Cellular Ontology as a Basis for Spatiotemporal Reasoning
Extended Abstract and Summary

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1. Spatiotemporal reasoning about the movement of vehicles

Consider the problem of guiding a vehicle that has to move within severe spatial constraints. It may be a car that is getting into or out of a busy parking lot, where it has to cooperate with the movements of other cars, possibly even in the style of a 15-puzzle. It may also be a helicopter that moves near buildings or other obstacles, and that is required to maintain line of sight to some objects (stationary or mobile ones) on the ground.

Although such problems may be viewed as purely spatial ones, they may also have a temporal aspect if it is required to minimize travel time, or to be at certain points at certain clock times. For most vehicles the spatial and temporal considerations must be interrelated, in particular since a small turning radius in a maneuver may severely restrict the velocity or the acceleration/deceleration during that maneuver.

It is natural to appeal to spatiotemporal reasoning techniques for mastering such tasks, particularly when the environment where the vehicle moves is well structured, as is typically the case e.g. in built-up areas and along roads. However, our problem has some characteristics that are not usually met by existing methods for spatiotemporal reasoning in the literature:

- It requires the integration of qualitative and quantitative considerations. The quantitative aspect is absolutely essential for carrying out maneuvers, but in complex structured environments it is not sufficient alone.
- In most situations vehicles have a possibility to "back up", more or less literally, that is to replan and recover when an intended maneuver has failed. Therefore, the original plan for a task does not have to be perfectly reliable; it can be fixed while it is being executed.
- The qualitative and quantitative considerations may be unevenly spread over the spectrum from planning to execution. More precisely, one may consider an architecture where the vehicle plans its movements on the basis of somewhat unreliable, qualitative information, and where the quantitative aspect is applied when the plan is executed: instantiated, and possibly revised.

Maneuvers may fail because of unexpected external events, such as the sudden appearance of another vehicle. Since the total system must be capable of dealing with such exceptions anyway, it can use the same plan-healing capability if the plan fails because of a mismatch between the qualitative model of the vehicle's environment and the environment itself.

2. Commonsense behavior as a correctness criterium for a formalization

Research on commonsense reasoning attempts to develop a logic that is able to draw *commonsense conclusions*, that is, the same conclusions as a person would draw from the same premises only using common sense. For commonsense spatiotemporal reasoning we propose another criterium: the logic should be able to define the behavior of an autonomous vehicle resulting in *commonsense behavior*, that is, behavior that is similar to the behavior of the vehicle when driven by a person in the same environment. The Turing test can be used, after an obvious modification, for testing whether an autonomous vehicle has indeed implemented commonsense driving behavior.

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3. Cellular ontology

As we proposed in [Features and Fluents] (Oxford University Press, 1994), a logic for reasoning about dynamic systems should be defined on three levels. The *material level* is expressed in quantitative terms, the *image level* defines models in terms of discrete mathematics, and the *logic level* defines the logical language and deduction system.

For a simple version of the cellular ontology, the material level is a twodimensional surface where vehicles move along trajectories formed from straight line segments and circular arcs which are each others' tangents at the points of transition. The image level is obtained by dividing the surface into equally sized *cells*, which may be e.g. quadratic or hexagonal. Each cell has a finite number of *ports* along its perimeter, and these are designed so that if a vehicle exits from one cell at one of its ports, it automatically enters another cell at one of its ports. Normally all cells are congruent with respect to size, shape, and the positions of ports.

A *port position* for a vehicle is specified as a triple consisting of a cell, a port in that cell, and an *orientation* that the vehicle has at the port. For example, if one of the edges of a quadratic cell is characterized as "north", and a particular port is located at the center of the northern edge, then some of the orientations for exit at that port may be "straight north", "northwest", and "northeast", corresponding to the ways that the vehicle can cross the edge at that port. Each port position is either an *entry position* or an *exit position*, depending on whether it leads to the vehicle entering or leaving the cell as it moves forward at the given port having the given orientation.

A *maneuver* defines a movement within a cell from an entry port position to an exit port position for that cell. For example, if a square cell has a western port at the center of its western edge and a northern port at the center of its northern edge, then a "left turn" maneuver may go from a position with eastward orientation at the western port, to a position with northward orientation at the northern port.

Composite movements are obtained by concatenating successive maneuvers where the exit port in one maneuver can be identified with the entrance port of the next maneuver.

For a given cell structure, with a finite set of ports and a finite set of orientations, and allowing also for some restrictions on vehicle movements, we obtain a finite set of possible maneuvers. Moreover, each maneuver imposes its own requirement on turning radius, so a finite set of maneuvers implies a finite set of relevant vehicle classes with respect to turning radius. The range of possible velocities also obtains a classification. Consequently, each of the finitely many maneuvers obtains its own maximal entry velocity, minimal execution time, and function from entrance velocity to range of possible execution times and exit velocities.

It is therefore possible to calculate in advance a qualitative information structure that can be used for analyzing and planning the movements of a vehicle in the cellular driving space. This structure will be based on some simplifying assumptions on e.g. the shape and size of cells, but it may anyway be capable of generating adequate plans for the vehicle. If these plans are not always entirely correct in the actual situation, due to the approximation of the actual environment with a cellular model, then it does not really matter as long as the plan is roughly right and as long as it can be adjusted while being executed.

4. Temporal aspects

For some purposes it may be possible to ignore the temporal aspect entirely when planning the movements of a vehicle. Unhurried movements in a parking garage, for example, are typically made well within the natural velocity limits even when minimal turning radii are used. A somewhat more detailed account of time can be obtained by introducing a number of qualitative velocities, such as "slow", "medium", "fast", and "very fast", and to extend port positions with a fourth component, for velocity. A similar set of qualitative durations is defined for maneuvers, as a sufficiently good approximation of exact maneuver times.

An even more precise account of time in the cellular ontology is obtained by associating port positions with quantitative velocities, and associating each maneuver instances with an interval of possible durations. Additional possibilities can also be considered, but these have illustrated the versatility of the cellular-ontology approach.

5. A worked example

A worked example for a cellular ontology is described in the full paper.