SailAway: Spatial Cognition in Sea Navigation

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Pedestrians, bicyclists, car drivers, boat and airplane pilots, as well as other cognitive agents participating in public traffic must respect rules in order to avoid dangerous situations and to ensure a smooth flow of traffic. The SailAway project [1] investigates traffic and related navigational rules from a formal and computational point of view. The aim is to enable artificial cognitive agents to act in compliance with such rules. Traffic rules, which are expressed in natural language, usually subsume distinct, but similar situations and actions under more abstract spatial or temporal concepts and relations. In this paper we describe an approach to representing rules that exploits this qualitative nature of natural language descriptions used in traffic laws. Based on this approach we present methods that enable an agent to determine actions that are rule-compliant with respect to its current spatial situation. Finally we present the prototype of a control system of boats in sea navigation that implements exactly these methods.

1 Introduction

A considerable part of everyday human activities is guided by regulations. Typical examples include regulations of how to behave in traffic scenarios, recommendations of how to use escalators, rules on how to enter subways and buses, or politeness rules at bottlenecks. These rules are usually formulated in natural language and thus can be expressed in a language, which uses *qualitative terms* to describe the situations that are governed by the rule as well as "correct" (i. e., rule-compliant) behavior of agents. Artificial cognitive agents that interact with humans should be able to process such rule sets. This entails that an agent must be able to *localize* itself in both the physical space and the normative space of laws, rules, etc. In particular, the agent must perceive its current spatial situation, identify rules that might be relevant in this situation and with respect to its current *role*, and finally select appropriate (in terms of the agent's agenda), but notwithstanding rule-compliant actions.

In the following, we report on a case study that accounts for some aspects of rule-compliant behavior in the domain of sea navigation (though most of the discussed techniques carry over to other navigation scenarios). In particular, we show how representation formalisms and reasoning techniques known from *qualitative spatial reasoning (QSR)*, namely constraint solving procedures and *neighborhood-based reasoning* techniques, can be applied for deriving suitable actions for an agent that comply with a given set of right-of-way rules. Qualitative spatial representation formalisms abstract from metric data by summarizing similar quantitative states into a single qualitative description [2]. For this reason, such formalisms are suited as a basis for representing rules in a formal way. Neighborhood-based reasoning methods allow for reasoning about spatial situations that change in time [4]. We use these methods to construct transition systems which encode rule-compliant behavior in situations with two agents—in fact, many navigation rules only describe correct behavior for situations that are limited to two agents. Finally, constraint solving techniques [5] help us to assign rule-compliant actions to all the agents involved in a particular situation.

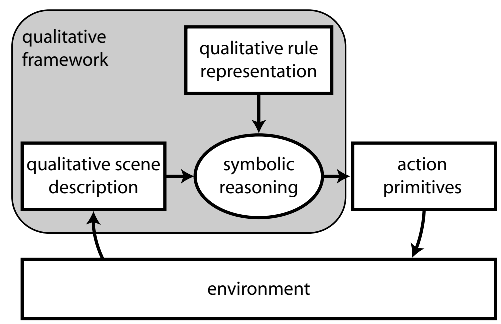

Figure 1: Qualitative methods underlying SailAway

The fundamental role of qualitative methods is reflected in the overall architecture of our demonstrator application *SailAway* (cf. Fig. 1). Based on a qualitatitive scene description that contains information about the relative position of each pair of vessels in an open sea scenario and a qualitative rule representation encoding parts of the *International Regulations for Preventing Collisions at Sea* (ColRegs—published by the International Maritime Organization), we use purely symbolic reasoning methods to select actions that avoid collisions between the involved agents.

2 Formalizing Spatial Knowledge

A qualitative representation formalism (or *qualitative calculus*) builds the basis for representing spatial knowledge in our project. The choice of such a formalism depends on the domain to be described and on the particular aspect of interest. A qualitative calculus then partitions the set of all possible constellations between objects into a finite set of relations summarizing similar constellations. Since we are interested in representing traffic rules such as "When two power-driven vessels are meeting head-on or nearly head-on courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the

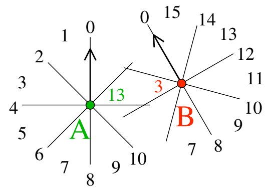

Figure 2: An instance of the qualitative spatial relation $A\,{}_4\angle^{3}_{13}B$

port side of the other", we need to use a calculus that allows for distinguishing the positions of vessels in an open sea scenario as well as their relative moving directions.

An appropriate calculus for this requirement is provided by the $\mathcal{OPRA}_m$ family of calculi [6], which describe relations between *oriented points*. Depending on the granularity parameter m, $4m$ angular sectors, are distinguished namely $2m$ cone-like and $2m$ line-like sectors, (see Fig. 2 for a specific $\mathcal{OPRA}_4$ example). $\mathcal{OPRA}_m$ is very expressive due to a double classification: Oriented points P and Q are classified with respect to the position of Q relative to P and vice versa (denoted by ${}_m\angle^{Q \rightsquigarrow P}_{P \rightsquigarrow Q}$, where $P \rightsquigarrow Q$ and $Q \rightsquigarrow P$ index the sector $0, 1, \ldots, 4m-1$ in which one point is positioned with respect to the other. For the domain of sea navigation a parameter value of $m = 4$ has proven to provide a reasonable level of granularity in our experimental analysis. Then, a configuration of "two vessels in head-on positions" (as mentionend in the above rule) can be represented by the relation ${}_4\angle^0_0$ and "nearly head-on" can be represented by a disjunction of relations neighbored to ${}_4\angle^0_0$ (as explained below).

3 Modeling Rule-Compliant Actions

Actions are performed in time and hence their formalization introduces a temporal aspect. Temporal information can be integrated into a static qualitative spatial representation by using *conceptual neighborhoods* [4]. The idea of conceptual neighborhoods is to specify the discrete relation transitions that are possible due to continuous transformation (in our case, object motion). Two relations are *conceptual neighbors* if the motion of objects can cause an immediate transition between these relations. For the context of sea navigation, we consider three aspects that influence the neighborhood structure: agent kinematics (motion capabilities), concurrency and asynchronicity of actions, and lack of superposition. For example, a slight movement can cause vessels originally in head-on position to take one of the relations ${}_4\angle^{15}_0$, ${}_4\angle^0_{15}$, ${}_4\angle^0_1$, ${}_4\angle^1_0$, ${}_4\angle^{15}_{15}$, and ${}_4\angle^1_1$, and hence these relations are considered conceptual neighbors of ${}_4\angle^0_0$ (cp. Fig. 2). The neighborhood relation induces a finite graph, which becomes directed if we augment it by information on the transition-causing actions of the involved vessels—currently, we consider the actions "turn starboard (S)", "turn portside (P)", and "keep course/midships (M)".

For each rule we define step-wise a *transition system* that describes rule-compliant actions of two vessels [3]. We first identify start configurations in which the rule is triggered and end configurations which are no longer covered by the rule. Then we define an idealized transition sequence (the *idealized thread*) assigning pairs of actions to configurations. An idealized thread

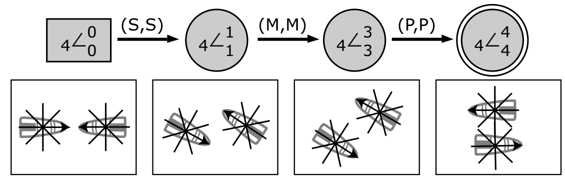

Figure 3: Idealized thread of a rule applied for avoiding head-on collisions between vessels of the same type (acc. ColRegs)

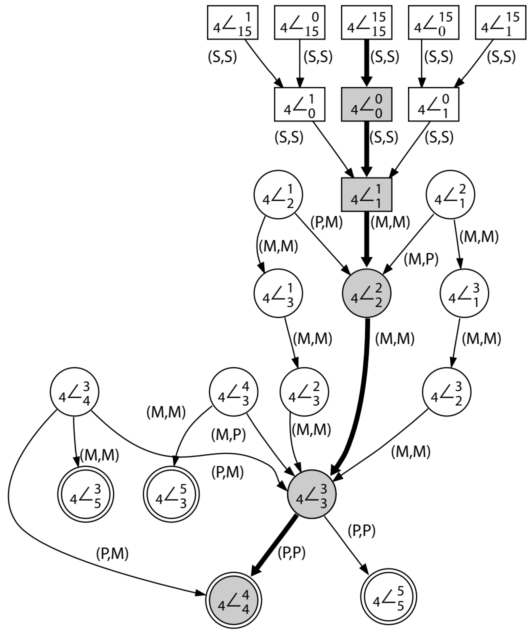

Figure 4: Complete model of the rule constructed from the idealized thread in Fig. 3

may be considered a temporally complete, rule-compliant plan of maneuvers from a start to an end configuration if we observed the vessels at each point in time. Fig. 3 depicts an example of two boats in head-on course that give way to one another.

The idealized thread is not yet a suitable formalization of rule-compliant actions, as it abstracts from alternative action effects that need to be considered: Depending on the precise position of the vessels, the same action may lead to different change-overs with respect to the qualitative relations as defined by the neighborhood graph. For example, two vessels which travel on perpendicular courses cross the sectors defined by the qualitative relations more rapidly when they are closer to one another or when they travel at higher speed. Therefore, the idealized thread is extended in a third step to a transition system that also includes neighbored configurations if they are still within the scope of the traffic rule at hand. For each of these added configurations, we derive actions that lead the vessels closer to the idealized thread. Analogously, we apply this method of *neighborhood-based relaxation* to start and end configurations. The resulting transition system for the example with two vessels of the same type is depicted in Fig. 4. Note that this transition system depends on the formalized rule and thus on the considered vessel types.

4 Global Rule Integration

Transition systems formalize rule-compliant actions for pairs of agents and hence allow a pair of agents to avoid collisions by performing the actions linked to their current relation. But this is generally not guaranteed in situations with more than two vessels. Therefore, we apply constraint-based reasoning methods to check whether actions according to the two-vessel transition systems are compatible from a global point of view as well. Additionally, constraint-based reasoning enables us to select a globally admissible action when a transition systems allows for alternative actions. For this, we first generate a constraint network that encodes all spatial relations between vessel positions that may result from admissible actions applied to the current configuration. A solution of the constraint network is computed (if possible), pinning globally consistent spatial relations among the agents. On this basis we can determine the actions that will lead to these spatial relations. The result is then repropagated to determine the suitable actions for the individual vessels that will lead to this particular constellation. This process ensures that the selected actions are admissible with respect to the individual rules (by construction of the constraint network) and with respect to the global scene (by global constraint satisfaction).

5 Results and Outlook

The approach presented here has been implemented in our SailAway demonstrator. The application simulates continuous movements of vessels in an open sea scenario. We formalized six rule types for four different classes of vessels. Whenever two or more vessels go below a pre-specified safety distance, the system calculates rule-compliant maneuvers for the involved vessels. The simple example depicted in Fig. 5 illustrates how collision-free navigation is achieved in a situation involving three boats.

The formalization of rules as transition systems was straightforward and led to a generally collision-free evolution of the system. However, situations involving multiple vessels can arise where no admissible action exists. In future work we aim at introducing a planning component that can foresee, and thus allows to avoid, such deadlocks. Furthermore, since we are interested in cognitive agents, we will modify our approach such that representation and reasoning processes occur at the level of the individual agents with partial knowledge, rather than at the level of a control system with a bird's eye view.

Acknowledgement

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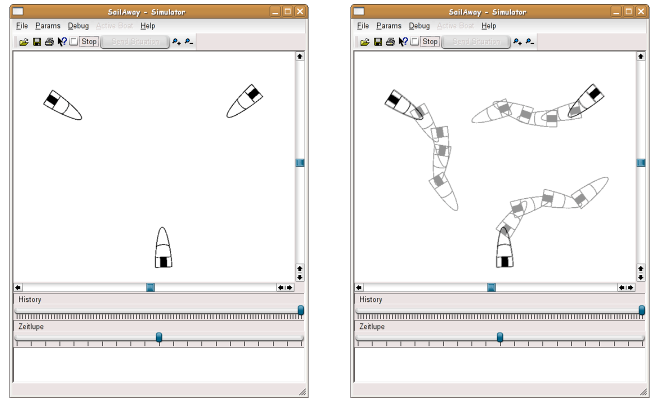

Figure 5: Configurations in the SailAway simulator window; left: an initial situation with three motor vessels; right: the resulting trajectories determined by the system

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R4-[LogoSpace] focuses on spatio-temporal representation formalisms and reasoning methods. The aim of the project is to develop qualitative spatio-temporal calculi including an analysis of their logical properties such as decidability and computational complexity.

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