Autonomous Inspection Of Complex Environments by Means of Semantic Techniques

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Abstract The autonomous inspection of complex environments is a challenging task. An autonomous inspection robot should actively examine entities of interest (EOIs), e.g. defects, and should perform additional inspection actions until the data analysis results reach an appropriate level of confidence. In this paper a semantic approach for inspection planning, plan execution, assessment of the data analysis results, decision making and replanning is proposed. The main idea is to incorporate human expert knowledge via a semantic inspection model. For the experimental evaluation of this approach the detection and classification of waste on irregular terrains with the hexapod walking machine LAURON is chosen. First preliminary simulation results are presented.

1 Introduction

The inspection of complex environments like sewers, pipelines, power transmission lines or dams is a challenging task for autonomous inspection robots.

Recently, there has been a lot of research in this area. The approaches can be roughly categorized into two categories. First, the hardware design and the control of the inspection robot itself are considered, e.g. Nassiraei et al. [5]. Second, appropriate sensor systems, their automatic placement and the corresponding data analysis components are examined, e.g. Duran et al. [2].

However, there exist only few integrated approaches aiming at fully autonomous inspection systems. In [1] the Onboard Autonomous Science Investigation System (OASIS) is described. OASIS is designed to operate onboard a planetary rover identifying and reacting to serendipitous science opportunities. It analyzes data the rover gathers during traverses, and then prioritizes the data for transmission back to earth

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based on criteria set by the science team. OASIS is also searching for specific targets it has been told to find. If one of these targets is found, it is identified as a new science opportunity and is sent to the planning and scheduling component. A continuous planning approach [3] is used to iteratively adjust the plan as new goals occur, while ensuring that resource and other operation constraints are met. The expert knowledge for identifying science opportunities is provided to the system by means of algorithms for feature extraction from images, analyzing the gathered data and prioritizing rocks.

Today, there exist only few semantic approaches regarding autonomous inspection missions. The authors of [6] present an approach for autonomous mission plan recovery for maintaining operability of unmanned underwater vehicles. The approach uses ontology reasoning in order to orient the planning algorithms adapting the mission plan of the vehicle. It can handle uncertainty and action scheduling in order to maximize mission efficiency and minimize mission failures due to external unexpected factors. In one of the simulation scenarios smart AUVs with fully autonomous inspection methods are briefly mentioned, otherwise nothing is stated on the on-line assessment of inspection data for mission planning and decision making.

Nevertheless, a semantic inspection approach offers several advantages. On the one hand, easy system extensibility and maintenance is achieved by the explicit separation of knowledge representation and execution control. On the other hand, the human comprehension of the system decisions is improved significantly. Moreover, the usability of the system is increased by allowing the user to communicate with the system on a semantic level.

In this paper we investigate a semantic approach for inspection planning, plan execution, assessment of the data analysis results, decision making and replanning. The main idea is to incorporate human expert knowledge via a semantic inspection model.

2 Semantic Inspection Approach

The proposed semantic inspection approach comprises a mission control architecture which is outlined in Sect. 2.1. At the core of this mission control architecture a knowledge base containing all knowledge relevant to the execution of inspection missions with autonomous service robots is located. The knowledge base is described in Sect. 2.2. The autonomous inspection process consisting of inspection planning, plan execution, assessment of the data analysis results, decision making and replanning is presented in Sect. 2.3.

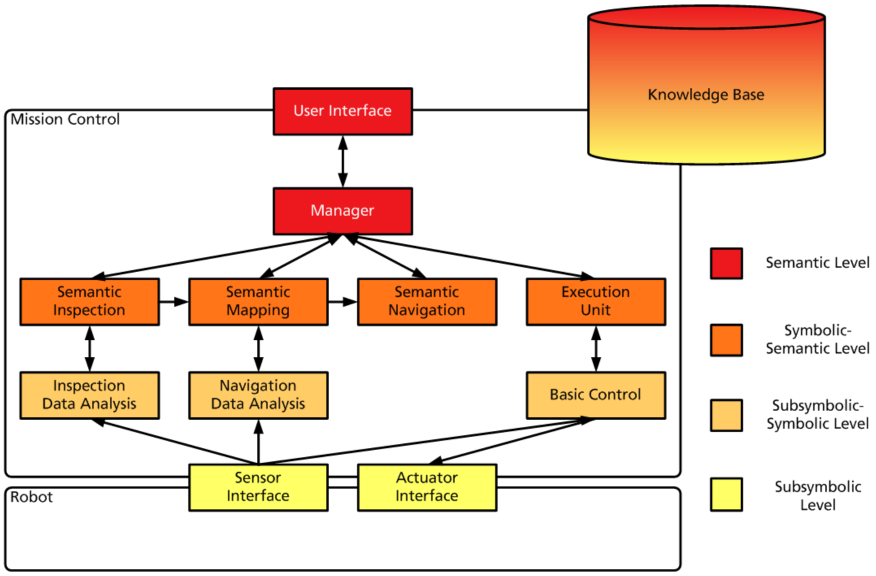

Fig. 1 The mission control architecture.

2.1 Architecture

The components of the mission control are arranged in an hierarchical architecture which consists of four distinguished levels. The four levels depend on the type of data that is processed and are depicted in Fig. 1. The mission control architecture has been implemented with *MCA2* [7] - a modular, network-transparent and real-time capable C++ framework for controlling robots. In the following, the individual components are described briefly.

Inspection Data Analysis The *Inspection Data Analysis* continuously reads data from the inspection sensors and searches for EOIs. If an EOI is detected, the corresponding region of the sensor data is segmented. For the segmented region features are computed which are used for classification. The *Inspection Data Analysis* is stateless and takes only the current measurement into account.

Navigation Data Analysis The *Navigation Data Analysis* continuously reads data from the navigation sensors. It locates and classifies regions in this sensor data and determines their parameters. Like the *Inspection Data Analysis* the *Navigation Data Analysis* is stateless and takes only the current measurement into account.

Semantic Inspection The *Semantic Inspection* receives abstract inspection goals from the *Manager*, computes appropriate plans to achieve those goals and passes them back to the *Manager*. Moreover, it performs a temporal fusion of the individual inspection data analysis results and assesses them. Depending on these results and based on the semantic inspection model, it proposes to the *Manager* whether and how a found EOI should be examined further.

Semantic Mapping The *Semantic Mapping* temporally fuses the data from the *Navigation Data Analysis* and computes respectively updates the semantic region map of the environment. Moreover, the EOIs found by the *Semantic Inspection* are registered within the semantic region map.

Semantic Navigation The *Semantic Navigation* receives abstract locomotion goals from the *Manager*, computes plans by means of the semantic region map to achieve those goals, and passes them back to the *Manager*.

Manager The *Manager* is the highest level control and decision component. It decomposes the given mission goals into inspection and navigation subgoals and passes them to the *Semantic Inspection* and the *Semantic Navigation* for planning. It fuses the resulting subplans, passes them to the *Execution Unit* and coordinates and monitors their execution.

Execution Unit The *Execution Unit* receives plans from the *Manager*. It decomposes these plans into individual actions, passes them to the *Basic Control* and monitors their execution.

Basic Control The *Basic Control* receives a single symbolic action or a set of parallel actions from the *Execution Unit* at a time. These are passed as subsymbolic commands to the sensor and actor interfaces of the robot platform and their execution is monitored.

2.2 Knowledge Base

The knowledge base consists of several ontologies which model the concepts and contexts required for the semantic inspection control in a general form (terminological box, T-Box), and concrete instances of concepts and relations which represent the current state of the world (assertional box, A-Box). The T-Box of the knowledge base is organized in three abstraction layers: a basic ontology, a core ontology and a specific domain ontology (cf. Fig. 2). The ontologies are realized with *OWL-DL*[1]. As framework for managing the ontologies and for reasoning processes regarding the ontologies *KAON2*[2] is used, which supports the SHIQ(D) subset of OWL-DL. For this paper, the description of the knowledge base concentrates on the mission and inspection subontologies of the core ontology.

Mission Subontology The core concept of the mission subontology is the plan. The structure of plans is modeled after so-called *Flexible Programs* [4]. A plan is represented as a tree of nodes. There are three types of nodes: branching nodes, action

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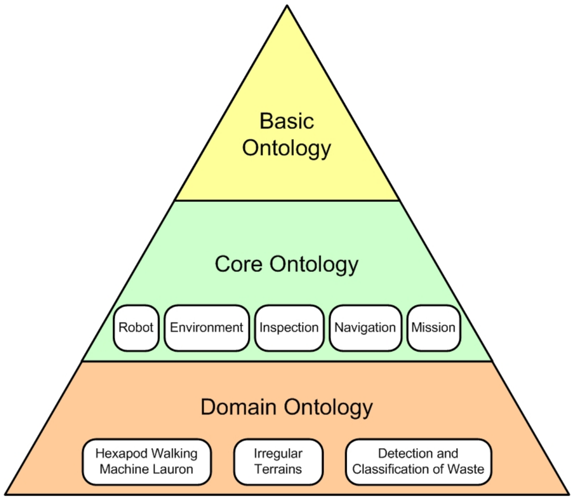
[1] OWL-DL: http://www.w3.org/TR/owl-features/

[2] KAON2: http://kaon2.semanticweb.org/

Fig. 2 The structure of the knowledge base. The basic ontology contains fundamental concepts like parameter, timestamp, condition, function, and data type. The core ontology includes robot, environment, inspection, navigation and mission subontologies modeling the central concepts and relations of the particular fields. The domain ontology contains application specific subontologies.



nodes and planning nodes. Each node contains a unique identifier Id, a precondition C_{pre}, a runtime condition C_{rt}, a postcondition C_{post}, a rating function R, and a success measure S. All inner nodes of a plan are branching nodes. They structure the plan into sequential and parallel parts. Therefore, they contain seats arranged in parallel groups. For each seat there can be several candidate nodes. The leaf nodes of a plan are either action or planning nodes. Action nodes contain elementary actions and planning nodes comprise subgoals.

Inspection Subontology The key concepts of the inspection subontology are the entity of interest (EOI) class and the inspection method.

An EOI class contains information about appropriate inspection methods for the detection and analysis of EOIs of a particular type. Moreover, it contains knowledge about characteristic features and potential locations as well as information about potential confusions with other EOI classes.

An inspection method consists of appropriate elementary actions for the detection and analysis of certain EOI classes. This comprises actions for acquiring sensor measurements, preprocessing sensor measurements, sensor data fusion, segmentation of potential EOIs, feature computation and classification. Moreover, each inspection method contains a reliability function and criteria for the assessment of the results.

2.3 Autonomous Inspection

An autonomous inspection robot should actively examine entities of interest (EOIs), e.g. defects. If the data analysis results are uncertain, additional inspection actions, e.g. activating a special sensor, approaching the EOI from a different perspective or employing a different data analysis algorithm, should be taken to increase the confidence of the results. The selection of these actions should be driven by the assessment of the individual circumstances.

Therefore, the inspection of complex environments should occur in cycles of inspection planning, plan execution, assessment of the data analysis results, decision making and replanning.

Inspection Planning We decided to choose an hierarchical approach for inspection planning: Complex inspection goals are recursively decomposed by the *Semantic Inspection* into simpler subgoals until the subgoals can be solved with elementary actions. The knowledge necessary for decomposing goals into subgoals is stored within the knowledge base in form of the available flexible program nodes. For each goal to be achieved a corresponding root node for a flexible program is selected. Based on the current situation stored in the knowledge base the inspection planner then decomposes this root node into an executable flexible program.

The knowledge about EOI classes and inspection methods is used to compute plans which gradually increase the classification confidence of an EOI. The plans can also contain planning nodes with navigation goals, which are used to change the robot position or to reposition sensors. The navigation goals are passed to the *Semantic Navigation* which decomposes them into executable flexible subprograms. The semantic navigation approach will be described in a future paper.

Plan Execution During plan execution the *Execution Unit* processes the given flexible programs by a depth-first strategy. The processing state of each node can be virtual (not yet visited), instantiated (candidates chosen) and finished (fully processed). The selection of candidate nodes takes place by checking the preconditions and evaluating the rating functions of the respective candidates. Both the precondition checks and the evaluation of the rating functions are based on the current situation stored in the A-Box of the knowledge base. Action nodes trigger elementary actions which are executed by the *Basic Control* until the postcondition is reached or the runtime condition is no longer satisfied. Planning nodes initiate replanning processes for subgoals.

Assessment of the Data Analysis Results For the assessment of the inspection data analysis results by the *Semantic Inspection* an assignment between previously found EOIs and current EOIs has to be conducted. This is based on the world coordinates of the EOIs and the EOI hypotheses. For EOIs assigned to previously found EOIs a temporal fusion of the hypotheses has to be performed. This is achieved by means of Bayesian networks and incorporates the reliabilities of the used inspection methods as well as other factors, e.g. the sensor resolution.

Decision Making In case of uncertainty regarding the data analysis results of an EOI a decision has to be made by the *Semantic Inspection* whether and how to proceed with the inspection of the EOI. Here we use a probabilistic approach in form of Bayesian decision networks. The available decision options correspond to goals stored in the knowledge base. Moreover, the different goals are prioritized according to the current inspection goals and criteria stored in the knowledge base.

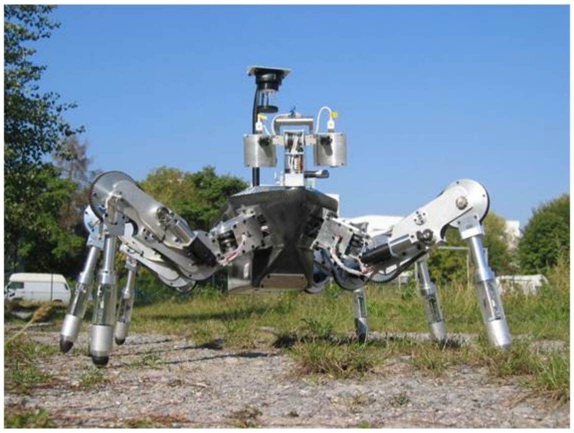


Fig. 3 The six-legged walking machine LAURON IVc is equipped with appropriate sensors for localization, navigation and perception of its environment, e.g. a stereo camera system and a 3D time-of-flight camera on a pan-tilt unit. Moreover, an extensive behavior repertoire for locomotion and navigation exists.

Replanning The new inspection goals from the decision making step are integrated into the overall plan by the *Semantic Inspection* according to their priorities and resource constraints by reinvoking the inspection planning process.

3 Preliminary Results

To be able to conduct experiments and evaluate the proposed semantic inspection approach an appropriate robotic platform and inspection scenario has to be chosen. For this purpose the hexapod walking machine LAURON IVc (cf. Fig. 3) is used. As inspection scenario the detection and classification of different kinds of waste on irregular terrains like river and channel banks, seashores, countryside areas such as dunes or forests, or areas along the highways, is chosen. The vision is to equip the front legs of the next LAURON generation with simple waste-grippers, extend the working area of the legs by an additional degree of freedom and place a garbage container on the back of the machine.

While the full realization of the mission control system for the proposed inspection scenario is still work in progress, a simulation environment has been established for early testing. The simulation environment contains a model of LAURON and is based upon the existing behavior repertoire for locomotion and navigation. It enables testing of fully implemented components together with component stubs. The component stubs are realized as question/answer methods for simulating the desired functionality, which can be used in an interactive as well as an automated way.

Several systematic experiments were conducted to validate the different components. First, the planning process and the suitability of the expert knowledge defined in the knowledge base were verified. Therefore, different inspection goals were passed to the inspection planner for decomposition. Second, the execution of the generated flexible programs in case of errors (e.g. malfunction of a sensor) was analyzed. Third, the assessment of the data analysis results and the decision making process were validated by simulating different inspection situations and data analysis results.

The results of these first functional tests were promising and showed the principal feasibility of the proposed semantic inspection approach. Nevertheless, more simulation and especially real-world experiments have to be done to detect potential improvements of the proposed approach.

4 Conclusion and Future Work

In this paper a semantic approach for inspection planning, plan execution, assessment of the data analysis results, decision making and replanning was presented. For the experimental evaluation of the proposed approach the detection and classification of waste on irregular terrains with the hexapod walking machine LAURON was chosen. First preliminary simulation results were presented.

Future work will focus on the further realization of the mission control system for the proposed inspection scenario to allow for real field tests. Moreover, an appropriate user interface for semantic interaction with the inspection control system will be developed. Finally, learning capabilities for self optimizing the resource usage, the data analysis process, the planning process and the decision making process will be investigated.

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