Motion and Action Planning for Multi-Agent-Object Systems under Temporal Logic Formulas

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***Abstract*—This paper presents a hybrid control framework for the motion and action planning of a multi-agent-object system including N robotic agents and M objects, under high level goals expressed as Linear Temporal Logic (LTL) formulas. In particular, we design control protocols that guarantee the transition of the agents as well as the cooperative transportation of the objects by the agents, among predefined regions of interest in the workspace. This allows to abstract the coupled behavior of the agents and the objects as a finite transition system and to design a high-level multi-agent plan that satisfies the agents' and the objects' specifications, given as temporal logic formulas.**

I. INTRODUCTION

Temporal-logic based motion planning provides a fully automated correct-by-design controller synthesis approach for autonomous robots. Temporal logics provide formal high-level languages that describe planning objectives more complex than the well-studied navigation algorithms, and have been used extensively in robotic applications [1]–[3]). The objectives are given as a temporal logic formula with respect to a discretized abstraction of the system and a high-level discrete path is found by off-the-shelf model-checking algorithms [4].

Most related works consider the motion planning problem for fully actuated, autonomous agents. Consider, however, cases where some unactuated objects must undergo a series of processes in a workspace with autonomous agents (e.g., car factories). In such cases, the agents are also responsible for coordinating with each other in order to transport the objects around the workspace. When the unactuated objects' specifications are expressed using temporal logics, then the abstraction of the agents' behavior becomes much more complex, since it has to take into account the objects' goals. In addition, the spatial discretization of a multi-agent system to an abstracted higher level system necessitates the design of appropriate continuous-time controllers for the transition of the agents among the states of discrete system. Moreover, since we aim at incorporating the unactuated objects' specifications in our framework, the agents have to perform (cooperative) transportation of the objects around the workspace, while avoiding collisions with each other

This work presents a novel hybrid control framework for the motion planning of a team of N autonomous agents and M unactuated objects under LTL specifications. We design feedback control laws for the collision-free i) navigation of the agents and ii) cooperative transportation of the objects by the agents, among predefined workspace regions. This allows us to model the coupled behavior of the agents and the objects with a finite transition system, which can be used for the design of high-level plans that satisfy the given LTL specifications.

II. CONTRIBUTION

We propose a novel control strategy for the coordination of a multi-agent-object system, consisting of multiple objects and 2nd-order mobile manipulator agents, subject to temporal logic tasks. The tasks are expressed as Linear Temporal Logic (LTL) formulas ϕ_i, ϕ_{O_j}, $i \in \{1,\dots,N\}$, $j \in \{1,\dots,M\}$, over the atomic propositions Ψ_i, Ψ_{O_j}, $i \in \{1,\dots,N\}$, $j \in \{1,\dots,M\}$, which express properties of interest of the workspace. We consider that these properties are boolean variables that hold true/false in predefined "Regions of Interest" (RoI) of the workspace. The proposed methodology can be divided in two main parts, which are analyzed next.

Firstly, we focus on the abstraction of the coupled continuous system to a finite transition system. More specifically, we partition the workspace based on the Regions of Interest and, based on previous results on multi-agent navigation functions, we design feedback controllers that guarantee the collision-free (i) multi-agent navigation among the RoI, and (ii) cooperative transportation of the objects by the agents among the RoI. Moreover, we assume that there exist appropriate controllers that guarantee the executions of other tasks by the agents, such as "grasping" and "releasing" the objects. Therefore, we design a finite transition system $\mathcal{T} = (\Pi, \mathcal{A}ct, \rightarrow, \mathcal{L}, \mathcal{L}_O)$ that captures the behavior of the multi-agent-object system; Π is a finite set of states, based on aforementioned workspace partition, $\mathcal{A}ct$ is the set of the aforementioned actions, $\rightarrow \subset \Pi \times \Pi$ is a transition relation, and $\mathcal{L}$, $\mathcal{L}_O$ are functions that provide which atomic propositions from Ψ_i, Ψ_{O_j}, respectively, hold true at the states Π.

The second part of the proposed methodology focuses on the derivation of a plan that satisfies the LTL formulas of the agents and the objects. We first consider the product $\phi = \wedge_{i\in\{1,\dots,N\}}\phi_i \wedge \wedge_{j\in\{1,\dots,M\}}\phi_{O_j}$, which is translated into a Büchi automaton $\mathcal{A}_B$, whose language is ϕ [4]. Next, we compute the product $\widetilde{\mathcal{T}} = \mathcal{T} \otimes \mathcal{A}_B$ and employ graph-search algorithms to find its accepted runs. These accepted runs satisfy ϕ (and hence ϕ_i, ϕ_{O_j}), and their projection to $\mathcal{T}$ provides a sequence of actions to be executed by the agents (sequence among the actions "grasp", "release", "navigate", "cooperative transport). The execution of the sequence produces a closed loop trajectory of the multi-agent-object system that satisfies the formulas ϕ_i, ϕ_{O_j}, $\forall i \in \{1,\dots,N\}$, $j \in \{1,\dots,M\}$.

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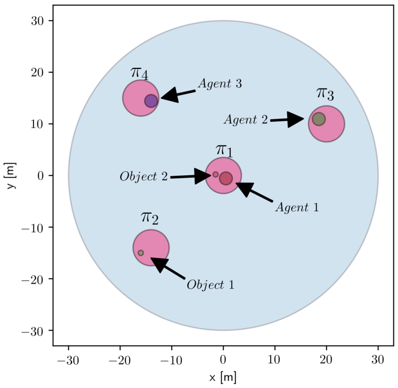

Fig. 1. The initial workspace of the second simulation example, consisting of 3 agents and 2 objects.

TABLE I
THE AGENT ACTIONS FOR THE DISCRETE PATH OF THE SECOND SIMULATION EXAMPLE

$\pi_{s,\ell}$	Actions
$\pi_{s,1}$	$(-)$
$\pi_{s,2}$	$(\pi_1 \rightarrow_1 \pi_2, \pi_3 \rightarrow_2 \pi_1, \pi_4 \rightarrow_3 \pi_1)$
$\pi_{s,3}$	$(-, 2 \xrightarrow{g} 1, 3 \xrightarrow{g} 2)$
$\pi_{s,4}$	$(-, \pi_1 \xrightarrow{T}_{\{2,3\},2} \pi_3,)$
$\pi_{s,5}$	$(-, -, 3 \xrightarrow{r} 2)$
$\pi_{s,6}$	$(-, -, \pi_3 \rightarrow_3 \pi_2)$
$\pi_{s,7}$	$(1 \xrightarrow{g} 1, 3 \xrightarrow{g} 1)$
$\pi_{s,8}$	$(\pi_2 \xrightarrow{T}_{\{1,3\},1} \pi_1, -)$
$\pi_{s,9}$	$(\pi_1 \xrightarrow{T}_{\{1,3\},1} \pi_4, -)$
$\pi^{\star}_{s,10}$	$(\pi_4 \xrightarrow{T}_{\{1,3\},1} \pi_1, -)$
$\pi^{\star}_{s,11}$	$(\pi_1 \xrightarrow{T}_{\{1,3\},1} \pi_4, -)$

III. EXAMPLE SCENARIO

Consider 3 agents, 2 objects and 4 Regions of Interest at an initial configuration as show in Fig. 1. The LTL formula is chosen as $(\square\neg\text{“}1\text{-}\pi_3\text{”}) \wedge (\square\Diamond\text{“}2\text{-}\pi_3\text{”}) \wedge (\square\Diamond\text{“}O_1\text{-}\pi_1\text{”}) \wedge \square(\text{“}O_1\text{-}\pi_1\text{”} \rightarrow \Diamond\text{“}O_1\text{-}\pi_4\text{”}) \wedge (\square\Diamond\text{“}O_2\text{-}\pi_3\text{”})$, which represents the following behavior. Agent 1 must never visit region π_3, which must be visited infinitely many times by agent 2, object 1 must be taken infinitely many times to region π_1, eventually followed by a visit in region π_4, and object 2 must be taken infinitely many times to region π_2. The resulting transition system $\mathcal{TS}$ consists of 3112 reachable states and 154960 transitions and it was created in $100.74\,\text{sec}$. The Büchi automaton $\mathcal{BA}$ contains 9 states and 49 transitions and the product $\widetilde{\mathcal{TS}}$ contains 28008 states and 1890625 transitions. Table I shows the agent actions for the derived path as the sequence of states $\pi_{s,1}\pi_{s,2}\ldots\ldots(\pi^{\star}_{s,10}, \pi^{\star}_{s,11})^{\omega}$. The three agents navigate first to regions π_2, π_1, and π_1, respectively, and agents 2 and 3 take object 2 to π_3. Next, agent 3 goes to π_2 to transfer object 1 to π_1 and then π_4 with agent 1. The latter transportations occur infinitely often. The time taken for the construction of the product $\widetilde{\mathcal{TS}}$ and the derivation of the path was $4573.89\,\text{sec}$.

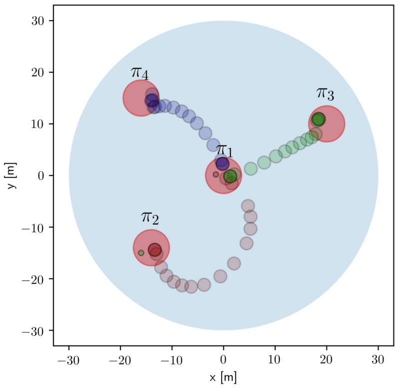

Fig. 2. The transition $\pi_{s,1} \rightarrow_s \pi_{s,2}$ (a), that corresponds to the navigation of the agents $\pi_1 \rightarrow_1 \pi_2$, $\pi_3 \rightarrow_2 \pi_1$, $\pi_4 \rightarrow_3 \pi_1$.

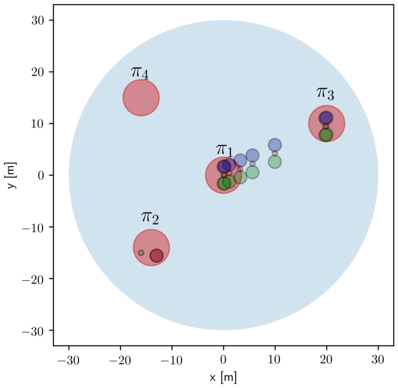

Fig. 3. The transition $\pi_{s,3} \rightarrow_s \pi_{s,4}$ (b), that corresponds to the transportation $\pi_1 \xrightarrow{T}_{\{2,3\}} \pi_3$.

IV. CONCLUSIONS

We have presented a hybrid control framework for the motion/action planning of a multi-agent-object system. We provide appropriate control protocols that model agent actions in the workspace and build an abstracted transition system for the coupled system, which is used to derive plans that satisfy complex LTL formulas.

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