Multiagent Strategic Reasoning in the IoV: A Logic-Based Approach

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1. INTRODUCTION

With the increasing need for reliable transportation, the rapid development of communication technologies, and the ongoing race for developing autonomous vehicles, the Internet of Vehicles (IoV) is emerging as one of the hottest topics in the AI research community with high relevance and potential impact in the transportation industry. The IoV is a distributed multiagent network that utilises the capacity for collaboration and self-coordination towards collective-level concerns such as safety and reliability of transportation and logistic systems [Kaiwartya et al. 2016; Hammoud et al. 2020]. Realising such a form of collaborative practice can be reduced to classic optimisation problems with standard solution concepts when we deal with obedient non-autonomous vehicles (as tools) that merely follow instructions [Gerding et al. 2016; de Weerdt et al. 2016]. However, in IoV systems[1] that involve autonomous agents, it leads to new forms of coordination and control problems [Silva and Iqbal 2018; Stein et al. 2017; Abramson et al. 2007]. In principle, giving more autonomy raises challenging problems on *whether* and *to what extent* such autonomous systems are capable of collaboration, self-coordination towards collective-level concerns such as safety, and implementing the concept of collective intelligence in vehicular systems [Amelkin et al. 2018; Crowston 2004]. To that end, IoV systems require operational methods to reason about the capacity of the involved agents to form *feasible* and *capable* coalitions as a means to ensure safety. Reviewing the literature on IoV coordination, in [Santini et al. 2015], the authors use a graph theoretical representation that is temporally expressive. However, the results are specific to platoon formation in a static topology with no room for expressing scenarios in which the set of available actions to each agent varies in time and with respect to the state of the IoV system. The presented approach in [Ghaffarian et al. 2012] removes the need for traffic lights and solves the coordination problem but under the strong assumption that involved vehicles are fully collaborative and that all the potential two-member coalitions are feasible to form in order to avoid pairwise collisions. Finally, in [Lee and Park 2012; Milanés et al. 2011], safety can be guaranteed under the assumption that vehicles share information regardless of their potential incompatibilities, e.g., caused by being produced by different manufacturers.

In this work, we present a formal approach to verify the self-coordination capacity of IoV systems using formal reasoning and develop a mechanism to ensure it. We employ the semantic machinery of Alternative-time Temporal Logic (ATL) [Alur et al. 2002] and extend it to model endogenous and exogenous constraints. In practice, this framework can be embedded in the IoV infrastructure as a safety-ensuring coordination service.

2. CONCURRENT GAMES AND STRATEGIC REASONING SEMANTICS

To reason about the abilities of agents and agent coalitions in a multiagent system such as the IoV, we employ Concurrent Game Structures (CGS). CGS, as the semantics machinery of Alternative-time

[1] We say *"IoV system"* to refer to a particular instance/scenario in the IoV as a whole (with millions of nodes).

Temporal Logic (ATL) [Alur et al. 2002], enables modelling the behaviour of IoV systems over time (capturing temporality) and is expressive for representing the ability of individual agents as well as coalitions to ensure/avoid a given situation (strategic abilities). Moreover, CGS-based notions can be implemented using established model-checking tools [Cermák et al. 2014; Kurpiewski et al. 2019]. Formally, a CGS is a tuple $\mathcal{M} = \langle \Sigma, Q, \Pi, \pi, Act, d, o \rangle$ where: $\Sigma = \{a_1, \dots, a_n\}$ is a finite, non-empty set of *agents*; Q is a finite, non-empty set of *states*; Π is a set of atomic propositions; $\pi : Q \mapsto \mathcal{P}(\Pi)$ is a valuation of propositions; Act is a finite set of atomic *actions*; function $d : \Sigma \times Q \mapsto \mathcal{P}(Act)$ specifies the sets of actions available to agents at each state; and o is a transition function that assigns the outcome state $q' = o(q, \alpha_1, \dots, \alpha_n)$ to state q and a tuple of actions $\alpha_i \in d(a_i, q)$ that can be executed by Σ in q. To represent *strategies* and *outcomes* we make use of the following auxiliary notions. *Successors and Computations:* For two states q and q', we say q' is a *successor* of q if there exist actions $\alpha_i \in d(a_i, q)$ for $a_i \in \{1, \dots, n\}$ in q such that $q' = o(q, \alpha_1, \dots, \alpha_n)$, i.e., agents in Σ can collectively guarantee in q that q' will be the next system state. A *computation* of a CGS $\mathcal{M}$ is an infinite sequence of states $\lambda = q_0, q_1, \dots$ such that, for all $i > 0$, we have that q_i is a successor of q_{i-1}. We refer to a computation that starts in q as a q*-computation*. For $k \in \{0, 1, \dots\}$, we denote the k'th state in λ by $\lambda[k]$. *Strategies and Outcomes:* A *memoryless strategy* for an agent $a \in \Sigma$ is a function $\zeta_a : Q \mapsto Act$ such that, for all $q \in Q$, $\zeta_a(q) \in d(a, q)$. For a coalition of agents $C \subseteq \Sigma$, a *collective strategy* $Z_C = \{\zeta_a \mid a \in C\}$ is an indexed set of strategies, one for every $a \in C$. Then, $out(q, Z_C)$ is defined as the set of potential q-computations that agents in C can enforce by following their corresponding strategies in Z_C. CGS is expressive to capture scenarios where we are interested in a combination of temporal, coalitional, and strategic properties. Being concerned about the occurrence of a crash or passing safely, we use the unique state formulae $\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi$ ($p \in \Pi$) to represent a crash. Then, we are interested in verifying if agents or agent coalitions are capable of avoiding such a crash using their available actions or sequences of actions.

3. MULTIAGENT IOV SYSTEMS: A FORMAL PERSPECTIVE

We build on the CGS machinery and adopt elements from argumentation theory to model multiagent IoV systems. The first element is a relation to represent potential incompatibilities while the second element is a preorder to represent priorities in the IoV context.

Definition 3.1. A multiagent IoV is a tuple $\mathcal{I} = \langle \Sigma, Q, \Pi, \pi, Act, d, o, \mathfrak{I}, \prec \rangle$ where $\langle \Sigma, Q, \Pi, \pi, Act, d, o \rangle$ is a CGS modelling the behaviour of the IoV, $\mathfrak{I} \subseteq \Sigma \times \Sigma$ is an antireflexive relation representing the potential incompatibilities between agents, and $\prec$ is a preorder on Σ representing priorities between agents. Moreover, we say $C \subseteq \Sigma$ is a feasible coalition if and only if there exist no two agents $a_i, a_j \in C$ such that $(a_i, a_j) \in \mathfrak{I}$ and a_j is not preferred over a_i (i.e., that $a_i \prec a_j$ is not in $\prec$).

Relation $\mathfrak{I}$ reflects potential incompatibilities in terms of inherent characteristics, e.g., competing manufacturers or owners of vehicles. The ordering $\prec$ is a contextual element in the IoV systems that models priorities. In the real-life cases—e.g., in applying our method to traffic coordination scenarios—priorities act as regulatory norms and override potential incompatibilities. For instance, regardless of the brand of an ambulance, other vehicles collaborate with it as it has priority. Next, we move to the "whether agents in an IoV system can safely self-coordinate".[2]

THEOREM 3.2. *Let $\mathcal{I}$ be a multiagent IoV and $S \subseteq Q$ a safety state of affairs represented by a set of states in the IoV. From a safe state $q \in S$, the IoV $\mathcal{I}$ can safely self-coordinate w.r.t. S if (1) there exists a $C \subseteq \Sigma$ with a collective strategy Z_C to ensure and maintain S, (2) C is a feasible coalition, and (3) no $C' \subset C$ satisfies both (1) and (2).*

[2]To respect the space limit, we mainly present the main results and intuitions behind them but exclude formal proofs.

Verifying whether an IoV is capable of self-coordination builds on model-checking instances, hence is implementable using standard tools (e.g., using [Cermák et al. 2014; Kurpiewski et al. 2019]).

4. SELF-COORDINATION ABILITY AND A SAFETY-ENSURING MECHANISM

Our notion of self-coordination in the IoV is essentially a *local* notion as it is about the ability of the IoV to remain safe (evolving) from a given safe state. The next result is on the *global* form of this capacity.

THEOREM 4.1. *IoV $\mathcal{I}$ can safely self-coordinate w.r.t. $S \subseteq Q$ if in all $q \in S$, there is a feasible coalition C with a strategy Z_C such that in any $\lambda \in out(q, Z_C)$, we have that $\lambda[2]$ is in S.*

Simply stated, $\mathcal{I}$ is capable of self-coordination globally only if in every safe state, there exists at least a feasible coalition capable of ensuring at an immediate safe state. Otherwise, when the conditions of Theorem 3.2 are not satisfied, the IoV is incapable of self-coordination in a safe manner, thus requires interventions to ensure safety. Next, we present mechanism $\mathfrak{M}^S$ (Algorithm 1) to ensure safety concern S as a function that takes $\mathcal{I}$ and updates it to $\mathcal{I}'$ capable of self-coordination with respect to S.

Input: IoV $\mathcal{I}$; state $q \in Q$; state of affairs $S \subseteq Q$.
Result: $\mathcal{I}'$ capable of safe self-coordination w.r.t. S.
$\varphi \leftarrow$ ATL formula (from $\mathcal{L}_{ATL}$) corresponding to S; $\hat{C}^S_q \leftarrow$ indexed set of groups C_k able to ensure and maintain φ from q (standard ATL model-checking [Bulling et al. 2010]); $index \leftarrow 0$; $u \leftarrow |\mathfrak{I}|$;
forall the $C_k \in \hat{C}^S_q$ **do**
  $u_k \leftarrow 0$; $U_k \leftarrow \varnothing$;
  forall the $(i, j) \in \mathfrak{I}$ **do**
    if $i \in C_k$ *and* $j \in C_k$ *and* $j \nprec i$ **then**
      $u_k \leftarrow u_k + 1$; $U_k \leftarrow U_k \cup \{(i, j)\}$;
  if $u_k = 0$ **then**
    return $\mathcal{I}$;
  else
    if $u_k \leq u$ **then**
      $u \leftarrow u_k$; $index \leftarrow k$;
$\prec' \leftarrow \prec$;
forall the $(i, j) \in U_{index}$ **do**
  if $j \nprec' i$ **then**
    $\prec' \leftarrow \prec' \cup \{i \prec j\}$;
return $\mathcal{I}' = \langle \Sigma, Q, \Pi, \pi, Act, d, o, \mathfrak{I}, \prec' \rangle$;

ALGORITHM 1: Safety Ensuring Mechanism $\mathfrak{M}^S$

THEOREM 4.2. *Let $\mathcal{I}$ be an IoV and non-empty $S \subseteq Q$ a safety state of affairs. If S is reachable and maintainable from $q \in Q$, mechanism $\mathfrak{M}^S$ ensures the self-coordinating capacity of the updated IoV $\mathcal{I}'$ to ensure S via minimal priority updates.*

5. FUTURE RESEARCH: TOWARDS A TRUSTWORTHY IOV

We aim to link our work to efforts on developing trustworthy autonomous systems [Yazdanpanah et al. 2021] and develop tools for reasoning about *responsibilities* in the IoV. To that end, we envisage integrating our approach with epistemic logics [van der Hoek and Wooldridge 2003] and multiagent responsibility reasoning methods [Yazdanpanah and Dastani 2016].

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