Evaluating the Impact of Knowledge Aggregation with Subjective Logic on the Overall System's Adaptivity in Multi-Agent Self-Adaptive Cyber-Physical Systems

Master thesis

Supervisor: Prof. Dr. Alexander Pretschner
Advisor: Ana Petrovska
Email: {alexander.pretschner, ana.petrovska}@tum.de
Phone: +49 (89) 289 - 17830
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Fakultät für Informatik
Lehrstuhl 4
Software & Systems Engineering
Prof. Dr. Alexander Pretschner

Boltzmannstraße 3
85748 Garching bei München

Tel: +49 (89) 289 - 17830
https://www4.in.tum.de

Context

Modern society has become increasingly reliant on Cyber-Physical Systems (CPSs). Therefore, these systems need to act reliably while facing different uncertain and changing internal and external (contextual) conditions. As a response to these changes and uncertainties, self-adaptive CPSs (SACPSs) can adjust their behavior or structure at run-time. In architecture-based self-adaptation [1, 2, 3, 4], a self-adaptive system—including SACPS—is comprised of a *managed element* and an *adaptation logic*. The managed element is the system that gains adaptation capabilities, and it can be either a software system or a CPS. The adaptation logic is the element that provides adaptation capabilities. It is commonly implemented using the MAPE-K (monitor, analyze, plan and execute on shared knowledge) closed feedback loop [1, 5, 6]. The knowledge in the adaptation logic can either be specified by the engineers of the system during the design of the system, or it can be obtained during run-time or system operation by monitoring the environment and integrating the observations with the existing knowledge base, based on which the next system's actions are decided. The process of incorporating the new observations with the existing knowledge base becomes even more complex when the observations are made by multiple decentralized CPSs and are not only uncertain but also partial and potentially conflicting. As a result, to build the knowledge, the need for run-time observations aggregation and reasoning emerges [7, 8].

Prior work

In our previous work [7, 8], based on an extended work of two master theses [9, 10], we have presented a methodology for knowledge aggregation and reasoning in multi-agent SACPSs (MA-SACPSs) that deals with reasoning on uncertain, partial, and conflicting observations. Concretely, our approach uses Subjective Logic (SL) [11, 12] to update the knowledge in the adaptation logic at run-time by aggregating observations of the context made by each CPSs. We have shown and evaluated the effectiveness of the proposed approach through extensive controlled experiments on an in-house, simulated, ROS-based multi-robot system. The robotics system was developed based on a previously created model problem in which multiple robots explore and attain tasks that are continuously appearing in a room with unknown patterns and locations. In the prior conducted experiments, we ran simulations under different settings, controlling various aspects of the system: (i) the SL aggregation schemes for knowledge aggregation, (ii) the number of robots and the observation uncertainties of the robots (e.g., the false negative (FN) and false positive (FP) observations), (iii) the frequency and the patterns of appearance of the tasks in the room (i.e., the context), (iv) the threshold with which the detected tasks are propagated as goals for the robots, etc. However, in all the experiments, we held constant the dimension and the layout (e.g., corridors, walls, etc.) of the room in which the robots operate.

Goal

To address the limitation mentioned above, the first goal of this master thesis is to extend the existing experiments by evaluating knowledge aggregation and the overall system behavior considering different room sizes and layouts and changing number of robots. Since the knowledge aggregation majorly benefits from situations in which the CPSs have overlapping sensing ranges, we want to investigate how different room layouts impact the knowledge aggregation process. In different room layouts we want to vary the shape and size of the room, the percentage of the room's occupancy, the number of the robots, etc. Please note that the current implementation of the robotics system already supports changing the room layouts and the number of robots, and the goal of this work would be to design and identify a representative set of rooms to be analysed in the extended evaluation. Therefore, identifying and designing a representative set of rooms is the second goal of this thesis.

Additionally, the results from the previous experiments indicated that there is a trade-off between the number of tasks completed by the MA-SACPS and the accuracy of the system. Although the observed general trends agreed with our expectations, with the prior conducted experiments there was a lack of data to make definitive statements. Therefore, as the third goal of this work, we want to investigate more in depth the trade-off between the number of completed tasks and the accuracy of the system, and what system parameters influence that trade-off. Based on the trade-off between the accuracy of the MA-SACPS and the total number of completed tasks, one can conjecture that there is an optimal threshold that will maximize the number of completed true positive (TP) tasks and which will vary with the FP and FN probabilities. However, more extensive and statistically significant tests are required to verify the results and the ocnclusions from the past experiments, and the third goal of this thesis will contribute towards this.

In overall, the main hypothesis behind the introduction of knowledge aggregation and reasoning with subjective logic for self-adaptive CPSs, was to update the knowledge in the adaptation logic only when there is a specific level of certainty in the observed tasks. This should lead towards better attainment of the adaptation goals, i.e., in this concrete case, shortening the time needed for the robots to attain the tasks in the room, since the robots will only pursue tasks that exist in the room in reality (the true positives, instead of the FP and the FN tasks). However, it is important to consider that aggregating the knowledge for the TP tasks is more time costly, since the same task might need to be observed multiple times, or observed by multiple robots, which results in an additional time overhead. Therefore, the third goal of this thesis should also enable us to reason on the impact of the knowledge aggregation on the overall system's adaptivity, and not only on the correctness, the accuracy and the sensitivity of the knowledge aggregation methodology in independence.

Working Plan

1. Get familiar with:
   - the theory of subjective logic
   - our prior work on knowledge aggregation with subjective logic
   - the implementation of the ROS multi-agent robotics system
   - the existing evaluation and data analysis
2. Design different experiments and experimental setups
   - identify representative sets of rooms with varying room characteristics, while considering the percentage sensing range overlap
3. Conduct the controlled experiments and collect data
4. Evaluate and analyse the collected data, and compare the results to address the goals identified above. Some of the questions that we are interested in answering are the following:
   - is there an optimal threshold that maximizes the number of completed true positive (TP) and generalizes to every setup, or it highly depends on specific room characteristics?
   - since aggregating knowledge leads to higher system accuracy but it is more time costly, how the knowledge aggregation impacts the overall performance of the self-adaptation system?
   - what knowledge aggregation accuracy is optimal for the overall performance of the self-adaptive system?
5. Write the final report.

Pre-requisite

- Good Python skills
- Good analytical and data analysis skills
- Ideally, previous knowledge and experience with ROS
- Ideally, previous experience with conducting evaluations of scientific contributions

Deliverables

- Source code of the implementation and the evaluation scripts.

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- The collected data.
- Technical report with comprehensive documentation of the implementation, i.e. design decision, architecture description, API description and usage instructions. Usually as part of the gitlab documentation.
- Final report written in conformance with TUM guidelines.

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