Hierarchical Abstraction Planning and Diagnostics for Human-Robot Collaboration

PHD THESIS

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1 Project Overview

This thesis aims to develop a domain-independent centralised reasoning system for teams of multiple heterogeneous robots which inherently supports the ability to perform planning, diagnostics and inference over any arbitrary number of desired abstractions of a state space. Our reasoning system is built in Answer Set Programming (ASP), a declarative non-monotonic logical programming paradigm supporting advanced Knowledge Representation and Reasoning (KRR) capabilities, including defeasible reasoning processes such as default and abductive reasoning [Gelfond and Kahl 2014].

The primary problem space that we seek to solve is that of automated planning for Human-Robot Collaboration (HRC) (Section 3) in highly un-structured and dynamic human-populated domains. Robots operating in such domains must be capable of more complex reasoning processes than those generally required by classical robotics domains, such as those in manufacturing, in which the sequence of control actions to be executed can be pre-determined by a human expert and fixed before operation commences. In contrast, robots operating in human populated spaces cannot be so rigid and must automatically generate plans in the presence of great uncertainty of what they will encounter in the future. Unfortunately, most planning problems are too complex to solve in time commensurate with the needs of the desired application and reactive decision making algorithms perform very poorly towards achieving long-term objectives.

In human populated domains, the presence of exogenous actors, whose behaviour is usually very difficult to predict, will cause frequent changes to the state unbeknownst to the robots. This is true even when humans are actively assisting robots in a cooperative team. Robots are therefore rarely able to obtain accurate projections of what they will encounter in the future, and any past observations are highly transient, causing existing domain knowledge to become rapidly subject to entropy. It is therefore likely that observations obtained during plan execution will often contradict the robots' expectations determined during plan generation. This may result in plan failure. This volatility in the domain state makes generating complete concrete plans a highly futile endeavour. Furthermore, for any planning problem of non-trivial complexity, it is not feasible to pre-generate even partial plans that account for all possible contingencies.

To overcome these problems we propose a novel approach to performing centralised planning and diagnostics over a hierarchy of abstraction spaces for discrete planning problems with multiple heterogeneous agents, including determining actions that must be performed by human collaborators. The central concept is that abstraction can reduce an exponential search space to a linear one, reducing planning time exponentially (Section 4). We propose a reasoning system which generates plans consisting of finite deterministic sequences of actions at each available level of abstraction by passing the effects of actions planned at the previous abstraction as sub-goals to the next. The resulting set of plans represent hierarchically decomposed sequences of actions containing relations defining which actions planned at the lower-levels achieve the effects of higher-level actions. Partial plans can be generated at any abstraction below the most abstract by splitting the planning problem into sub-problems inferred from the previous abstraction. The planner is guaranteed to return, and if the planning problem is satisfiable, the plan will achieve a cardinality maximal number of goals in a minimal number of actions. When observations obtained during execution contradict expectations determined during planning, the system enters diagnostics to resolve this contradiction and re-generate or repair its previous plan.

2 Possible Applications of Spot in our work

We aim to demonstrate the domain-independency of our reasoning system by showing its applicability to a range of HRC planning domains, and that it can be hybridised with a variety of application specific systems for executing its plans at the concrete level. Further, we aim to show that founding our approach upon non-monotonic logic makes it capable of dealing with the large amounts of incomplete knowledge that must be handled in HRC planning domains.

Spot is very well suited to our work because the extent of its capabilities make it highly applicable to HRC. Its state-of-the-art locomotion and mountable manipulator arm enable it to operate in a variety of HRC application domains. The following is a list of challenging but highly commercially interesting potential applications of Spot in our work:

- **Service Robots**: The use of service robots in applications such as healthcare [Roy et al. 2000], tourism [Thrun et al. 1999], and hospitality [Pinillos et al. 2016] has been studied extensively. Service robots are one of the most ubiquitous type of robot and are likely to be become prevalent on almost all civilian domains. Our initial and most basic use of spot may be as a service robot, most likely fetching various items for office staff.
- **Human-Robot Collaborative Disassembly (HRCD)**: In re-manufacturing, HRCD is the field which deals with the semi-autonomous disassembly of End-Of-Life (EOL) products ready for reuse, repair or recycling [Liu et al. 2019]. Disassembly Sequence Planning (DSP) is critical to re-manufacturing, made necessary by the diversity of available products and uncertainty in the quality of their components. DSP for HRCD provides a middle ground in terms of cost, efficiency and flexibility but remains an unsolved problem in robotics [Zhou et al. 2019]. An interesting and novel application of Spot would be its integration into a HRCD domain involving coordination between static robotic manipulator arms, human operators and Spot itself, towards robust disassembly of products such as recovered lithium-ion batteries from disposed battery electric vehicles.
- **Human-Robot Collaborative Construction (HRCC)**: The construction industry is the seminal field of HRC and has seen some of the greatest commercial interest [Bauer et al. 2008]. Robots are capable of efficiently performing the physically intensive tasks prevalent on construction sites, increasing productivity and safety. As a possible extension, it may be possible employ Spot as a test bed for a mock HRC construction site domain.

3 Human-Robot Collaboration

We refer to HRC as the general act of humans and robots operating in close proximity to one another [Bauer et al. 2008]. HRC is not the same as Human-Robot Interaction (HRI), which is a much more general term encompassing HRC, but refers to any form of interaction between humans and robots [Grosz 1996, Thrun 2004]. HRC is also not the same as human-robot cooperation, which is strictly the act of humans working jointly as part of a team towards a common goal usually to provide physical assistance towards the accomplishment of a shared task [Cohen and Levesque 1991].

In HRC the group of collaborating humans may contain a variety of human participants including; (1) a team of cooperating humans who are available to provide physical effort towards completion of some goal, (2) a diverse group of commanding humans who will assign various goals to the planning agents, (3) and various exogenous humans who do not fall into either of the previous categories but whose activities in the environment may change the state and therefore must still be considered in the planning problem. To plan in HRC domains, robots must therefore not only plan what actions must be performed by cooperating humans but also be robust and flexible to the activities of other non-cooperative humans in the domain whose behaviour and intentions are usually very difficult to predict.

4 Reasoning over a Hierarchy of Abstraction Spaces

The use of abstraction is integral to human reasoning and problem solving, and is employed extensively in almost all areas of engineering, science and AI [Newell et al. 1972]. Humans often employ abstraction when solving complex problems such as planning actions and providing explanations [Giunchiglia and Walsh 1992]. Through abstraction one is able to focus on only that which is most relevant to the problem at the current time. Low-relevancy details of a problem can be simplified away to reduce complexity or assumptions can be made to cope with unknowns [Timpf et al. 1992]. Abstract problem representations are in general exponentially faster and easier to solve, and the resulting abstract solutions are far less likely to fail compared to concrete solutions, as long as assumptions hold [Knoblock 1990].

In planning, abstraction can be used to reason with higher-level descriptions of actions and state than those defined in the original ground planning problem. The robots are usually given descriptions of there domain at at least two different levels of abstraction. The problem is first solved in the abstract spaces and the resulting solution is then used to guide the generation of a solution in the ground space. The abstract solution can further be used to split the original problem into independent sub-problems, allowing the computation of partial plans [Knoblock et al. 1991].

A simple example of the use of abstraction by a planning agent may involve the generation of an abstract plan consisting of a sequence of way-points between which to travel to reach a desired destination. Initially it does not need to decide exactly how to traverse between each given way-point. The assumption the agent makes is that there exists at least one traversable path between each of these way-points. When the agent proceeds to execute this plan, it will then continuously generate a ground plan in a short horizon into the future, updating this plan as it obtains more knowledge about its environment. In this example, the way-point based plan only fails if our only assumption is untrue. Therefore, even if it becomes necessary to revise the ground level plan, revisions to the abstract plan are rarely necessary.

A plan generated over multiple abstractions can be represented by a decomposition tree which relates actions planned at the higher abstractions to those planned at the lower which achieve the same effects. Figure 1 shows an example decomposition tree a robot r_0 may generate when solving a path planning problem starting is from an office and whose goal is to reach a library. There are three abstractions, at the highest the robot can travel to any location in a single action with the assumption being the same as the previous example, at the second the robot can move only between directly connected rooms, and at the lowest the robot must find a path between individual cells of each room.

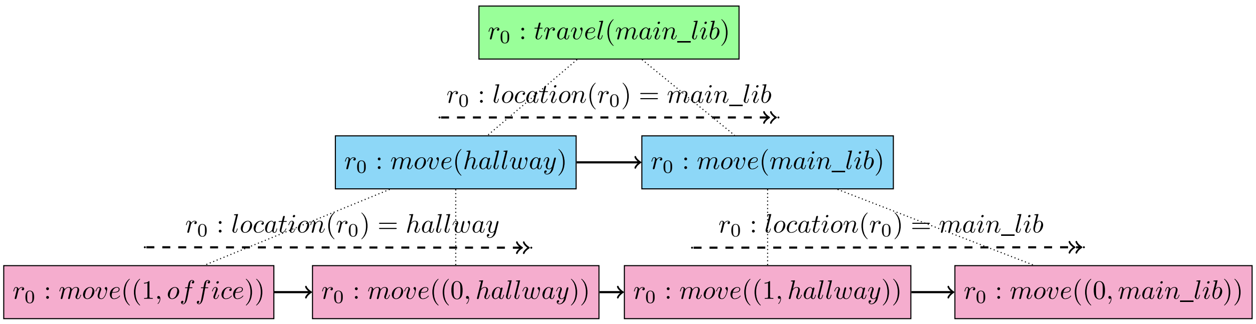

Figure 1: A decomposition tree mapping actions over three abstractions for a simple example path planning problem.

Figure 2 visually represents how planning domain descriptions can be defined over multiple different abstractions in the context of the proposed reasoning system. Where level $N \geq 1$ is known as the *maximum abstraction level*, and level 1 is known as the *ground level* which is the lowest abstraction level and must always be present in planning domain descriptions. The ground level is seen as the original problem from which abstractions are created through a number of simplifications and should be designed first to ensure that the ground level is sufficiently expressive to handle the planning problem specific to that application. Level 0 is not part of the reasoning system and represents the continuous concrete space domain description used by the application specific system which executes individual abstract actions.

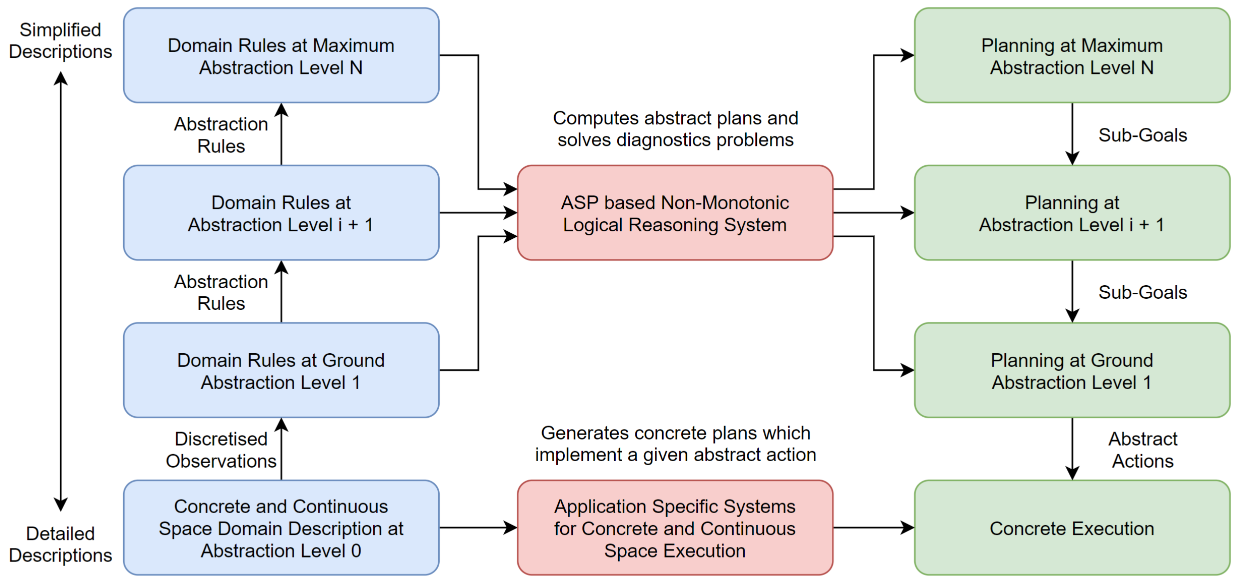

Figure 2: A representation of planning domain descriptions defined over multiple abstractions. A collection of domain rules at each abstraction level defines the nature of the planning problem at that level. Abstraction rules map the state space between adjacent levels in an upwards manner and sub-goals ensure plan conformance in a downwards manner.

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