Adaptive Abstraction of Constraint-Based Models for Self-Diagnosis and Planning

Paul Maier
PhD student
Chair for Image Understanding & Knowledge-Based Systems
Department of Informatics
Technische Universitaet Muenchen
Boltzmannstrae 3, 85748 Garching, Germany
email: maierpa@in.tum.de
Adviser: Dr. Martin Sachenbacher

Introduction

Today's embedded systems like printers, cars, satellites or factory plants are composed of numerous complex, interconnected components, yielding a huge number of possible system states. This makes handling such systems, specifically diagnosing and repairing failures, increasingly harder. This problem can be tackled by fitting systems with an increasing degree of autonomy to, e.g., automatically diagnose faults' causes and plan workaround actions, and to generally reduce the need of human intervention (which is costly and possibly dangerous for humans). Autonomous intelligent systems might even fulfill tasks which humans can't do, like collecting scientific data on mars.

Such autonomy can be achieved through model-based reasoning: based on a model of the system's structure and behaviour, usually a Hidden Markov Model, in each time step a hypothesis about the current system state, i.e. a probability distribution over all states, is generated from prior states and sensor data. This is the well known problem of belief state update. An existing implementation is *Livingstone 2 (L2)*, developed at NASA and employed in the satellite EO-1 (Hayden, Sweet, and Christa 2004). In my work I aim to integrate diagnosis and planning in a single framework employing constraint-based modeling and optimization, develop new methods for a flexible belief state approximation and test these methods on the *CoTeSys* applications *cognitive factory* and *assistive kitchen* (Beetz, Buss, and Wollherr 2007), building on existing tools like L2.

Problem: Approximation of Belief State in Embedded Systems

The complexity of belief state update is exponential in the number of system variables, which is especially a problem for embedded systems. In L2 on EO-1 it is solved by computing only the k best states. (Mikaelian, Williams, and Sachenbacher 2005) introduce an improved method called *N-Stage Best First Trajectory Enumeration* (N-Stage BFTE), that uses an N-step time window to track the k best state trajectories. Both approaches might miss out on the true system state/trajectory if it is among the remaining states or trajectories. L2 needs to be restarted in this case. Currently the risk of missing the true state can only be influenced through the decision to keep or discard states. This decision is a big step which might push the computation effort beyond the tight resource limits. Resources could be used more efficiently if intermediate steps were possible. The mentioned approaches are however not flexible enough. Another problem is that systems like L2 use different representations and algorithms for diagnosis and for planning. A tighter integration of them could also improve resource efficiency.

In my thesis I aim to address these two problems by framing both diagnosis and planning as constraint optimization problems (COP), using soft constraints (Dechter 2003, Chapter 13) as common representation, and by developing a more flexible approximation of the belief state based on this representation. Soft constraints allow very flexible modeling and easy extension (by adding constraints) and they naturally handle state or transition probabilities. Within this context they are used to represent probability distributions over sets of states. A complete system model is then represented as constraint-based HMM, which one could retrieve, e.g., by translating from known industry modeling standards like Modelica (Elmqvist, Mattsson, and Otter 2001). Formulating both diagnosis and planning problems as COPs allows for applying a number of well known COP algorithms to both of them, resulting in a tighter integration of diagnosis and planning.

A more flexible approximation of the belief state can be achieved through an adaptive abstraction of the state space. Sets of states are combined into single abstract states, varying the "coarseness" of the abstraction through the number of concrete states which are combined into a single abstract state. With their representation as soft constraints, state sets may be abstracted by abstracting soft constraints. An existing method to achieve this is *domain abstraction*, where variable values are aggregated to form abstract values. The probability of an abstract state is retrieved by conservatively approximating the probabilities of the according states it combines. Probabilities can be used to choose the degree of "coarseness", with a high probability prompting a finer abstraction.

A belief state approximation implementing adaptive abstraction would improve on L2's k-best method or N-Stage BFTE because it provides a more fine grained control than just to keep or discard state information. In conclusion I would like to summarize the aims of my thesis: I would like to develop diagnosis and planning algorithms for embedded systems based on COP that use abstraction to approximate the belief state more flexibly. Furthermore, by using the same representation (COP) for them I hope to gain a tighter integration of diagnosis and planning.

Research Plan

My research plan consists of three task groups, which are 1) preparation/development of a testbed and tools, 2) development of a theoretical foundation and 3) the main research focus.

The first group is dedicated to the development of a testbed which allows for evaluation of different diagnosis and planning algorithms. A crucial component are models of real systems, which will be acquired by collaborating with other projects like the *cognitive factory* or the *assistive kitchen* (Beetz, Buss, and Wollherr 2007). For instance, one *CoTeSys*-group is concerned with modeling the cognitive factory as a set of hybrid automata. As a first step, models like this will be discretized in order to run them on L2. A suitable translation tool will be developed based on existing work. A second step is then to leverage COP for diagnosis and planning by extending L2 to incorporate COP solving, using existing solvers. An additional aim is to store models using open formats like *HyAuLib* (Tiziano Pulecchi and Francesco Casella 2008), a Modelica library for hybrid automata.

In the second group, I plan to develop a mathematical basis for abstraction transformations of constraints as a theoretical foundation for my work. The aim is to define what abstract constraints are, how different abstraction transformations are related and how all this is tied to system states. Ideally methods like *domain abstraction* are contained as special cases.

With the third task group I will explore, develop and test new COP algorithms to address the two problems stated above. An existing solver like *toolbar* (Bouveret et al. 2004) will serve as basis, which allows for comparison with existing COP algorithms. The developed algorithms will be run on benchmarks like those from the *toolbar* suite[1], and their complexity will be analyzed. One algorithm has already been implemented and now needs further development and testing. The next research direction is to explore ideas considering iterative refinement of abstraction (Koster 1999, Chapter 4).

Progress to Date

Up to now I have implemented a new COP algorithm based on the existing dynamic programming COP algorithm *Mini-Bucket Elimination (MBE)* (Dechter 2003, Chapter 13).

MBE decomposes a COP into a connected tree of sub problems and infers solutions by passing messages between them, which is especially apt since the decomposition might actually reflect a system's modularity. Exact message generation is exponential in the size of the message scope, but MBE limits the complexity by conservatively approximating a message with size bound mini-messages and discarding constraints which exceed this limit. MBE doesn't allow for intermediate steps (other than keep or discard), which makes it less suitable for typical COPs in diagnosis and planning, which have big constraints and variable domains (e.g., domains with 2-9 values and many constraints with over 4 variables in a EO-1 L2 diagnosis problem).

The new algorithm addresses this problem by combining tree decomposition with the afore mentioned domain abstraction: given a size limit for all messages, domain sizes are automatically adapted in order to reduce the COP's constraint sizes and thus the messages, which are computed from them. This allows finer abstraction steps, i.e. a more flexible approximation of the exact messages. The algorithm, called *Bucket Elimination with Domain Abstraction (BEDA)*, was integrated in toolbar to allow comparison with MBE and other COP algorithms.

Preliminary results of tests with an EO-1 diagnosis problem indicate a better performance than the existing MBE algorithm in terms of space complexity. Further tests and a complexity analysis will be conducted to reveal the algorithm's potential. Also, the domain size adaption needs to be refined.

[1] See toolbar benchs `http://mulcyber.toulouse.inra.fr/gf/project/toolbar/scmcvs/`

References

Beetz, M.; Buss, M.; and Wollherr, D. 2007. Cognitive technical systems - what is the role of artificial intelligence? In *KI 2007: Advances in Artificial Intelligence*, 19–42.

Bouveret, S.; Heras, F.; Givry, S.; Larrosa, J.; Sanchez, M.; and Schiex, T. 2004. Toolbar: a state-of-the-art platform for wcsp. `http://www.inra.fr/mia/T/degivry/ToolBar.pdf`.

Dechter, R. 2003. *Constraint processing*. San Francisco, CA 94104-3205: Morgan Kaufmann Publishers.

Elmqvist, H.; Mattsson, S. E.; and Otter, M. 2001. Object-oriented and hybrid modeling in modelica. *Journal Europen des systmes automatiss* 35.

Hayden, S. C.; Sweet, A. J.; and Christa, S. E. 2004. Livingstone Model-Based Diagnosis of Earth Observing One. In *AIAA 1st Intelligent Systems Technical Conference*.

Koster, A. M. C. A. 1999. *Frequency assignment—models and algorithms*. Ph.D. Dissertation, Universiteit Maastricht, Maastricht, The Netherlands.

Mikaelian, T.; Williams, C. B.; and Sachenbacher, M. 2005. Model-based Monitoring and Diagnosis of Systems with Software-Extended Behavior. In *National Conference on Artificial Intelligence*.

Tiziano Pulecchi, and Francesco Casella. 2008. HyAuLib: Modelling Hybrid Automata in Modelica. In *Proceedings 6th International Modelica Conference*, 239–246.