Stream-Based Reasoning Grounded Through Sensing

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1 Introduction

An increasing number of products and devices, ranging from mobile phones to trucks and aircraft, are becoming equipped with advanced sensors providing information about the system itself and its environment. In many cases, this wealth of information is not very useful in its raw form. On the other hand, given suitable processing using high-level relational, spatial and temporal reasoning techniques, a great deal of interesting knowledge could be extracted, significantly improving the situational awareness of the system itself and the decision support provided to its human users, something that would greatly improve the usefulness of unmanned aerial vehicles and the fault diagnosis and isolation capability in trucks.

Though a rich and varied set of useful high-level reasoning techniques already exist, they usually require information at a level of abstraction that is far higher than that which is normally acquired through sensing. For example, existing methods for detecting complex events occurring in the environment tend to assume a set of primitive but meaningful symbolic events as input, whereas a camera only provides a raw stream of bitmap images. Thus, there is a wide gap between assumed and provided abstraction levels, which we call the sense-reasoning gap.

Bridging this gap is a fundamental and very challenging problem. Information must continuously be extracted from the environment through all available sensors. Suitable representations of this information must be constructed at a low level. Then, the available information must continuously be processed using well-defined and proven methods, in order to raise its level of abstraction. Since the gap in abstraction levels can be very wide, an incremental methodology is often required, where information passes through a sequence or network of methods that eventually produce the desired knowledge. At all times, information at any level must be properly connected and correlated to information at lower levels, ensuring that all levels of reasoning are grounded in the external environment.

How to bridge the sense-reasoning gap in a principled and systematic manner is largely an unstudied problem in itself. Our hypothesis is that a stream-based approach provides a highly appropriate structure, since streams capture the incremental nature of the information available from sensors and the continuous reasoning process of making inferences with minimal latency necessary to react to rapid changes in the environment.

DyKnow provides both conceptual and practical support for stream-based reasoning grounded through sensing by organizing the many levels of information processing in an autonomous system as a coherent network of sensing and reasoning processes connected by streams. DyKnow is fully implemented and a central component in our distributed UAV architecture.

The purpose of this project has been to extend the theoretical basis for DyKnow, to develop techniques and algorithms for stream-based reasoning grounded through sensing, and to explore their use in academic and industrial applications in cooperation with companies such as Scania and Saab. The long term vision is to establish a strong stream reasoning group focusing on formal reasoning techniques based on grounded representations and their use in autonomous systems.

2 Main Scientific Results

The first major scientific result is the semantic grounding of symbols through a technique called *semantic matching* [C7, C8, C11, C16, C17]. Semantic matching allows symbols in a logical formula to automatically be matched to streams providing an interpretation of the symbol through reasoning about the meaning of the symbols and the content of streams as represented by one or more ontologies. The semantic matching functionality has been extended with support for finding and automatically applying transformations [C8]. This allows situations when the requested streaming information is not directly available but has to be generated or adapted through transformations to be handled. Two types of transformations are considered, automatic transformation between different units of measurements and between streams of different types. Another extension is to allow basic integration with semantic event processing [C11]. Lately we have generalized the semantic matching approach to support introspection in stream processing systems [C16, C17]. Daniel de Leng has been awarded the Swedish AI Society Best AI Master's Award in 2014 for his Master's Thesis on semantic matching.

The second major scientific result is the work on *spatio-temporal stream reasoning* [C12, C19]. We have extended the metric temporal stream reasoning with qualitative spatial reasoning using for example RCC-8 [C12]. This allows us to evaluate spatio-temporal formulas expressing spatial relations within a single time-point. To achieve this we had to extend the progression-based stream reasoning approach to handle incomplete information. This was done using a three valued Kleene Logic approach. We have also extended the spatio-temporal reasoning to support spatial relations between different time-points [C19]. The major challenge here is that a robot can never directly observe these spatial relations. We therefore define the concept of a landmark as a region that does not change between time-points and use these landmarks to infer qualitative spatio-temporal relations between dynamic regions at different time-points. The qualitative spatial reasoning is done in RCC-8, but the approach is general and can be applied to any similar qualitative spatial formalism.

The third major scientific result is the work towards *unsupervised learning of spatio-temporal activities* [C13, C15, C18]. We have studied how unsupervised learning can be used to automatically learn activities and how these activities relate to each other based on observations of trajectories of objects [C13, C18]. The idea is to take a bottom-up approach to learning the hierarchical spatio-temporal patterns that our stream reasoning framework can then detect and reason about. To achieve the unsupervised learning we had to developed a new method for online sparse gaussian process regression for trajectory modeling [C15]. Mattias Tiger has been awarded the Swedish AI Society's Best AI Master's Thesis Award in 2015 for his Master's Thesis on unsupervised learning of spatio-temporal activities.

We have also made progress towards providing support for stream-based reasoning in the Robot Operating System (ROS) which is a very popular framework for developing robotic applications [C9]. When finished the software will be available as open source. This will allow stream-based reasoning to be used by a wide range of robots including our LinkQuad micro air vehicles and commercially available platforms such as the PR2 from Willow Garage.

3 Degrees and Promotions

The project has contributed to the promotion of Fredrik Heintz to Docent in January 2014 and to Lektor in November 2014 as well as the licenciate degree of David Landén in 2011. The project has also led to the following Master's and Bachelor's degrees:

1. Stefan Bränd, completed his Bachelor's degree in December 2015.

2. Erik Junholm and Philip Zanderholm completed their Master's degrees in May 2015.
3. Mattias Tiger, **winner of the Swedish AI Society Best AI Master's Thesis Award 2015**, completed his Master's degree in November 2014.
4. Daniel de Leng, **winner of the Swedish AI Society Best AI Master's Thesis Award 2014**, complete his Master's degree in November 2013.
5. Anders Hongslo, completed his Master's degree in June 2012.
6. Viet Ha Nguyen, jointly supervised with Unmesh Bordoloi, completed his Master's degree in June 2012.
7. Daniel Lazarovski, completed his Master's degree in March 2012.
8. Zlatan Dragisic, completed his Master's degree in October 2011.
9. Erik Lundqvist, completed his Master's degree in September 2011.
10. Anders Skoglund, completed his Bachelor's degree in June 2011.

4 Staff

The project has contributed to financing Fredrik Heintz, Daniel de Leng, Mattias Tiger, David Landén, and Olov Andersson.

5 Industrial Contacts

The main industrial cooperation is with Saab Aerosystems. Besides this project also through multiple NFFP projects and through LinkLab, a center for future aviation systems. Results have been reported through both technical reports and peer-reviewed publications, and demonstrated and discussed at several joint workshops and live demonstrations.

We also have had active collaboration with Scania, mainly through an industry-based doctoral student (Håkan Warnquist) who worked on the use of planning for diagnosis of heavy trucks. This provided an excellent connection to another important industrial partner. His co-adviser docent Mattias Nyberg at Scania was our primary contact person. The main result is the Master's Thesis "Design Patterns for Service-Based Fault Tolerant Mechatronic Systems" by Erik Lundqvist. The thesis studies the use of service-based fault tolerant control on a real system for selective catalytic reduction developed at Scania. It identifies a number of design patterns that are used for typical signal flow architectures in mechatronic systems and extends these design patterns to support fault tolerance according to the service-based fault tolerant control approach. The services in this framework are similar to the knowledge processes in DyKnow and both use streams to communicate (they are called signals in Scania's framework) so the design patterns are relevant for stream-based applications as well.

6 Contacts with Other CENIIT Projects

In the beginning of the project there was successful cooperation with the CENIIT project "Robust Planning Systems for Aerospace Applications" led by Jonas Kvarnström, which ended in 2011.

We also cooperated with Unmesh Bordoloi's CENIIT project "A Cross-layer Approach to Reliability Optimization for Automotive Electronic Systems". Together we supervised a Master's thesis about formal timing analysis of stream reasoning. The idea is to use formal analysis tools from real time systems to do design space exploration of stream reasoning applications. Using these tools it is possible for example to analyze how many temporal logical formulas can be evaluated given a particular sampling frequency. It is also possible to analyze the effect on delays in the stream reasoning based on the jitter in the delivery of the different streams.

7 New Research Group

The CENIIT project has strongly contributed to the creation of a Stream Reasoning group in IDA/AIICS led by Fredrik Heintz. The group was until very recently called the Cognitive Robotics group, but to focus the activities to the interesting and important topic of stream reasoning the group has changed names. The group currently has three members, Fredrik Heintz (PhD, Docent), Daniel de Leng (PhD student) and Mattias Tiger (PhD student).

8 Publications

Refereed Journal Articles

[J4] Patrick Doherty, **Fredrik Heintz**, and Jonas Kvarnström. High-level Mission Specification and Planning for Collaborative Unmanned Aircraft Systems using Delegation. *Journal of Unmanned Systems*, World Scientific, 1(1):75–119, 2013.

[J3] **Fredrik Heintz**, Jonas Kvarnström, and Patrick Doherty. Stream-Based Hierarchical Anchoring. *Künstliche Intelligenz*, Springer Verlag, 2013.

[J2] **Fredrik Heintz**, Jonas Kvarnström, and Patrick Doherty. Bridging the Sense-Reasoning Gap: DyKnow – Stream-Based Middleware for Knowledge Processing. *Journal of Advanced Engineering Informatics*, Elsevier, 24(1):14–26, 2010.

[J1] Mattias Krysander, **Fredrik Heintz**, Jacob Roll, and Erik Frisk. FlexDx: A Reconfigurable Diagnosis Framework. *Journal of Engineering Applications of Artificial Intelligence*, Elsevier, 23(8):1303–1313, 2010.

Refereed Conference Papers

[C19] Daniel de Leng and **Fredrik Heintz**. Qualitative Spatio-Temporal Reasoning Between Time-Points from Instantaneous Observations using Landmarks. In *Proceedings of the 30th AAAI Conference on Artificial Intelligence*, 2016.

[C18] Mattias Tiger and **Fredrik Heintz**. Towards Unsupervised Learning, Classification and Prediction of Activities in a Stream-Based Framework. In *Proceedings of the Thirteenth Scandinavian Conference on Artificial Intelligence (SCAI)*, 2015.

[C17] Daniel de Leng and **Fredrik Heintz**. Ontology-Based Introspection in Support of Stream Reasoning. In *Proceedings of the Thirteenth Scandinavian Conference on Artificial Intelligence (SCAI)*, 2015.

[C16] Daniel de Leng and **Fredrik Heintz**. Ontology-Based Introspection in Support of Stream Reasoning. In *Proceedings of the 1st Joint Ontology Workshops (JOWO)*, 2015.

[C15] Mattias Tiger and **Fredrik Heintz**. Online Sparse Gaussian Process Regression for Trajectory Modeling. In *Proceedings of the 18th International Conference on Information Fusion (FUSION)*, 2015.

[C14] Olov Andersson, **Fredrik Heintz** and Patrick Doherty. Model-Based Reinforcement Learning in Continuous Environments Using Real-Time Constrained Optimization. In *Proceedings of the 29th AAAI Conference on Artificial Intelligence*, 2015.

[C13] Mattias Tiger and **Fredrik Heintz**. Towards Learning and Classifying Spatio-Temporal Activities in a Stream Processing Framework. In *Proceedings of the 7th European Starting AI Researcher Symposium (STAIRS)*, 2014.

[C12] **Fredrik Heintz** and Daniel de Leng. Spatio-Temporal Stream Reasoning with Incomplete Spatial Information. In *Proceedings of the 21st European Conference on Artificial Intelligence (ECAI)*, 2014.

[C11] Daniel de Leng and **Fredrik Heintz**. Towards On-Demand Semantic Event Processing for Stream Reasoning. In *Proceedings of the 17th International Conference on Information Fusion (FUSION)*, 2014.

[C10] Patrick Doherty, **Fredrik Heintz** and Jonas Kvarnström. Robotics, Temporal Logic and Stream Reasoning. In *Proceedings of Logic for Programming Artificial Intelligence and Reasoning (LPAR)*, 2013.

[C9] **Fredrik Heintz**. Semantically grounded stream reasoning integrated with ROS. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2013.

[C8] **Fredrik Heintz** and Daniel de Leng. Semantic information integration with transformations for stream reasoning. In *Proceedings of the 16th International Conference on Information Fusion (FUSION)*, 2013.

[C7] **Fredrik Heintz** and Zlatan Dragisic. Semantic Information Integration for Stream Reasoning. In *Proceedings of the 15th International Conference on Information Fusion (FUSION)*, 2012.

[C6] Patrick Doherty and **Fredrik Heintz**. Delegation-Based Collaboration. In *Proceedings of the 5th International Conference on Cognitive Systems (CogSys)*, 2012.

[C5] Patrick Doherty and **Fredrik Heintz**. A Delegation-Based Cooperative Robotic Framework. In *Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2011.

[C4] **Fredrik Heintz** and Patrick Doherty. Federated DyKnow, a distributed information fusion system for collaborative UAVs. In *Proceedings of the International Conference on Control, Automation, Robotics and Vision (ICARCV)*, 2010.

[C3] **Fredrik Heintz**, Jonas Kvarnström, and Patrick Doherty. Stream-Based Middleware Support for Autonomous Systems. In *Proceedings of the 20th European Conference on Artificial Intelligence (ECAI)*, 2010.

[C2] Patrick Doherty, David Landén, and **Fredrik Heintz**. A Distributed Task Specification Language for Mixed-Initiative Delegation In *Proceedings of the 13th International Conference on Principles and Practice of Multi-Agent Systems (PRIMA)*, 2010.

[C1] David Landén, **Fredrik Heintz**, and Patrick Doherty. Complex Task Allocation in Mixed-Initiative Delegation: A UAV Case Study. In *Proceedings of the 13th International Conference on Principles and Practice of Multi-Agent Systems (PRIMA)*, 2010.

Survey Articles, Book Chapters, and Books

[B2] Patrick Doherty, Jonas Kvarnström, Mariusz Wzorek, Piotr Rudol, **Fredrik Heintz**, and Gianpaolo Conte. *Handbook of Unmanned Aerial Vehicles*, chapter HDRC3: A Distributed Hybrid Deliberative/Reactive Architecture for Unmanned Aircraft Systems. Springer Verlag, 2014.

[B1] Patrick Doherty, **Fredrik Heintz**, and David Landén. A Delegation-Based Architecture for Collaborative Robotics. In Agent-Oriented Software Engineering edited by Danny Weyns et al., Springer Verlag, 2011.