Commentary: Onboard Planning for Geological Investigations using a Rover Team

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1. Summary of paper

For coordinating multiple rover behaviour within a closed-loop data flow [data collection, data analysis & planning], the paper addresses a "distributed" planning system, with goals interdependency information. This very interesting approach integrate and optimise the standard planning domain, based on CASPER iterative planner, with problem specific "goals dependencies" and their meta-level "representation and objective function" (CASPER version named CASPER+IDGS).
The objective function for "goals dependencies" is there, a simple sum up of the values of all goals that occur in the plan along with the weight for each goal combination, where all named goals appear in the plan. The paper concentrates on the algorithmic optimisation meta-level for this objective function, added as an improvement heuristic within CASPER .
At first, CASPER creates a plan with the mandatory goals or activities. Then, a series of optimisation steps leads to the final optimum plan with additional goals. Each meta-level optimisation step, use the CASPER iterative planning process either to solve conflicts through an iteration of repair or to optimally generate a new conflict-free plan with a next goal. The meta-level optimisation algorithm, i.e. "random hill-climbing search with restart", randomly selects this new goal and score the generated plan: this continuous optimisation step stops when the highest score is reached, then a new step restarts, till it cannot find any new additional goal. Planning convergence is guaranteed by the algorithm randomness, avoiding repeatedly adding to the plan, an unachievable goal.
This iterative planner, optimising "goals dependencies" (CASPER+IDGS) is then tested and compared, for two goals relational scenarios, with two other "distributed" versions of CASPER (+ Random and +Simple Reward). All versions of the planner use the same optimisation algorithm, i.e. "random hill-climbing search with restart", but differ by their Objective function. (CASPER +random) selects a goal at random, without considering rewards, whereas for (CASPER +Simple Reward), the objective function considers individual goals rewards, without considering goal interdependencies. Particular attention is put on each problem acquisition through human experts, its bounding & simplification and it's description, sized from 30 to 90 different goals to examine 10 to 30 rocks in the surrounding terrain.
The tests & statistics results demonstrate clear benefit for CASPER+IDGS, e.g. with achieving higher optimisation score when using fewer goals, with (15%) shorter average traverse distance required by each plan, with higher quality plan under tight time constraints.
The paper mentions other planning & optimisation techniques, applied in cooperative robotic system, and identify issues for further continuation work, like "more complex goal relations" and uncertainty, sciences observations requiring more than a rover.

2. Related Issues

"Multi-rover Integrated Sciences Understanding System" (MISUS) for space, with key words like "data analysis modeling", "goals interdependency information", "utility", "dynamic change during system use", comply with a certain rational for its implementation and its utilisation, and raise a high number of related issues.

2.1 Rational for MISUS implementation and utilisation

The paper diversely mentions few drivers and requirements, such as:
The behavioural coordination between rovers, the possible change of science objective (inc. multi-mission re-use), new science goals either from the obtained scientific value or from improved data analysis and improved environment knowledge & model accuracy, planning optimisation for *dynamic dependencies* among goals, "utility", repair & plan modification in case of un-expected event (e.g. unexpected obstacle) or in case of operation & resources constraints violation.
Requirements for the (central and local) planning include safety (e.g. collision avoidance between rovers), minimization of the resources utilization and of the needed traverse distance.
The most stringent considered requirement was to avoid static predefined goals relationships and metrics, in the

close loop data flow (data collection-data analysis-planning).

It would be interesting for consistent & rationalized system architecture with layered abstractions, i.e. for the parameters and algorithms justification, to flow-down, more in depth, the contributing requirements of such multi-sciences (inc. multi-mission) “leader-follower” rovers team.

It is understood that each rover has its own set of goals in a coordination scheme, without on-line cooperation, i.e. without on-line share of goals between rovers.

The paper did not express specific requirements for the motion planning of the each rover, i.e. timing & positional constraints applied to specific observations, neither specific multi-rovers coordination and temporal constraints (e.g. related to activation horizon, reasoning horizon, plan execution horizon, global behavior assessment horizon, etc.) . In my sense, it would be beneficial to specify the correlation (in state-action-time variables, events) between sciences observations (incl. inferring (sciences) geological relationships among data) and the rovers real time operation and control.

2.2 Abstraction Levels, their role and organisation (interconnection)

The abstraction levels and their significant expressiveness obviously depend on the system architecture (layered planning system), on the modelling (e.g. sciences data representation out of the data analysis), on the role of the deliberative algorithm levels (e.g. (multi)objective function), on the efficiency and predictability of its inter-operability with the real time executive layer.

The authors, aware of the difficulty, propose a primarily simple & pragmatic approach for this key issue: i.e. modelling, data representation & scientific value of the goals, insertion of the goals dependencies, choice of the (multi)objective function and planning metrics. In fact, standard data representation and standard planning language are active research domains, worth to correlate with.

A very interesting aspect, driven by the requirement of excluding static goals pre-definition, is the approach of defining the goals and their dynamic dependencies, as part of the problem specification (the objective function) instead of in the original domain description (model).

The issue of scientific value for the goals representation and the choice of the objective function appear even more crucial for space exploration, with uncertainty and unexpected situation.

This raises the question of the data analysis modelling and of the “automatic” change of the objective function. One can envisage a meta-level for “reconfiguring the problem specification”, applying a policy, such as based on heuristics or reinforcement learning or other, statistically based.

2.3 Planning Algorithms design in [deliberative & executive] System Layers

Drivers for the planning design, include requirements of *broad utilisation* for multi-sciences or multi missions, of extensive & *reliable re-use*, of the *planning robustness* [plan quality stays acceptable in non-nominal or uncertain context], of the *planning stability* [minimisation of plan modification, especially in uncertain environment, especially with possible frequent change of conditions], safety & reliable real time predictability in the (multi-rovers) embedded system.

The (global and local) time bounds analysis may become a driver in the trade-offs & chosen solution for the “leader-follower” *system design layering* (inc. deliberative & reactive) and for the algorithms. For example, unexpected delays may impact the activation of a particular planner. The planning generation time may change from one rover to another rover. Besides, during each plan generation process, the state of the physical system and its context may change. The executive module (centrally or locally in each rover) shall be able to control and to stop the planning activities, in a consistent & safe manner.

The planning representation (inc. the objective function) and optimisation algorithms drive the issue of “Quality” and “Utility” of a plan as a function of time. The “Utility”, tightly coupled to the objective function, may require an optimal delivering time (deadline) for the start of the plan execution, with un-complete optimisation (or sub-optimal quality).

It would be worth to analyse how the “random hill-climbing search” provide a good compromise (Utility x Quality) for the chosen simple objective function, but also if this objective function change. This raises the issue of defining a Metrics.

Besides, “bounded” Predictability Proof and Validation for complex goals dependencies scenarios drive the planning system layering design, the data representation and the algorithms solution. The author aware of the complexity & breadth of the “randomly generated problems” (with only 2 goals relationship) use utility value for “goals interdependencies”, as considered by the geologists experts, and try to increase the variance among goal combinations. The bound in term of solution acceptability and the cost of its validation testing is a real combinatorial complexity, for which the knowledge of the human expert, “tbd learning” algorithmic and other reduction techniques (probabilistic based) may help to solve. I subscribe to the remarks of the authors, concerning the Markov Decision Process.

3. Conclusion

The paper provides a very interesting innovative step in considering the use of goal interdependency information, for plan optimisation and in demonstrating its benefits. Additional necessary work, will stimulate the research community, in non exhaustive issues like abstractions representation, expressiveness & complexity reduction, decision making algorithms, proof & validation of on-line planning. This project provides a very concrete framework, to focus and to federate the research towards a pragmatic operational multi-rovers system in remote hostile & unknown environment

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