Planning for Continuous Resilient Agent Organizations

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Innovative claims

The project proposed in this white paper is part of a larger vision to build a new cognitive architecture that supports "intelligent agents" that:

- Robustly accomplish their tasks, responding appropriately to failures
- Communicate flexibly with humans and software agents
- Explain their behavior both on success or failure
- Dynamically compose new agents and behaviors from existing agents
- Rapidly build personalized agents without manual programming
- Learn from their past experience

Towards this vision, we previously developed a system called Electric Elves [C+2002], which applies agent technology in service of the day-to-day activities of a human organization. We successfully deployed the Elves in both an office and travel environments. The travel application, called the Travel Elves, is in use today and provides a tremendously useful set of services for a traveler, making travel plans and monitoring their execution.

The new agent architecture will address the limitations of the Electric Elves system, supporting a wider variety of agents as well as agents embedded in other systems, and a wider variety of tasks, as diverse as battlefield awareness, network management, and disaster response. We have described in detail this architecture in a separate white paper, entitled “Beyond the Electric Elves”, also submitted to this BAA.

Achieving complex tasks in these environments requires the coordination of the activities of multiple agents. The ability to communicate plan decisions, generate plans, monitor and detect plan failures, repair plans, and replan is essential to achieve coordinated behavior in a community of agents and to ensure resilient and adaptive operation in response to changing conditions.

In this white paper we propose a 3-5 year research project to develop a comprehensive planning framework that will enable such agent organizations, and we propose a 3-4 month seedling effort for designing the planning framework and produce a prototype implementation.

The key innovations of our proposed planning framework include:

- Dynamic, interactive, and distributed planning, where tasks can be posted or withdrawn at any time and agents and communication links can likewise appear and disappear, but the system adapts to such changes.
- Resilient and adaptive planning, through a combination of (1) algorithms for generation of robust plans, (2) algorithms for efficient plan repair, and (3) replanning techniques. In addition, continuous plan monitoring and probabilistic models can predict which plan fragments are likely to fail making recovery efforts more efficient and less costly. The repair mechanisms can also improve the quality of the plans at runtime.
- Support learning and explanation of system behavior by having comprehensive reporting and monitoring of agent action commitments, execution status, and the information used during planning.

Technical Rationale and approach

Desiderata for continuous resilient planning in agent organizations

The operation of a human organization involves dozens of critical everyday tasks to ensure coherence in organizational activities, to monitor the status of such activities, to obtain information relevant to the organization, to keep everyone in the organization informed, and so on. These activities are often well-suited for software agents, which can devote significant resources to perform these tasks, thus reducing the burden on humans. Such software agents enable organizations to act coherently, to attain their mission goals robustly, to react to crises swiftly, and to adapt to events dynamically.

We envision an agent infrastructure supporting the operation of such human organizations. This vision imposes a strong set of requirements on the planning capabilities of the agents:

- Continuous, long-lived operation: the agent community must operate as long as the human community it serves without interruption.
- Interactive behavior: Humans interact with the agents at any moment posing tasks to be achieved, canceling other tasks, and requesting explanations of success or failure.
- Dynamic environment: Agents monitor information outside the control of the system that can change at anytime. Agents and communication links can fail or function unreliably. New tasks appear, change, or disappear.
- Multiple task support: Both humans and agents concurrently pose tasks to be achieved. The agent community must solve them in the most cost effective manner, avoiding whenever possible duplicating work across different agents.
- Resilient: we expect the agent community to respond to unexpected events, overcome failures, repair current plans, and replan autonomously.
- Adaptive: we expect the agents to improve their performance over time. This includes reducing the cost of planning and plan repair, and improving plan quality.

In this white paper we propose to develop a comprehensive planning approach that will meet these requirements and produce a prototype implementation.

Planning Framework

We propose a novel planning approach based on distributed goal task matching. At a high level, humans and software agents post tasks that need to be satisfied. An agent accepts responsibility for the completion of the task and achieves it by itself or enlisting the help of other agents.

To simplify the problem initially we will assume that there exists a common ontology of actions, a common planning theory with predicates for preconditions and effects that are well understood, and a consistent global task structure. Each agent may only be aware of and operate with a small part of the global domain theory, but the meaning of the tasks that an agent receives and delegates to others will be well defined. This assumption is consistent with the initial assumptions of our proposed new cognitive agent architecture. As the global architecture addresses bridging among different domain ontologies for different participant agents, we will incorporate their results for bridging across the diverse planning knowledge of different agents.

Our proposed agent infrastructure is composed of heterogeneous agents, each with different complexity and capabilities. We distinguish three roles for the agents with respect to the planning framework:

- Planning Agents: have general generative planning and repair capabilities.
- Scripted Agents: execute given plans to achieve their goals, but cannot generate alternative plans. Although these plans may incorporate monitoring and contingent actions, they are generally less flexible in responding to changes or failures. However, these scripted plans may be more expressive than those generated by the planning agents.
- Information Agents: These agents do not affect the world, but provide information that can be used by other agents (including humans) to modify their behavior.

In spite of the their heterogeneity, the agents follow a shared planning protocol that ensures that they have the appropriate information to plan and adapt to changes, and thus achieve global coordination. The protocol includes messages for task distribution and task status reporting:

- Goal posting and commitment: An agent can post a goal to be achieved to the community of agents. We plan to explore different mechanisms to assign tasks to agents, including (1) enlisting the help of a matchmaker agent, (2) explicitly delegating to another agent, (3) posting a goal to a blackboard, (4) global and limited broadcast, and (5) using market mechanisms in which agents bid to perform the required services.
- Status reporting: When an agent accepts the commitment to achieve a goal, it is also responsible for reporting on the status of such commitment. At a minimum, an agent must report on the success or failure of the committed task. The success messages are critical to build informative explanations of agent behavior. Failure messages facilitate the repair or replanning process (as well as explanations). More collaborative agents may also report intermediate status information such as cost changes or timing information, which may trigger replanning or retasking by the contracting agent.
- Commitment changes: An agent can break or change the parameters of a commitment for a variety of reasons. For example, an agent may choose to achieve a higher priority task, thus delaying other currently committed tasks. The only requirement is that the agent informs the contracting agent, so that it can replan. Similarly, an agent can withdraw interest in a delegated task.

Following this basic protocol, agents exchange delegations and commitments for achieving and reporting about tasks. A planning agent may further decompose a task according to its domain theory to form a plan that may include the agent's own actions, as well as obtaining commitments from other agents for action and informational subgoals. A scripted agent would just execute the plan that matches the committed goal. The planning architecture poses no restrictions on task-agent assignments. For example, an agent may assign the same task to several other agents in order to increase the reliability of its plan.

This planning approach provides the flexibility necessary to satisfy the requirements for responding to dynamic environments and interactive behavior since the planning protocol allows tasks commitments to be established and withdrawn in a principled and informed way. Also agents can opportunistically accept tasks that they are already working on or could achieve with minimum effort, so that the community operates efficiently as a whole.

In the next section we discuss how we achieve the remaining requirements of resilience and adaptability.

Resilient and Adaptive planning

A long-lived community of agents must continuously adapt to changes in order to operate effectively. Moreover, it is desirable that the performance of the agents improves over time. Increasing plan robustness, plan repair, and replanning are the critical capabilities that an agent needs to respond to a dynamic environment.

The first approach to deal with uncertain dynamic environments is for agents to produce plans that are as robust as possible before execution begins. These robust plans may include contingency steps, which are parts of the plan designed to be executed only under certain conditions, usually providing an alternative way to achieve some goal in the plan after an execution failure. Plans can also be made more robust ahead of time without contingencies, by choosing actions that are less likely to fail, or by executing 'conformant' actions, which reduce the executor's uncertainty in the world state after the action is executed. Plans can also include "redundant" steps to increase the probability of success. We plan to build on our previous work on generating robust plans on uncertain environments [B1998]. In that work, we took a decision-theoretic view of planning and used a probabilistic model of actions that allows the planner to focus on the contingencies with greatest impact on overall plan reliability. We used Bayesian belief networks to rapidly evaluate the expected utility of a plan fragment. We also used explicit models of uncertain exogenous events, which is likely to be a significant factor for our communities of agents.

The second approach is to repair failed plans at run-time. Several properties of the repair algorithm are desirable. First, the repair must be aware of the current planning context, so that both the disruption to current pending plans is minimized and the reuse of already executed subplans is maximized. Second, the repair algorithm should behave in an anytime fashion, so that the violation of time constraints in the plans is minimized. Finally, plan repair need not only be invoked due to plan failure, it can also be used to improve plan quality if a currently executing plan is not meeting expectations. We plan to build on our previous work on Planning by Rewriting (PbR) [AK2001] and extend the approach to support this more distributed and dynamic environment. PbR repairs a plan by applying a set of plan rewriting rules. These rules match a subplan within a given plan, for example a failed or underperforming subplan, and replace it with an alternative, possibly of better quality, subplan. The PbR algorithm explores the space of plan rewritings using local-search techniques so that if has an anytime behavior. The longer the rewriting process continues the better quality of the resulting plan may be, but a correct plan is available at anytime.

Finally, if the changes are such that a repair is not possible, a third approach involves replanning over the failed goals using the agent's generative planning capabilities. All three approaches are needed if the agents are to create plans that are as reliable as possible in all circumstances.

In addition to the planning and repair capabilities, monitoring plan execution status can identify when a plan is likely to fail, allowing time to generate alternative plans and put them in place before any undesired outcomes occur, or making recovery more efficient and less costly. In particular, the belief networks created to evaluate plan robustness provide an efficient method for propagating evidence. We expect to enhance these probabilistic methods with information about agent behaviors, possibly learned, such as predictions of failure based on time elapsed without a response.

Each repair or replanning episode is an opportunity for learning and improving the performance of the agents. An approach that builds on the PbR framework is to learn new rewriting rules that speed up the repair process or improve the quality of the resulting plans. Essentially, after repair or replanning, the agent has replaced a given subplan by another subplan. A rewriting rule can then be learned after an appropriate generalization of the transformation of one subplan into another. We plan to build upon our previous approach to learning plan rewriting rules [AK2000]. Probabilistic information can also be used in conjunction with the plan re-write rules, for example, to focus attention on potentially high-impact plan modifications. We plan to integrate and support the learning and instruction approaches described in a separate white paper submitted to this BAA, titled "Learning and Instruction in the New Electric Elves Architecture".

Proposed seedling Project

This white paper presents the main ideas of a comprehensive planning framework for resilient continuously-operating agent organizations. In the seedling project, we propose to produce a detailed design of the flexible planning approach described above. In particular, we will (1) define the plan language supported by the agents, (2) define the planning protocol for task assignment and withdrawal, and status reporting, (3) analyze the different task-agent assignment strategies, (4) explore the different mechanisms for robust plan generation and plan repair, and (5) provide an initial implementation of the planning approach.

References

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