An \textit{ALC}(\mathcal{D})\textit{-based combination of temporal constraints and spatial constraints suitable for continuous (spatial) change

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Abstract. We present a family of spatio-temporal theories suitable for continuous spatial change in general, and for continuous motion of spatial scenes in particular. The family is obtained by spatio-temporalising the well-known \textit{ALC}(\mathcal{D}) family of Description Logics (DLs) with a concrete domain \mathcal{D}, as follows, where TCSPs denote "Temporal Constraint Satisfaction Problems", a well-known constraint-based framework: (1) temporalisation of the roles, so that they consist of TCSP constraints (specifically, of an adaptation of TCSP constraints to interval variables); and (2) spatialisation of the concrete domain \mathcal{D}: the concrete domain is now \mathcal{D}_x, and is generated by a spatial Relation Algebra (RA) \mathcal{R}, in the style of the Region-Connection Calculus RCC8. We assume durative truth (i.e., holding during a durative interval). We also assume the homogeneity property (if a truth holds during a given interval, it holds during all of its subintervals). Among other things, these assumptions raise the "conflicting" problem of overlapping truths, which the work solves with the use of a specific partition of the 13 atomic relations of Allen’s interval algebra.

Keywords: Temporal Reasoning, Spatial Reasoning, Reasoning about Actions and Change, Constraint Satisfaction, Description Logics, Knowledge Representation, Qualitative Reasoning

1 Introduction

We start with our answer to the question of whether Artificial Intelligence (AI) should reconsider, or revise its challenges:

"AI to the service of the Earth as the Humanity’s global, continuous environment: the role of continuous (spatial) change in building a lasting global, locally plausible democracy: (Cognitive) AI which is guided by cognitively plausible assumptions on the physical world, such as, e.g., "the continuity of (spatial) change", will start touching at its actual success, the day it will have begun to serve, in return, as a source of inspiration for lasting solutions to challenges such as, a World’s globalisation respectful of local, regional beliefs and traditions. One of the most urgent steps, we believe, is the implementation, in the Humanity’s global mind, of the idea of “continuous change”, before any attempt of discontinuous globalisation of our continuous Earth reaches a point of non return.”

Standard \textit{CSP}s (Constraint Satisfaction Problems) \cite{10, 11} were originally developed for variables with discrete domains. With the aim of extending \textit{CSP}s to continuous variables, Dechter et al. \cite{3} developed what is known in the literature as \textit{TCSP}s (Temporal Constraint Satisfaction Problems), whose variables are continuous, in the sense that they range over a continuous domain.

Constraint-based \textit{QSR} (Qualitative Spatial Reasoning) languages very often consist of finite RAs (Relation Algebras) \cite{16}, with tables recording the results of applying the different operations to the different atoms, and the reasoning issue reduced to a matter of table look-ups: a good illustration to this is the well-known topological calculus RCC8 \cite{12} (see also \cite{4}).

The goal of the present work is to combine \textit{TCSP}-like quantitative temporal constraints with RCC8-like qualitative spatial constraints. The targetted applications are those involving motion, and spatial change in general, and include reasoning about dynamic scenes in (high-level) computer vision, and robot navigation. The framework we get can be seen as a spatio-temporalisation of the well-known \textit{ALC}(\mathcal{D}) family of Description Logics (DLs) with a concrete domain \mathcal{D} \cite{2}, which is obtained by performing two specialisations at the same time: (1) temporalisation of the roles, so that they consist of \textit{TCSP} constraints (specifically, of an adaptation of \textit{TCSP} constraints to interval variables); and (2) spatialisation of the concrete domain \mathcal{D}: the concrete domain is now \mathcal{D}_x, and is generated by a spatial Relation Algebra (RA) \mathcal{R}, such as the Region-Connection Calculus RCC8 \cite{12}. The final spatio-temporalisation of \textit{ALC}(\mathcal{D}) will be referred to as \textit{TCSP-ALC}(\mathcal{D}_x), and its main properties can be summarised as follows: (1) the (abstract) domain (i.e., the set of worlds in modal logics terminology) of \textit{TCSP-ALC}(\mathcal{D}_x) interpretations is a universe of time intervals; (2) the roles consist of 4-argument tuples providing \textit{TCSP} constraints on the different pairs of endpoints of two intervals; and (3) the concrete domain \mathcal{D}_x is generated by an RCC8-like constraint-based qualitative spatial language \mathcal{R}.

Constraint-based languages candidate for generating a concrete domain for a member of our family of spatio-temporal theories, are spatial RAs for which the atomic relations form a decidable subset —i.e., such that consistency of a CSP expressed as a conjunction of n-ary relations on n-tuples of objects, where n is the arity of the RA relations, is decidable. Examples of such RAs known in the literature include the Region-Connection Calculus RCC8 in \cite{12} and the projection-based Cardinal Direction Algebra CD in \cite{8}, for the binary case; and the RA CYC\ell_2 of 2D orientations in \cite{3} for the ternary case.
Examples of work in the literature on, or related to, change include \[8, 14, 5\]. In this work, we are interested in continuous change, and the approach we follow has many similarities with the one in \[5\]. A first difference with \[5\] is that, we will be interested in representing continuous change, not only in propositional truth (or knowledge), but in (relational) spatial truth as well. Both truths hold during intervals. But contrary to the approach in \[5\] (second difference), we consider that truth is durative, in the sense that it holds during durative, non-null intervals (intervals are thus interpreted as in \[1\]). An endpoint of an interval may or may not belong to the interval (see, e.g., \[6\] on this issue, and on the issue of continuity in general).

The work can be seen as an extension of CSPs (Constraint Satisfaction problems) of Allen’s interval constraints \[1\]. An Allen’s CSP is, in some sense, blind, in the sense that, a solution to it is just a (consistent) collection of intervals with the qualitative relation on each pair of them. The solution tells nothing about possible change in truth (or truths) in the real world. In this work, as mentioned above, we consider two kinds of truth, propositional truth and (relational) spatial truth. The first truth can be seen as a propositional formula, and the second as a similar formula, where, instead of literals, we have qualitative spatial constraints on objects of the spatial domain of interest (the domain of interest may be a topological space, the objects regions of that space, and the relations \(\text{RCC8} \) relations \[12\]). The conjunction of the two truths, transformed into \(\text{DNF} \) (Disjunctive Normal Form), has disjuncts\(^a\) consisting of conjuncts of literals and qualitative spatial constraints. The \(\text{DNF} \) is true during an interval, if one of its disjuncts is true during that interval. As a consequence, if \(I_1 \) is true during interval \(I_1 \) and \(I_2 \) during interval \(I_2 \), and if \(I_1 \) and \(I_2 \) have a 1-dimensional intersection, then the conjunction of \(I_1 \) and \(I_2 \) should be consistent. It follows that the following partition of Allen’s 13 atoms into three convex relations will be primordial to our work: (1) the relation consisting of the union of the before and meets atoms; (2) its converse, containing the after and met-by relations; and (3) the relation containing the remaining 9 atoms, which holds between two intervals \(\iff \) they have a 1-dimensional intersection. Now, given truth \(I_1 \) holding during \(I_1 \) and truth \(I_2 \) holding during \(I_2 \), \(C_1 \) and \(C_2 \) interact (i.e., their conjunction is required to be consistent) \(\iff \) \(I_1 \) and \(I_2 \) are related by the third relation of the partition.

The paper, without loss of generality, will focus on a concrete domain generated by one of the three binary spatial RAs mentioned above, \(\text{RCC8} \) \[12\], and on another concrete domain generated by the ternary spatial RA \(C_3 \) \(\cap \) \(C_1 \) in \[9\].

2 Constraint satisfaction problems

A constraint satisfaction problem (CSP) of order \(n \) consists of the following: (1) a finite set of \(n \) variables, \(x_1, \ldots, x_n \); (2) a set \(U \) (called the universe of the problem); and (3) a set of constraints on values from \(U \) which may be assigned to the variables. The problem is solvable if the constraints can be satisfied by some assignment of values \(a_1, \ldots, a_n \in U \) to the variables \(x_1, \ldots, x_n \), in which case the sequence \(a_1, \ldots, a_n \) is called a solution. Two problems are equivalent if they have the same set of solutions.

An \(m \)-ary constraint is of the form \(R(x_1, \ldots, x_m) \), and asserts that the \(m \)-tuple of values assigned to the variables \(x_1, \ldots, x_m \) must lie in the \(m \)-ary relation \(R \) (an \(m \)-ary relation over the universe \(U \) is any subset of \(U^m \)). An \(m \)-ary CSP is one of which the constraints are \(m \)-ary constraints. We will be considering exclusively binary CSPs and ternary CSPs.

3 Temporal Constraint Satisfaction Problems —\(\text{TCSPs} \)

\(\text{TCSPs} \) have been proposed in \[3\] as an extension of (discrete) CSPs \[10, 11\] to continuous variables.

Definition 1 (\(\text{TCSP} \) \[3\]) A \(\text{TCSP} \) consists of (1) a finite number of variables ranging over the universe of time points; and (2) Dechter, Meiri and Pearl’s constraints (henceforth \(\text{DMP} \) constraints) on the variables.

A \(\text{DMP} \) constraint is either unary or binary. A unary constraint has the form \(R(Y) \), and a binary constraint the form \(R(X, Y) \), where \(R \) is a subset of the set \(\mathbb{R} \) of real numbers, seen as a unary relation in the former case, and as a binary relation in the latter case, and \(X \) and \(Y \) are variables ranging over the universe of time points: the unary constraint \(R(Y) \) is interpreted as \(Y \in R \), and the binary constraint \(R(X, Y) \) as \((Y - X) \in R \). A unary constraint \(R(Y) \) may be seen as a special binary constraint if we consider an origin of the World (time 0), represented, say, by a variable \(X_0 \): \(R(Y) \) is then equivalent to \(R(X_0, Y) \). Unless explicitly stated otherwise, we assume, in the rest of the paper, that the constraints of a \(\text{TCSP} \) are all binary.

Definition 2 (\(\text{STP} \) \[3\]) An \(\text{STP} \) (Simple Temporal Problem) is a \(\text{TCSP} \) of which all the constraints are convex, i.e., of the form \(R(X, Y) \), \(R \) being a convex subset of \(\mathbb{R} \).

The universal relation for \(\text{TCSPs} \) in general, and for \(\text{STPs} \) in particular, is the relation consisting of the whole set \(\mathbb{R} \) of real numbers; the knowledge \((Y - X) \in \mathbb{R} \), expressed by the \(\text{DMP} \) constraint \(\mathbb{R}(X, Y) \), is equivalent to “no knowledge”. The identity relation is the (convex) set reducing to the singleton \(\{0\} \): the constraint \(\{0\}(X, Y) \) “forces” variables \(X \) and \(Y \) to be equal.

4 A quick overview of Allen’s interval algebra

Allen’s RA \[1\] is well-known. Its importance for this work is primordial, since it handles relations on temporal intervals, instead of relations on temporal points as in the RA in \[17\]: as such, it captures much better the idea of continuity of spatial change in the physical world \[6\]. Briefly, the algebra is qualitative and contains 13 atoms, which allow to differentiate between the 13 possible configurations of two intervals on the time line. The atoms are \(< \) (before), \(m \) (meets), \(o \) (overlaps), \(s \) (starts), \(d \) (during), \(f \) (finishes); their respective converses \(> \) (after), \(mi \) (met-by), \(oi \) (overlapped-by), \(si \) (started-by), \(di \) (contains), \(fi \) (finished-by); and \(eq \) (equals), which is its proper converse.

A partition suitable for continuous change. We will be using the partition of the set of Allen’s atoms into three \(\text{JEPD} \) (Jointly Exhaustive and Pairwise Disjoint) sets, which are \(\text{PRECEDES} \), \(\text{INTERSECTS} \) and \(\text{FOLLOWS} \), defined as follows: \(\text{PRECEDES} = \{(<, m)\}, \text{INTERSECTS} = \{o, oi, s, si, d, di, f, fi, eq\}, \text{FOLLOWS} = \{mi, >\} \). The importance of this partition for handling continuous (spatial, but also propositional) change will appear later, but an intuitive explanation can be given right now. If a relation \(r \) holds on a pair \((x, y)\) of spatial objects during interval \(I \), then it holds during all subintervals of \(I \) (homogeneity property, see, e.g., \[8\]. In the case of \(r \) being disjunctive, we also assume that there exists an atom \(s \) in \(r \) that holds on pair \((x, y)\) during interval \(I \) —without such an

\(^a\) A disjunct of a \(\text{DNF} \) is a conjunction (of literals in the case of propositional calculus).
additional assumption, if could be that an atom \( s_1 \) holds on \((x, y)\) during, say, the first half of \( I \), and another, distinct atom \( s_2 \) holds on \((x, y)\) during the other half of \( I \). Given this property, if we have the knowledge that (1) a relation \( r_1 \) holds on pair \((x, y)\) of spatial objects during interval \( I_1 \); (2) a relation \( r_2 \) holds on the same pair during interval \( I_2 \); and (3) intervals \( I_1 \) and \( I_2 \) are related by the relation \( \text{INTERSECTS} \), then we conclude that relations \( r_1 \) and \( r_2 \) should have a nonempty intersection (in particular, if they both consist of atomic relations, they should be the same relation) —one atom of \( r_1 \cap r_2 \) holds then on \((x, y)\) during \( I_1 \cup I_2 \). This also applies to propositional knowledge. If a propositional formula \( \phi \) holds during interval \( I \), then it holds during all subintervals of \( I \). In the case of \( r \) being disjunctive, we also assume that there exists a disjunct \( c \) of the decomposition of \( \phi \) into DNF (Disjunctive Normal Form) such that \( c \) holds during interval \( I \) —here also, without such an additional assumption, if could be that a disjunct \( c_1 \) holds during, say, the first half of \( I \), and another disjunct \( c_2 \), distinct from \( c_1 \), holds during the other half of \( I \).

5 A quick overview of the spatial relations to be used as the predicates of the concrete domain

The RA \( \mathcal{RCC}^8 \). The \( \mathcal{RCC} \)-8 calculus (see \([12]\) for details) consists of a set of eight JEPD atoms, \( DC \) (DisConnected), \( EC \) (Externally Connected), \( TPP \) (Tangential Proper Part), \( PO \) (Partial Overlap), \( EQ \) (EQual), \( NTTP \) (Non Tangential Proper Part), and the converses, \( TPPi \) and \( NTTPi \), of \( TPP \) and \( NTTP \), respectively.

The RA \( \mathcal{CYC}^t \). The set 2DO of 2D orientations is defined in the usual way, and is isomorphic to the set of directed lines incident with a fixed point, say \( O \). Let \( h \) be the natural isomorphism, associating with each orientation \( x \) the directed line (incident with \( O \)) of orientation \( x \). The angle \( \langle x, y \rangle \) between two orientations \( x \) and \( y \) is the anticlockwise angle \( \langle h(x), h(y) \rangle \). The binary RA of 2D orientations in \( \mathcal{CYC}^t \), contains four atoms: \( e \) (equal), \( l \) (left), \( o \) (opposite) and \( r \) (right). For all \( x, y \in 2DO \): \( e(x, x) \Leftrightarrow \langle x, y \rangle = 0 \); \( l(x, x) \Leftrightarrow \langle x, y \rangle \in (0, \pi) \); \( o(x, x) \Leftrightarrow \langle x, y \rangle = \pi \); \( r(x, x) \Leftrightarrow \langle x, y \rangle \in (\pi, 2\pi) \).

Based on \( \mathcal{CYC}^t \), a ternary RA \( \mathcal{CYC}^3 \), for cyclic ordering of 2D orientations has been defined in \([9]\). \( \mathcal{CYC}^t \) consists of 24 atoms, thus \( 2^{24} \) relations. The atoms of \( \mathcal{CYC}^t \) are written as \( b_1b_2b_3 \), where \( b_1, b_2, b_3 \) are atoms of \( \mathcal{CYC}^3 \), and such an atom is interpreted as follows: \( \forall x, y, z \in 2DO \): \( b_1b_2b_3(x, y, z) \Leftrightarrow b_1(y, x) \land b_2(z, y) \land b_3(z, x) \). The reader is referred to \([9]\) for more details.

6 Concrete domain

The role of a concrete domain in so-called DLs with a concrete domain \([2]\), is to give the user of the DL the opportunity to represent, thanks to predicates, knowledge on objects of the application domain, as constraints on tuples of these objects.

Definition 3 (concrete domain \([2]\)) A concrete domain \( D \) consists of a pair \( (\Delta_D, \Phi_D) \), where \( \Delta_D \) is a set of (concrete) objects, and \( \Phi_D \) is a set of predicates over the objects in \( \Delta_D \). Each predicate \( P \in \Phi_D \) is associated with an arity \( n: P \subseteq (\Delta_D)^n \).

Definition 4 (admissibility \([2]\)) A concrete domain \( D \) is admissible if: (1) the set of its predicates is closed under negation and contains a predicate for \( \Delta_D \); and (2) the satisfiability problem for finite conjunctions of predicates is decidable.

7 The concrete domains \( D_x \), with \( x \in \{ \mathcal{RCC}^8, \mathcal{CYC}^t \} \)

The concrete domain generated by \( x \), \( D_x \), can be written as \( D_x = (\Delta_{D_x}, \Phi_{D_x}) \), with \( D_{\mathcal{RCC}^8} = (RTS, \mathcal{RCC}^8\text{-at}) \) and \( D_{\mathcal{CYC}^t} = (2DO, \mathcal{CYC}^t\text{-at}) \), where:

1. \( RTS \) is the set of regions of a topological space \( TS \); 2DO is the set of 2D orientations; and
2. \( \text{-at} \) is the set of atoms \(-2\text{-at} \) is thus the set of all \( x \) relations.

Admissibility of the concrete domains \( D_x \) is a direct consequence of (decidability and) tractability of the subset \( \{ \tau \} | r \in x\text{-at} \) of \( x \) atomic relations (see \([13]\) for \( x = \mathcal{RCC}^8 \), and \([9]\) for \( x = \mathcal{CYC}^t \)).

8 Syntax of TCSP-ALC(\( D_x \)) concepts, with \( x \in \{ \mathcal{RCC}^8, \mathcal{CYC}^t \} \)

Let \( x \) be an RA from the set \( \{ \mathcal{RCC}^8, \mathcal{CYC}^t \} \). TCSP-ALC(\( D_x \)), as already explained, is obtained from \( \mathcal{ACC}(D) \) by temporalising the roles, and spatialising the concrete domain. The roles in \( \mathcal{ACC} \), as well as the roles other than the abstract features in \( \mathcal{ACC}(D) \), are interpreted in a similar way as the modal operators of the multi-modal logic \( K_{\text{cons}} \) \( (K_{\text{cons}} \) is a multi-modal version of the minimal normal modal system \( K \)), which explains Schild’s correspondence between \( \mathcal{ACC} \) and \( K_{\text{cons}} \). In this work, the roles will be 4-argument tuples, \((R^{bb}, R^{bc}, R^{cb}, R^{cc})\), with \( R^{xy}, x, y \in \{b, c\} \), being a convex subset of the set \( \mathbb{R} \) of real numbers. The abstract objects are intervals each of which is associated with (spatial) constraints on objects (of the scene) of the spatial domain in consideration, and with propositional knowledge consisting of primitive concepts and negated primitive concepts (literals): during the whole interval, the scene has to fulfill the constraints (durativeness of spatial relational truth), and the propositional knowledge has to remain true (durativeness of propositional truth). The roles, thus, express temporal constraints on pairs of abstract objects. Given an interval \( I \), \( I_0 \) and \( I_e \) will denote the beginning endpoint of \( I \) and the ending endpoint of \( I \), respectively. Given two intervals \( I \) and \( J \), \( R^{xy}(I, J) \), with \( x, y \in \{b, c\} \), is intended as, the difference \( J_y - I_x \), representing the temporal distance between the endpoints \( I_x \) and \( J_y \), belongs to the convex subset \( R^{xy} \) of \( \mathbb{R} \).

The assertion “\( I \) is an interval in the sense of Allen” \([1]\) (a pair of temporal points such that the second strictly follows the first) can be expressed as \((\{0\}, R^{cc}, \{0\})\)(\( I \), \( I \)). Now, given two intervals in the sense of Allen, and an Allen atom, say \( r \), the constraint \( r(I, J) \) is expressed as \( s(I, J) \), where \( s \) is the translation of \( r \) as given by the following tables.

| Atom | Translation |
|------|-------------|
| \( < \) | \( (R^{cc}, R^{cc}, R^{cc}, R^{cc}) \) |
| \( m \) | \( (R^{cc}, R^{cc}, \{0\}, R^{cc}) \) |
| \( o \) | \( (R^{cc}, R^{cc}, R^{cc}, R^{cc}) \) |
| \( s \) | \( \{0\}, R^{cc}, \{0\} \) |
| \( d \) | \( \{0\}, R^{cc}, R^{cc}, \{0\} \) |
| \( f \) | \( \{0\}, R^{cc}, \{0\}, R^{cc} \) |
| \( g \) | \( \{0\}, R^{cc}, R^{cc}, \{0\} \) |

The concepts of the TCSP-ALC(\( D_x \)) specialisation of the \( \mathcal{ACC}(D) \) family of DLs we will be interested in, are built from three kinds of basic concepts:

1. Primitive concepts (which play the role of atomic propositions in propositional calculus) and negated primitive concepts.
The other basic concepts we will be using are of the form \( P(x, y) \), where \( P \) is a relation, and \( x \) and \( y \) variables, we use a predicate concept of the form \( \exists(g_1)(g_2).P \), where \( g_1 \) and \( g_2 \) are concrete features referring, respectively, to the same concrete objects of the spatial concrete domain in consideration as variables \( x \) and \( y \). Similarly, a ternary constraint of the form \( P'(x, y, z) \) will be represented by a predicate concept of the form \( \exists(g_1)(g_2)(g_3).P \).

2. Predicate concepts whose function can be described as follows. To describe an \( \text{RCC8} \)-like spatial constraint of the form \( \Delta P(x, y) \), where \( P \) is a relation, and \( x \) and \( y \) variables, we use a predicate concept of the form \( \exists(g_1)(g_2).P \), where \( g_1 \) and \( g_2 \) are concrete features referring, respectively, to the same concrete objects of the spatial concrete domain in consideration as variables \( x \) and \( y \). Similarly, a ternary constraint of the form \( P'(x, y, z) \) will be represented by a predicate concept of the form \( \exists(g_1)(g_2)(g_3).P \).

3. The other basic concepts we will be using are of the form \( \exists(g_1)(g_2).P \), where \( R = \langle R^{ab}, R^{bc}, R^{cd}, R^{de} \rangle \) is a role and \( A \) is a defined concept.

Formally, the \( \text{TCSP-ALC}(D_x) \) concepts are defined as follows:

**Definition 5 (TCSP-ALC(D_x) concepts)** Let \( x \) be an RA from the set \{\( \text{RCC8}, \text{CYC} \}_1 \}. Let \( N_C \) and \( N_{C,F} \) be mutually disjoint and countably infinite sets of concept names and concrete features, respectively. We suppose a partition \( N_C = N_{pC} \cup N_{dC} \) of \( N_C \), where \( N_{pC} \) is a set of primitive concepts, and \( N_{dC} \) is a set of defined concepts. The set of \( \text{TCSP-ALC}(D_x) \) concepts is the smallest set such that:

1. \( \top \) and \( \perp \) are \( \text{TCSP-ALC}(D_x) \) concepts
2. a \( \text{TCSP-ALC}(D_x) \) primitive concept is a \( \text{TCSP-ALC}(D_x) \) (atomic) concept
3. the negation, \( \neg A \), of a \( \text{TCSP-ALC}(D_x) \) primitive concept \( A \) is a \( \text{TCSP-ALC}(D_x) \) concept
4. if \( A \) is a \( \text{TCSP-ALC}(D_x) \) defined concept; \( C \) and \( D \) are \( \text{TCSP-ALC}(D_x) \) concepts; \( \langle R^{ab}, R^{bc}, R^{cd}, R^{de} \rangle \) is a role; \( g_1, g_2 \) and \( g_3 \) are concrete features; and \( P \) is a \( \text{TCSP-ALC}(D_x) \) predicate, then:
   
   \( \exists(g_1)(g_2).P \), if \( x \) is a binary, and \( \exists(g_1)(g_2)(g_3).P \), if \( x \) is ternary, are \( \text{TCSP-ALC}(D_x) \) (atomic) concepts; and
   
   \( \exists(g_1)(g_2)(g_3).P \), if \( x \) is a ternary, are \( \text{TCSP-ALC}(D_x) \) (atomic) concepts; and
   
   \( \exists(g_1)(g_2).P \), if \( x \) is binary, and \( \exists(g_1)(g_2)(g_3).P \), if \( x \) is ternary, are \( \text{TCSP-ALC}(D_x) \) (atomic) concepts; and

A \( \text{TCSP-ALC}(D_x) \) (terminological) axiom is an expression of the form \( A \equiv C \), \( A \) being a defined concept and \( C \) a concept. A TBox is a finite set of axioms, with the condition that no defined concept appears more than once as the left hand side of an axiom.

**Example 1 (illustration of \( \text{TCSP-ALC}(D_x) \))** Consider the moving spatial scene depicted in Figure 1 (Right), composed of three objects \( o_1, o_2 \) and \( o_3 \). Three snapshots of three submotions are presented, and associated with concepts \( C_1, C_2 \) and \( C_3 \). The configuration described by the concept \( C_1 \) is so that, \( o_1 \) is externally connected to \( o_2 \), and is tangential proper part to \( o_3 \), and the time interval during which the configuration holds overlaps the time interval during which the configuration described by the concept \( C_2 \) holds. The configuration described by the concept \( C_2 \) is so that, \( o_1 \) is externally connected to \( o_2 \), and \( o_2 \) is non-tangential proper part to \( o_3 \), and the time interval during which the configuration holds overlaps the time interval during which the configuration described by the concept \( C_3 \) holds. The configuration described by the concept \( C_3 \) is so that, \( o_1 \) is non-tangential proper part of \( o_3 \), and the time interval during which the configuration holds is overlapped by the time interval during which the configuration described by the concept \( C_1 \) holds.

We make use of the concrete features \( g_1, g_2 \) and \( g_3 \) to refer to the actual regions corresponding to objects \( o_1, o_2 \) and \( o_3 \) in the scene. The TBox composed of the following axioms represents the described moving spatial scene:

\[
\begin{align*}
C_1 & \equiv \exists(g_1)(g_2).EC \cap \exists(g_1)(g_2).TPP \cap \exists(\{0\}, R+, R-, \{0\}).C_1 \\
C_2 & \equiv \exists(g_1)(g_2).EC \cap \exists(g_2)(g_3).NTPP \cap \exists(\{0\}, R+, R-, \{0\}).C_2 \\
C_3 & \equiv \exists(g_1)(g_2).NTPP \cap \exists(\{0\}, R+, R-, \{0\}).C_3 \\
C_3 & \equiv \exists(g_1)(g_2).NTPP \cap \exists(\{0\}, R+, R-, \{0\}).C_3
\end{align*}
\]

The situation described by the TBox is inconsistent for the following reason. A defined concept describes a configuration of the spatial scene which remains the same during the time interval associated with the defined concept. As a consequence, if the time intervals associated with two defined concepts overlap, the conjunction of the corresponding two configurations of the scene should be consistent. Concepts \( C_1 \) and \( C_3 \) in our example are so that, the associated intervals overlap, but the conjunction \( \exists(g_1)(g_2).EC \cap \exists(g_1)(g_3).TPP \cap \exists(g_1)(g_3).NTPP \) is not consistent.

**9 Semantics of \( \text{TCSP-ALC}(D_x) \), with \( x \in \{\text{RCC8}, \text{CYC} \}_1 \)**

As stated in the introduction, we intend our work to extend Allen’s CSPs \( \Pi \), to make them “see” the reality of the physical world, reality consisting, on the one hand, of (relational) spatial knowledge, recording, e.g., the (durative) look of a spatial scene of interest at specific intervals (spatial situation), and, on the other hand, of propositional knowledge, recording the truth values of propositional variables at specific intervals (propositional situation). We consider thus linear time, and a \( \text{TCSP-ALC}(D_x) \) interpretation will consist of a collection of intervals of the time line, together with, on the one hand,
a truth assignment function, assigning with each interval the set of atomic propositions true during that interval, and, on the other hand, of a finite number, say $n$, of concrete features $g_1, \ldots, g_n$, which are partial functions from the set of intervals in the collection onto a universe of concrete spatial values. Clearly, if such an interpretation is so that a given concrete feature is defined for both of two intervals related by the INTERSECTS relation, then the value of the concrete feature at one of the intervals should be the same as the one at the other interval. Furthermore, if two intervals $I$ and $J$ are so that $I$ is a subinterval of $J$ (i.e., related to it by the disjunctive relation $\{s, eq, d, f\}$) then the atomic propositions true during $J$ should all be true during $I$ as well. Formally, a TCSP-ALC interpretation is defined as follows:

**Definition 6 (interpretation)** Let $x \in \{RCC8, CYC_1\}$. An interpretation $T$ of TCSP-ALC($D_a$) consists of a pair $T = (t, 2)$, where $t$ is a finite collection of intervals of the time line, and $2$ is an interpretation function mapping each primitive concept $A$ to a subset $A^T$ of $t$, and each concrete feature $g$ to a partial function $g^2$:

1. from $t$ onto the set RTS of regions of a topological space $TS$, if $x = RCC8$;
2. from $t$ onto the set 2DO of orientations of the 2-dimensional space, if $x = CYC_1$.

**Definition 7 (satisfiability of a TBox)** Let $x \in \{RCC8, CYC_1\}$ be a spatial RA, $T$ a TCSP-ALC($D_a$) TBox, and $I = (t, 2)$ a TCSP-ALC($D_a$) interpretation. $T$ is satisfiable by $I$, denoted $I \models T$, if there exists a one-to-one mapping $\phi$ from the set $t$ of intervals of $I$ to the set $D_T$ of defined concepts appearing in $T$, so that $I, s \models (\phi(s), T)$, for all $s \in t$. Satisfiability by $s \in t$ of a concept $C$ w.r.t. $T$, denoted by $I, s \models (C, T)$, is defined recursively as follows:

1. $I, s \models (B, T) \iff I, s \models (C, T)$, for all defined concepts $B$ given by the axiom $B \equiv C$ of $T$
2. $I, s \models (\top, T)$
3. $I, s \not\models (\bot, T)$
4. $I, s \models (\neg A, T) \iff s \in A^T$, and $I, s \not\models (\neg A, T)$
5. $I, s \models (\exists g_1 (g_2) P, T) \iff P(g_1(s), g_2(s))$
6. $I, s \models (\exists g_1 (g_2) g_3 P, T) \iff P(g_1(s), g_2(s), g_3(s))$
7. $I, s \models \langle \exists R^k \mathcal{R}^k R^{k'}, R^j \mathcal{R}^j \mathcal{R}^{j'}, \mathcal{R}^{j''} \rangle (s, \phi^{-1}(C))$ and $I, s \models (C, T)$, for all defined concepts $C$
8. $I, s \models (C \cap D, T) \iff I, s \models (C, T)$ and $I, s \not\models (D, T)$
9. $I, s \models (C \cup D, T) \iff I, s \models (C, T)$ or $I, s \models (D, T)$

10 Deciding satisfiability of a TBox — an overview

We describe briefly how to decide satisfiability of a TBox. We suppose the particular case with all right hand sides of axioms being conjunctions, and each role implying either of the three relations in the already defined partition of Allen’s atoms into three disjunctive relations, PRECEDES, INTERSECTS and FOLLOWS. The general case can be solved by combining this particular case with recursive search. The idea is to associate with the TBox a temporal CSP where the interval variables are the defined concepts, and each subconcept of the form $\exists R.D (D$ is a defined concept), appearing in the right hand side of the axiom defining a defined concept $C$, giving rise to the constraint $R(C, D)$. The second step is to associate with each of the temporal variables a conjunction consisting of one subconcept which is a propositional formula, and another subconjunction which is a spatial CSP expressed in the RA $x$. Furthermore, if two interval variables are related by the INTERSECTS relation, then the propositional-spatial conjunction associated with one is augmented with that associated with the other (so that the homogeneity property gets satisfied). Decidability now is a consequence of decidability of a propositional formula, of a spatial CSP expressed in the RA $x$, and of a temporal CSP involving only PRECEDES, INTERSECTS and FOLLOWS (and the universal relation) — which can solved polynomially by translating it into the convex part of TCSPs [3], known as STPs.

11 Summary

We have presented an $ALC(D)$-based combination of temporal constraints and spatial constraints suitable for the representation of continuous change in the real physical world. The approach handles both spatial and propositional change. Knowledge about continuous change is represented as a TBox, and we have shown that satisfiability of such a TBox is decidable.

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Dear Amar Isli:

We regret to inform you that your submission C0693 An ALC(D)-based combination of temporal constraints and spatial constraints suitable for continuous (spatial) change - first results Amar Isli cannot be accepted for inclusion in the ECAI 2004’s programme. Due to the large number of submitted papers, we are aware that also otherwise worthwhile papers had to be excluded. You may then consider submitting your contribution to one of the ECAI’s workshops, which are still open for submission.

In this letter you will find enclosed the referees’ comments on your paper.

We would very much appreciate your participation in the meeting and especially in the discussions.

Please have a look at the ECAI 2004 website for registration details and up-to-date information on workshops and tutorials:
http://www.dsic.upv.es/ecai2004/

The schedule of the conference sessions will be available in May 2004.

I thank you again for submitting to ECAI 2004 and look forward to meeting you in Valencia.

Best regards
Programme Committee Chair

REVIEW ONE

— ECAI 2004 REVIEW SHEET FOR AUTHORS ——

PAPER NR: C0693

TITLE: An ALC(D)-based combination of temporal constraints and spatial constraints suitable for continuous (spatial) change

1) SUMMARY (please provide brief answers)
- What is/are the main contribution(s) of the paper?
The paper describes the integration of quantitative representations of temporal constraints with qualitative representations of spatial constraints within a framework of ALC(D) Description Logics.

2) TYPE OF THE PAPER
The paper reports on:
[X] Preliminary research
[] Mature research, but work still in progress
[] Completed research
The emphasis of the paper is on:
[] Applications
[X] Methodology

3) GENERAL RATINGS
Please rate the 6 following criteria by, each time, using only one of the five following words: BAD, WEAK, FAIR, GOOD, EXCELLENT

3a) Relevance to ECAI: FAIR
3b) Originality: FAIR
3c) Significance, Usefulness: FAIR
3d) Technical soundness: FAIR
3e) References: WEAK
3f) Presentation: BAD

4) QUALITY OF RESEARCH
4a) Is the research technically sound?
[ ] Yes [X] Somewhat [ ] No
4b) Are technical limitations/difficulties adequately discussed?
[ ] Yes [X] Somewhat [ ] No
4c) Is the approach adequately evaluated?
[ ] Yes [ ] Somewhat [X] No

FOR PAPERS FOCUSING ON APPLICATIONS:
4d) Is the application domain adequately described?
[ ] Yes [ ] Somewhat [X] No
4e) Is the choice of a particular methodology discussed?
[ ] Yes [ ] Somewhat [X] No

FOR PAPERS DESCRIBING A METHODOLOGY:
4f) Is the methodology adequately described?
[ ] Yes [X] Somewhat [ ] No
4g) Is the application range of the methodology adequately described, e.g. through clear examples of its usage?
[ ] Yes [ ] Somewhat [X] No

Comments:
The quality of presentation of the paper is not sufficient to make a reliable judgment regarding the general quality of the research, hence the largely neutral ratings of this section.

5) PRESENTATION
5a) Are the title and abstract appropriate?
[ ] Yes [ ] Somewhat [X] No
5b) Is the paper well-organized?
[ ] Yes [X] Somewhat [ ] No
5c) Is the paper easy to read and understand?
[ ] Yes [X] Somewhat [ ] No
5d) Are figures/tables/illustrations sufficient?
[ ] Yes [ ] Somewhat [X] No
5e) The English is:
[ ] very good [ ] acceptable [X] dreadful
5f) Is the paper free of typographical/grammatical errors?
[ ] Yes [ ] Somewhat [X] No
5g) Is the references section complete?
[ ] Yes [X] Somewhat [ ] No

Comments:
The presentation of this work lets it down completely. It is below the standard necessary for a general international audience of AI researchers, and this virtually debarrs it from the possibility of a measured technical evaluation. The paper tries to cram far too much technical detail into too little space, at the expense of any high-level, informal or intuitive description of the work, or any detailed indication of its applicability. The one example in the paper is badly described, and comes too late to help readability. The grammar is in many places tortuously long-winded and over-complex, uses commas gratuitously, and in some places is virtually unparsable (e.g. the first sentence of the fourth paragraph of the introduction). The unsigned, utterly pretentious and absurd quotation at the beginning of the introduction is particularly unhelpful and inappropriate.

6) TECHNICAL ASPECTS TO BE DISCUSSED (detailed comments)
- Suggested / required modifications:
  To be acceptable for publication within the given page limitation, the paper needs to be restructured, and a different presentational style needs to be adopted. At the level of overall structure, I suggest that the authors describe their work at least partially with the aid of illustrative, running examples and/or application-based problems. At a more detailed level, I suggest adopting a much more concise grammatical style.
- Other comments:

— ECAI 2004 REVIEW SHEET FOR AUTHORS ——

PAPER NR: C0693

REVIEW TWO
TITLE: An ALC(D) based combination of temporal and spatial constraints

1) SUMMARY (please provide brief answers)
   - What is/are the main contribution(s) of the paper?
     The authors try to combine Allen's interval algebra, Dechter et al's TCSP, Randell et al's RCC8 and Isli's Cyc into an ALC(D) framework for dealing with spatio-temporal change.

2) TYPE OF THE PAPER
   The paper reports on:
   [X] Preliminary research
   [ ] Mature research, but work still in progress
   [ ] Completed research
   The emphasis of the paper is on:
   [ ] Applications
   [X] Methodology

3) GENERAL RATINGS
   Please rate the 6 following criteria by, each time, using only one of the five following words: BAD, WEAK, FAIR, GOOD, EXCELLENT
   3a) Relevance to ECAI: GOOD
   3b) Originality: FAIR
   3c) Significance, Usefulness: WEAK
   3d) Technical soundness: FAIR
   3e) References: FAIR
   3f) Presentation: WEAK

4) QUALITY OF RESEARCH
   4a) Is the research technically sound?
      [ ] Yes [X] Somewhat [ ] No
   4b) Are technical limitations/difficulties adequately discussed?
      [ ] Yes [X] Somewhat [ ] No
   4c) Is the approach adequately evaluated?
      [ ] Yes [X] Somewhat [ ] No
   FOR PAPERS FOCUSING ON APPLICATIONS:
   4d) Is the application domain adequately described?
      [ ] Yes [X] Somewhat [ ] No
   4e) Is the choice of a particular methodology discussed?
      [ ] Yes [X] Somewhat [ ] No
   FOR PAPERS DESCRIBING A METHODOLOGY:
   4f) Is the methodology adequately described?
      [ ] Yes [X] Somewhat [ ] No
   4g) Is the application range of the methodology adequately described, e.g. through clear examples of its usage?
      [ ] Yes [X] Somewhat [ ] No
   Comments:
   It is tried to put too many things together without giving sufficient motivation why it is done and what is the use of it. The chosen calculi have nothing to do with each other and the combination seems completely arbitrary. E.g. how does Cyc fit into it and why is it chosen. Any other calculus could have been chosen as well. All in all it is much too dense and too confusing for readers being able to extract the main ideas of the paper. I suggest that either it is tried to restrict to a combination of only two calculi first or to write a longer version (with substantial motivation and explanation) and submit it to a journal.

5) PRESENTATION
   5a) Are the title and abstract appropriate?
      [ ] Yes [X] Somewhat [ ] No
   5b) Is the paper well-organized?
      [ ] Yes [X] Somewhat [ ] No
   5c) Is the paper easy to read and understand?
      [ ] Yes [X] Somewhat [ ] No
   5d) Are figures/tables/illustrations sufficient?
      [ ] Yes [X] Somewhat [ ] No
   Comments:
   Maybe add a reference to Gerevini and Nebel's ECAI 2002 paper on the combination of interval and RCC8 relations.

6) TECHNICAL ASPECTS TO BE DISCUSSED (detailed comments)
   - Suggested / required modifications:
     Sections 3 and 4 could be made shorter and more precise.
     Do you consider all 13 interval relations or just the three you introduce in section 4?
     Figure 1. How is it possible that C1, C2 (and C3) hold at the same time (the intervals during which they hold overlap)?
   - Other comments:
     What is "RCC8-like"?
     Section 8, the e,b notation should be explained. I guess it means beginning and end point?

REVIEW THREE

--- ECAI 2004 REVIEW SHEET FOR AUTHORS ---

PAPER NR: C0693
TITLE: An ALC(D)-based combination of temporal constraints and spatial...

1) SUMMARY (please provide brief answers)
   - What is/are the main contribution(s) of the paper?
     It's hard to find a contribution in this paper.

2) TYPE OF THE PAPER
   The paper reports on:
   [X] Preliminary research
   [ ] Mature research, but work still in progress
   [ ] Completed research
   The emphasis of the paper is on:
   [X] Methodology

3) GENERAL RATINGS
   Please rate the 6 following criteria by, each time, using only one of the five following words: BAD, WEAK, FAIR, GOOD, EXCELLENT
   3a) Relevance to ECAI: WEAK
   3b) Originality: BAD
   3c) Significance, Usefulness: BAD
   3d) Technical soundness: BAD
   3e) References: BAD
   3f) Presentation: BAD

4) QUALITY OF RESEARCH
   4a) Is the research technically sound?
      [ ] Yes [X] Somewhat [ ] No
   4b) Are technical limitations/difficulties adequately discussed?
      [ ] Yes [X] Somewhat [ ] No
   4c) Is the approach adequately evaluated?
      [ ] Yes [X] Somewhat [ ] No
   FOR PAPERS FOCUSING ON APPLICATIONS:
   4d) Is the application domain adequately described?
      [ ] Yes [X] Somewhat [ ] No
   4e) Is the choice of a particular methodology discussed?
      [ ] Yes [X] Somewhat [ ] No
   FOR PAPERS DESCRIBING A METHODOLOGY:
   4f) Is the methodology adequately described?
      [ ] Yes [X] Somewhat [ ] No
   4g) Is the application range of the methodology adequately described, e.g. through clear examples of its usage?
      [ ] Yes [X] Somewhat [ ] No
   Comments:
   It is tried to put too many things together without giving sufficient motivation why it is done and what is the use of it. The chosen calculi have nothing to do with each other and the combination seems completely arbitrary. E.g. how does Cyc fit into it and why is it chosen. Any other calculus could have been chosen as well. All in all it is much too dense and too confusing for readers being able to extract the main ideas of the paper. I suggest that either it is tried to restrict to a combination of only two calculi first or to write a longer version (with substantial motivation and explanation) and submit it to a journal.

5) PRESENTATION
   5a) Are the title and abstract appropriate?
      [ ] Yes [X] Somewhat [ ] No
   5b) Is the paper well-organized?
      [ ] Yes [X] Somewhat [ ] No
   5c) Is the paper easy to read and understand?
      [ ] Yes [X] Somewhat [ ] No
   5d) Are figures/tables/illustrations sufficient?
      [ ] Yes [X] Somewhat [ ] No
   Comments:
   Maybe add a reference to Gerevini and Nebel's ECAI 2002 paper on the combination of interval and RCC8 relations.
4f) Is the methodology adequately described?
[ ] Yes [ ] Somewhat [X] No
4g) Is the application range of the methodology adequately described, e.g. through clear examples of its usage?
[ ] Yes [ ] Somewhat [X] No
Comments:
5) PRESENTATION
5a) Are the title and abstract appropriate?
[ ] Yes [ ] Somewhat [X] No
5b) Is the paper well-organized? [ ] Yes [ ] Somewhat [X] No
5c) Is the paper easy to read and understand?
[ ] Yes [ ] Somewhat [X] No
5d) Are figures/tables/illustrations sufficient?
[ ] Yes [X] Somewhat [ ] No
5e) The English is [ ] very good [X] acceptable [ ] dreadful
5f) Is the paper free of typographical/grammatical errors?
[ ] Yes [X] Somewhat [ ] No
5g) Is the references section complete?
[ ] Yes [ ] Somewhat [X] No
Comments:
6) TECHNICAL ASPECTS TO BE DISCUSSED (detailed comments)
- Suggested / required modifications:
  This is a very confusing paper in many respects.
  1. It is claimed to develop a Spatio-Temporal description logic starting from the concrete domain approach ALC(D). Anyway, there is no evidence the author understood that a DL MUST have an object domain while, as far as I understood, the semantics is based on a combination of spatial and temporal domain. Thus, the semantics is based ONLY on a concrete domains and there is no mention of the abstract object domain. DLs are mainly formalism for representing and reasoning about domain objects. Then, for sure, you can EXTEND them by introducing other concrete domains. Indeed, in the pseudo-DL presented here roles are JUST Allen temporal relations.
  2. The Pseudo-DL is not even ALC since there is NO full negation but just primitive negation. Indeed, using full negation the logic would be a sub-case of the undecidable Halper and Shoham interval modal logic.
  3. Homogeneity. First of all, the reference of Halpern and Shoham has nothing to do with such property. There are many papers studying such property (e.g., Allen, Shoham, etc.) but they are not mentioned. Furthermore, the claimed homogeneity is not reflected by the semantic presented in Section 9.
  4. The Semantic is hard to understand. Definition 7 makes few sense. Furthermore, the temporal domain used (finite collection of intervals) is not interesting at all. Temporal structures should be based on Natural, Real or Rational numbers.
  5. Related works. It’s quite amazing that the author(s) disregard the literature on temporal and spatial DLs. I would like to mention that many papers appeared in the literature in the last 10 years but there is no mention of them AT ALL! Just to mention few authors: Artale-Franconi, Bettini, Schmiedel (interval based DLs); Baader, Lutz (complexity results on various concrete domain extensions); Zachariashev-Wolter, Schild (point-based DLs); Zachariashev-Wolter (spatial extensions of DL’s).
- Other comments: