World Modeling for Autonomous Systems

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Abstract This contribution proposes a universal, intelligent information storage and management system for autonomous systems, e.g., robots. The proposed system uses a three pillar information architecture consisting of three distinct components: prior knowledge, environment model, and real world. In the center of the architecture, the environment model is situated, which constitutes the fusion target for prior knowledge and sensory information from the real world. The environment model is object oriented and comprehensively models the relevant world of the autonomous system, acting as an information hub for sensors (information sources) and cognitive processes (information sinks). It features mechanisms for information exchange with the other two components. A main characteristic of the system is that it models uncertainties by probabilities, which are handled by a Bayesian framework including instantiation, deletion and update procedures. The information can be accessed on different abstraction levels, as required. For ensuring validity, consistence, relevance and actuality, information check and handling mechanisms are provided.

1 Introduction

Efficient operational autonomous systems require a comprehensive overview on their environment. The present contribution proposes a universal, intelligent system for information storage and management, which is applicable to a wide variety of types of autonomous systems. The primary application of the system is a humanoid robot, designed to help with domestic applications.

The proposed system uses a three pillar information architecture and aims at modeling the environment of an autonomous system. The three pillars represent the main components of the architecture: prior knowledge, environment model, and real world. The first two components can be compared to the long and short term memory of the human brain.

Being the central component of the autonomous system, the environment model acts as an information hub, which stores sensory information and prior knowledge, and delivers it to cognitive processes. The information is represented in the environment model as instances of classes with class specific attributes and
relations. Instances in the environment model correspond to entities in the real world, their classes map object types of the real world. Classes equate concepts in prior knowledge, their realization are instances.

Besides the pillar architecture, the proposed system is characterized by the following features: object oriented representation of information, use of probability distributions in a Degree-of-Belief (DoB) interpretation, information management and fusion based on a Bayesian framework, and information access on different abstraction levels.

Commonly used approaches for the modeling of information comprise semantic nets, predicate logic or formal languages, see e.g. [1]. Recently presented methods involve ontologies, object oriented and probabilistic approaches [2,3]. Current research combines object oriented with probabilistic approaches [4,5,6,7]. The combination of object oriented approaches and ontologies is also being discussed in literature [8]. Probabilistic ontologies are proposed in [9].

The proposed approaches in literature for modeling the environment of autonomous systems are mostly domain specific and not transferable to other applications [4]. [10] proposes an object oriented world modeling approach with the purpose of creating virtual environments for simulation or engineering and for automation of specific tasks, e.g., financial transactions. Some of the main characteristics of the approach are the separation between real world and system objects and the development of the model using class diagrams. [6] proposes a dynamic approach for cooperative intelligent vehicles, which models the relevant environment for neighboring vehicles. Main characteristics are the incorporation of uncertainties for attributes, the modeling of conceptual objects, the inheritance in the object hierarchy, and the development of check and simple inference mechanisms. In robotics, the approaches proposed are generally simple and task specific. They require large amounts of prior information, e.g., the main task of the robot or his context.

This contribution focusses on describing the structure of the proposed system with accent on information management. The main characteristics and their advantages are presented in Sec. 2. Section 3 discusses the information exchange mechanisms and the construction of the environment model. Inference realizations are not part of the proposed architecture and are thus not within the scope of this contribution.

2 Three Pillar Information Architecture

The three pillar information architecture is mainly characterized through the separation and interaction between prior knowledge, environment model, and real world, see Fig. 1.

In the center of the architecture, the object oriented environment model is situated (middle pillar in Fig. 1). It represents the information the autonomous system has about the entities (objects and persons) in its current relevant environment. In the human memory, its correspondent is the short term memory. The information is represented here in form of instances with attributes and
Prior knowledge
instances of concepts

Environment model
instances of classes

World
entities of object types

Figure 1. Three pillar information architecture.

relations. The main function of the environment model is to act as information hub, i.e., all relevant information is stored and made available to cognitive processes, e.g., path planning or inference. For modeling the environment model, dynamic progressive mapping of instances and their attributes is employed. The relations are represented by means of multiple semantic networks [11,12].

A second pillar (left in Fig. 1) of the architecture is established by prior knowledge. It is equivalent to the long term memory of the human brain and contains prior information of two types:

- concepts expressed by ontologies (structural information about classes with attributes, relations, and rules);
- instance related knowledge (e.g., on instances of persons or objects, maps of the environment).

This information is available to the system directly after the instantiation of the environment model. Moreover, the information can be organized in context specific modules, which can be loaded or unloaded on-the-fly, as required. Thus, the environment model is kept lean.

The third information pillar (right in Fig. 1) represents sensory information which is acquired by the autonomous system when operating. The acquired information regards entities, their attributes, and relations. The entities correspond to instances in the other two components and are pooled in object types, which correspond to classes (in the environment model) and concepts (in the prior knowledge).
3 Information Management

In the following, attributes and relations of instances and entities are the considered pieces of information. Each information is characterized by its uncertainty in form of a Degree-of-Belief (DoB) distribution. Details on how uncertainties can be expressed and on the advantages of DoBs are given in [5,7,12,13,14].

Representation of Information in the Environment Model Attributes can be descriptive or non-descriptive. A typical example of a non-descriptive attribute is the existence expressed in the probability that the entity modeled by the instance exists in the real world. Examples for descriptive attributes are type, position, or color. The attribute type is in this case also represented by a DoB distribution; it is therefore not deterministic. The advantage of this modeling is that an instance can be created without knowledge on which class it belongs to. The challenge, however, is the mapping of classes to concepts in prior knowledge.

Representation of Information in Prior Knowledge A part of prior knowledge is the instance related knowledge consisting of instances with attributes and relations that are „important“ to the autonomous system, e.g., persons that often appear in the real world or maps of certain environments. This information is detailed in general, i.e., many attributes are specified, and may be acquired through external sensors or learned by the autonomous system itself.

Another part is the ontology knowledge containing concepts with attributes, relations, and rules modeling contexts. The attributes and relations are represented by DoB distributions over the domains, e.g., according to the observed frequency of possible values in the real world. Thus the DoB distributions of attributes and relations of concepts describe all entities that may appear in the real world, whereas the attributes and relations of instances in the environment model characterize one particular observed entity.

For example, the DoB distribution for the attribute color of the concept of a cup may be defined as a uniform distribution over all colors, following the assumption that cups may be of any color. In the environment model, the DoB distribution would have a maximum at a certain color according to the entity observed in the world.

Building-up of the Environment Model The base element is an instance of the concept of the blanc object, which only needs to have one attribute: the existence. Other attributes are allowed, but not mandatory on instantiation. Starting with blanc objects, the environment model is completed combining top-down and bottom-up strategies, see Fig. 1.

The top-down strategy means that the environment model is complemented by mapping new acquired information to attributes of existing instances or by creating new instances [5,7]. In Fig. 1, this strategy is outlined by the arrow “information acquisition”. The bottom-up strategy implies using prior knowledge for the environment model; this is indicated in Fig. 1 by the arrow “providing prior knowledge”. Here,
the type of an instance is determined and/or its attributes are supplemented. Additionally, according to the context of the autonomous system, instance related knowledge may be used to create new instances. For example, in a kitchen scenario, kitchen appliances may be instantiated.

For handling information in the environment model, certain mechanisms are required:

- **Creation of new instances** according to sensory information is performed by means of Bayesian fusion, considering the probability for the existence of the entity. If the posterior probability is higher than an initialization threshold, a new instance is inserted in the environment model. In the case of attributes and relations, a similar calculus is employed [5,7].

- **Information update** with new sensory information or with information from prior knowledge is also accomplished by means of Bayesian fusion using the common prediction-update scheme:
  - The prediction step is equivalent to propagating the information in the environment model from one time step to the other, modeling that the knowledge about the real world becomes more uncertain. In consequence, the entropy of the DoB distributions increases [15].
  - The update step consists in the fusion of the information in the environment model (interpreted as prior) with the new information (interpreted as likelihood function). If more pieces of information regarding the same attribute or relation are available, a recursive Bayesian fusion is used. If no new information is provided from one time step to the other, a function proportional to the Maximum Entropy distribution is used as dummy likelihood function. This is equivalent to assuming the result of the prediction step [5,7].

- **Deletion of instances** If the DoB of the existence attribute of an instance drops under the deletion threshold, the instance is deleted from the environment model. In the case of attributes and relations, the deletion is equivalent to setting the DoB distributions to Maximum Entropy distributions over the respective domain.

*Information Exchange between the Three Pillars* Information flows to and from the environment model. First, instance related and ontology knowledge are transferred from prior knowledge into the environment model, as part of the bottom-up strategy. This flow is indicated in Fig. 1 by the arrow “providing prior knowledge”. The main problem here is the classification, i.e., how to determine the value of the attribute type based on known attributes and their DoB distributions. In other words, the challenge is assigning instances in the environment model to concepts of prior knowledge. Moreover, the information in ontologies (especially the rules) can be used for consistency, validity, and relevance checks.

In the opposite direction, the flux of information represents learning of new concepts, attributes, relations, rules, and instance related knowledge. The main difficulty here is inserting new concepts in the ontology at the right place.

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1 Due to the probabilistic approach, the classification is equivalent to lowering the uncertainty regarding the attribute type.
Second, sensory information is inserted in the environment model. This information flow is outlined in Fig. 1 through the arrow “information acquisition”. The main problem here is the data association between the observed entity and an instance in the environment model.

The information flux in the opposite direction consists in information requests for filling in the gaps, i.e., exploring unknown attributes and relations. The information request is a result of inference processes. For example in the kitchen context, the autonomous system may ask questions regarding the positions of certain appliances known to be existent.

**Abstraction Levels** Depending on the task, information with different degree of detail is needed. Accordingly, the information in the environment model can be accessed on different abstraction levels. For example considering a path planning task, only information regarding existence, position, and dimensions of entities is necessary, i.e., information with a low level of detail and a high level of abstraction. On the contrary, for a grasping task, detailed information regarding form, grasp possibilities, and footprint is required, see Fig. 2.

**Check Mechanisms** Check mechanisms are necessary for ensuring constant quality of the environment model:

- The most basic check mechanisms regard the validity of the information. They assure that the information incorporated in the environment model fulfills formal correctness restrictions, e.g., DoB distributions are valid.
- **Consistency** checks ensure that basic physical rules are satisfied, e.g., cups cannot fly.
- **Relevance** checks assure that the information is relevant in the present context, e.g., cups are irrelevant when washing the car.
- **Actuality** checks ensure that the information is always up to date, e.g., by triggering exploration requests for transient entities.
4 Realization

The three pillar information architecture has been developed within the DFG project SFB 588 “Humanoid Robots—Learning and Cooperating Multimodal Robots” [16]. Its purpose is to design humanoid robots assisting in household applications. To solve this task, the humanoid robot needs a comprehensive state of knowledge on its environment. To this end, the described information architecture has been employed. Figure 3 shows the humanoid robot in a kitchen scenario. Development and implementation details are given in [11,12].

5 Conclusions

The present contribution proposes a universal, intelligent information storage and management architecture for autonomous systems. The separation into three components (prior knowledge, environment model, real world) permits an efficient information handling. The central component (the environment model) contains a comprehensive overview on the part of the world which is relevant for the autonomous system. Other components are sensory information and prior knowledge. Thus, the environment model acts as an information hub for all other components of the autonomous system. The environment model can be compared with a Lego landscape, where the Lego bricks compose virtual substitutes (instances) of real objects and persons (entities). The main advantage of the proposed architecture refers to the probabilistic approach, which enables a consistent information management based on the Bayesian framework. This includes standard mechanisms for instantiation, deletion, and update. In addition, information exchange mechanisms between the components of the architecture, along with quality check mechanisms, are provided. An additional powerful feature is the abstraction pyramid, giving the possibility of retrieving information in the desired degree of detail. Together with other cognitive processes, the three pillar information architecture provides autonomous systems with situation awareness.
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