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Hierarchy aware distributed plan execution monitoring

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ABSTRACT

Collaborative plan execution is becoming increasingly important given its potential for operational agility and cost reduction. In this paper we propose a distributed and hierarchy aware monitoring procedure for operational plan execution taking place in a dynamic environment characterized by unreliable communication and exogenous events. The contribution of this paper consists in employing a hierarchical clustering approach supporting a multi-party and hierarchy aware information sharing mechanism that is resilient to disruptions in the execution environment. The proposed distributed monitoring procedure uses asymmetric clustering to reflect hierarchical relationships along with gossip based communication across the clusters. Of significance is the information sharing mechanism formalization which utilizes a fresh information window in conjunction with communicating Markov Decision Processes. We show the usefulness of assessing shared information awareness via probabilistic model checking for various combinations of clustering topology and disruption conditions. In this context, we assess formal specifications expressed in probabilistic temporal logic and show how the model checking results can be used to derive the best fresh window value to maximize an information awareness utility function. An illustrative case study is also presented.

1. Introduction and motivation

Execution monitoring of operational plans involves the assessment of variables related to control functions and global aggregates (Wuhib, Stadler, & Spreitzer, 2010) representing process parameters of interest. Traditional monitoring seeks a trade-off between timely response and thorough data gathering and analysis. In the centralized setup, one or more collections of monitoring nodes send information to a central station as discussed by Delgado, Gates, and Roach (2004), Myers (1999). Conversely, distributed monitoring involves the participation of distributed and autonomous nodes. This setup can be particularly suitable in the case where information is shared in a dynamic environment prone to disruption and exogenous events. While a centralized coordination center can be used in such context, it exhibits a characteristic single point of failure along with a potential information bottleneck.

In this paper, we propose a distributed monitoring approach that can provide effective support for hierarchy aware information sharing with respect to the generation of plan execution events (e.g. positional changes) in the local environment of the participants. This entails achieving high level of common knowledge on the same levels in hierarchy and aggregated information across the hierarchical levels. In this pursuit, the present work extends the peer-to-peer gossip based technique presented by Soeanu, Ray, Debbabi, Allouche, and Berger. (2013) which considers a peer-to-peer setup with no hierarchy among the participants. Compared to the aforementioned work, the contribution of the present work is as follows: (i) Considering the presence of a chain of command whereby the participants can be at the same or different levels in the command hierarchy in contrast to Soeanu et al. (2013), which considers no hierarchy among participants. In this respect, the hierarchical levels are reflected in the clustering relationships of the participants which involve symmetric cluster membership for the participants on the same hierarchical level and asymmetric cluster membership for higher in command participants. (ii) Theoretical characterization of the information sharing mechanism which utilizes a fresh information window and is formalized using communicating Markov Decision Processes that can be analyzed via probabilistic model checking. (iii) Shared information assessment based on formal verification of specifications expressed in probabilistic temporal logic in contrast to the approach of Soeanu et al. (2013) which uses simulation. (iv) Leveraging model checking results in order to maximize an information awareness utility function.

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Collaborative planning and execution represent a noteworthy trend both in national and international context, potentially involving military with OGD (other governmental organizations). This promotes a synergy resulting from the specific area of specialization of various organizations working together toward a common goal.

In international arena, multi-national coalitions can benefit from sharing resources and information in order to reduce operational cost while increasing agility during disaster relief operations and humanitarian missions. Also, at national level, various agencies can interoperate in order to carry out development and contingency plans. In this respect, adaptive planning plays an important role in a wide range of operational plans that are executed in dynamic environments. This allows to provide appropriate response when faced with evolving circumstances. The potential changes in transport infrastructure due to natural disasters, emergency situations, etc., along with potential disruptions of communications, represent significant challenges for plan execution. This highlights the importance of having adequate supplies for conducting operations along with a corresponding level of information awareness. Thus, effective decision support mechanisms encompassing such concerns are needed for operational and logistic planning and execution.

We investigate a hierarchy aware distributed monitoring procedure applicable on generic operational plans which typically include logistic support components that require up-to-date shared information awareness. Given that monitoring mandates an effective reporting component, in the context of a command hierarchy, an important aspect is to assure that reporting occurs accordingly. Here we distinguish between command information flow that propagates from higher to lower levels and reporting which represents a flow of information from the bottom of the hierarchy toward the top. Thus, in our scope of interest, we focus on the latter.

The execution of the plan is assumed to be taking place in a dynamic environment prone to the occurrence of disruptive exogenous events and unreliable communication. In this setting, our objectives are as follows:

- Highlight the importance of collaborative plan execution in dynamic environments prone to communication disruption.
- Elaborate a hierarchy aware distributed monitoring approach for shared information awareness.
- Formalize the information sharing mechanism using communicating Markov Decision Processes in order to analyze the underlying dynamics using probabilistic model checking.
- Assess the degree of information awareness via formal specifications expressed in Probabilistic Computation Tree Logic (PCTL) (Hahn, Han, & Zhang, 2011).
- Conduct an illustrative case study in order to provide important observations with respect to the hierarchical aggregation of information and leveraging model checking results to maximize an information awareness utility function.

The need for collaborative plan execution typically involving the provision of logistic support is of high interest in the context of operations management ranging from unit management to provisioning critical supplies as part of disaster relief efforts. An important aspect in this setting is the aggregation of distributed nodes into clusters. This allows to localize the information exchange at the corresponding level of the distributed nodes. Moreover, cluster heads (Jain & Dubes, 1988) can be used to aggregate the information relevant for the area covered by their respective clusters. Cluster heads can then further exchange information. Fig. 1 depicts typical arrangements of distributed nodes that are aggregated into clusters and related cluster heads. In this context, we address the distributed monitoring problem involving a hierarchy of distributed participants collaborating in the execution of a generic plan taking place in a dynamic environment prone to communication disruption.

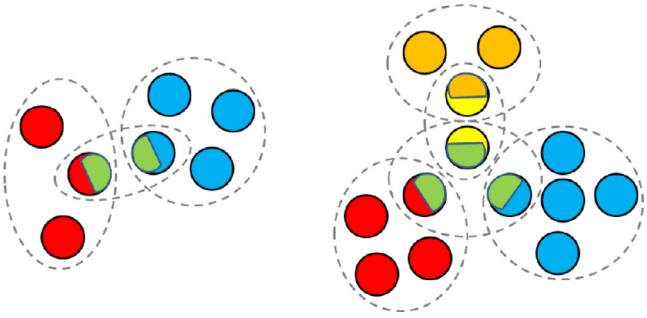

Fig. 1. Hierarchical clustering example for collaborative plan execution.

We consider that multiple distributed participants (e.g. plan executing agents) are responsible to carry out the actions required for the plan. Moreover, the participants can support monitoring activities by sharing information (notify/report noteworthy events) to their cluster peers in pursuit of coordination while executing plan related actions. However, the participants must also respect a command hierarchy. In this respect, we bring forth the concept of asymmetric clustering which involves non-reciprocal neighborhood relationships among cluster peers and higher in command participants. Asymmetric clustering allows for data exchange among coordinating peers on the same hierarchical level while propagating the information on the higher levels in command hierarchy. During execution, the environment might prompt the agents to deviate from their established actions thus potentially requiring plan adaptation and re-planning. Therefore, monitoring is necessary to correct the execution if needed. Our aim is toward a lightweight, hierarchy aware distributed monitoring protocol whereby the participants can use simple rules and procedures for effective communication in a hostile environment in order to obtain a high level information awareness of the overall situation. Moreover, in such hierarchy aware distributed setting, the participants can join or leave a cluster at their appropriate hierarchical level thus mitigating the potential issue of single point of failure. For instance, the plan execution may lead an agent at tactical level to separate (break away) from a cluster, no longer needing to coordinate with that cluster, subsequently joining another cluster with which it may need to coordinate with.

The reminder of the paper is organized as follows. In Section 2, we review the state-of-the-art with respect to relevant approaches for monitoring and associated challenges. We also highlight various shortcomings specific for different techniques in our scope of interest. Then, Section 3 states our assumptions. Section 4 details our approach for information sharing underpinning the distributed monitoring protocol and its formalization along with related algorithms and evaluation via probabilistic model checking. Section 5 presents the application of the approach on a case study along with results analysis. Section 6 discusses the need for distributed coordination and its usefulness for re-planning. Finally, Section 7 summarizes our efforts and highlights the advantages, limitations and the scope of future work.

2. Related work

In the context of collaborative plan execution, decentralization allows distributed parties to pursue specific goals according to their capabilities while aiming toward effective information sharing. For government and military organizations, the established hierarchy can be reflected in a tree structure for decision making. In such structure, each level needs to receive information from the level below in order to analyze and extract the meaningful information to be provided to the level above. Tree-based protocols are discussed in Dam and Stadler (2005) and Madden, Franklin, Hellerstein, and Hong (2002)