Situation Awareness in Synthetic Environments: Towards a Computational Model

Mehul Bhatt[1], Wenny Rahayu[1], and Gerald Sterling[2]

[1] Department of Computer Science
La Trobe University
Melbourne, Australia 3086.
+61-3-94791280
{mbhatt, wenny}@cs.latrobe.edu.au

[2] Air-Operations Division
Defence Science Technology Organisation
PO Box 4331 Melbourne
Australia 3001
+61-3-96267728
Gerald.Sterling@dsto.defence.gov.au

Abstract. The simulation of the behaviour of autonomous entities in space is an interesting research method to advance our understanding of the interaction of human beings with the environment. Although rather complex cognitive models of human-level *Situation Awareness* (SA) in dynamic environments exist, computational approaches to represent the same remain at best ad-hoc – *cognitively inadequate* or bearing little or no resemblance to the qualitative manner in which humans seemingly represent & reason about knowledge. The aim of our research is to investigate the computational aspects of situation awareness of autonomous entities in large-scale simulated spaces, called *Synthetic Environments* (SE). This is done within the scope of an understanding of situation awareness that encompasses common-sense conceptual reasoning and integrated qualitative reasoning about space, time & causality. As a product of our research, we envisage to develop a logic based computational framework based on a unified representational semantics for space, time & causality – the essence of which is a process model involving abstract ontological commitments involving spatial, temporal and action/event oriented concepts, alongwith a capability to handle concurrent and continuous phenomena. The framework, which is representative of our model of situation awareness, will be most beneficial for systems involving the representation of physical and/or intelligent autonomous processes. However, as an exemplar of our approach, we are interested in applying the framework for the representation of autonomous behaviour in defence Modelling & Simulation (M&S) applications.

1 Introduction

The simulation of the behaviour of autonomous entities in space is an interesting and powerful research method to advance our understanding of spatial cognition, particularly, the interaction of human beings with the environment. Various attempts have been made [12, 13] so as to provide a cognitive account of the mental processes that contribute towards an overall appreciation of a situation. However, there still exists a wide gap between such cognitive models and their computational counterparts. More precisely, computational models aimed at simulating human decision-making processes in large scale virtual spaces fail to account for the *cognitive adequacy* that is often ingrained into their theoretical counterparts – the computational models hardly bear any resemblance to the qualitative manner in which humans seemingly make decisions in real life situations.

Our research addresses the issue of the *Situational Awareness* (SA) of an autonomous entity functioning in a large scale virtual space or a *Synthetic Environment* (SE). We adopt the generally accepted definition of *Situation awareness* (SA): *the perception of elements within the volume of time & space, the comprehension of their meaning and the projection of their status in the near future* [11]. This definition is mostly used within the context of human/operator in the loop real/simulated systems whereby the operators SA is his capability to maintain a continued, overall assessment of the system or the environment with an objective of making critical operational decisions. However, we use this definition of SA within the context of an autonomous entity functioning in a large scale synthetic environment. The environment is large not in the sense that its structure is necessarily massive or complex, but in that the space cannot be perceived as a whole at once by the autonomous entity; the exact degree or extent of the perception being limited by the entity's sensory capabilities[3]. Such a view is similar to the scale-dependent *psychological spaces* [34] that regard the properties of space, or relations between objects in space, as scale-dependent when studied as a problem for human perception, thought and behavior (i.e., as a psychological problem). Specifically, Montello [34] proposes four major classes of psychological spaces on the basis of the projective size of the space relative to a subject: figural, vista, environmental, and geographical. Our conception of a large-scale synthetic environment can be likened to Montello's *environmental space*, which is '*larger than the subject and surrounds it*' and cannot be apprehended directly without '*considerable locomotion*'.

Modelling the situation awareness of an autonomous entity necessitates an explicit account of the manner in which it is to be computationally represented; this is the main objective of our research. Based on a rather simplified model of situation awareness, encompassing domain specific conceptual reasoning and integrated reasoning about space, time & causality, we provide a formal account of the computational aspects of our model of situation awareness. The contribution of our research will be a logic-based computational framework based on a unified representational semantics for space, time & causality. The framework will be most beneficial for systems involving the representation of physical and/or intelligent autonomous processes. However, as an exemplar of our approach, we envisage to apply the framework for the representation of autonomous behaviour in defence Modelling & Simulation (M&S) applications.

[3] Note that we assume the co-existence of entities with non-uniform sensory capabilities, which themselves depending on what is actually being modelled.

2 Motivation

Reasoning about space, time and actions in a unified manner is not a trivial task. Human beings effortlessly perform such integrated reasoning in the discourse of their everyday existence. Cognitive models of situational awareness acknowledge the importance of such integrated reasoning – this is evident from the fact that the issue of such integration manifests itself clearly in these cognitive models. However, the mapping of such a model into its computational equivalent is far from achieved – even whilst restricting the model to one if its more simpler forms. More importantly, it is the human element of qualitative reasoning reasoning that we intend on capturing in our model of situation awareness. Qualitative reasoning [48, 28], as opposed to precise quantitative reasoning, is characterized by the usage of variables which can only take a small, predetermined number of values and the inference rules use these values and not numerical quantities approximating them [47]. From a practical viewpoint, qualitative reasoning is an abstraction that summarizes similar quantitative states into one qualitative characterisation. It is clear that the qualitative approach loses some precision, but simplifies reasoning and allows deductions when precise information is not available. To quote Weld and de Kleer [48] on the subject, "*The goal of approaches that take the human point of view is to develop languages that allow one to express a variety of physical theories and model the reasoning of experts and neophytes with these theories*" – We see our computational model of SA as contributing towards this broader research goal. As will be elaborated in the rest of the paper, we achieve our goal via the medium of computer-simulated synthetic environments, an approach regarded to be a major development in spatial cognition research [35], [7], [36].

Representing and reasoning about spatial knowledge is problematic & complex – It involves considering the many aspects of space - *distance, orientation, size, topology, shape* etc. Development of a unified (logic-based) framework that accounts for these various aspects itself is a open problem within the field of spatio-temporal reasoning [47]. Our research is a direct contribution towards this end. Development of a comprehensive framework encompassing various aspects of spatial reasoning is beyond the scope of our work; Our research will contribute towards this aim to an extent that is necessary to provide a computational account of the spatial reasoning within the context of our model of situation awareness. We adopt the rather conventional approach that is used in the field of qualitative spatial reasoning involving the use of a topological theory of spatial changes. All spatial information in our model is represented as a set of topological relations between spatial entities. Spatial change (over time) is then represented as change in the topological relationships between spatial entities in such a theory. Our contribution in this regard is to incorporate sub-theories of motion, distance, and relative size[4] into the theory of topological changes being utilised. The motivation for incorporating such sub-theories being that a theory of spatial changes based on topology alone is too general or weak to be used in realistic scenarios. In so far as realistic applications such as simulated virtual environments are concerned, additional information relevant to distance, size etc is readily available and therefore must

[4] Our work in this are is ongoing. In this paper, we only discuss the integration of topology, distance and size.

be utilised [47]. As such, in so far as integration of various spatial aspects is concerned, our work shall be an important contribution.

3 A Computational Model of Situation Awareness and its Application

3.1 The Proposed Model

Our proposed model is based on the premise that increased formality and rigour in the specification of the various reasoning tasks deemed essential in a theoretical account of situation awareness is a necessary foundation on which a its computational model rests. We envisage to develop a computational model of situational awareness in the form of a logic based computational framework that can be used to represent and reason about the agents world – to reason about space, time and actions in a unified manner. In our model, situation awareness is deemed to be the synergistic product of domain specific conceptual, spatio-temporal & causal reasoning; here, temporal reasoning being an element of significant overlap between reasoning about spatial changes and reasoning about causality, i.e., actions and their effects. Note that such a view is consistent with a minimal understanding of situation awareness and is based on its generally accepted definition – *the perception of elements within the volume of time & space, the comprehension of their meaning and the projection of their status in the near future* [11]. In the following, we briefly elaborate the differing aspects considered within the model.

Domain Specific Conceptual Reasoning Conceptual reasoning in our model refers to inference patterns typically involving the classification of concepts & individuals and the identification of subconcept-superconcept relationships between the concepts of the agents domain-specific vocabulary. Such a vocabulary, more formally referred to as an ontology, is specified using a class of languages called Description Logics (DL) [3]. It is the enhanced degree of formality in capturing the ontology using DL based languages that facilitates machine understanding [26], i.e. the following set of inference patterns encompassing our notion of conceptual reasoning: **(1)** *Subsumption*: The subsumption inference task is to determine which out of two concept descriptions is a more general one. The more general one is said to subsume the more specific concept description. **(2)** *Satisfiability*: The satisfiability task determines whether a concept has a non-empty extension, i.e., the instance level admits atleast one individual satisfying the class axioms for that concept. **(3)** *Equivalence*: The equivalence task determines whether two concepts have the same extension in the instance level. **(4)** *Disjointness*: The disjointness task determines whether the intersection of the extensions of two concepts is NULL. **(5)** *Instance Checking*: The instance checking task is to determine whether a given concept is an instance or belongs to a particular class. **(6)** *Consistency*: Verify whether every concept in the ontology admits atleast one individual. **(7)** *Realization*: Find the most specific concept from the ontology that an individual is an instance of. **(8)** *Retrieval*: Find the individuals from the instance level that are instances of a given concept from the ontology.

We have comprehensively investigated the representational aspects of domain specific conceptual reasoning using ontologies in the synthetic environment domain [4, 6]. As such (and because of space restrictions), we only briefly touch upon the accomplished and ongoing work in this area in Section 4.2. Please refer to the relevant papers for details.

Integrating Space, Time and Causality Space is usually characterised via various aspects – topology, position, location, orientation, size, shape and some other attributes that are not purely geometrical [19]. Spatial reasoning in our work corresponds to qualitative reasoning about these spatial aspects. Likewise, reasoning about *causality*, i.e., cause & effect, involves an explicit account of the teleological aspects of the autonomous behaviour of an entity (or a process in general). It is based on a causal & functional specification of an entity and its environment and basically involves reasoning about actions & change. As a digression, a related issue within the context of the formalisation of common-sense knowledge worth mentioning here is the subdivision of endeavours in AI – McCarthy [30] singled out spatial reasoning as an important task, mostly concentrating on the aspects necessary to resolve some specific tasks. Such separation of tasks is necessary and important from an AI research viewpoint; however, within the context of the integration of such sub-divided endeavours, an important question is what is more fundamental: spatial reasoning or general logic-based reasoning [16]. To quote Freksa [16] on the issue: *"From a formal position, these two viewpoints may appear equivalent; however, from a cognitive and computational position they are not; the logic-based view assumes that spatial reasoning involves special assumptions regarding the properties of space which must be taken into account while the space-based view assumes that abstract (non-spatial) reasoning involves abstraction from spatial constraints which must be treated explicitly*." Our approach in this regard is more pragmatic; Rather than being embroiled in a debate on the on the primacy of a certain endeavour, we intend on according every aspect, viz - spatial, temporal & causal, the same level in the entity's common-sense conceptualization. As shall be illustrated in Section 4, we do this by formalizing an ontology encompassing spatial-temporal & causal concepts. The ontological commitments we make in this regard are a necessary pre-condition to the precise formalisation of the rules of behavioural dynamics encompassing space, time and causality.

3.2 Envisaged Application Scenario

There exist a varied range of modelling and simulation systems in the defence sector primarily pertaining to support procurement, force development, mission rehearsal & training etc [29]. Within the context of such applications, especially military simulation systems, it is often necessary to model individual human reasoning or more generally, the autonomous execution of entities that model humans or other military artifacts. For example, these systems often involve a digital representation of a restricted part of some terrain consisting of natural and synthetic entities - *buildings, trees, humans, tanks & other machinery* etc. The digital representation is usually complete with (mostly quantitative) information pertaining to various geometrical (sizes, topology etc) and other aspects of the environment being modelled. The task then is to represent the autonomy of the active objects contained within the environment, i.e., their interaction with the environment & the modelling of their decision making abilities across time. We regard such an application to be a ideal test-bed for our notion of situation awareness and its associated computational model. However, the exact scenario or details of the application of our model is a matter of further investigation.

4 Representational and Computational Aspects of Situation Awareness

4.1 Ontological Issues

Every aspect of an entity's situational awareness, the ontological and global formalisation of the agents common-sense conceptualization and reasoning, needs to be be made explicit. The nature and structure of the space and objects contained therein, processes, its notion of time, actions, events and their effects, continuous & concurrent phenomena etc are some of the key mutually dependent ontological elements that must be accounted for in such a conceptualization. Especially, within the context of temporal elements, which represent a significant overlap between spatial reasoning and reasoning about causality, similar or non-conflicting ontological commitments need to be made. At a slightly higher-level of abstraction, the ontology of a simulated virtual environment system includes actors or agents (including autonomous and human-controlled), an environment or geometry in which the actors behave, and a set of rules of behavioural dynamics attached to the actors [7]. In the following sub-sections, we provide a brief overview of some of the ontological issues aforementioned and the commitments we make thereof. Note that this is done in a rather narrow context of our model of situation awareness involving the integration of space, time and causality.

Extended Entities or Points as Fundamental ? Models of spatial knowledge can either represent abstract point objects or spatially extended objects. There has been a tendency within the qualitative spatial reasoning community to take regions of space[5] as the primitive spatial entity [8]; or formally speaking taking 3-D volumes, 2-D areas or 1-D intervals as primitive [16]. Such an ontological commitment is common in the work on topology, which is usually regarded as the fundamental aspect of qualitative spatial reasoning since topological distinctions are inherently qualitative in nature. Synonymous with topology in the QSR domain is the Region Connection Calculus (RCC) [40]. The approach of RCC is that extended spatial entities, i.e the regions of space they occupy, are taken as primary rather than the dimensionless points of traditional geometry. Note however that RCC is a very general theory of topology and makes no distinction between rigid[6] and non-rigid bodies, which is likely to be very important for our work. Within the context of reasoning about the motion of rigid bodies in space,

[5] An ontological distinction is usually made between an object and the region of space it occupies; A region is regarded as the spatial extension of an object.
[6] Rigid bodies refer to non-penetrable material objects

[17] identifies a number of interesting properties for the RCC theory specialised to rigid bodies.

Not all work in the QSR treats the region abstraction as primitive. For example, Freksa [16] uses point locations as basic entities towards the representation of qualitative orientational information, i.e, relations describing where objects are placed to one another. Freksa view is more pragmatic in his use of points as fundamental abstraction: "*First, the properties of points and their spatial relations hold for the entire spatial domain and that shapes can be described in terms of points at various level of abstraction . . . in some contexts, we view objects as 0-dimensional spatial points whereas in others we may be interested in their one, two or three-dimensional extensions.*" A similar view is adopted by Hernandez [23] where objects with no extensions (i.e., points) are considered towards to the representation of orientation information. Likewise, a similar assumption is made in [24] towards the representation of qualitative distances. Although an approach to handle spatially extended objects is provided in both [23, 24], it must be noted that their spatial ontology regards points as primitive entities. In so far as the work we have completed so far is concerned, we deal with the level of abstraction and generality offered by the RCC theory and its region based ontology. However, in our future work relevant to the incorporation of orientational information, we will also use the point abstraction in the encoding of relative orientational knowledge.

The Temporal Framework The notion of time plays a crucial role in the representational aspects of systems that are dynamic, i.e., systems that *change* their state over time. The fundamental question her being, over what do we interpret temporal assertions – *How do we interpret the truth of a temporal assertion* - over a interval or a time point? [45]. Though most work in theoretical computer science and AI takes time points as primitive, there are notable exceptions like the formalism in [1] which takes time intervals as the basic primitive. Proponents of the interval based approach cite the intuitive appeal of intervals and the artificial nature of points. To quote [45]: "*After all, people never experience anything that is durationless – A point is merely a mathematical abstraction that has no manifestation our life*". In their qualitative simulation system (QSSIM), Cui et al. [10] introduce temporal regions, called *periods*, into their ontology. Periods are sub-divided into *intervals* and *moments*, where a moment is defined as a period that has no constituent parts such that one part is before another. Following the general approach used in interval temporal logics (e.g., Allen [1] and Allen and Hayes [2]), temporal precedence is then axiomatically defined over the temporal regions, which is then exploited in the form of a dyadic $Meets$[7] predicate that is defined over two *periods*.

Alternative approaches to Allen's standard linear time theory and its derivatives has been the implicit temporal framework provided by the situation calculus [32]. The early situation calculus formalism by McCarthy and Hayes [32] viewed time as discrete and provided only a implicit account of it. Various extensions have been provided, most notably by Pinto [38], Ternovskaia [46], & Pinto and Reiter [37], so as to explicitly

[7] $Meets$ is just one of the many predicates that are definable within a system of jointly exhaustive and pair-wise disjoint relations. We specifically cite $Meets$ because it is the only predicate used in [10].

accommodate continuous time within situation calculus[8]. Of particular interest to us are the ontological extensions by Pinto and Reiter [37] for the representation of time and events. In their formalism, Pinto and Reiter define a time line, which is isomorphic to the non-negative reals, corresponding to a sequence of situations. This sequence basically corresponds to one directed path, starting at the initial situation, in the overall branching tree[9] structure of situations. Our work appeals to the ontology of such an extended situation calculus; the justifications for which, for the time being, may be informally cited as follows: **(1)** The extensions aforementioned easily realise the essential features of linear temporal theories such as Allen [1] & Kowalski and Sergot [27]. **(2)** As has been shown in [39] and [41], these extensions lead to rather intuitively meaningful formalisations for concurrent and continuous phenomena. **(3)** More importantly for our work, the *action* (or *event* [31]) based ontology of the situation calculus is preserved – conventional temporal logics do not provide for actions and their effects in their ontologies.

Within the context of our framework, temporal reasoning represents an area of significant overlap between reasoning about spatial change and reasoning about action. With the integration of the two as our aim, it is very important that out ontological commitments with regard to time be non-conflicting with regard to spatial change and reasoning about actions and how they affect the world. As such, we regard the extended situation calculus ontology as serving towards a unified representational semantics of space, time and actions.

The Primacy of Events In the context of the situation calculus, McCarthy [31] presents a formalism featuring events (called internal events) as primary and the usual actions (called external events) as a special case. According to McCarthy, actions are just a kind of event, and formalized *reasoning about action and change*[10] needs to treat events as the general case and those events which are actions as special. To quote McCarthy on the subject, "*Whether an event is external depends on the theory. If we can formulate when an event will occur, then we can make our theory more powerful by including an occurrence axiom for that event. If we assume a deterministic world, the limiting case is a theory in which all events are internal*". A deterministic world, interpreted in the rather restricted context of a dynamic system, implies that all events or happenings in the system are governed by known laws of physics, i.e., there is No Free Will. A similar differentiation has also been made by Pirri and Reiter [39] in the form of *Natural* and *Free Will* actions. According to their distinction, free will actions are actions on the part of agents with the ability to perform or withhold their actions, like choosing to pick up an object, or deciding to walk to some location. In contrast, natural actions are the ones whose occurrence times are predictable in advance, in which case they must occur at those times unless something happens to prevent them, for example, objects moving under Newtonian laws, or trains arriving and departing in accordance with

[8] A comprehensive account of the situation calculus with all its extension so far can be found in [41].

[9] This branching tree structure represents the overall possible evolution of the system being modelled.

[10] Later, McCarthy suggests *events and change* might be a better terminology

known schedules. Nature has no free will; her actions must occur provided the time and circumstances for their occurrence are right [39]. There seems to be relatively few studies in the qualitative spatial reasoning domain aimed at integrating actions/events in the overall spatial cognition process. In [25], a theoretical account of the impact of action related factors on the organisation of spatial information in perception and memory is provided. Likewise, in [33], connections between spatial information and actions has been explored by way of an empirical study. More practical (and important for our work) is the work done by [10], [9] and [20] in the area of qualitative simulation. Postponing a detailed discussion of our interest in these works to Section 5, for now, it suffices to point out that Gooday and Cohn [20] utilize a *event* based approach for the qualitative simulation of spatial changes whereby the behaviour of a system with time is measured in terms of the landmark events that occur in it, i.e. events that result in interesting changes to the system being modelled. Gooday and Cohn's behaviour model corresponds not to a sequence of qualitative state descriptions but to a set of event sequences from which a corresponding sequence of qualitative states can be easily derived should they be required.

4.2 Domain Specific Conceptual Reasoning - A DL Based Approach

We propose a novel approach involving the use of ontological primitives for the specification of synthetic environment representational semantics [4]. A prototype, namely STOWL - *Sedris to OWL Tranform* [6], has been implemented to automate the creation of the desired representation scheme, based on *sed*Onto, from a SEDRIS[11] based synthetic environment database. The use of a industry based standard (namely SEDRIS) as the basis of our SE ontology, called sed*Onto*, makes our approach practically applicable in industrial settings such as Defence and/or Environmental Simulation systems where SEDRIS is generally used. Moreover, *sed*Onto and STOWL are also in line with the broader research goals within the Modeling & Simulation community for the development of Web-Enabled Simulation systems (XMSF). By mapping the UML based SEDRIS Data Representation Model (DRM) to the OWL language, we make explicit the SE representational semantics of the DRM using a language, which unlike UML is inherently suitable to do so. The logical basis of the OWL language means that automated reasoning procedures can be utilized to perform ontological reasoning over SE objects – namely, *subsumption*, *satisfiability*, *equivalence*, *retrieval* etc [3]. Currently, work pertaining to the applications of *sed*Onto and STOWL, viz Terminological reasoning over SE objects, is in progress. We are extending a description logic based reasoner, namely RACER [21], in order to provide synthetic environment specific query answering capabilities over SE data described using *sed*Onto. An indepth account of *sed*Onto, STOWL and their applications can be found in [4, 6]. It must also be pointed out here that from the viewpoint of our cognitive model, it is not essential that we use the SEDRIS technology (or its DRM) as the basis of out synthetic environment data representation ontology. Our model is equally capable of subscribing to any vocabulary for the representation of SE data. The main reason we resort to utilizing SEDRIS

[11] SEDRIS is a de facto standard used within the Defence Sector for the representation, sharing and interoperability of synthetic environment data. For details, see https://www.dmso.mil/public/transition/sedris

in our work is that it fits well within the future scheme of our research – our model is strongly influenced by practical considerations in the defence sector where SEDRIS is a de facto standard. SEDRIS technologies, to achieve the objectives of broad use, have been standardized under the International Standards Organization (ISO) and International Electro-technical Commission (IEC) and as *Standardization for Agreements* (STANAGS) for NATO use. Since we envisage our model to be functional mainly in the defence modelling and simulation scenario, our synthetic environment data representation ontology (sedOnto) subscribes to the SEDRIS vocabulary.

4.3 An Integrated Approach to Qualitative Spatial Reasoning

A Topological Approach based on RCC In our framework, topology is used as a basis of the representation of qualitative spatial knowledge. Specifically, a system of eight mutually exhaustive and pair-wise disjoint qualitative topological relations, namely the Region Connection Calculus (RCC-8) [40] is utilized for out purposes. As mentioned previously in Section 2, one of the main motivations for the use of the RCC-8 system is their similarity to human spatial congnition: RCC-8 relations have been shown to be cognitively adequate for the representation of qualitative spatial knowledge [43], [8]. RCC is a many-sorted first-order axiomatic theory of spatial relations based on a dyadic primitive relation of *connectivity* $(C/2)$ between two regions, a region here being the *spatial extension* of an object. Given two regions x and y, the relation $C(x,\ y)$ is read as *"'x is connected with y"'*, is true if and only if the topological closures of x and y have atleast a point in common. Assuming the $C/2$ relation, and that x and y are variables for spatial regions, RCC goes on to derive a set of other mereotopological dyadic relations on regions of which the following eight are singled out: $DC(x,\ y)-$ x is *disconnected* from y, $EC(x,\ y)$- x is *externally connected* to y, $PO(x,\ y)$- x *partially overlaps* y, $EQ(x,\ y)$- x is *equal* to y, and $TPP(x,\ y)$- x is a *tangential proper part* of y & $NTPP(x,\ y)$- x is a *non-tangential proper-part* of y along with their inverses TPP^{-1} and $NTPP^{-1}$ respectively.

(A1) $\forall x \forall y Region(x) \wedge Region(y) \rightarrow DC(x,y) \vee EC(x,y) \vee PO(x,y) \vee EQ(x,y) \vee TPP(x,y) \vee NTPP(x,y) \vee TPP(y,x) \vee NTPP(y,x)$

Together with 28 axioms of the following form: $\forall x \forall y \neg R_1(x,y) \wedge R_2(x,y)$

An important property the RCC8 set of relations is that they are jointly exhaustive and pair-wise disjoint (JEPD). This property, expressed formally above, basically means that for any given pair of regions, atleast one and atmost one relation from the set of eight primitive relations holds.

Associated with the RCC-8 system is its *Continuity Network* or *Conceptual Neighbourhood Diagram* (CND) (see Fig. 1), a term originating from [15]. Given a relational theory for representing spatial information, a CND associated with that theory is essentially a graph that tries to systematically capture the continuity of a change of relation between spatial objects – with the nodes representing primitive relations from the theory and edges representing direct, continuous transitions between them. For example, Fig. 1 shows the direct transitions possible for a RCC-8 set of jointly exhaustive and

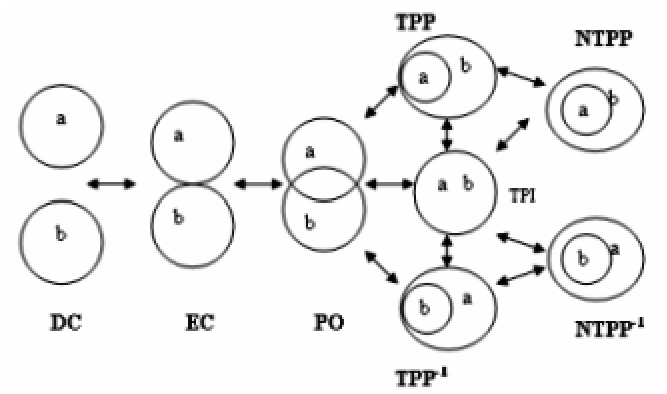

Fig. 1. Direct Topological Transitions for RCC8 Relations

pair-wise disjoint (JEPD) relations. It consists of the following set of eight RCC-8 relations aforementioned. In essence, two spatial relations are neighbours in a CND if a continuous change can yield a direct transition from one relation (node) to the other. This idea of the continuity of spatial change, with respect to a background theory for representing spatial information, inherent in the CND has been previously exploited towards qualitative reasoning about spatial changes in [10, 22, 17]. The RCC-8 CND in Fig. 1 can be formally specified by way of *envisionment axioms* [9] with one axiom for every direct, continuous transition between two base relations. As as example[12], consider axiom **(A2)**, which can be read as: "If the bodies x and y are disconnected during period z, and both continue to exist during the period v after the end of z, there will be a period w, which is part of v and immediately after the end of z, throughout which x and y are either disconnected or externally connected. "

(A2) $\forall xyzv\,[\,DC(x,\ y,\ z)\ \wedge\ Meets(z,\ v)\ \wedge\ \neg NULL(x,\ v)\ \wedge\ \neg Null(y,\ v) \rightarrow$
$\exists w\ Meets(z,\ w) \wedge P(w,\ v) \wedge [DC(x,\ y,\ w)\ \vee\ EC(x,\ y,\ w)\,]\,]$

For the inference part of the theory, RCC uses a compositional approach for topological reasoning, for example ensuring local consistency of RCC based topological information. Using this approach, a basic inference step is: Given that $R_i(x,\ y) \wedge R_j(y,\ z)$, find all R such that $R(x,\ z)$ is $true$, where every such R is one of the topological relations from the RCC theory. A pre-computed compositional table in the form of a 2-dimensional matrix has been computed for various classes of the RCC system, including RCC-8, with every i^{th} and j^{th} entry in such a table representing the composition of relations R_i and R_j from RCC. For a detailed analysis, including a study of the computational properties of such compositional reasoning, please refer to [42].

A General Framework Based on Dynamic Constraints We propose a general framework consisting of a suite of sub-theories, each encompassing a different aspect of spatial change such as distance, size, motion etc, within a theory of spatial changes that is

[12] A complete axiomatisation can be found in [9]

based on topology alone. A constraint (see Def. 1) is dynamic in the sense that it can only be satisfied when dynamic information, pertaining to distance, size, position etc, is available.

Definition 1. *A **Dynamic Constraint** within our framework is a n-ary temporal predicate that may or may not hold a certain point in time. Dynamic constraints are of the form $\phi(arg_1,\ \ldots,\ arg_n)$ and every such constraint has a implicit temporal argument t. A **Dynamic Constraint Set**, denoted as $\Theta_{subtheory}$, is a set consisting of a finite number of such dynamic constraints.*

All dynamic constraints in this paper are binary (temporal argument not included) and will be of the following form: $\phi(arg_1,\ arg_2,\ t)$. For clarity, we may omit the temporal argument in certain cases. Every dynamic constraint set $\Theta_{subtheory}$ characterizes a sub-theory pertaining to a certain aspect of spatial change that needs to be explicitly modelled so as to complement the basic theory of topological changes. As an example consider the sets $\Theta_M\ and\ \Theta_S$ in section 4.3, which denote the class of motion and size constraints that have been included within the theory of topological changes. The inclusion of these constraints has the effect of providing an explicit account of the the relative motion and sizes of the objects involved.

Definition 2. *A **Dynamic Constraint Suite**, denoted by Σ, is the set consisting of all dynamic constraint sets to be included as sub-theories with the framework. More formally, $\Sigma\ \equiv\ \{\Theta_1,\ \Theta_2,\ \ldots\ \Theta_n\}$, where each of the Θ_i represents dynamic constraints relevant to a certain aspect of spatial change being modelled within the framework.*

We refer to a collection of such sub-theories as a dynamic constraint suite. Important, from a computational viewpoint, is the idea of the satisfiability of a set of dynamic constraints $\Theta_{subtheory}$, or $\Sigma - Satisfiability$ in general. Within the context of our framework, the same has been stated more precisely in Def. 3 below:

Definition 3. ***Satisfiability*** *- A set of dynamic constraints, given by $\Theta_{subtheory}$, on a transition between two qualitative states is satisfiable iff $\forall\phi\ holds(\phi,\ t)$*[13]*, where $\phi\ \in\ \Theta_i$. Here, $holds(\phi,\ t)$ should be interpreted as the successful validation of the constraint ϕ based on the dynamically available information at time point t. Likewise, satisfiability of all dynamic constraints within our framework Σ is defined to be the satisfiability of every dynamic constraint set $\Theta_{subtheory}$ contained therein.*

Def. $1-3$, which provide a general representational framework for the specification of the dynamic constraints, will be used to formalise the incorporation of dynamic constraints within the theory of topological changes. We introduce the idea of a ***transition constraint*** - *A transition constraint is essentially a dynamic constraint, but one that is imposed on a certain transition between two topological relations*. The satisfiability criteria for a transition constraint is similar to that of a dynamic constraint expressed in **Def.** 3. Again, intuitively the satisfiability entails that a certain relational transition with

[13] Where possible, we use reified version of predicates for representational flexibility. Reified version are helpful in that they facilitate quantification over relations without resorting to second-order formalisations. The advantages are however, not visible in this paper.

respect to the base topological theory is consistent with the dynamically available (for e.g. sensory) information relevant to the respective spatial aspect that the constraint is supposed to model. A more precise formulation is presented in the following.

Let **R** denote the set of JEPD relations included in the RCC-8 theory – **R** $\equiv \{dc,\ ec,\ po,\ eq,\ tpp,\ ntpp,\ tpp^{-1},\ ntpp^{-1}\}$. Let **T** be a set consisting of ordered pairs of the form $< r_i,\ r_j >$ (a binary relation on **R**). For clarity, we refer to such a ordered pair using the predicate $trans(r_i,\ r_j)$. Its intended semantics is that a direct, continuous transition from $r_i\ to\ r_j$ is legal (though not necessarily possible). Note that the set **T** can be easily defined by simple enumeration on the basis of the transition network of RCC-8 shown in Fig. 1 or be derived from the envisionment axioms like **(A2)** defined in the preceding sub-section. Also, the scope of the universally quantified region variables $x\ and\ y$ in the definition **P** below is understood to be the subset of regions that are related by r_i at time point t_1. The following is the formal definition for a transition constraint:

(P) $poss(< r_i,\ r_j >,\ t)\ \equiv [(\forall x,\ y)\ (\exists\, t_1\ t_2)]$
$$(t_1\ <\ t_2) \wedge (t_2\ <\ t) \wedge holds(r_i,\ x,\ y,\ t_1) \wedge \phi_1(x,\ y,\ t_2) \wedge\ \ldots\ \wedge \phi_k(x,\ y,\ t_2).$$
where $< r_i,\ r_j >\ \in\ \mathbf{T},\ and\ \phi_i\ \ldots\ \phi_k\ \in\ \Theta\ from\ \Sigma$

The intended interpretation for **P** defined above is that a direct, continuous and legal transition from $r_i\ to\ r_j$ is *possible* at time point t if regions $x\ and\ y$ have the relation r_i between them at some time-point t_1 before t and that at other time-point t_2 between $t_1\ and\ t$, the dynamic constraints imposed on the the legal transition $trans(r_i,\ r_j)$ can be *satisfied* on the basis of the dynamically available information pertaining to the spatial aspect being modelled by the respective constraint.

The idea of ***minimal and Σ-consistency*** has been informally defined below in Def. 4. Minimal consistency essentially entails that absolutely no transition constraints have been imposed on the direct topological changes possible between RCC-8 relations. It can be easily verified that the concept of $\Sigma - Consistency$ is much more richer than the minimal/general account of spatial changes provided by the RCC-8 direct topological transitions. This is because depending on the number and nature of the additional sub-theories included within Σ, additional information that is dynamically available will be utilised whilst simulating the physical system.

Definition 4. ***Consistency of an Envisionment*** *- An envisionment*[14] *of a physical system, either partial or complete, is* ***minimally consistent*** *iff the transitions between qualitative states (topological relations between objects) of the system are solely based on the direct topological transitions possible wrt the RCC-8 conceptual neighbourhood diagram. Similarly, the envisionment is* ***maximally consistent***[15]*, also referred to as '*Σ***-Consistent****', iff the transitions between the states* satisfy *every set of constraints included in the* Σ*, in addition to being consistent with the RCC-8 CND.*

A formal account of the Σ-Consistency of transitions between qualitative states or a complete envisionment of a physical system can be derived by generalizing the

[14] An envisionment is a temporal partial ordering of all the qualitative states a modelled physical system can evolve into given some indexed/initial state [48]

[15] Of Course, within the context of our theory of dynamic constraints.

definition of a transition constraint **(P)** given previously. Precisely, the definition of $poss(r_i,\ r_j)$ entails the consistency of a single transition, for e.g., from DC to EC, involving two objects. This definition needs to be generalised for a arbitrary chain of *legal transitions* $r_0,\ r_1,\ \ldots,\ r_n$ involving more than two objects. Such a chain of transitions is $\Sigma - Consistent$ *iff* $poss(r_i,\ r_{i+1})$ is true for all $< r_i,\ r_{i+1} >$. These definitions can easily be extended to handle domains consisting of a arbitrary number of objects. However, the definitions already presented are sufficient for the purposes of this paper.

Motion and Size Constraints on Topological Transitions In this section, we illustrate how the formal framework developed in the previous sub-section can be applied - we illustrate the incorporation of dynamically available information pertaining to the relative movement and sizes of objects. Note that this paper does not attempt to provide a full-scale treatment of motion or relative sizes of spatial objects. Our use of motion and size constraints in this section is only exemplary of the manner in which the proposed framework involving dynamic constraints is to be utilised.

(A3) $DC(x,\ y)\ \equiv_{def}\ dist(x,\ y)\ >\ \delta$
(A4) $EC(x,\ y)\ \equiv_{def}\ dist(x,\ y)\ \leq\ \delta\ \wedge dist(x,\ y)\ \neq 0$
(A5) $Co(x,\ y)\ \equiv_{def}\ dist(x,\ y)\ =\ 0$

We define a class of motion constraints Θ_M (see Def. 5) that are based on a simple notion of time-varying distances between objects. These constraints are in turn based on three dyadic relations, DC - disconnected, EC - externally connected and CO - coalesce, between pairs of regions expressed using the function $dist(x,\ y)$ (see A3-A5). For e.g., two regions are *disconnected* if the degree of displacement between them is greater a certain δ, where δ is a domain dependent parameter. We sometimes use the primitive function $dist(x,\ y)$ with a temporal argument, as in $dist(x,\ y,\ t)$, to denote the distance between x and y at time-point t. The distance function can be intuitively understood as the size of the shortest line connecting any two points in the two region boundaries. The concept of distance should be understood as a qualitative notion of displacement, i.e., the accurate measurements are not important [44], but how the distance between regions varies with time so as to capture their relative movement.

Definition 5. *The class of* ***motion constraints*** Θ_M *includes dynamic constraints of the form discussed in Def. 1. Specifically,* Θ_M *consists of the five motion relations based on the primitive notion of distance between two regions that are defined axiomatically in C1-C5:* $\Theta_M\ \equiv\ \{\phi_{ap},\ \phi_{re},\ \phi_{sp},\ \phi_{co},\ \phi_{st}\}$.

(C1) $\phi_{ap}(x,\ y,\ t)\ \equiv_{def}\ [(\exists\, t_1\, t_2)]\,(t_1\ <\ t)\wedge(t\ <\ t_2)\wedge holds(DC,\ x,\ y,\ t_1)\wedge$
$\neg\, holds(CO,\ x,\ y,\ t_2)\wedge dist(x,\ y,\ t_1)\ >\ dist(x,\ y,\ t_2)$
(C2) $\phi_{re}(x,\ y,\ t)\ \equiv_{def}\ [(\exists\, t_1\, t_2)]\,(t_1\ <\ t)\wedge(t\ <\ t_2)\wedge[holds(DC,\ x,\ y,\ t_1)\vee$
$holds(EC,\ x,\ y,\ t_1)]\wedge dist(x,\ y,\ t_1)\ <\ dist(x,\ y,\ t_2)$
(C3) $\phi_{sp}(x,\ y,\ t)\ \equiv_{def}\ [(\exists\, t_1\, t_2)]\,(t_1\ <\ t)\wedge(t\ <\ t_2)\wedge[holds(DC,\ x,\ y,\ t_2)\vee$
$holds(EC,\ x,\ y,\ t_2)]\ \wedge\ holds(CO,\ x,\ y,\ t_1)$
(C4) $\phi_{co}(x,\ y,\ t)\ \equiv_{def}\ [(\exists\, t_1\, t_2)]\,(t_1\ <\ t)\wedge(t\ <\ t_2)\wedge[holds(DC,\ x,\ y,\ t_1)\vee$
$holds(EC,\ x,\ y,\ t_1)]\ \wedge\ holds(CO,\ x,\ y,\ t_2)$

(C5) $\phi_{st}(x,\ y,\ t)\ \equiv_{def}\ [(\exists\, t_1\, t_2)]\ (t_1\ <\ t)\ \wedge\ (t\ <\ t_2) \wedge$
$dist(x,\ y,\ t_1)\ =\ dist(x,\ y,\ t_2)$

The following interpretation holds for the motion constraints defined in Θ_M: $\phi_{ap}(x,\ y,\ t)$ – x & y are approaching each other at time-point t, $\phi_{re}(x,\ y,\ t)$ – x & y are receding from each other, $\phi_{sp}(x,\ y,\ t)$ – x & y are splitting, $\phi_{co}(x,\ y,\ t)$ – x & y are coalesce, and $\phi_{st}(x,\ y,\ t)$ – x & y are static.

We also define define a class of size constraints Θ_S (see Def. 6) that are based on primitive comparison relations between the sizes of the regions involved. We assume that the size of a $n-dimensional$ region corresponds to its $n-dimensional$ measure. For example, the size of a sphere in R^3 corresponds to its volume. The function $size(x)$ will be used to denote the size of an region x.

Definition 6. *The class of* ***size constraints*** Θ_S *includes the following dynamic constraints that relate the size of two regions at a certain time point:* $\Theta_S \equiv \{\phi_<,\ \phi_>,\ \phi_\leq,\ \phi_\geq,\ \phi_=\}$. *Each of the size constraints is of the form* $\phi_{size\_rel}(x,\ y,\ t)$*, where* $\phi_{size\_rel} \in \Theta_S$*. For notational convenience, the interpretation of* $\phi_{size\_rel}(x,\ y,\ t)$ *is explained with an example:* $\phi_<(x,\ y,\ t)$ *should be interpreted as '*$size(x)\ <\ size(y)$*' at time t, where* $size(x)$ *is the size of region* x*, and* $size(y)$ *is the size of region* y*.*

We now have a dynamic constraint suite $\Sigma\ \equiv\ \{\Theta_M,\ \Theta_S\}$. Dynamic constraints that make up the theory Σ can now be used for the definition of transition constraints, i.e., dynamic constraints imposed on the topological transitions. The precise representational form of the transition constraints definable within the context of our theory Σ will follow the generic definition in **P**.

(T1) $poss(trans(dc,\ ec),\ t)\ \equiv [(\forall x,\ y)\ (\exists\, t_1\, t_2)]$
$(t_1\ <\ t_2)\ \wedge\ (t_2\ <\ t)\ \wedge\ holds(dc,\ x,\ y),\ t_1)\ \wedge\ \mathbf{[}\phi_{ap}(x,\ y,\ t_2)\mathbf{]}$
(T2) $poss(trans(ec,\ dc),\ t)\ \equiv [(\forall x,\ y)\ (\exists\, t_1\, t_2)]$
$(t_1\ <\ t_2)\ \wedge\ (t_2\ <\ t)\ \wedge\ holds(dc,\ x,\ y,\ t_1)\ \wedge\ \mathbf{[}\phi_{re}(x,\ y,\ t_2)\mathbf{]}$
(T3) $poss(trans(po,\ eq),\ t))\ \equiv [(\forall x,\ y)\ (\exists\, t_1\, t_2)]$
$(t_1\ <\ t_2) \wedge (t_2\ <\ t) \wedge holds(po,\ x,\ y,\ t_1) \wedge \mathbf{[}\phi_{co}(x,\ y,\ t_2) \wedge \phi_=(x,\ y,\ t_2)\mathbf{]}$
(T4) $poss(trans(po,\ tpp),\ t))\ \equiv [(\forall x,\ y)\ (\exists\, t_1\, t_2)]\ (t_1\ <\ t_2)\ \wedge\ (t_2\ <\ t)$
$\wedge\, holds(po,\ x,\ y,\ t_1)\ \wedge\ \mathbf{[}\neg\phi_{co}(x,\ y,\ t_2)\ \wedge\ \phi_<(x,\ y,\ t_2)\ \wedge\ \neg\phi_{sp}(x,\ y,\ t_2)\mathbf{]}$

For parsimony of space, we only illustrate a subset of the transition constraints that are definable by way of the axioms **T1-T4** above. The dynamic constraints from our framework that are imposed on the transitions are highlighted in the brackets. An an example, consider transition constraint **T4** $- -poss(trans(po,\ tpp),\ t))$. It enforces the condition that a legal transition between two regions from po to tpp is *possible* at time-point t iff at some time-point $t_1\ <\ t$, $x\ and\ y$ were po at t_1, and at another time-point t_2, such that $t_1\ <\ t_2\ <\ t$, the dynamic constraints imposed on the transition are *satisfiable*. Notice how this simple axiom integrates three differing aspects of spatial change – topology, motion & size. A similar discussion applies for other transition constraints as well and will been left out in this paper. Details can be found in [5].

4.4 Discussion and Related Work

The overall context of our work in Section 4.3 is centered around the idea of an envisionment based qualitative simulation program [48]. The theoretical underpinnings of such a system support a planning or a synthetic function that we intend on exploiting: *Given an initial and a desired configuration, one can synthesize valid paths (sequence of qualitative spatial transitions over time) to achieve the goal*. The work in [10] utilizes the the same approach and is based on a logical theory of topological changes alone. Although their work utilizes constraints, they are used in a static and domain dependent manner in the form of inter & intra-state constraints. Motion, size or any other aspect of space is not treated explicitly and dynamically available information has not been utilized. Using our approach, the specification of some of the domain specific constraints becomes redundant – for r.g., Consider two regions a and b, such that $size(a) \ < \ size(b)$ at all times. Since a is smaller than b, one constraint that always need to be maintained (an inter-state constraint) is that b can never be a tangential or non-tangential proper-part of a. Since size constraints are explicitly accounted for in the form of transition constraints in our theory, no domain specific constraint to the effect needs to be specified by the domain modeller.

The formulation of motion constraints in Section 4.3 is based on the idea of defining connectedness between two objects using the primitive notion of displacement between them. Albeit in a slightly different context, this idea arises from [44]. Using this formulation, the relation of *partial overlap* (PO) between two regions cannot be expressed when connectedness is defined using the primitive the notion of distance (see $A3 - A5$). As such, dynamic constraints on $trans(ec,\ po)$ or $trans(po,\ ec)$ are not definable. This, however, reflects the lack of expressivity of the manner in which motion is defined. Dealing with such inadequacies or providing a full-scale treatment of motion, which is beyond the scope of our research interests, has already been treated elsewhere [17, 18].

5 A Unified Representational Semantics for Space, Time & Causality – Work In Progress

The most important problem to be addressed in our research is the formalisation of a unified representational semantics for spatial, temporal and action logics. There is a need for the incorporation of information pertaining to causality and processes in within a theory of spatial changes [10]. In our view, this necessitates the use of action logics. We are interested in the use of non-monotonic approaches to represent and reason about causality in general and spatial changes in particular; the non-monotonicity being useful for the incorporation of default behaviours in the presence of incomplete information. Similar work can be found in [20] where a non-monotonic formalism for reasoning about action & change, namely the transition calculus, was utilised for the representation of qualitative simulation systems; however, the formalism's non-monotonic capabilities were not utilised. Moreover, concurrency of change, which is a crucial phenomena that must be accounted for, too has not been dealt with inspite of the capability of transition calculus to handle such phenomena.

Our work in this regard is at a preliminary stage; For completeness, here we provide an succinct description of the approach we have adopted. We are currently formalizing a process model, something along the lines of the qualitative process theory [14], using the ontological commitments discussed in Section 4.1. The fundamental building block will still be a qualitative simulation system based on a theory of topological changes; however, unlike [10], it will also encompass other spatial aspects using our framework of dynamic constraints. In our process model, actions, events, temporal points & intervals will be regarded as first class objects – i.e., the extended situation calculus ontology will be used to specify the semantics of our process model. The important point here being that this process model would incorporate space, time and causality within one framework. We use the purported process model as the basis of representing continuous and concurrent phenomena. Although the issue of continuous and concurrent processes has been dealt within extensively in the vast amount of research on reasoning about action & change [45, 41], the same (concurrency) has not been accounted for in the case of spatial changes. Within the context of our integrated framework, an important research goal, which has strongly motivated some of the ontological commitments we made, is to account for such phenomena.

6 Conclusion

Based on the generally accepted definition of situation awareness, we propose a computational model that encompasses common-sense conceptual reasoning and reasoning about space, time and actions within a unified framework. The proposed model of SA, which takes the form of a logic-based framework, will be most beneficial for systems involving the representation of physical and/or intelligent autonomous processes. However, we are primarily interested in applying the model in the defence Modelling & Simulation domain. Our intended application notwithstanding, the generality of our approach should not be taken for granted; the said framework is essentially based on a process model comprised of rather rich (or abstract) ontological commitments involving spatial, temporal and action/event oriented concepts, with its support for concurrent and continuous phenomena. With these elements, the proposed model is general enough to be used to support a synthetic planning function within an online simulation system or statically derive temporal projections for a dynamic system with a view to answer queries based on such projections.

References

[1] J. F. Allen. Towards a general theory of action and time. *Artif. Intell.*, 23(2):123–154, 1984. ISSN 0004-3702. doi: http://dx.doi.org/10.1016/0004-3702(84)90008-0.

[2] J. F. Allen and P. J. Hayes. A common sense theory of time. In *Proceedings of IJCAI*, Los Altos, 1985. Morgan Kaufmann.

[3] F. Baader, D. Calvanese, D. L. McGuinness, D. Nardi, and P. F. Patel-Schneider. *The description logic handbook: theory, implementation, and applications*. Cambridge University Press, 2003. ISBN 0-521-78176-0.

[4] M. Bhatt, W. Rahayu, and G. Sterling. sedOnto: A Web Enabled Ontology for Synthetic Environment Representation Based on the SEDRIS Specification. In *Proceedings of the Fall Simulation Interoperability Workshop*, September 2004.

[5] M. Bhatt, W. Rahayu, and G. Sterling. A general framework based on dynamic constraints for the enrichment of a topological theory of spatial simulation. In *Ninth International Conference on Knowledge-Based Intelligent Information and Engineering Systems*. Springer, 2005. To Appear.

[6] M. Bhatt, W. Rahayu, and G. Sterling. Synthetic environment representational semantics using the web ontology language. In *Sixth International Conference on Intelligent Data Engineering and Automated Learning (IDEAL)*, pages 9–16. LNCS, 2005.

[7] C. Christou and H. H. Bülthoff. Using realistic virtual environments in the study of spatial encoding. In *Spatial Cognition*, pages 317–332, 2000.

[8] A. G. Cohn. Qualitative spatial representation and reasoning techniques. In *KI '97: Proceedings of the 21st Annual German Conference on Artificial Intelligence*, pages 1–30, London, UK, 1997. Springer-Verlag. ISBN 3-540-63493-2.

[9] A. G. Cohn, N. M. Gotts, D. A. Randell, Z. Cui, B. Bennett, and J. M. Gooday. Exploiting temporal continuity in qualitative spatial calculi. In R. G. Golledge and M. J. Egenhofer, editors, *Spatial and Temporal Reasoning in Geographical Information Systems*. Elsevier, 1997.

[10] Z. Cui, A. G. Cohn, and D. A. Randell. Qualitative simulation based on a logical formalism of space and time. In *Proceedings of AAAI-92*, pages 679–684. AAAI Press, 1992.

[11] M. Endsley. Design and evaluation for situation awareness enhancement. In *Proceedings of the Human Factors and Ergonomics Society 32nd Annual Meeting*, pages 97–101. Human Factors and Ergonomics Society, Inc., 1988.

[12] M. Endsley. *Situation Awareness in Dynamic Human Decision Making*. PhD thesis, University of Southern California, Los Angeles, CA, 1990.

[13] M. Endsley. Toward a theory of situation awareness in dynamic systems. *Human Factors*, 37(1):32–64, 1995.

[14] K. D. Forbus. Qualitative process theory. *Artif. Intell.*, 24(1-3):85–168, 1984. ISSN 0004-3702. doi: http://dx.doi.org/10.1016/0004-3702(84)90038-9.

[15] C. Freksa. Conceptual neighborhood and its role in temporal and spatial reasoning. In M. Singh and L. Travé-Massuyès, editors, *Decision Support Systems and Qualitative Reasoning*, pages 181–187. North-Holland, Amsterdam, 1991.

[16] C. Freksa. Using orientation information for qualitative spatial reasoning. In *Proceedings of the International Conference GIS - From Space to Territory: Theories and Methods of Spatio-Temporal Reasoning on Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, pages 162–178, London, UK, 1992. Springer-Verlag. ISBN 3-540-55966-3.

[17] A. Galton. Towards an integrated logic of space, time and motion. In *IJCAI*, pages 1550–1557, 1993.

[18] A. Galton. Towards a qualitative theory of movement. In A. U. Frank and W. Kuhn, editors, *Spatial Information Theory - A Theoretical Basis for GIS (COSIT'95)*, pages 377–396. Springer, Berlin, Heidelberg, 1995.

[19] A. Galton. *Qualitative Spatial Change*. Oxford University Press, 2000. ISBN 0198233973.

[20] J. Gooday and A. Cohn. Transition-based qualitative simulation. In *Proceeding of the 10th International Workshop on Qualitative Reasoning*, pages 74–82. AAAI press, 1996.

[21] V. Haarslev, R. Möller, and M. Wessel. Renamed ABox and Concept Expression Reasoner. http://www.sts.tu-harburg.de/ r.f.moeller/racer/.

[22] D. Hernandez. Reasoning with qualitative representations: Exploiting the structure of space. In N. Carrete and M. Singh, editors, *Qualitative Reasoning and Decision Technologies*, pages 493–502. Barcelona: CIMNE, 1993.

[23] D. Hernandez. *Qualitative Representation of Spatial Knowledge*. Springer-Verlag New York, Inc., Secaucus, NJ, USA, 1994. ISBN 0387580581.

[24] D. Hernandez, E. Clementini, and P. D. Felice. Qualitative distances. In *Spatial Information Theory: A Theoretical basis for GIS*, number 988, pages 45–58. Lecture Notes in Computer Science, 1995.

[25] B. Hommel and L. Knuf. Action related determinants of spatial coding in perception and memory. In *Spatial Cognition*, pages 387–398, 2000.

[26] I. Horrocks. DAML+OIL: A Reasonable Ontology Language. In *Proceedings of EDBT-02, Volume 2287 of LNCS*, pages 2–13, 2002.

[27] R. Kowalski and M. Sergot. A logic-based calculus of events. *New Gen. Comput.*, 4(1):67–95, 1986. ISSN 0288-3635.

[28] B. Kuipers. *Qualitative reasoning: modeling and simulation with incomplete knowledge*. MIT Press, 1994. ISBN 0-262-11190-X.

[29] A. Lucas and S. Goss. The potential for intelligent software agents in defence simulation. In R. Evans, L. White, D. McMichael, and L. Sciacca, editors, *Proceedings of Information Decision and Control 99*, pages 579–583, Adelaide, Australia, February 1999. Institute of Electrical and Electronic Engineers, Inc. URL http://www.eleceng.adelaide.edu.au/ieee/idc99/abstracts/lucas1.html.

[30] J. McCarthy. Epistemological problems of artificial intelligence. pages 46–52, 1987.

[31] J. McCarthy. Actions and other events in situation calculus. In *KR*, pages 615–628, 2002.

[32] J. McCarthy and P. J. Hayes. Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer and D. Michie, editors, *Machine Intelligence 4*, pages 463–502. Edinburgh University Press, 1969.

[33] S. Mecklenbräuker, W. Wippich, M. Wagener, and J. E. Saathoff. Spatial information and actions. In *Spatial Cognition*, pages 39–62, 1998.

[34] D. R. Montello. Scale and multiple psychologies of space. In A. U. Frank and I. Campari, editors, *Spatial Information Theory: A Theoretical Basis for GIS, International Conference COSIT'93*, volume 716 of *Lecture Notes in Computer Science*, pages 312–321, 1993. ISBN 3-540-57207-4.

[35] D. R. Montello. Spatial cognition. In N. J. Smelser and P. B. Baltes, editors, *International Encyclopedia of the Social and Behavioral Sciences*, pages 14771–14775. Oxford, Pergamon Press, 2001.

[36] P. Péruch, L. Belingard, and C. Thinus-Blanc. Transfer of spatial knowledge from virtual to real environments. In *Spatial Cognition*, pages 253–264, 2000.

[37] J. Pinto and R. Reiter. Reasoning about time in the situation calculus. *Annals of Mathematics and Artificial Intelligence*, 14(2-4):251–268, 1995.

[38] J. A. Pinto. *Temporal reasoning in the situation calculus*. PhD thesis, 1994. Supervisor-Raymond Reiter.

[39] F. Pirri and R. Reiter. Planning with natural actions in the situation calculus. pages 213–231, 2000.

[40] D. A. Randell, Z. Cui, and A. Cohn. A spatial logic based on regions and connection. In B. Nebel, C. Rich, and W. Swartout, editors, *KR'92. Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference*, pages 165–176. Morgan Kaufmann, San Mateo, California, 1992.

[41] R. Reiter. *Knowledge in action: Logical foundations for describing and implementing dynamical systems*. MIT Press, 2001.

[42] J. Renz. *Qualitative Spatial Reasoning with Topological Information*, volume 2293. Springer-Verlag Heidelberg, 2002. ISBN 3-540-43346-5.

[43] J. Renz, R. Rauh, and M. Knauff. Towards cognitive adequacy of topological spatial relations. In *Spatial Cognition II, Integrating Abstract Theories, Empirical Studies, Formal Methods, and Practical Applications*, pages 184–197. Springer-Verlag, 2000. ISBN 3-540-67584-1.

[44] P. Santos and M. Shanahan. From regions to transitions, from transitions to objects. In C. Baral and S. McIlraith, editors, *AAAI-02 Cognitive Robotics Workshop, Working notes of the AAAI Workshop on Cognitive Robotics*, 2002.

[45] Y. Shoham. *Reasoning about change: time and causation from the standpoint of artificial intelligence*. MIT Press, 1988. ISBN 0-262-19269-1.

[46] E. Ternovskaia. Interval situation calculus. In *KI '94: Proceedings of the 18th Annual German Conference on Artificial Intelligence*, page 400, London, UK, 1994. Springer-Verlag. ISBN 3-540-58467-6.

[47] L. Vieu. Spatial representation and reasoning in AI. In O. Stock, editor, *Spatial and Temporal Reasoning*, pages 5–40. Kluwer Academic Publishers, 1997. ISBN 0792346440.

[48] D. S. Weld and J. de Kleer. *Readings in Qualitative Reasoning about Physical Systems*. Morgan Kaufmann Publishers, 1989.