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Artificial Intelligence for Mobility and Maneuver (AIMM) World Model Progress Report: Spatial Concepts in Route Reconnaissance

by Robert St. Amant

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Artificial Intelligence for Mobility and Maneuver (AIMM) World Model Progress Report: Spatial Concepts in Route Reconnaissance

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| 14. ABSTRACT This report summarizes a small selection of research on qualitative spatial reasoning in the context of world modeling in the US Army Combat Capabilities Development Command Army Research Laboratory autonomy architecture. Our focus is on a simple robot, an autonomous system capable of sensing and navigating through its environment, on a route reconnaissance mission. Four types of qualitative representations are covered: regions, based on the Region Connection Calculus; paths, based on the Trajectory Calculus; orientation, based on the Cardinal Direction Calculus and the Rectangle Algebra; and qualitative distances. Each of these areas is evaluated with respect to coverage of a set of qualitative relations associated with route reconnaissance. Current status is summarized and directions for the future are outlined. | | | | | |
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1. Introduction

This report summarizes progress to date on ontology development in the domain of route reconnaissance, with a focus on spatial abstractions. Our focus is on a simple robot, an autonomous system capable of sensing and navigating through its environment. The robot is tasked with route reconnaissance: obtaining necessary information concerning the conditions, obstacles, critical terrain features, and enemy along the assigned route, through observation and inference. Route reconnaissance is generally carried out by a platoon of mounted and dismounted Soldiers. This research examines the plausibility of a robot carrying out some or all of the necessary tasks, including communicating with a commander.

1.1 Background and Motivation

Army Field Manual FM 7-92^{1*} states that

Route reconnaissance focuses on obtaining information on a specified route and all terrain from which the enemy could influence movement along that route.

This is a challenging adversarial task of terrain traversal plus information gathering and interpretation. The interpretation aspect of reconnaissance requires that *semantics* be considered—the identification of information that is relevant and the determination of how it is relevant (i.e., meaningful). Semantic information is qualitative in nature: *danger*, for example, is a qualitative concept. To associate danger with some specific area, we need a way to refer to that area. This means being able to attach qualitative labels to portions of space at a minimum.

The importance of qualitative representations of space for robot exploration was pointed out in early work by Kuipers² on his spatial semantic hierarchy. For example, the topological level of the hierarchy contains “the ontology of places, paths, and regions”, with abduction generating explanations of causal patterns at lower levels.

More recently Izmirlioglu and Erdem³ offer the following justification of the application of qualitative spatial concepts to robotics:

Various tasks, like navigating to a destination or describing the location of an object, involve dealing with spatial properties and relations of objects. . .

^{*} *Army Techniques Publication No. ATP 3-20.98 Scout Platoon* and *Army Techniques Publication No. ATP 3-34.81 Engineer Reconnaissance* are also relevant; in future work, those perspectives will be incorporated into our analysis.

[F]or some applications (e.g., exploration of an unknown environment), quantitative data may not always be available due to incomplete knowledge about the environment. . . . understandable interactions and acceptable explanations are often more desirable than high precision (Kuipers 1983). For these applications, qualitative spatial relations seem more suitable.

For an unmanned ground vehicle (UGV) tasked with route reconnaissance, different modules in its architecture will consume and produce semantic information: modules responsible for semantic perception and object recognition, planning and execution, natural language dialogue, and so forth, plus a semantic world model with primary responsibility for maintaining the information. For example, in the US Army Combat Capabilities Development Command Army Research Laboratory autonomy architecture, the semantic/symbolic world model is used “to achieve symbolic goals (e.g., going near a particular object)”,* where *near* is a semantic concept.

A key question is how to allocate responsibilities for maintaining and processing different types of semantic information between the world model and other modules. Taking a semantic world model perspective, it depends on how much symbolic inference is appropriate. For example, suppose that the object to be approached is in a location in a given area, not near the outer boundary of the area. Once the robot is near the object, it can be inferred that the robot is near the object’s location and that it is also in the same region. If metric information is available, this conclusion could be reached with geometrical routines. Do situations arise in which metric information is *not* available, where inference is useful in a purely qualitative space?

This report does not address this issue. Our goal is rather to identify *what* should be represented, leaving the *how* and the *where* to future work.

1.2 Route Reconnaissance

The following fragments are taken from the description of route reconnaissance in FM 7-92.^{1†} Spatial expressions are colored, with some surrounding text for context.

Route reconnaissance focuses on obtaining *information on a specified route* and all terrain from which the enemy could influence movement *along that route*. Route reconnaissance can be oriented on *a road, a narrow axis* (such

* <https://www.arl.army.mil/business/collaborative-alliances/current-cras/sara-cra/sara-overview/>

† *Army Techniques Publication No. ATP 3-20.98 Scout Platoon* and *Army Techniques Publication No. ATP 3-34.81 Engineer Reconnaissance* are alternative sources that provide related descriptions of route reconnaissance; in future work, those perspectives will be incorporated into our analysis.

as an infiltration lane), or a *general direction* of attack . . . *defense positions* . . . *available space* in which a force can maneuver . . . *location* and types of all *obstacles* and the location of any available *bypass*. Obstacles can consist of minefield, barriers, steep ravines, marshy areas, or NBC contamination . . . *observation and fields of fire along the route and adjacent terrain* . . . *locations along the route* that provide good cover and concealment . . . *bridges* by construction type, dimensions, and classification. . . landing zones and pickup zones . . . Roads and trails intersecting or traversing the route. . . If all or part of the proposed route is a road, the platoon considers the road a *danger area*. It moves *parallel to the road* using a covered and concealed route. When required, reconnaissance and security teams move *close to the road* to reconnoiter key areas.

The result of a route reconnaissance is a report, in the form of a diagram accompanied by a text description. FM 7-92 gives an example, from which we can extract a few more necessary concepts:

Grid references. . . *Magnetic north arrow*. . . *Road curves*. . . *Steep grades*. . . Road width of *constrictions* (bridges, tunnels, and so forth). . . Location of *fords*. . . *tunnels*. . .

Let us create a consolidated list of the concepts mentioned in this description of route reconnaissance, focusing on spatial concepts and retaining the military terminology as much as possible.

- 1) Locations, routes, areas, and objects of interest in the environment must be specified. Call these “entities”.
- 2) Spatial relationships between such entities are relevant (e.g., one location north of another). Notably, relationships between different *types* of entities are specified:
 - a. Objects (e.g., obstacles) are in locations or areas.
 - b. Some locations are spatially related to the route (e.g., along the route, adjacent, or close to the road).
 - c. Locations may represent larger areas (e.g., the location of a minefield).
 - d. Roads and trails can be related to routes: they may intersect, overlap (partial superposition), or run parallel.
- 3) Some entities have tactical value, either offensive or defensive, with respect to the route (e.g., a minefield).

- a. Some locations have directional orientation with respect to other locations or areas (e.g., a defensive position).
 - b. Some areas are defined by their relationship to another area or location, which may not be a local relationship (e.g., observation and fields of fire are defined by a potentially remote location that has a line of access to an area on the route).
- 4) Routes may be blocked by obstacles, which may be explicit objects or larger areas (e.g., a barrier vs. a minefield).
 - 5) The 3-D geometrical properties of routes and terrain are relevant: sharp curves in the road, steep grades, and the like.
 - 6) It is sometimes important to characterize physical infrastructure (e.g., roads, bridges) and their properties.

1.3 Route Reconnaissance Abstractions

Route reconnaissance collects and interprets information of different kinds and from different sources.

- Background knowledge. This includes information about the types of environmental features and objects that are expected to be part of the task, including roads, barriers, gullies, bridges, and so forth.
- Task specification. The area and route for reconnaissance are identified, along with any information available at the time.
- The environment. Relevant features of the environment are identified by spatial analysis (including geometry, topology, etc.), perception, off-line image processing of map satellite data, and other types of analysis.
- Communication during task execution. We assume that the commander or a human operator may pose queries or commands to the UGV during its reconnaissance, providing new information or focusing attention.
- A report, as described previously.

In principle, all of this information is combined in some abstract form in a semantic world model. We have called the physical properties and features of the environment “entities”. Call the abstractions that we use to represent these entities and relationships between them “concepts”.

Concepts for entities of different types. Hierarchies are common in semantic representations to capture general knowledge about types of entities encountered in

the world. A type is a concept, and types are organized in a hierarchy: an MRZR is a light, tactical, all-terrain vehicle, which is a type of wheeled ground vehicle, which is a type of ground vehicle, and so on. Properties and relationships can be associated with a given concept, and subordinate concepts inherit those properties. In route reconnaissance, if information becomes available that there is a road in a given area but no more details, it is still possible to make inferences about its expected properties from the concept of a road: it is much longer than it is wide; it leads between locations of interest to people; and all else being equal, it is likely to be faster to travel on than surrounding terrain. Pragmatically, this means that a semantic world model need not record every piece of relevant information about something if it is possible to categorize that something as a known concept.

Concepts for the purpose and use of entities. A concept that represents the typical use of a road allows for the further semantic distinction between its length and its width, which in turn leads to distinctions between the concepts *across* and *along*, *crossing* and *following*, and so forth. This would enable a UGV to treat the commands “Scout that area across the road” and “Scout the road ahead” differently. *The road ahead* is also a semantic concept: it depends on the knowledge of where one has been in the past.

Concepts to represent partial information. Sometimes qualitative information may be available. Imagine that part of the task specification is information that a minefield is present along the planned route but not exactly where, or that the location of the minefield is known but not its extent. This kind of ignorance can easily be captured in the concept representing the entity.

New concepts for new contexts. Another example of communication may be informative. Imagine a UGV communicating with a remote commander as it traverses an east–west road, and the commander asks, “What’s that on the north side of the road?”* Objects to be identified may not be literally on the boundary of the road and the terrain (contrast with “the side of the building”) but are instead within some area of interest bounded by the edge of the road and a short distance north and some distance east and west from the UGV’s location. That area may not have been demarcated in advance as a concept; instead, it is constructed or inferred

* Kristin Schaefer-Lay of DEVCOM Army Research Laboratory observes (personal communication) that a robot able to listen to Soldiers speaking to each other would benefit significantly from the ability to infer intent and meaning from their conversation, even without direct commands for the robot to do something. The value would be for teaming: it would help the robot understand a human’s change in behavior and potentially change its associated maneuver without being directed to do so.

in the current context. This is an interesting case of a concept not being abstracted from metric data but instead being imposed on metric data.

Adaptation and combination of concepts in context. Imagine that analysis of a map produces a decomposition into concepts representing areas, roads, and so forth. These concepts may be directly appropriate for some purposes: The concept tied to a road would be useful in reasoning about navigation between two points, for example. In other cases, however, the concepts may need to be adapted or combined with others. If a road is designated a “danger area”, for example, the concept for that area plausibly extends beyond the boundaries of the road a distance into the surrounding terrain.

2. Representation Preliminaries

Leaving aside the specifics of tactical content, we have a relatively small number of spatial concepts. Spaces, zones, fields, and areas are mentioned; we will use the concept of a *region* to describe these. *Locations* are even more common. Locations may be specific places of interest; they may also act as references to larger areas (e.g., the location of a minefield). A road, infrastructure designed to facilitate movement from one region or location to another, can be abstracted as a kind of *path* concept. A route is also a path but distinct from physical roads. It is typically directional. Some of its components may have no necessary physical extent; it can be modeled as a sequence of dimensionless locations. Finally, we have *object* concepts. For conciseness, when referring to one of these concepts of a specific type, let *rgn* be a region, *loc* a location, *pth* a path, and *obj* an object, with subscripts for differentiation when necessary. In addition to concepts representing entities, we have concepts representing relationships between entities.

A list of concepts is given in Table 1 (regions), Table 2 (locations), and Table 3 (paths). All are intended to have a straightforward mapping back to the summary list in Section 1.2. Concepts are expressed in the same form as logic relations, but the set should not be viewed as a formalization.

Table 1 Reconnaissance concepts in which a region participates

| Region concept | Description | Notes |
|--------------------------|---|---------------|
| $part(rgn_x, rgn_y)$ | rgn_x is part of rgn_y . | RCC |
| $adjacent(rgn_x, rgn_y)$ | rgn_x is adjacent to rgn_y . | RCC, RCC + QD |
| $contain(rgn, loc)$ | rgn contains loc . | RCC |
| $toward(rgn_x, rgn_y)$ | rgn is oriented toward rgn_y . | CDC |
| $away(rgn_x, rgn_y)$ | rgn_x is oriented away from rgn_y . | CDC |
| $LOS(rgn_x, rgn_y)$ | rgn_x is under line-of-sight from rgn_y . | RCC + CDC |
| $LOS(rgn, loc)$ | rgn is under line-of-sight from loc . | RCC + CDC |
| $represent(loc, rgn)$ | loc represents rgn . | RCC |
| $along(rgn, pth)$ | rgn is along pth . | RCC + TC + QD |
| $adjacent(rgn, pth)$ | rgn is adjacent to pth . | RCC + TC + QD |
| $start(pth, rgn)$ | pth starts in rgn . | RCC + TC |
| $end(pth, rgn)$ | pth ends in rgn . | RCC + TC |
| $through(pth, rgn)$ | pth moves through rgn . | ... |
| $contain(rgn, obj)$ | rgn contains object obj . | RCC |

Note: RCC = Region Connection Calculus, Section 3.1; QD = Qualitative Distance, Section 3.4; CDC = Cardinal Direction Calculus, Section 3.3; TC = Trajectory Calculus, Section 3.2.

Table 2 Reconnaissance concepts in which a location participates

| Location concept | Description | Notes |
|------------------------|---|---------------|
| $toward(loc_x, loc_y)$ | loc_x is oriented toward loc_y . | CDC |
| $away(loc_x, loc_y)$ | loc_x is oriented away from loc_y . | CDC |
| $LOS(loc_x, loc_y)$ | loc_x is under line-of-sight from loc_y . | RCC + CDC |
| $start(pth, loc)$ | pth starts at loc . | TC |
| $end(pth, loc)$ | pth ends at loc . | TC |
| $waypoint(loc, pth)$ | loc is a waypoint on pth . | TC |
| $on(loc, pth)$ | loc is on pth . | RCC + TC |
| $along(loc, pth)$ | loc is along pth . | RCC + TC + QD |
| $adjacent(loc, pth)$ | loc is adjacent to pth . | RCC + TC + QD |
| $close(loc, pth)$ | loc is close to pth . | RCC + TC + QD |
| $represent(loc, pth)$ | loc represents pth . | TC |
| $at(obj, loc)$ | obj is at loc . | RCC |

Table 3 Reconnaissance concepts in which a path participates

| Path concept | Description | Notes |
|---------------------------|--------------------------------------|---------------|
| $part(pth_x, pth_y)$ | pth_x is part of pth_y . | TC |
| $intersect(pth_x, pth_y)$ | pth_x intersects pth_y . | TC |
| $overlap(pth_x, pth_y)$ | pth_x overlaps pth_y . | TC |
| $parallel(pth_x, pth_y)$ | pth_x runs parallel with pth_y . | TC + QD |
| $along(obj, pth)$ | obj is along pth . | RCC + TC + QD |
| $adjacent(obj, pth)$ | obj is adjacent to pth . | RCC + TC + QD |
| $on(obj, pth)$ | obj is on pth . | RCC + TC |
| $block(obj, pth)$ | obj blocks pth . | RCC + TC |
| $curve(pth)$ | pth curves (severely). | QD |
| $steep(pth)$ | pth is (very) steep. | QD |

Note the set is almost certainly incomplete. It is suggestive, though, even in an unfinished state. There are more qualitative descriptions and distinctions than one might expect. Moving to individual concepts, most have an obvious inverse. For example, if $at(obj, loc)$, then $occupied\ by(loc, obj)$. These are not listed. Line of sight (LOS) generalizes over “observation and field of fire”, to represent the status of some entity under LOS observation or threat from a location or region. LOS is not the only example of a concept that might be split into two or more. In other cases, such as with *adjacent* and *along*, it may be that two concepts should be merged into one. The *represent* concept is included because of the way some areas and parts of a route are specified. “A minefield is located here” means that the specified location represents the region. Some plausible concepts have not been included but might be part of an expanded set:

- $equal(rgn_x, rgn_y)$: rgn_x is the same as rgn_y .
- $overlap(rgn_x, rgn_y)$: rgn_x overlaps rgn_y .
- $in(obj, rgn)$: obj is in rgn .
- $bound(rgn, pth)$: rgn forms the boundary of pth .
- $bound(rgn, obj)$: rgn forms the boundary of obj .
- $equal(loc_x, loc_y)$: loc_x is the same as loc_y .
- $equal(obj_x, obj_y)$: obj_x is the same as obj_y .

All of these concepts might be implemented in specialized (and parameterized) spatial/geometrical computer routines. To give an idea of the advantages and limitations of a qualitative approach, however, Section 3 introduces a few well-known formalisms that give coverage of the concepts. As argued in Section 1.1, a qualitative representation is needed if we want to characterize some entity in semantic terms. It will become apparent, though, that for some reconnaissance concepts there is little value in purely qualitative reasoning over them.

3. Qualitative Spatial Reasoning

Work in the interdisciplinary field of qualitative spatial reasoning⁴ provides a possible foundation for the concepts discussed in the previous section. The general areas covered are approaches to representation and reasoning about regions, paths, orientation, and distance. The original intention was to build a coherent, self-consistent picture of a qualitative representation of the reconnaissance concepts.

That turned out not to be possible. It may be possible to integrate the independent pieces, but the costs (e.g., tractability of reasoning) and feasibility (e.g., consistency) of doing so are not yet clear. The discussion is also incomplete, in that a detailed translation between the concepts in Tables 1–3 to a given formalism has not been carried out; rather, only suggestive examples have been given.

3.1 Regions

The Region Connection Calculus (RCC), for reasoning about the topology of spatial regions and their relationships, is possibly the best-known extant formalism in qualitative spatial reasoning.⁵ RCC is sometimes described as a spatial analog to Allen’s interval-based temporal logic,⁶ which defines 13 base pairwise relations for reasoning about time: ‘precedes’, ‘meets’, ‘overlaps with’, ‘starts’, ‘during’, ‘finishes’, ‘is equal to’, and inverses of all but the last.

RCC similarly defines relations between regions: Every pair of regions has a unique relation. The defined relations are based on one primitive, ‘connects with,’ $C(x, y)$. Table 4 gives all defined topological relations in RCC. The relations form a lattice, with those eight marked ‘base’ at the bottom, a set referred to as RCC-8. Other relations act as generalizations of the base relations. For example, TPP (‘is a tangential proper part of’) and $NTPP$ (‘is a non-tangential proper part of’) generalize to PP (‘is a proper part of’).

Table 4 RCC relations

| Relation | Definition | Note |
|------------------------|--|----------------------------------|
| base $PO(x, y)$ | $O(x, y) \wedge \neg P(x, y) \wedge \neg P(y, x)$ | ‘partially overlaps’ |
| base $TPP(x, y)$ | $PP(x, y) \wedge \exists z[EC(z, x) \wedge EC(z, y)]$ | ‘is a tangential proper part of’ |
| base $NTPP(x, y)$ | $PP(x, y) \wedge \neg \exists z[EC(z, x) \wedge EC(z, y)]$ | ‘. . . non-tangential. . .’ |
| base $EQ(x, y)$ | $P(x, y) \wedge P(y, x)$ | ‘is equal to’ |
| base $TPP^{-1}(x, y)$ | $TPP(y, x)$ | TPP inverse |
| base $NTPP^{-1}(x, y)$ | $NTPP(y, x)$ | NTPP inverse |
| base $EC(x, y)$ | $C(x, y) \wedge \neg O(x, y)$ | ‘is externally connected to’ |
| base $DC(x, y)$ | $\neg C(x, y)$ | ‘is disconnected from’ |
| $P(x, y)$ | $\forall z[C(z, x) \rightarrow C(z, y)]$ | ‘is part of’ |
| $PP(x, y)$ | $P(x, y) \wedge \neg P(y, x)$ | ‘is a proper part of’ |
| $O(x, y)$ | $\exists z[P(z, x) \wedge P(z, y)]$ | ‘overlaps’ |
| $DR(x, y)$ | $\neg O(x, y)$ | ‘is discrete from’ |
| $P^{-1}(x, y)$ | $P(y, x)$ | P inverse |
| $PP^{-1}(x, y)$ | $PP(y, x)$ | PP inverse |

RCC also supports an axiomatization of “atomic” regions in terms of points, which correspond to locations. (To my knowledge, this is not as widely accepted as RCC itself. We will simply assume that locations can be accommodated.) Under this

assumption, RCC directly supports the representation of some reconnaissance concepts, as marked in Tables 1–3. For example, *part* and *contain* are *PP* or *P*. If we treat objects as being equivalent to the region or location they occupy with respect to spatial relations, then these are also accommodated.

For other concepts, however, some thought must be given to translation. For example, what does it mean when we say “A minefield *m* is adjacent to region *r*”? If *m* is a region, tagged with appropriate semantics, then we might mean *EC*(*m*, *r*) because the two regions literally abut each other. But in some contexts “adjacent” is interpreted as being only nearby, as with a building that is adjacent to a road. These may be only issues of connecting the formal relations to real-world entities, but it may instead mean that some of the concepts we have defined are a mismatch to the formalism.

A challenge is posed by the concept LOS (*rgn*, *loc*) and relatives. A given *rgn* might be represented in RCC, but it is not obvious how or whether it should be related to other regions even though there is obviously *some* spatial connection. It may be that different representations are needed for the meaning of connectedness, depending on what we need it for. Again, this is partly a modeling/real-world challenge.

Some advantages come automatically with RCC. In the reconnaissance domain, it is natural to say that some properties of a region apply to all locations within the region, for example. If a road or a minefield is represented as a dangerous region, then internal locations are also dangerous. Such information might be used to populate a cost map for path planning rather than evaluating specific individual locations. Region connectivity might be directly used as a coarse representation for a planner.

Because RCC relations are topological, they do not encompass all of our concepts; however, we describe other formalisms next.

3.2 Paths

The Trajectory Calculus (TC) formalism of Baryannis et al.⁷ builds on RCC to model relationships between the trajectories of moving objects in terms of regions. In our terms, their trajectories are what we call paths; for consistency, we will use the expression *region-based paths*. (Alternative formalizations of paths, based on locations rather than regions,⁸ are available but not discussed here.) A region-based path is a sequence of regions visited in order on a map. TC-6 defines six base relations, as shown in Table 5. For consistency, Baryannis et al.’s notations have been altered, and their definitions have been slightly condensed. These are the notation conventions: If *X* is a region-based path, let $|X|$ be the number of regions

X passes through; let X^j be the j th region passed through. X^1 is then the starting region, and $X^{|X|}$ the end region of path X .

Table 5 TC-6 relations

| Description | Relation | Definition |
|---------------------|----------------|--|
| ‘is equal to’ | $EQ(X, Y)$ | $ X = Y \wedge X^i = Y^i, 1 \leq i \leq X $ |
| ‘is alternative to’ | $Altern(X, Y)$ | $X = Y \wedge X^1 = Y^1 \wedge X^{ X } = Y^{ Y }$ |
| ‘starts’ | $Start(X, Y)$ | $X^1 = Y^1 \wedge X^{ X } \neq Y^{ Y }$ |
| ‘ends’ | $End(X, Y)$ | $X^1 \neq Y^1 \wedge X^{ X } = Y^{ Y }$ |
| ‘intersects with’ | $Inter(X, Y)$ | $X^1 \neq Y^1 \wedge X^{ X } \neq Y^{ Y } \wedge \exists i, j X^i = Y^j, 1 \leq i \leq X , 1 \leq j \leq Y $ |
| ‘is disjoint with’ | $Disj(X, Y)$ | $\forall i, j X^i \neq Y^j, 1 \leq i \leq X , 1 \leq j \leq Y $ |

We can now define paths. Because a region-based path is a set of regions, the advantages and limitations of using RCC apply. We can say, for example, that if part of a path is in a region with a specific property (e.g., being dangerous), that part of the path has the same property. But the same questions of translation arise. Are “adjacent” and “along” distinct concepts when it comes to paths as regions, for example?

TC extends RCC in some ways. Some basic reconnaissance concepts, such as intersection, are primitives. Superposition can be modeled by analogy to Allen’s temporal intervals⁶ for ‘is equal to’, ‘overlaps’, ‘starts’, ‘during’, and ‘finishes’, along with inverse relations. Region-based paths also allow for a natural representation of obstacles blocking a path. The basic idea is that obstacles remove connectivity relations between regions on a map. (Change in RCC can be modeled,⁹ but we do not go to that level of detail here.) Consider a partition of a map, R , under TC representational constraints, and a path P over R . Choose some $r_o \in P$. Replace each relation $EC(r_o, r)$, $r \in R$ with $DC(r_o, r)$. Region r_o is now disconnected in R . Because a path can only pass through connected regions, the path P no longer exists; r_o is effectively an obstacle.

The only conceptual translation that seems problematic is *through*. Consider a planned route P that cuts entirely *through* some zone Z . P is a region-based path, a sequence of regions, and Z is a single region. It might be useful to model Z as being split into distinct pieces, as allowed in RCC, but I do not know how to make that explicit in the combination of RCC and TC.

The TC formalism does rely on a strong assumption that we should examine⁸:

Given a map M , a partitioning R of the map M is defined as a set of non-overlapping regions $ri. . .$ such that $M = \bigcup_{r_i \in R} r_i$. Following RCC8 notation, each region is related through EQ (equal) only to itself, EC

(externally connected) to its neighboring regions, and DC (disconnected) with all other regions.

This does not appear to be a conceptual problem, in that the other RCC relations aside from those given do not seem to play a role in the reconnaissance concepts for path–path relationships. Relations between paths and other types of concepts can be handled by decomposing a path into regions, as in our previous example of obstacles (e.g., the start of a path may be contained in some region, even if P and PP are not allowed in the definition of the path itself). One practical issue is raised, however. The path relations in Table 5 depend on the paths X and Y being defined on the same region partitioning. It may happen that the information about roads comes in separate overlays—surface roads versus walking trails, for example. For these to be related in TCC, the representation must be “flattened” so that all region-based paths share the same map partitioning.

With this caveat in mind, TC expands the number of reconnaissance concepts we can cover, as marked in Tables 1–3.

3.3 Orientation

Attempts have been made to model orientation relations between regions. Combining orientation formalisms directly with RCC is also possible. One approach is the Cardinal Direction Calculus (CDC), as discussed by Liu et al.¹⁰ Consider an arbitrary planar shape a with a superimposed 3×3 grid. The bounding box of a constitutes the middle cell of the grid (imagine a tic-tac-toe board, though with lines that may be unevenly spaced). The Cartesian plane, arbitrarily oriented with respect to a , is thus decomposed into nine discrete areas.

Now consider another shape b in the same plane. It has arbitrary shape, possibly having complex convexities, as with a . Shape b may fall into any one of the grid areas around a . In fact, b may fall into multiple grid areas, and even all of them in the case that b surrounds a and also overlaps a 's bounding box. This means that for a given reference object (a in our example), any one of $2^9 - 1 = 511$ unique relations may exist with respect to another object.

CDC is more flexible than earlier approaches (e.g., the rectangle algebra [RA],¹¹ which is limited to axis-aligned rectangles in a Cartesian plane). The representation would require some interpretation to be used to model *toward* and *away* in Tables 1 and 2 (i.e., the bounds on directions), but it seems plausible. We can express such relationships as “The target area is north and northwest of our current location” in CDC, for example.

3.4 Distance

In early work, Hernandez et al.¹² introduce the basics of reasoning about distances:

A distinction has to be made between comparing the magnitudes of distances and naming distances. For comparing distances, the obvious set of predicates is $<$, $=$, $>$, which characterize the result of direct comparison. With respect to naming, the types of objects involved and the context in which they are embedded are decisive factors for establishing the set of relations to be used. . . Characteristic of the semantic of qualitative distance relations is that they partition the physical space into regions of different sizes (where the difference can be even in the order of magnitude).

Once named distance relations are identified (e.g., *close* vs. *far*), they are organized in a distance system, which describes how they are related to each other. One of the issues that needs to be resolved is how distance between regions should be understood rather than the more common distance between locations.

A variety of alternatives to qualitative reasoning about distance are summarized as QDs in Tables 1–3. At least one formalism¹³ for reasoning about distance also supports representation of shape information in particular angles. This may be applicable to representation of road curvature and steepness.

4. Discussion

Eventually it becomes necessary to choose a formalism and implement it, ideally taking advantage of existing software infrastructure. In our case, the target is the Web Ontology Language (OWL). We have only addressed representation in this report rather than reasoning, and all of the formalisms we have discussed fit neatly into OWL’s ontological categories of classes, individuals, and properties.

A small test has been run on one relation, *EC*, in Protégé. With a single relation (*DC* being implicit), finding whether two regions are connected by transitivity is a graph search problem. Test cases were generated as graphs with edges between vertices chosen at random up to a fixed ratio of the number of edges to the size of a completely connected graph. These graphs were converted to a region representation in OWL with uniquely labeled region individuals and a symmetric, transitive connectivity property between them. A reasoner (FaCT++ or Pellet) was then used to infer all indirect connectivity properties. Timing results are given in milliseconds in Table 6 for a few sample runs. The runs include inference time but not loading time, which is significant.

Table 6 Time to infer connectivity in random graphs, in milliseconds

| Vertices | Edges | FaCT++ | Pellet |
|----------|---------|--------|--------|
| 100 | 1,000 | ~50 | ~150 |
| 100 | 3,000 | ~80 | ~190 |
| 100 | 5,000 | ~110 | ~200 |
| 1000 | 100,000 | ~520 | ~800 |
| 1000 | 300,000 | ~1700 | ~2200 |
| 1000 | 500,000 | ~3400 | ~4000 |

The reasoners do surprisingly well, with the largest example including half a million connectivity relations. Neither reasoner incorporates specialized routines for spatial reasoning, to my knowledge, though proposals have been made.¹⁴

In another small test, performance on a task related to qualitative distances was explored. OWL supports association between individuals and metric data by so-called data properties. We can say that a given individual X *hasDV* (int), for example. OWL also supports inference of class membership by tests of object or data properties. In other words, from scalar data OWL can automatically assign a qualitative label to individuals with data values that fall within specific bounds.

Test cases were generated as a set of individuals, each with a data property dx containing a random integer between 1 and 100. An inference rule was defined to assign an individual to a target class if $dx < 50$. Conceptually, this is a test assigning a *near* label to individuals within dx of a given point. Timing results are given in Table 7, in milliseconds, for a few sample runs. Protégé was unable to load a larger test case of 100,000 individuals.

Table 7 Time to assign near labels to individuals based on distance, in milliseconds

| Individuals | FaCT++ |
|-------------|--------|
| 10 | ~50 |
| 100 | ~90 |
| 1000 | ~130 |
| 10,000 | ~3250 |

If it turns out that OWL reasoners are too inefficient for the qualitative spatial reasoning tasks we would like to carry out, a Qualitative Spatial Reasoning library* includes RCC-2 through RCC-8; a point-based version of TC; RA and Cardinal Directions, also point-based rather than region-based; and the Qualitative Distance Calculus.

* <https://qsrlib.readthedocs.io/en/latest/rsts/handwritten/qsrs/qsrs.html>

5. Conclusion

The qualitative representations described have been implemented in part; some already exist in the ontologies inherited by our own. Our approach for continuing this work will be incremental. We will adopt qualitative representations if they appear appropriate and if the results of reasoning over them cannot be obtained as easily with other functionality already part of the ARL autonomy architecture.

6. References

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List of Symbols, Abbreviations, and Acronyms

| | |
|------------|---|
| 3-D | three-dimensional |
| AIMM | Artificial Intelligence for Mobility and Maneuver |
| ARL | Army Research Laboratory |
| CDC | Cardinal Direction Calculus |
| DC | is disconnected from |
| DEVCOM | US Army Combat Capabilities Development Command |
| DR | is discrete from |
| EC | is externally connected to |
| EQ | is equal to |
| <i>loc</i> | location |
| LOS | line of sight |
| NTPP | non-tangential proper part of |
| <i>obj</i> | object |
| O | overlaps |
| OWL | Web Ontology Language (name of the web ontology) |
| P | is part of |
| PO | partially overlaps |
| PP | is proper part of |
| <i>pth</i> | path |
| QD | qualitative distances |
| RA | rectangle algebra |
| RCC | Region Connection Calculus |
| <i>rgn</i> | region |
| TC | Trajectory Calculus |
| TPP | tangential proper part of |
| UGV | unmanned ground vehicle |

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TECH LIB

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