**Re-submission of ISF application No. 720/16 – Interaction Oriented Multi-Agent Planning**

**By Roni Stern**

Dear ISF reviewing committee

I appreciate the hard work of last year's reviewers and thank them for their helpful comments and suggestions. In the new proposal I addressed these comments and suggestions. In particular, I have made the following changes to the proposal:

1. To strengthen the impact of the proposed research, I extended the scope of the proposed research to include
   1. Developing a distributed mechanism for IOP that will support distributed planning (and not just distributed execution as in the previous proposal).
   2. Applying IOP to single agent planning problems as well, using problem decomposition methods to create multiple "agents".
   3. Studying the applicability of IOP to planning for data mules, an important multi-agent setting that is of interests to several research communities beyond the AI literature.
2. The relation to Transition Independent Dec-POMDP, Sparse Interaction Dec-POMDP, and similar variants of Dec-POMDP is clarified.
3. The challenges in detecting PIFs are explicitly discussed.
4. Explicit discussion of the challenges in detecting PIFs.

Below please find my detailed response to each of the reviewers' comments.

## Reviewer 1.

The reviewer wrote:

*Apart from the work cited, I think in particular the following papers*

*contain relevant ideas for exploiting known limited interaction:*

*Becker, R., Zilberstein, S., Lesser, V., & Goldman, C. V. (2004). Solving transition*

*independent decentralized Markov decision processes. Journal of Artificial Intelligence Research, 423-455.*

*Spaan, Matthijs TJ, and Francisco S. Melo. "Interaction-driven Markov games for*

*decentralized multiagent planning under uncertainty." Proceedings of the 7th*

*international joint conference on Autonomous agents and multiagent systems-Volume 1.*

*International Foundation for Autonomous Agents and Multiagent Systems, 2008.*

*Melo, Francisco S., and Manuela Veloso. "Decentralized MDPs with sparse interactions." Artificial Intelligence 175.11 (2011): 1757-1789.*

*Having said this, even in that field, the many forms of interactions and algorithms for*

*exploiting them have not yet completely settled down into a coherent framework.*

**Response.**

I agree with the reviewer that these works should have been included and their relation to IOP discussed, and we do so in the new proposal. Briefly, in IOP we intend to automatically discover the required interactions, while in these works (and others along this line) the planning agents know upfront that the interaction between the agent is limited, e.g., to only affecting the reward (as in the work of Becker et al.) or to only be relevant to predetermined situation (as in the work of Melo et al.). By contrast, in IOP we aim to discover during planning the interactions that need to be considered, allowing a broader range of problems.

The reviewer wrote:

*Regarding the problem of automatically finding/recognizing the type and frequency of*

*interactions (exploration), I can see some relation to machine learning and pattern*

*recognition, but I am not aware of any work in this direction. Only on a very general*

*level, I see some relation to the exploration/exploitation balance in reinforcement*

*learning, which may be worth diving deeper into. (See also the discussion on broader*

*implications below.)*

**Response.**

In the new proposal we discuss relationship to machine learning – learning from past planning sessions which PIF resolution methods are most suitable for a given PIF and MAP parameters, thus providing better search guidance for suboptimal search of the IRT. A relation to reinforcement learning exists, but where in reinforcement learning the exploration/exploitation balance is with respect to actually acting in the world and learning the world dynamics, in our case the exploration/exploitation is in the planning process.

The reviewer wrote:

*This proposal aims to make one important contribution towards this ultimate goal. The ideas may even have implications to single agent planners, because also single agent planning problems may be decoupled and then solved in a much more efficient manner. There is some initial work on decoupling in planning problems and I think it would be worthwhile to include such a possible use in the proposed research.*

**Response.**

We thank the reviewer for pointing out this important application of IOP and discuss it in the new proposal. Specifically, we cite prior work in classical and in factored planning in which the agent's set of actions were partitioned into a set of sets of action, decoupling the planning efforts. Each such set of action can be viewed as an agent (as was done by Nissim et al. 2012), allowing us to use IOP to improve single agent planning. This has been added to the proposal.

The reviewer wrote:

*Moreover, this reviewer believes that the ideas and a framework for identifying may have implications even outside planning community. It would be very good to at least briefly review such possible implications to prevent creating a mostly self-referencing community of planning and search. There must be other domains, possibly where already good algorithms exist that exploit independencies between subproblems. I advise the PI to talk to people from operations research and find industrial-size example domains.*

**Response.**

To expand beyond the planning community, I have consulted with colleagues from various departments, and in particular the Industrial Engineering department, and have decided to add to the scope of the proposal applying IOP to plan for a team of data mules. Data mules are of interest to a broad range of research communities as well as industry, and various planning tasks for data mules have been studies using other techniques (e.g., Mixed Integer Linear Programming). Thus, successfully applying IOP to solve planning problems in this domain is expected to have a significant impact beyond the planning and search communities.

The reviewer wrote:

*Still, I would like to propose here to generalize at least to a setting where the input*

*description does not contain a break-down into agent-specific problems, but where*

*instead the complete domain is presented as one. The task of analyzing the types and*

*degrees of interaction then becomes much harder (algorithm 1 will not work). I believe, however, this could sometimes still be done, by introducing techniques from machine learning.*

**Response.**

Such a break-down of a complete domain to individual sub-domains that can be solved in a relatively decoupled manner has been discussed in the context of factored planning (e.g., the work of Amir and Engelhardt, 2003) and even specifically for MA-STRIPS (Nissim et al., 2002). As mentioned above, we have added to the proposal research a specific task to explore and evaluate the use of IOP for single agent planning, based on these prior work.

The reviewer wrote:

*In the step of tuning the approach towards solving the possible conflicts, it could be*

*useful to refer to more general approaches to tuning algorithms towards the task at hand, such as in:*

*Kadioglu, Serdar, et al. "ISAC-Instance-Specific Algorithm Configuration." ECAI. Vol.2010.*

**Response.**

In the new proposal we also include using general-purpose automated algorithm selection to provide an effective heuristic for exploring the IRT and choosing how to expand each node (i.e., choosing appropriate conflict resolution methods), in the context of suboptimal planning.

The reviewer wrote:

*On a more detailed level, it looks like one step is missing in the following:*

*"There are many possible ways to generate and search the IRT. "*

*and then a few lines later in the proposal:*

*"Therefore, a major theme of the proposed research is in the development of smart*

*algorithms for searching the IRT cost-effectively. "*

*I wonder what happened with the generation of the IRT. That seems also relevant.*

*Especially since:*

*"This approach – searching the IRT with a BFS – to find a cost-optimal plan was applied by us in prior work on MAPF, resulting in the development of a family of successful optimal MAPF solvers [60, 8, 9]." there are already three publications on searching IRTs.*

**Response.**

Our writing was not clear: the IRT is expected to be too large to be represented fully in an explicit manner, so it is not efficient to fully generate the IRT and then search it. The IRT is searched, such that when a node is expanded we generate its children. We clarify this in the new proposal. Indeed, there are publication on searching the IRT for MAPF, but not for general multi-agent planning. As outlined in the proposal this more general setting poses several challenges we aim to address in the proposed research.

The reviewer wrote:

*Additionally...*

*" If time permits, we will also explore implementing IOP in more complex MAP models that directly address these issues during planning such as Dec-POMDP [5], building on the MADP toolbox of Dec-POMDP algorithms [49]."*

*"If time permits"? I think this is essential to have some incentive to generalise results*

*beyond the often unrealistic and limited classical planning setting.*

*My grade for "Adequacy of methods" is under the assumption that the phrase "If time*

*permits" is removed and the evaluation is also done using the MADP toolbox.*

**Response.**

We committed to evaluating our approach on MADP and omitted the "if time permits" phrase.

The reviewer wrote:

*Weaknesses:*

*- with limited extra effort, the proposed contributions could be more general, and*

*therefore the impact could be widened*

**Response.**

As noted above we address this weakness by proposing to generalize IOP to factored single agent planning and to domains outside the standard planning community, namely planning for data mules.

## Reviewer 2.

The reviewer wrote:

*I have slight reservations in the direction of resolving PIFs during execution as plan*

*adaptation (repairing) methods are notoriously known for their sensitivity to the*

*particular (and a priori unknown) types of the failures, however the other proposed*

*method relying on predefined recipes is adequate and seems to be by itself sufficient if*

*the practical usable of plan adaptation will provide weaker results.*

*…*

*The only weakness is in possibly inappropriate technique chosen for one*

*of the proposed methods which is in the overall view on the project only minuscule*

*drawback.*

**Response.**

Replanning and using pre-defined recipes are two alternative ways to handle PIFs during execution. Indeed replanning is often too costly to be performed during execution and predefined recipes provide a convenient solution in such cases. Still, there are cases where replanning is feasible and preferable. In general, I expect that the role of replanning will be more significant as we expect more autonomy from the acting agents. Choosing the appropriate method to handle a PIF during execution in one of the challenges I will address in the proposed research.

## Reviewer 3.

The reviewer wrote:

*Also, the proposer could have opted for game-theoretical approach to multiagent planning should the aspect of adversarial behaviour been presented in the problem specification (which it is not).*

**Response.**

Indeed, we focus on the collaborative setting (as oppose to self-interested or adversarial) and thus preferred a search-based approach over a game-theoretic one, as the former is more suitable for cost-optimality and time-optimality while the latter usually aim for notions such as social welfare, equilibrium, and fairness.

## Reviewer 4.

The reviewer wrote:

*Within multi-agent planning, the proposed work seems to be focused primarily on centralized planning, which is a very limited form of this general problem. For example, self-interested agents with distributed planning is*

*considered to be out of the scope of the proposed work. This removes a lot of interesting*

*issues in multi-agent planning such as privacy. As a result, while the proposed work*

*would undoubtedly impact planning research, there is a concern on its potentials to*

*benefit practical applications.*

**Response.**

I agree that planning for self-interested agents is an important topic as well as planning with privacy constraints. In fact, I have published on both of these topics in the past.

However, I disagree that research on planning for a cooperative group of agents (i.e., not self-interested) severely limits the set of practical applications. In fact, it is safe to say that the huge body of work on multi-agent planning has primarily focused on the collaborative setting, with many applications such as sensor networks and search-and-rescue robot teams. In general, most teams of robots these days are prime examples of applications for multi-agent planning for cooperative agents. Thus, I did not extend the scope of the proposed research project to include self-interested agents. That being said, I added developing IOP for distributed planning as a final objective for the proposed research, to partially address this reviewer's concern. We aim to achieve this objective by following message passing schemes such as those developed by Nissim et al. (2014) in his work on the MAFS algorithm and other distributed protocols.

The reviewer wrote:

*Another limitation of the proposed work is that it assumes that agents have their*

*individual goals. However, the motivation for agents to have their individual goals is not*

*as clear as that in MAPF. This is especially an issue since the proposal does not consider*

*self-interested agents. In centralized planning, it is often more common to specify an*

*overall goal for all agents. In the proposal, it is argued that this issue can be addressed by*

*running existing task allocation algorithms to divide the overall goal into individual*

*goals. However, given the problem formulation of the proposed work (predicate-based*

*representation), most of the existing task allocation algorithms may not be applicable.*

**Response.**

In the proposal we do not assume that the agents have individual goals. Indeed, some of the methods for generating provisional plan require allocating goals to agent, and we propose to build on existing task allocation mechanisms to do so.

The reviewer wrote:

*Are there any expected limitations in extending the CBS formulation to general multi-agent planning?*

**Response.**

The are two key challenges in extending CBS to general multi-agent planning: (1) in general planning agents can also help each other raising the issue of positive PIFs, which is not accounted for CBS, and (2) CBS accepts as input a goal for each agent, while in general planning we may get a set of goals for all agents to achieve (without assigning specific goals to specific agents). This is given in the paragraph starting with "Resolving PIFs by searching the IRT generalizes our conflict-based search".

The reviewer wrote:

*A technical issue about the proposed work is about the finding of PIFs with non-temporal*

*models, which seem to be where the research work would start. However, given that the*

*plans are ultimately going to be executed by the agents, execution is always going to be*

*temporal. It is unclear how PIFs can be efficiently identified using non-temporal models*

*without making certain assumptions, e.g., time is discretized and all actions take the same*

*amount of time to finish, which, however, do not often hold during actual plan execution.*

**Response.**

This comment by the reviewer was very helpful in improving our proposal and we now discuss the challenge of identifying PIFs in greater detail. Indeed, without some assumption about the temporal aspect of the agents' execution, the only PIFs that can be detected are open preconditions (facts that one agent assumes another will achieve but it does not) and cyclic causal-link threats (e.g., having two actions such that each action depends on the other to achieve its preconditions). This is discussed in the new proposal and is part of the proposed research.