A Framework for Cognitive Situation Control

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***Abstract*—The emergence of a new class of complex applications in bio-medical and health-care systems, intelligent transportation, disaster situation management systems and others, has defined new requirements to the methods of control of these systems. Central to those applications is the requirement to understand the meaning of complex situations happening in dynamic environments, and to act based upon those situations so that certain goal situations will be reached. Often actions of situation control face hardly definable goal situations and lack of control optimality. Although the importance of theories such as situation awareness has been well recognized, we are still away from a broadly accepted understanding of the mechanisms of situation control. We argue that augmenting situation control with capabilities exhibited by human cognition provides more effective mechanisms for organizing goal-directed behavior of complex systems. The paper presents conceptual framework of cognitive situation control and discusses details of the main components of the proposed architecture, including situation recognition, negative situation control feedback, and action planning.**

Keywords—cognitive situation control; situation theory; partial world semantics; negative feedback; situation recognition; action planning; computational ontologies

I. Introduction

The classical and the modern control theories [1] have dealt successfully with the task of controlling engineering devices and systems, applying mostly analytical and numerical control methods. The introduction of large-scale applications, such as complex telecommunication and power networks, showed a need to process symbolic information, as well the control methods were advanced with solutions based on research in fuzzy control, expert systems, and artificial neural networks [2].

The emergence of a new class of complex human-in-the-loop cyber-physical applications in health-care, robotic mission control, disaster situation management, asymmetric warfare operations, and in other areas has demonstrated the need to understand the meaning of situations happening in the operational theatre, and to undertake required situation control actions. Situation control could be defined as a space and time-bound process of impacting the behavior of a dynamic system so that the system either stays in a predefined goal situation resisting the external disturbances, or the system follows a required goal situation. Handling situations as first class objects, focusing on the meaning of situations, reasoning about and acting upon situations, and organizing situation control activities in a hierarchical multi-tier manner are the delineating features of situation control. From the control theory the situation control has adopted several fundamental control principles like the time-domain state-space representation, system observability, and closed loop negative feedback.

Further expansion of situation control with models that simulate the mental faculties of human cognition [3], such as consciousness (awareness), reasoning, formation of beliefs, memory, adaptation, and learning, leads to the notion of cognitive situation control. The importance of cognitive aspects of control was first raised in cognitive neuroscience [4]. A perceptual control model that suggests how a negative feedback control could work in living organisms was described by Powers [5]. In technical communities the methods of cognitive control are still in the early stages of research. Recently, the features of cognitive control within the context of control engineering tasks were raised in [6]. An approach based on situation semantics and situation theory for capturing the dynamics of modern battlefield control was described by Devlin [7]. A method of situation control for achieving situation stability in cyber physical environments was proposed by Singh and Jain [8]. The use of semiotic models for situation control of engineering processes was proposed by Pospelov [9]. Still, the approaches to cognitive situation control are far from a unified conceptual framework.

In this paper we will present basic principles and a framework of cognitive situation control, and discuss technical solutions of the main components of the proposed architecture. The paper is organized as follows. Section 2 illustrates the operational environment and the issues of situation control using disaster situation control as an example. Section 3 presents the conceptual framework of cognitive situation control. Section 4 gives a review of the basic notions of situation semantics and situation theory. Section 5 describes the situation recognition process, and Section 6 discusses potential solutions for automatic action planning. Section 7 draws conclusions and outlines future research directions.

II. Situation Control – Reality and Perception

Situation control happens in the actual world of physical reality, in the world of things “as they are”. This world of physical reality comprises the totality of all space and time bound real distinguishable things that include different entities, agents, messages, actions, situations, etc. We will assume that physical reality is in principal observable and exists objectively. We also assume that there are agents (humans or machines), usually called intelligent agents, who are capable of reflecting the physical reality and creating the corresponding worlds of perceived reality. The world of perceived reality is an artifact; it is a subjective collection of informational models that reflect how a particular intelligent agent interprets situations that are happening in the physical reality. Physical reality could be broken into different sub-worlds that we will call operational theatres. An operational theatre is associated with some domain of knowledge and interest (e.g., medical domain, transportation domain, etc.). There may be different operational theatres in physical reality.

As an example of situation control, consider an operational theatre of disaster situation control [10]. The operational environment of disaster situation control might include significant infrastructure components, such as roads, bridges, buildings, power and communication networks, transportation systems, water supply systems, and other components. Usually hundreds of medical, transportation, construction, repair, law enforcement, public safety and other services that include personnel and equipment may be involved in disaster relief operations. These services require radio, cellular, satellite and other communication networks to support their location, coordination, navigation, weather, and other information support services. There may be a variety of data sources available in the operation theatre that may be used to evaluate the state of the environment, infrastructure components, and entities involved in disaster situation control operations. Those sources might include sensor devices, satellite imaging systems, data feeds from drones, reports from human site observers, social-media reports, alerts and notification messages from technical devices, infrastructure documentations that could be retrieved from various databases, etc. Sensing the primary physical parameters of entities in physical reality and transferring them into quantifiable data are essential in constructing the situation awareness picture of the affairs taking place in physical reality. The activities happening in disaster situation control may include different actions of bringing, moving or removing things in the operational theatre, changing their individual characteristics, or taking actions that change the state of affairs in the operational theatre (e.g., bringing in more medical emergency vehicles, increasing the water supply, or re-organizing groups of firefighters).

A prerogative for building the methods for cognitive situation control is the existence of a sound metaphysical classification of basic world entities, or so-called ontology. In philosophy ontology is defined as "the science of what is, of the kinds and structures of objects, properties, events, processes, and relations in every area of reality" [11]. The metaphysical studies by Vendler [12], Ryle [13] and Bach [14] on temporal analysis of discourse resulted in a classification, where the top level class (called eventualities) was divided into two main subclasses: states and non-states. The states were considered as static eventualities, and non-states as dynamic eventualities. The non-states were classified into activities and events. It should be noted that research on ontology in philosophy deals with the nature of all reality and is interested in very general ontological classes. However, in the past decade many practical applications of ontological principles led to the development of narrower domain-specific ontologies that deal with only a limited portion of reality. These developments also aim for an additional goal to create ontologies that include domain-specific constraints, relations and axioms that can be presented in a computational format. Such ontologies are mostly a subject of research in computer science and artificial intelligence, and are often called computational ontologies [15]. A conceptual classification of things in a world of reality aimed for modeling situation control processes was discussed in our earlier work [16]. A computational ontology for supporting situation awareness processes was developed by Kokar, Matheus and Baclawski [17]. In the proposed approach to cognitive situation control the computational ontologies are used as a basis for constructing informational models for all entities, situations, actions, processes, and events that are involved in situation control operations.

III. Conceptual Architecture

Further in this paper we will refer to situations happening in physical reality as physical situations (or simply - situations, if this is clear from the context). Physical situations will be distinguished from the corresponding abstract situations that are part of the perceived world constructed by the intelligent agents. Abstract situations are subjective perception of the physical situations in the mind of an intelligent agent.

Situation changes in the physical reality are caused by actions that are undertaken by situation control agents, operational agents on ground, or hostile adversary agents. Situation changes could also be caused by natural forces, technological accidents, or internal system faults. Talking about situations, we are following the classical informal definition given by McCarthy and Hayes [18] that situations are snapshots of the state of the world.

We see actions referring to something that an agent might do in affecting the physical reality. By undertaking an action, an agent causes a situation change in the physical reality. While controlling or observing situation changes it is convenient to talk about events as situation changes. For us situations and actions are real things happening in the world of reality, while events are artifacts. Usually, an elementary event is considered as a pair of situations, the situation before and after the change. Finally, we should mention that solely for the purpose of building situation control systems it is practical to introduce the type of notification messages that manifest about the occurrence of events, actions and situations.

There are several key principles that underlie our proposed framework of cognitive situation control:

- Partial World Semantics: While modeling physical reality, we will assume that situation changes that an agent is able to understand are only a part of the world situations that are theoretically possible. Here, we follow the theory of situation semantics, where the notion of partial world semantics was introduced by Barwise and Perry [19].
- Causal Situation Transitions: Since we are dealing with situation control in dynamic environments, we assume that there is a causal link from actions or any kind of forces to situation changes (i.e., events).
- First Class Objects: In the proposed framework the situations, events and actions are handled as first class

objects [20] (i.e., they can be dynamically created, saved, processed and destroyed).

- Situation Control Feedback: As in the control theory [1], we will use the phenomenon of negative feedback to implement the situation control processes. The difference from the control theory is that the situation deviation (error) function is defined not between the current state and the goal signals, but between the current situation and the goal situation.
- Hierarchical Situation Control: The multi-level hierarchical situation control architecture is the basis for implementing large scale situation control processes: the situation control function at one level in the hierarchy may be a function of multiple situation control processes at a lower level. Hierarchies may be organized by different levels of abstraction, multi-level information correlation processes, or using an embedded functionality.

A high-level diagram of the proposed cognitive situation control architecture is presented in Figure 1. The diagram depicts two basic parts of the architecture: The World of Physical Reality and Situation Control Agent (SCA). The physical situations that are happening in the operational theatre are recognized and interpreted by the Situation Recognition component of SCA. The Situation Recognition component creates a current abstract situation s(t) that corresponds to the actual physical situation in the operational theatre.

The central part of the situation control process within SCA is the negative situation feedback loop, where the Situation Comparator of SCA takes the current abstract situation s(t) and the goal situation g(t) and determines deviation $\Delta(t)$ of the current abstract situation s(t) from the goal situation g(t), $\Delta(t) = s(t) - g(t)$, and passes it to the Action Planning component of CSA. Then the situation control process loops through the physical reality involving actuators, sensors and human observers. The actuators transform the action plans into physical actions that impact the state of objects and the environment in the operational theatre, and ultimately force situation changes in the operational theatre. Such situation changes are registered by two channels: the "hard" channel of sensed data and messages generated by the entities active in the operational theatre, and the "soft" channel of human observations.

The constructed abstract situation s(t) is passed to Agent Memory for future use (e.g. when there is a need for creating more complex situations). The situation recognition process itself is a knowledge-intensive pattern matching process and may contain multiple sub-processes, such as situation perception and comprehension as identified by Endsley [21]. The goal situation is given to SCA by a higher level control agent, or may be automatically detected by the agent depending on the content of the situation that was recognized

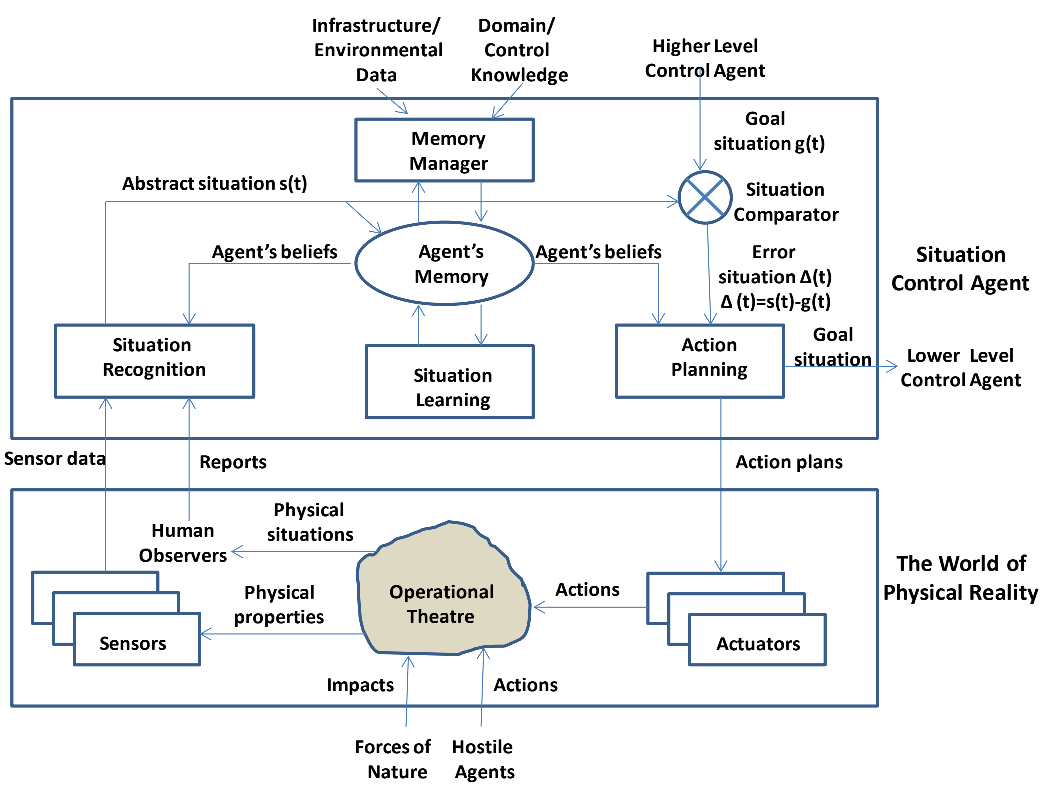

Fig. 1. Conceptual diagram of cognitive situation control.

by the agent. In addition to the action plan generation, SCA might send a specific goal that it has identified to another agent. The diagram in Figure 1 also depicts exogenous sources that impact the operational theatre, the forces of nature, and the actions undertaken by hostile agents. Usually, in such a case the situation control task is to move the operational theatre back to the situation that existed before the exogenous forces were applied (it is the so-called situation stability control). Consequently, if the initial situation was s(t) and the situation after the impact of the exogenous force is d(t), then the situation control task is specified by the situation deviation $\Delta(t) = d(t) - s(t)$.

The Situation Learning and Situation Teaching components perform two knowledge acquisition tasks that support the other components of SCA: (1) Teaching - all required procedural and declarative knowledge, such as ontologies, rules, constraints, etc., are provided by domain experts; (2) Learning – new situational knowledge is acquired by situation learning processes. The situation learning and teaching processes are subject for our future research. The diagram shows only one Situation Control Agent; however, there may be many other agents that control situations happening in the same or other operational theatres. The agents may be inter-connected and may be working as a multi-agent system. Our earlier work on using multi-agent systems for post-disaster relief operations support was presented in [10].

IV. Situation Semantics

In this section we will introduce several main ideas of situation semantics that we found to be of interest in regards to our approach to cognitive situation control. Situation semantics was originally proposed by Barwise and Perry [19] as a realistic approach to semantics of propositional attitudes in natural language discourse. Situation semantics was developed as an alternative to possible world semantics of McCarthy and Hayes [18]. While possible world semantics defines the informational content of sentences in terms of complete descriptions of the way the world is or might be, situation semantics defines the informational content of sentences in terms of partial worlds called situations. Situation semantics was further advanced by Devlin by introduction of the ontology-based theory of information units (infons) or situation theory [22]. Situation theory carries with it a rich basic ontology of objects that includes individuals (individual objects), relations, roles, parameters, spatial locations, temporal locations, infon polarities, situations, and types (classes).

In situation theory a basic unit of semantic content (also a basic unit of information) is called infon σ. Infons belong to an abstract world of relational semantic constructs and represent the meaning of real world situations. Infons are denoted as $\ll r; ,a_1,...,a_n ; i\gg$, where r is an n-place relation, $a_1, ..., a_n$ are the objects appropriate for r (including temporal location t, and often spatial locations l), and i is polarity of the infon, where $i = 0$ or 1. The infon polarity values may be thought of as indicators of whether the relation r does or does not hold on the set of appropriately given objects. If an agent is able to recognize appropriate objects from reality so that relation r in infon σ holds, one can say that situation s supports infon α (alternatively, one can say that situation s makes infon σ factual) , and write $s \models \sigma$.

Definition 1. For a real situation s(t), a set of infons $I(t) = \{\sigma(t) / s(t) \models \sigma(t)\}$ is called an abstract situation representing the meaning of the situation s(t), where t is a common observation time of the real situation s(t), infon σ(t) and abstract situation I(t). We say that situation s(t) supports the abstract situation I(t), $s(t) \models I(t)$.

Situation theory recognizes two types of infons: basic and complex infons, where the complex infons are structural composites that are inductively constructed from basic or other complex infons. Infons may contain variable-like objects called parameters that during instantiation of an infon can be replaced by values. Parameterization of infons supplies situation theory with a powerful tool of abstraction by creating types (classes) of objects. Basic types include types of individuals, relations, infons, and situations.

V. Situation Recognition

In this section we will discuss how the situation recognition process (see Figure 1) can be organized and describe one particular approach to situation recognition based on temporal real-time event correlation [23]. As mentioned in Section 3, information about real situations is coming to the situation recognition process through two channels, the “hard” channel of instrumented sensor data and the messages generated by some objects active in the operational theatre, and the “soft” channel of human observed descriptive reports. The situation recognition process constructs an abstract situation, which is a situation control agent’s perception of the corresponding physical situation. Let’s have a collection of abstract situations H, given to the agent by an expert, or learned by the agent itself. For a some observable physical situation s(t) the process of construction of a set of abstract situations $\{I(t) \in H(t) \setminus s(t) \models I(t)\}$is called the process of recognition of the situation s(t). We should mention that the actual method of situation recognition is out of scope of the situation theory [22].

In general, the overall situation recognition process can be decomposed into a tree-like hierarchical structure of component situation recognition sub-processes, where the terminal nodes correspond to the inputs from the low-level sensing procedures, and the root node corresponds to the final constructed abstract situation. Each situation recognition sub-processes is implemented as a local event correlation procedure. There are no limits to how the situation recognition process is decomposed, however, for all practical purposes, the decomposition process depends on how well the domain analysis is performed and what the pre-defined situation classes (situation ontology) are. Still, there are already available important research results in situation awareness models proposed by Endsley [21] that can be used as a guideline for decomposition of the situation recognition process. Endsley considers a situation awareness process containing three stages: (a) situation perception – recognizing individual, semantically isolated component situations; (b) situation comprehension – fusion of component situations into a coherent situational picture; and (c) situation projection – construction and evaluation of potential future situations. In this paper we are considering the first two situation awareness stages, situation perception and situation comprehension.

To illustrate the task of situation recognition consider the following example from the disaster situation control domain. Two medical emergency vehicles (MEV) are dispatched as a group into a disaster area. According to the rules of operation, after one MEV has issued an identification message, the second MEV should issue a responding identification message, but not later than 10 minutes after the first message. If the second message was not issued, the LOST-MEV-CONTACT situation is declared. The LOST-MEV-CONTACT situation can be recognized by the following event correlation rule EXPECTED-EVENT-RULE. We should note that expressions that start with "?" (e.g. ?msg1 refer to a variable).

```
CorrelationRuleName:  EXPECTED-EVENT-RULE
    Conditions:
          MSG: EVENT-TYPE-Identification ?msg1
          TIME ?t1
          VEHICLE: VEHICLE-TYPE-MEV ?mev1
    Not   MSG: EVENT-TYPE-Identification ?msg2
          TIME ?t2
          VEHICLE: VEHICLE-TYPE-MEV ?mev2
          GROUP: GROUP-TYPE-MEV ?mev1 ?mev2
          AFTER:?t1 ?t2 600
    Actions:
AssertSituation: LOST-MEV-CONTACT-SITUATION
        VEHICLE1 ?mev1
        VEHICLE2 ?mev2
        EVENT1 ?msg1
        EVENT2 ?msg2
AssertNotification: LOST-MEV-CONTACT-SITUATION
        VEHICLE1 ?mev1
        VEHICLE2 ?mev2
AssertActionPlan: SEND-EMERGENCY-HELICOPTER
```

EXPECTED-EVENT-RULE rule has Conditions part and Actions part. The Conditions part contains a sequence of expressions stating that Identification event message ?msg1 came from MEV ?mev1 at time ?t1, but the matching Identification event message ?msg2 didn't come from MEV ?mev2 at time ?t2. The additional conditions state that both MEVs are tied by a domain-specific relation GROUP-TYPE-MEV, and the time moments ?t1 and ?T2 are in a temporal relation AFTER. The Actions part of the rule contains three actions: AssertSituation LOST-MEV-CONTACT-SITUATION for updating the Agent's Memory, AssertNotification LOST-MEV-CONTACT-SITUATION for generating an output notification message to be sent to other agents, and AssertActionPlan SEND-EMERGENCY-HELICOPTER to be sent to Actuator for execution in the operational theatre. As it is shown in this example, the action plan is directly embedded into the situation recognition rule.

VI. Action Planning

Research in modeling actions, as well understanding the interplay between actions, situations and events has been under constant focus in situation semantics and situation theory, although without intensity that one might wish. In its early stages the situation semantics theory introduced a notion of a constraint defined between various situation types to model (natural) laws, conventions and regularities [22]. A simple constraint S => S' was introduced as a factual relation between two situation types S and S'. If S => S' then it is said that situation type S involves the situation type S'. In situation semantics the constraints were used to model information flow from one situation to other ones. Constraints were expanded into satisfaction diagrams by Devlin [7] that allowed representing rules of natural situation reasoning. Two approaches to reasoning about actions based on situation semantics were proposed by Osawa [24] and Kovacs [25]. Both approaches were focused on the "frame problem" [18] and were not concerned on situation action planning, which is a subject of this paper. An alternative approach to model actions and events based on temporal interval \logic was proposed by Allen and Ferguson [26]. Here, we introduce notion of coherent situation [27].

Definition 2**.** A situation s(t) is considered coherent if at a time t it does not assign two different values to any infon $\sigma(t) \in I(t)$, where I(t) is an abstract situation corresponding to the situation s(t) (see Definition 1).

With each action a we associate a pair of situations (pre(a), post(a)), where pre(a) is called the presituation pre(a) of *a*, and post(a) is called the postsituation post(a) of a. The situation pre(a) is a required precondition for action a to be applied, while situation post(a) becomes factual as result of execution of the action a. Here, we have two coherent situations *s* and *s*', and say that action *a* enforces situation transition a: s → s', if the following condition is true

$$pre(a) \subseteq s \text{ and } post(a) \subseteq s'$$

For example,

a = establish-contact (mev1, mev2)
pre(a) = << LOST-MEV-CNT-SIT, mev1, mev2, 1>>
post(a) = << LOST-MEV-CNT-SIT, mev1, mev2, 0>>

In the above-given example the action establishes a contact between two medical emergency vehicles mev1 and mev2. The precondition pre(a) is a situation that two vehicles mev1 and mev2 have lost the communication, while post(a) defines an opposite situation.

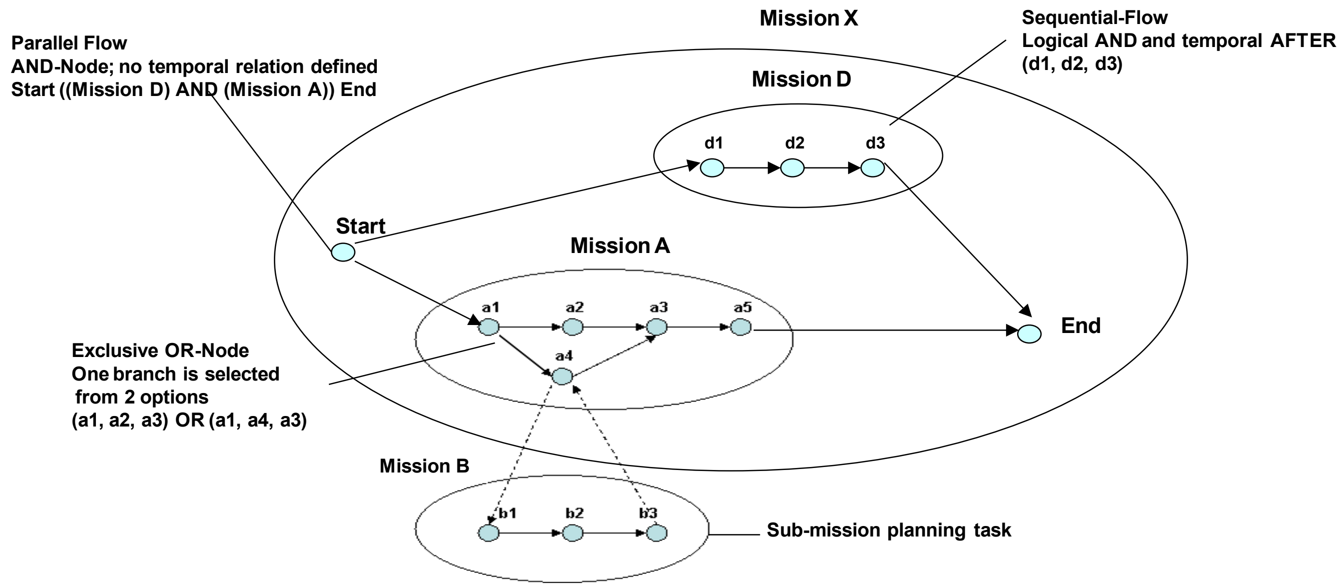

Fig. 3. Mission action flow graph

An action in the form of a: s → s’ is called an elementary action. Elementary actions can be combined into compound actions called missions [28]. Informally, a mission is defined as a sequential or parallel flows of actions that are controlled by AND/OR logic and by temporal operators [29] that are based on Allen’s interval algebra [30]. Figure 2 illustrates a mission X that has two main parallel branches that are forked at Starting point by an AND-node. The first branch contains mission D and the second branch contains mission A. Mission D is a sequential flow of actions tied by a temporal relation AFTER, while the mission A is an exclusive OR-forked parallel flow of two alternative sequences of actions. Instantiation and execution of the mission A assumes a real-time communication between the SCA and the mission control agent to decide potential mission control options: to take the first branch (a1, a2, a4), or the second branch (a1, a4, a3). Figure 2 also illustrates a specific case, where the mission B has to be planned on-fly, where the planning task is described in the in the mission step a4 in the Mission A. The step a4 is not a specific executable action, but rather a specification for an action. Mission X itself could be embedded into a situation, similarly as it happened with the action SEND-EMERGENCY-HELICOPTER in the situation LOST-MEV-CONTACT-SITUATION shown in the previous Section 5.

Below is an outline of two methods how action planning can be organized:

- Method of Embedded Actions: Here we assume that actions can be embedded into a situation as it was shown in the situation recognition example in Section 5.
- Method of Automatic Action Planning: This is a 2-way process of chaining of actions, the first one is a forward chaining of exercising of applicability of all actions, and the second one is a backward chaining for eliminating redundant actions (not discussed here). Let’s have a set of elementary actions A. The task of action planning is to construct a mission that brings the current situation *s* to a goal situation *s’*. The action planning procedure can be organized as follows:

1. Take an action *a* ϵ A that pre (a) ⊆ s. If no action a is available, stop: no action plan generated, otherwise go to 2.
2. Construct a new situation s”= s □ post (a).
3. Add action a into the action plan.
4. Test is the goal situation s’⊆ s”. If yes, stop: action plan generation process completed, otherwise assign new value to s, s: = s”. Go to 1.

For example, it is assumed that a system should be in a stable situation s. Due to an impact of a natural force the system ended up in a state s’. The situation deviation from the goal state is Δ = s’ \ s (a set-theoretic difference between the set of infons corresponding to s’ and s, correspondingly. We can use the method of automatic action planning either reaching a deviation situation Δ = Ø, or reaching the initial situation s from the situation s’.

The given algorithm of action planning is a simple one and is suitable for sequential mission planning.

VII. Conclusion

In this paper, we presented a conceptual framework for cognitive situation control, and discussed several technical details of the main components of the framework. The aim of this paper was to present one possible solution for understanding situation control in dynamic environments that mimic some elements of human cognitive behavior. Our future research will include research on methods of estimating situation deviations (i.e., how to understand differences between current and goal situations, and how situation deviations can be used for automatic action generation). Our interest will also be on situation learning and teaching.

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