

Plan recovery in reactive HTNs using symbolic planning

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Abstract—Hierarchical reactive methods are very popular in the field of controlling complex artificial intelligent agents in dynamic environment. However, dynamic environments are incompletely known and can change in unpredictable way which make the planning systems fail. In this paper, we describe a hybrid planning system called *Discolog* which extends a reactive planning system with a linear symbolic planning system to propose a strategy to recover from breakdown. Our solution has been implemented on the reactive system *Disco* which been extended with the symbolic planning system STRIPS.

I. INTRODUCTION

Automatic planning is an important field of controlling artificial agents in complex and dynamic environments where research built two different approaches. The first one is symbolic planning: this approach consists in constructing a complete symbolic and logical model of the environment that allows the agent to reason about this model and define a complete plan to carry out its goals. The most popular architecture used to describe the environment is HTN (i.e Hierarchical Taks Network) [Ero96], which allows a recursive decomposition of complex goals into sub-goals or primitive actions. The HTN architecture eases the design of the environment and gives more expressiveness. One limit of symbolic planning is to assume that the environment is fully defined. By consequence, the agent is able to predict all the possible situations to plan in advance. However, it becomes clear that authoring a complete representation of a dynamic and complex environment such as simulation of human behavior [CGS98] or the definition of dialog systems [AF02] requires significant knowledge-engineering effort [ZHH⁺09], and even reveals to be impossible [Mae90]. However, with incomplete knowledge the agent cannot anticipate the future and the generated plan might be not executed as expected. Therefore, if at any point of the execution the plan breakdown (i.e action execution fails), the planner has to stop the execution and build another plan that achieves the agent's goals. Such operation might be costly in terms of time and resources.

Because of these limitations, another planning approach called reactive planning was proposed [Fir87]. Reactive planning avoids long-term prediction in order to make the execution faster. For this reason, it leaves all the planning during the execution phase: the agent plans only for the next step to be executed from the current state of the environment. Thus,

it can adapt its next step according to the observed changes. The main advantage of reactive planning systems is they don't need a complete definition of the environment. Instead, they aim to define the policy of the agent in its environment by running through a pres-authored HTN structure with procedural knowledge. Procedural knowledge defines conditions in the HTN domain knowledge as black-box procedures (for example : JavaScript code) that contains no logical information (i.e no symbolic knowledge). This type of reactive HTN eases the design, reduce the complexity of planning and still can cope with complex dynamic environments [Bro05]. They are used in numerous application domains, such as dialog systems [BR03], games [Isl05] and simulating human behavior [Bro05].

Nevertheless, breakdowns can still appear in reactive planning. An action execution can fail and leads the HTH to a state where no possible action can be applicable to achieve the goal. In such situation, the agent has to stop and think of a strategy to reach its goal. Reactive HTNs are unable to construct a plan repair to recover from breakdowns for two main reasons. First, reactive planning avoid long term prediction. Thus, it is not able to construct a plan based on a projection into the future states of the environment. Second, procedural knowledge is defined with any logical information to allow the HTN reason about the breakdown and eventual plan recovery.

We claim in this paper that with a minimum definition of symbolic planning, Agents can build efficient local plans to recover from breakdowns. Procedural task's operators defined in the reactive HTN domain knowledge are, for the most of them boolean procedures which can be thought as logical predicates. Therefore, we propose to the HTN designer to convert theses procedures to a symbolic knowledge to have a support for reasoning. Since reactive HTNs cannot reason on theses knowledge, we propose to extend the reactive HTN with a linear symbolic planner to compute plans recovery. We study the capacity of such hybrid model to recover from breakdowns in dynamic environment.

In section 2, we briefly present existing works in this domain. In section 3, we formalize the proposed solution *Discolog* and describe its implementation. Section 4, presents the preliminary evaluation to our model. We discuss the obtained solutions and the impact of both quantity and quality of the extracted symbolic knowledge in the recovery process.

II. BACKGROUND AND RELATED WORKS

Basic requirements to build planning systems is to have a formal representation of the environment (i.e domain knowledge) and planning engine to reason about this knowledge. Several approaches have been proposed for this purpose.

A. Symbolic planning

The first contribution in planning was symbolic linear planning systems (STRIPS)[FN72] which model the environment as a set of actions and transitions between those actions . Linear planning attempt to generate a plan (i.e. a sequence of actions) which once executed transform the initial state of the environment to a final state where the agent goal is achieved.

Due the complexity of planning problems description, HTN (Hierarchical Task Network) [Ero96] was proposed. HTN domain knowledge can be represented as AND/OR tree. AND nodes represents tasks. each task is defined with preconditions to check the applicability of the task and postconditions that checks the success of the task execution. There are two different types of tasks: primitive tasks (leaf nodes) are similar to linear planning actions which can directly be performed in the environment. Compound tasks have to be decomposed into subtasks using a corresponding recipe. Recipes of tasks are defined as OR nodes and represent a method of decomposition of compound tasks. each recipe has applicability conditions.

HTN planners intent to plan for one or more goal task. Planning proceeds using task decomposition that decomposes goal task using a corresponding recipe into a sequence of simpler subtasks. This process is applied recursively until a conflict-free plan (sequence of primitive tasks or actions) that can make the goal task successful is found. HTN planners become popular this last decade where several systems were developed such as SHOP [NCLMA99], SIPE [Wil88] or NOAH [Sac75].

During the execution in a highly dynamic environment, an action execution might drift from what was expected because of the lack of information about all the changes in the environment. Such situation causes an execution failure or *breakdown* and the planner can no longer achieve its goal. Several researchers in symbolic planning have been attacking this problem by integrating a plan repair module [BD02], [VDKDW05], [HTHO06], [AKYG07], [WHLUMA07]. Thus, if a breakdown is detected, the plan repair module uses a causal graph that contains all the logical dependencies between the HTN task to calculate the task candidate to repair (the strategy for computing the task candidate differs). Next, the planning system is called again to propose a new decomposition to the task candidate. The presented solutions avoid replanning from the scratch and proposes a local repair with minimal costs. However, they presents some limitations. first, the plan repair remain dependent to the initial planning system. Thus, if this latter is unable to find a plan repair, then the HTN definitively fails to achieve the goal. Second, theses systems inherit the limitations of symbolic planning: with limited knowledge, the HTN can not always find other decompositions to tasks. Finally, These solutions are only applicable for the HTN they

trying to repair. In addition, the plan repair solutions can not be generalized to reactive HTN, they exploit logical dependencies to calculate the task candidate which make them and are impossible to apply in reactive HTN due to the absence of logical knowledge in procedural formalism.

B. Reactive planning

The problem of planning in highly dynamic environment with incomplete knowledge has been tackled in reactive planning systems [Sch87]. Reactive planning systems have two main characteristics. The first is the hierarchical tree-like structure of the planning system which is similar to HTNs. in the following we will name "Reactive planning systems" directly "reactive HTNs". The second is that HTN planning avoids long term prediction. Instead, it plans only for the next act to perform at every moment which allows reactive HTN adapting its next act to the observed changes in the real environment. Therefore, action execution is not selected from a pre-constructed plan but it is computed directly in the execution process. Actions to perform are selected from a hand coded domain knowledge proposed by the planner designer. Instead of modeling the environment, reactive HTNs attempt to model the policy of the agent in its environment (i.e all the tasks that it can perform). In addition, action's operators don't contain any logical information and are represented as simple code procedure (for example JavaScript, XML). Thus, the planner cannot reason about this knowledge. This type of domain knowledge is called *Procedural domain knowledge*.

Reactive planning becomes very popular in AI and for most of cases uses an HTN formalism to model their domain knowledge. For instance, in Robotics where [Fir87] defends a parallel reactive architecture with *Reactive Action packages* representing autonomous process used to achieve the different goals of the robot. [Bry01] and [Bro05] propose a reactive planning system for prototyping human-like behavior in a virtual environment to ensure a natural behavior with respect of time constraint and reactivity with the real world. Reactive planning is also used in Gaming with the name of behavior trees [Isl05]. Behaviors trees have the same hierarchical structure of HTNs and do real time decision which can be seen as reactive planning.

Reactive planning also rise the problematic of *breakdowns* among researchers dealing with investigations in reactive planning. The work presented in [Fir87] suggests that robots need strategic planning to detect problematic situations before they occur. Therefore, it proposes to add a strategic planner's job which put constraints on the planner behavior before its execution in order to prevent inefficiencies. Theses constraints can be an ordering tasks in the execution queue of the planner or choosing the most promising decomposition for compounded tasks.

C.Brom [Bro05] discussed the observed limitations of the Hierarchical Reactive planning (HRP) used to control human agents or IVAs (Intelligent Virtual Agent) that degrade the believability of the IVA behavior. Among the limits discussed in his work, he discussed the necessity of planning to maintain

believable and intelligent behavior of the agent. For example to be able to see the distance of its tasks especially to achieve goals with time constraint. To overcome these limitations, HPR's execution was extended by a semantic StateFull plans (SPF) and the resulting architecture is named StateFull HRP [Plc]. SPF is a Finite State Machine that integrate HRP's reactive plan as part of its workflow. In addition, a semantic layer is added to allow the agent reasoning, planning and cleaning up its behavior. The results of this architecture is a more structured plan execution that ensure a more believable behavior of IVA.

In this paper we support the claim of strategic planning to extend reactive planning. Therefore, we present a different approach based on a hybrid system that extends a reactive planning system with a symbolic planner to recover from breakdowns. This solution is simple to implement and can be generalized to different reactive HTN's architecture.

III. MOTIVATION EXAMPLE

In order to better understand our model, we present in this section an example of a robot responsible for charging object into trucks. The goal task decomposition to achieve the load task is described in figure 1.

To load an object into the truck, the robot has to move it from its initial place and put it into the truck. The agent starts by decomposing the goal task "LoadObject", then the first task to perform is the "MoveObject" task. This task is defined with two recipes to hold the object. Depending on the object's weight, the robot will choose the corresponding recipe as described in figure 1: the first recipe proposes the robot to use one arm if the object weight is below than 5 kilograms. The second recipe proposes to use both of the robot arms if the object weight is higher than 5 kilos and below than 10 kilos. The same is done for the "PutDownObject" task.

If we consider an object with the weight of 20 kilos. The "LoadTask" execution is as performed as follows: The robot decomposes the "LoadObject" task. Next, it decomposes the "MoveObject" task. The robot tries the first recipe "holdWithOneArm". Thus it invokes a sensor to calculate the object's weight, the object is heavier than 5 kilos which doesn't correspond the the script of the applicability condition. Therefore, it tries the second recipe "holdWitwoArm" and holds the object with both of its arms but it fails again because the object is heavier than 10 kilos which make the applicability condition of the recipe also fails. At this moment, all the recipes to decompose the "MoveObject" task are inapplicable. by consequence, the execution is blocked with no possible task to execute. A breakdown is then reached by the robot. When a breakdown is detected, the robot has to think of a strategy or a plan to get out from this breakdown. In the next section we present our proposition to overcome the breakdown problem.

IV. HYBRID MODEL: EXTENDING REACTIVE HTNS WITH SYMBOLIC PLANNING

To overcome the breakdown problem, we propose in this paper, to extend the reactive HTN with a symbolic linear

planner that construct a local strategy to recover from the faced breakdown. The hybrid system combines the reactive formalism of the HTN and the symbolic formalism of the linear planning system. To construct the symbolic knowledge requisite to the symbolic planner for reasoning. We propose thus, to the HTN designer to extend all boolean procedures defined in the task's and recipe's conditions which the structure is similar to logical predicates into a symbolic formalism. Since linear planner reason on primitive tasks (i.e actions) (see section II-A), the HTN designer extends only the primitive tasks which contains boolean procedures.

Algorithm 1 Reactive planning and plan recovery algorithm

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procedure HYBRID SYSTEM(DomainKnowlege,Goal)
   $\pi \leftarrow \text{ReactiveHTN}(\text{DomainKnowlege}, \text{Goal})$ 
  If ( $\pi \leftarrow \text{Success}$ )
    return Success
  else  $\text{plan} \leftarrow \text{Recover}(\text{Goal})$ 
  If ( $\text{plan} = \text{null}$ )
    return Failure
  else
    foreach action  $a_i \in \text{plan}$ 
       $\text{Discolog}(\text{HTN}, a_i)$ 
    end procedure

procedure RECOVER(Goal)
   $\text{Candidates} \leftarrow \text{findCandidate}(G)$ 
  If  $\text{Candidates} = \emptyset$ 
    return null
  else  $\Pi \leftarrow \emptyset$ 
    foreach  $\text{candidate} \in \text{Candidates}$ 
       $\Pi+ = \text{LinearPlanner}(\text{candidate}, \text{CurrentState})$ 
       $\text{Cost} \leftarrow \{\text{cost}(\pi) | \pi \in \Pi\}$ 
      return  $\pi \in \Pi$  with minimum  $\text{cost}(\pi)$ 
    end procedure

procedure FINDCANDIDATES(Goal)
  foreach  $\text{child} \in \text{Goal}$ 
    If ( $\text{precondition}(\text{child})! = \emptyset$  and  $\text{status}(\text{child}) \notin \{\text{Done}, \text{Live}, \text{Blocked}\}$ )
      add  $\text{precondition}(\text{child})$  to Candidates
    else If ( $\text{postcondition}(\text{child})! = \emptyset$  and  $\text{status}(\text{child}) \in \{\text{Failed}\}$ )
      add  $\text{postcondition}(\text{child})$  to Candidates
    If ( $\text{status} \in \{\text{Live}\}$  and  $\text{nonPrimitive}(\text{child})$  and  $\text{applicability}(\text{child})! = \emptyset$ )
      add  $\text{App-condition}(\text{child})$  to Candidates
       $\text{findCandidates}(\text{children}(\text{child}))$ 
    return Candidates
  end procedure

```

The hybrid planning system proceeds as described in the algorithm 1. It calls the reactive HTN to achieve the goal. The environment is monitored at each step of the execution to check the success of the execution. Nevertheless, a breakdown might occur and make the HTN execution fails.

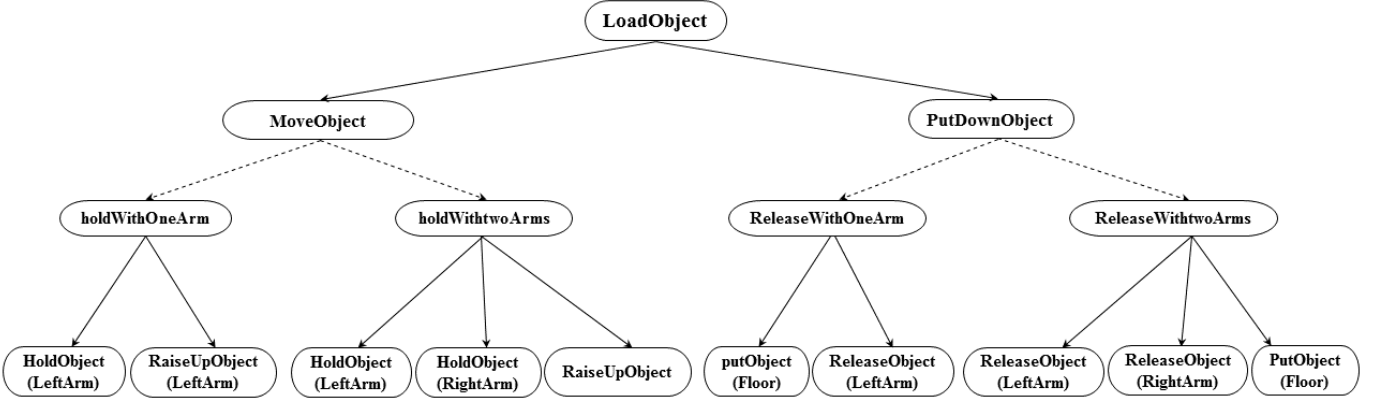


Fig. 1: Load Object task decomposition for robot arm motion

When a breakdown is detected, the hybrid system invokes the recover algorithm. First, The recover algorithm traverses the hierarchy of the goal task to detect all the children tasks affected by the breakdown and attempt to propose a plan repair for them. A task is considered as failed if one of its conditions are no longer valid. Thus, the algorithm computes the task's failed conditions to repair them, using for that the task's status. A task status can be *Live* (Task preconditions are valid and the task can be performed), *Done* (The task has been executed successfully), *Failed* (Task execution failed) or *Blocked* (Task preconditions are not valid). The algorithm then takes a task preconditions as candidate if its status is *Blocked*, or its postconditions if its status is *Failed*. If the task is a compound task with its status to *Live* and none of its recipes are valid then the applicability condition of those recipes are considered as candidates. For instance, taking back the example described in section III, a breakdown is detected because no recipe can be applied to decompose the "MoveObject" task. The system, then calls the recover procedure to detect all the affected tasks by this breakdown. The candidates list includes both applicability conditions of the failed recipes, the postconditions of the "MoveObject" task and the "LoadObject" task. Note that a condition is considered as candidate only if it can be converted to a symbolic formalism. Otherwise, the recover procedure ignores this condition.

Once the list of candidates has been determined, the linear planning system is called for each candidate. As linear planning systems plan to reach a state rather than achieving goals, then each task's conditions candidate is considered as goal state to reach. The linear planner plans for each candidate and tries to return a list of possible plans to recover from the breakdown. The most promising plan is calculated to be executed. We define the most promising plan as the shortest plan (i.e the plan that contains the less actions) to ensure local task repair and prevent other breakdowns due to the execution of pre-constructed plan. Thus, in the example, the planner proposes to repair the failed recipe "HoldWithTwoArm". Thus, the proposing plan repair consists on using a, existing task

"Separate the Object" to separate the object into two objects of 10 kilos and load them separately.

V. IMPLEMENTATION AND EXPERIMENTAL RESULTS

A. Discolog implementation

The proposition presented in this paper has been implemented using a reactive HTN called Disco [Ric09] and a simple linear STRIPS planner, the STRIPS version used in this system is an existing Prolog implementation proposed in [PGM98]. Thus, we named the produced system *Discolog*.

Disco uses the ANSI/CEA-2018 standard for the procedural definition of its domain knowledge and a Java-based reactive planning system. Tasks are modeled using the XML format. Primitive tasks contain grounding script parameter defined as JavaScript programs which represent the effect of primitive task execution in the environment.

The integration of STRIPS in the Disco system is performed using *tuProlog*¹ framework. The use of *tuProlog* presents two mains advantages. First, *tuProlog* is a Java-based framework that exploits a Prolog engine directly from a Java program. Thus, STRIPS can locally raised without any call to an external system. Second, it has specific libraries for the prolog predicates that eases the conversion of recovery candidates from the procedural knowledge to symbolic knowledge.

B. Experiments and results

In this section, we present ou experiment with the *Discolog* system. The aim of this experiment is first to validate the hybrid architecture of Discolog system. Second, we want to test the contribution of the symbolic knowledge in the performances of recovery. We make the assumption that the effectiveness of the recovery process is relied to the level of knowledge in the symbolic domain knowledge. In fact, we assume that the more information STRIPS planner gets from the procedural domain knowledge, the more effective recover plans it can generates. The result of this experiment should

¹<http://apice.unibo.it/xwiki/bin/view/Tuprolog/>

proves that plan recovery follows a monotonic evolution in function of the level of knowledge defined in STRIPS.

In order to validate Discolog, we had to test it on different HTNs domain knowledge and analyze its ability of recovery on every possible breakdown. Nevertheless, in the absence of accurate models including reactive and symbolic knowledge, we implemented our own evaluation data.

As theses primary tests purpose is to validate the hybrid architecture of Discolog, we actually don't need a domain knowledge with a semantic description of its tasks. Therefore, we defined a procedural domain knowledge based only on synthetic data structured in such way to ensure a believable execution. Each compound task (T) is defined with a set of recipes (R) and each recipe is constituted by a set of children tasks (C) to decompose the parent task (T). Preconditions of compound task are propagated to its first child in each recipe, and the postconditions are propagated to its last child. The rest of task children in each recipe are defined with chained conditions: The postconditions of the $task_i$ activate the preconditions of the $task_{i+1}$. Symbolic knowledge is extracted from the procedural one. Depending on the level of knowledge we want to study, we randomly extract primitive tasks from the HTN procedural knowledge. The goal is to study the affect of the level of symbolic knowledge defined on recovery.

We tested Discolog on different HTNs model. We denote (α, β, γ) respectively the depth of the HTN, number of recipes per each task, number task children per recipe. For each HTN, we varied first, the level of symbolic knowledge to be extracted $\{25\%, 50\%, 75\%\}^2$. For each level of knowledge, we randomly extracted different symbolic domain knowledge. Second, the initial state is randomly defined. This later affects the decomposition that the HTN will choose and the plan recover procedure. Once theses parameters are set, for each primitive task, a breakdown is caused and the plan recovery for this task is analyzed. The experiments have been done on two different HTN configuration as presented in table I.

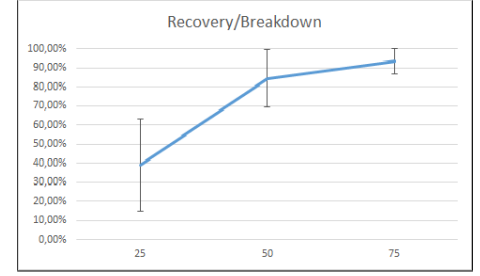
TABLE I: Configuration of the HTNs

Configuration	Total Nb of nodes	Init state	Nb of symbolic DN
(3,3,3)	91	10	60
(5,1,4)	341	10	60

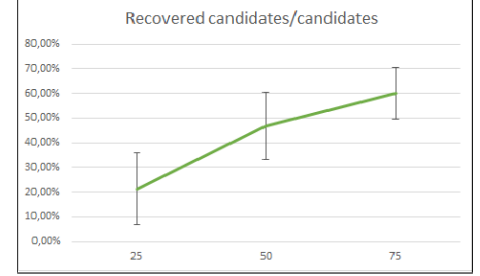
Figures 2a and 3a display the recover rate for HTNs. We notice that the hybrid system is able to propose plans recovery and switch between the procedural and the symbolic environment. Moreover, the results confirm our assumption: the graph follows a monotonic assumption in function of the symbolic knowledge. Thus, the more symbolic knowledge Discolog has the more it can recover from breakdowns.

The error bars defined in the graphs represent the standard deviations for each execution in function of the level of symbolic knowledge. We notice that the less symbolic knowledge Discolog has the bigger is the standard deviation. For the

²0 % of symblic knowledge means no possible recovery and 100 % is not realistic taking in account the dynamic definition of environment



(a) Recover rate for each level of knowledge



(b) Average number of candidates repaired for each level of knowledge

Fig. 2: Results for the (3, 3, 3) HTN

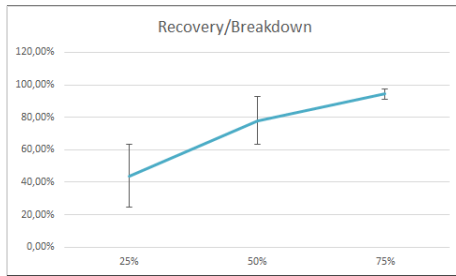
same HTN, Discolog gets different rates of performances. For example for HTNs defined with the 25 % of symbolic knowledge, Discolog performances varies from 0% to 65% of recover. This is noticed in the case of HTN with 25 % and 50 % of defined symbolic knowledge. Thus, HTNs defined with limited symbolic domain knowledge, are unable to cover from all the possible breakdowns because of their lack of symbolic knowledge.

Figures 2b and 3b show the average of the number of candidates repaired during the execution. The results for repairing candidates also confirm our assumption. However, the error bars as demonstrated in graphs show that Discolog performances varies for repairing all the possible candidates and this independently of the level of symbolic knowledge defined. Theses result raise a new question of the quality of the symbolic knowledge defined by the designer. Symbolic knowledge is limited, then it has to be expressive and very representative of the agent policy, or Discolog will not have the precise knowledge to recover from all the possible breakdowns.

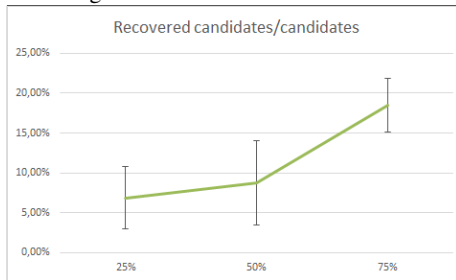
These tests are very promising but remain far from being definite experimental analysis. An extensive tests on a set of realistic domain knowledge is the object of futures works to detail the problematic of the quality of knowledge and test Discolog on real planning problems.

VI. CONCLUSION

In this paper we have presented *Discolog*, an algorithm to recover from breakdowns in reactive HTN planning systems. Despite the ability of reactive planning to deal with high



(a) Recover rate for each level of knowledge



(b) Average number of candidates repaired for each level of knowledge

Fig. 3: Results for the (4, 1, 5) HTN

dynamic world, breakdowns might occur because of the lack of knowledge on the different possible changes in the world and the ineptitude of reactive HTN to reason in long term to define a recover strategy.

The proposed algorithm extends reactive HTNs with linear symbolic planner to produces a plan to recover from the breakdown. The symbolic knowledge is extracted from the procedural knowledge by the HTN designer. Thus if a breakdown is detected, the algorithm calculates the candidates (conditions which are not valid in the non-executed HTN tasks), then STRIPS is called to propose plans to repair these conditions. The most promising plan is then converted to procedural formalism and executed.

The solution have been implemented. It combines a reactive HTN Disco with the symbolic linear planning system STRIPS in Prolog. The results of our preliminary experiments demonstrated, first, the ability of the hybrid planning system Discolog to propose viable plans recovery and for the different breakdowns. Second, the contribution of symbolic knowledge in the performances of the recovery. Finally, the experiments raise another problematic of the quality of knowledge in limited domain knowledge that we wish address. In addition, we intend to validate Discolog on real applications such as social dialog systems, we believe that with real applications, we can study the problem of the quality of the symbolic knowledge.

Future prospects of this research are, first, to construct a modeling tool for HTN model design. This tool will help the HTN designer in one hand to define the level of knowledge to integrate in the HTN. In the other hand, the system will

use the history of breakdowns to propose adding knowledge in the HTN where breakdowns occurred. As second step, we propose to integrate Discolog in social dialog system between an agent and a human in order to support the dynamic nature of a social dialog.

REFERENCES

- [AF02] James Allen and George Ferguson. Human-machine collaborative planning. In *Proceedings of the Third International NASA Workshop on Planning and Scheduling for Space*, pages 27–29, 2002.
- [AKYG07] N Fazil Ayan, Ugur Kuter, Fusun Yaman, and Robert P Goldman. Hotride: Hierarchical ordered task replanning in dynamic environments. In *Planning and Plan Execution for Real-World Systems—Principles and Practices for Planning in Execution: Papers from the ICAPS Workshop*. Providence, RI, 2007.
- [BD02] Guido Boella and Rossana Damiano. A replanning algorithm for a reactive agent architecture. In *Artificial Intelligence: Methodology, Systems, and Applications*, pages 183–192. Springer, 2002.
- [BR03] Dan Bohus and Alexander I Rudnický. Ravenclaw: Dialog management using hierarchical task decomposition and an expectation agenda. 2003.
- [Bro05] Cyril Brom. Hierarchical reactive planning: Where is its limit. *Proceedings of MNAS: Modelling Natural Action Selection*. Edinburgh, Scotland, 2005.
- [Bry01] Joanna Joy Bryson. *Intelligence by design: principles of modularity and coordination for engineering complex adaptive agents*. PhD thesis, Massachusetts Institute of Technology, 2001.
- [CGS98] Rosaria Conte, Nigel Gilbert, and Jaime Simão Sichman. Mas and social simulation: A suitable commitment. In *Multi-agent systems and agent-based simulation*, pages 1–9. Springer, 1998.
- [Ero96] Kutluhan Erol. Hierarchical task network planning: formalization, analysis, and implementation. 1996.
- [Fir87] R James Firby. An investigation into reactive planning in complex domains. In *AAAI*, volume 87, pages 202–206, 1987.
- [FN72] Richard E Fikes and Nils J Nilsson. Strips: A new approach to the application of theorem proving to problem solving. *Artificial intelligence*, 2(3):189–208, 1972.
- [HTHO06] Hisashi Hayashi, Seiji Tokura, Tetsuo Hasegawa, and Fumio Ozaki. Dynagent: An incremental forward-chaining htn planning agent in dynamic domains. In *Declarative Agent Languages and Technologies III*, pages 171–187. Springer, 2006.
- [Isl05] Damian Isla. Handling complexity in the halo 2 ai. In *Game Developers Conference*, volume 12, 2005.
- [Mae90] Pattie Maes. *Designing autonomous agents: Theory and practice from biology to engineering and back*. MIT press, 1990.
- [NCLMA99] Dana Nau, Yue Cao, Amnon Lotem, and Hector Muñoz-Avila. Shop: Simple hierarchical ordered planner. In *Proceedings of the 16th international joint conference on Artificial intelligence—Volume 2*, pages 968–973. Morgan Kaufmann Publishers Inc., 1999.
- [PGM98] David I Poole, Randy G Goebel, and Alan K Mackworth. *Computational Intelligence*. Oxford University Press Oxford, 1998.
- [Plc] T Plc. Towards believable intelligent virtual agents with statefull hierarchical reactive planning.
- [Ric09] Charles Rich. Building task-based user interfaces with ansi/cea-2018. *Computer*, 42(8):20–27, 2009.
- [Sac75] Earl D Sacerdoti. A structure for plans and behavior. Technical report, DTIC Document, 1975.
- [Sch87] Marcel Schoppers. Universal plans for reactive robots in unpredictable environments. In *IJCAI*, volume 87, pages 1039–1046. Citeseer, 1987.

- [VDKDW05] Roman Van Der Krogt and Mathijs De Weerd. Plan repair as an extension of planning. In *ICAPS*, volume 5, pages 161–170, 2005.
- [WHLUMA07] Ian Warfield, Chad Hogg, Stephen Lee-Urban, and Héctor Muñoz-Avila. Adaptation of hierarchical task network plans. In *FLAIRS Conference*, pages 429–434, 2007.
- [Wil88] David E Wilkins. *Practical planning: Extending the classical AI planning paradigm*. Morgan Kaufmann Publishers Inc., 1988.
- [ZHH⁺09] Hankz Hankui Zhuo, Derek Hao Hu, Chad Hogg, Qiang Yang, and Hector Muñoz-Avila. Learning htn method preconditions and action models from partial observations. In *IJCAI*, pages 1804–1810, 2009.