriate cognitive stability. Such cognitive functions could be additional resources in the form of supervisors, mediators or automated links that provide a better common understanding. Of course, their implementation and operational costs should be evaluated with respect to relevant human and technological factors. The choice of their effective implementation in the real world depends on these evaluations.

Other approaches, such as cognitive systems engineering/joint cognitive systems (Hollnagel & Woods, 2005), consider the growing complexity of socio-technical systems, problems and
failures of clumsy technology, and the limitations of linear models and the information-processing paradigm. They also recognize the need for cognitive function (Boy, 1998) “in the mind”, i.e., processes that mediate responses to events. In fact, this anthropological approach of cognition was already started with the identification of situated actions (Suchman, 1987) and distributed cognition (Hutchins, 1995). All these contributions emphasize context as the main research issue. In fact, people are both goal-driven and event-driven; they are opportunistic according to context. This is why context is so important to identify and take into account. “Situated activity is not a kind of action, but the nature of animal interaction at all times, in contrast with most machines we know. This is not merely a claim that context is important, but what constitutes the context, how you categorize the world, arises together with processes that are coordinating physical activity. To be perceiving the world is to be acting in it—not in a linear input-output relation (act—observe—change)—but dialectically, so that what I am perceiving and how I am moving co-determine each other” (Clancey, 1993).

Context is an extremely difficult concept to grasp and identify since it is directly associated to the persistence of situations and events (Boy, 1998); some are long enough to be captured, and some others are too short to even be perceived. This is why a scenario-based approach carried out by domain-expert professionals is necessary. The Orchestra model is a metaphoric framework that enables handling context in a functional and structured way, since the cognitive function representation includes the context attribute by construction. The identification and categorization of the possible connections and interactions among agents through their cognitive functions enables to better understand various relevant issues of situation awareness. In fact the way we identify and categorize the world is crucial in the perception of context when acting. It is clear that all metaphors are very limited, and the Orchestra metaphor has limitations when we use it to describe socio-technical systems. However, it incrementally emerged as an acceptable model of the evolution of our software-immersive environment, and the ATM environment in particular.

As already described in a previous paper (Boy, 2002), the cognitive function analysis has many similarities with the activity theory, the Russian approach to cognition, which considers that people learn from their environment, and human activity is mediated by surrounding artifacts. The concept of cognitive function is very similar to Leont’ev’s functional organs (Leont’ev, 1981). “Functional organs are functionally integrated, goal-oriented configurations of internal and external resources. External tools support and complement natural human abilities in building up a more efficient system that can lead to higher accomplishments. For example, scissors elevate the human hand to an effective cutting organ, eyeglasses improve human vision, and notebooks enhance memory. The external tools integrated into functional organs are experienced as a property of the individual, while the same things not integrated into the structure of a functional organ (for example, during the early phases of learning how to use the tool) are conceived of as belonging to the outer world.” (Kaptelinin, 1995).

Another dimension that is not extensively presented in this paper is time. Time is very important in music. The Orchestra model is a very insightful metaphor for time-wise investigation. We have already described this dimension in another paper by describing the time sequences developed by the various cognitive functions involved in the Überlingen accident (Boy & Grote, 2009). The specificity of the Orchestra model is to encapsulate both design and performance times, i.e., the time of the composer and the time of the conductor and musicians. Information flows are important to capture in the form of useful and usable contracts (scores) designed and developed by composers at design time, and in the form of coordination patterns emerging from performance and handled by conductors at operations time.

7. CONCLUSION

Since context is a major concern in the design of appropriate safety-critical systems, scenarios are very good tools to support the elicitation of emergent cognitive functions. Scenario-based engineering requires to be supported by a strong conceptual model. The Orchestra model was found a good conceptual tool to categorize cognitive functions in air traffic management problems, their allocation among human and machine agents, as well as the various relevant relationships between them.

This paper presents a conceptual model for function allocation and scenario-based engineering in multi-agent safety-critical systems. This model takes into account the fact that allocation can be done a priori, but is also dynamic by nature. Indeed, relationships between agents are supported by contracts that are very similar to scores in music. Despite the initial planning, i.e., the coordination of contracts, there are always events that are not anticipated either because they are intentions from some of the agents that differ from the original plans, or unexpected external events. These events require dynamic re-allocation of functions, and therefore modification of initial contracts. This is typically the role of a conductor. Agents, as musicians, need not only to be competent to perform their functions; they also need to understand what the other agents are doing. This is why we need interaction models also. In the best case, they communicate between each other by common understanding, but they may require being supervised or mediated when they do not have acceptable situation awareness.

As many other contributors suggested, new technologies and automation do not have only quantitative effects, but have also qualitative shifts (Dekker & Woods, 2002), induce the emergence of new practices (Flores et al., 1988), and even may alter the tasks for which they were designed (Carroll & Campbell, 1988). The Orchestra model provides a conceptual framework that supports the elicitation of this kinds of emergences.

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9. REFERENCES


