NOVELTY DETECTION FOR SEMANTIC PLACE CATEGORIZATION

André Susano Pinto†

Supervised by: Andrzej Pronobis‡, Luis Paulo Reis†

†Faculdade de Engenharia da Universidade do Porto, Portugal

‡Royal Institute of Technology (KTH), Stockholm, Sweden

1. Motivation

For a long time humanity has dreamed that one day robots will be among us. They will explore our world and interact with us, understand our concepts and reason. An important step in that direction is endowing robots with knowledge about human concepts and semantics. However, it is unrealistic to believe that the human world can be fully modeled in the robot's brain at the design stage. Therefore, robots must be able to adapt and learn when confronted with novel situations. Detection of novel situations, where the knowledge of the robot is not sufficient plays an important role in adaptation and learning of new concepts and is the main topic of this thesis.

In the context of mobile robotics, spatial concepts and semantics are crucial to enable the robot to perform complex human-like tasks and human interactions. For handling those, a robot builds a representation of space extended with semantic properties, process which is known as semantic mapping. This representation identifies spatial entities and classifies them according to their meaning to humans allowing the robot to reason at a high abstraction level. For example, humans categorize spaces as kitchens, bedrooms, corridors, offices, theaters, computer labs, etc. based on spatial properties, objects and actions that are characteristic of those spaces. Similarly, if a robot had a knowledge about those spatial concepts, it could answer such questions as: "Where are cornflakes?"

2. Problem and Goals

The semantic mapping process plays an important role for allowing artificial mobile agents to reason at a high level and is dependent on the knowledge that the agent has about the spatial concepts and semantic categories. For that reason there is high interest in creating methods that are capable of detecting gaps in the agent's knowledge. For that purpose, this thesis, studies novelty detection techniques and how they can be applied to detection novel room categories during the semantic mapping process. To this end, the semantic mapping process proposed in [1] is studied and a method to detect novel categories using graphical models is suggested.

3. Semantic Mapping

Semantic mapping is the process by which an agent builds a representation of the environment and augments the identified spatial entities with semantic values (i.e. human semantics). In this thesis the semantic mapping process proposed in [1] is used as base.

3.1. Spatial Knowledge Representation

In order to perform semantic mapping an agent needs to possess knowledge on how to segment and identify entities existent in space by analysing the sensed data. For that, Pronobis [2] presents a spatial knowledge representation consisting of four layers: the *sensory layer* maintains an accurate and exact description of the environment in a machine-friendly representation, the *place layer* represents the world in terms of a set of discrete places and connectivity between them, the *categorical layer* defines knowledge about properties and categories that allow to extract higher-level information from the sensed data, and the *conceptual layer* maintains knowledge about spatial entities and concepts as well as the relations between them.

3.2. Conceptual Map

The semantic mapping is based on the instantiation of a conceptual map that uses the ontology defined in the conceptual layer in order to build a probabilistic graphical model that relates and propagates probabilities across all the entities and properties detected by the other layers.

By using probabilistic graphical models, the conceptual map becomes a generative model that permits inference about different variables. This enables the use of the conceptual map as a tool for detection of unknown categories.

4. Novelty Detection

Novelty detection, also known as outlier or anomaly detection, is a classification problem related to identification of new or unknown data patterns that the system is not aware of [3]. The ability to identify novel cases is crucial in any autonomous system that is deployed in unknown or uncontrolled environments, as it permits detection of cases that do not conform to the robot's knowledge and therefore should be treated with caution.

4.1. Novelty Detection as Thresholding

Due to the nature of the sensed data which are noisy and uncertain, novelty ought to be treated in a probabilistic way where each sample has certain probability of being generated by a class not known to the agent and a complementary probability $P(\overline{novel}|x)$ of being generated by a known class.

Additionally, any detector can be uniquely described by the set N of samples that it classifies as novel. With that, it is possible to show that by including a new sample a into N, an agent can increase its detection rate at a cost of producing more misclassifications. This describes the base of the *error and rejection tradeoff* described in [4]. Due to the goal of having the highest detection rate with a given minimum error rate, any optimal detector can be described as a *continuous knapsack problem* of the sample space. The resulting greedy ordering can be shown to be equivalent to:

$$P(\overline{novel}|x) = \frac{P(x|\overline{novel})P(\overline{novel})}{P(x)} \quad (1)$$

4.2. Assumption about Constant $P(novel)$

By considering $P(novel)$ to be constant, a ratio between conditional and unconditional probabilities of the sensed variables is obtained. Although it sounds reasonable to assume that the probability of a specific room belonging to a novel category is constant, this thesis points out that this assumption might be very strong and not reasonable in realistic scenarios. The main problem is related to the fact that the graph structure changes as the robot gathers new samples and some structures might be more prone to produce novel samples. This is different from the normal classification scenarios where its clear that the category is indeed the only generator of features.

4.3. Modeling Conditional Probability

Since the graphical model produced by the conceptual map tries to model the distribution of variables assuming that the knowledge of the agent is representative of the world, it models $P(x|\overline{novel})$.

4.4. Modeling Unconditional Probability

With no knowledge about the real distribution of samples, the correct approach is to model it with a uniform distribution. Nonetheless in the presented case, it was assumed that only the room category of a specific room is unknown and that the remaining knowledge holds true. In that case, the correct approach is to replace the variable that represents the room where the novelty is detected with a single factor connecting all variables directly dependent on it.

Due to its high-dimensionality, approximating that factor with unlabelled data is infeasible and approximations have to be done. In this thesis two approximations were presented: a uniform model and an independent model. In the independent model, the single-connected factors are trained from unlabelled data and its expected that they create a better approximation to the unconditional probability than an assumption about the uniform model.

5. Results

A synthetic dataset modelling the features expected when deployed in a real scenario and enforcing a constant $P(novel)$ was used for testing the developed models. The two suggested models where compared to each other and to an optimal case. The tests across several situations show how the behaviour changes as more information is sensed from the environment.

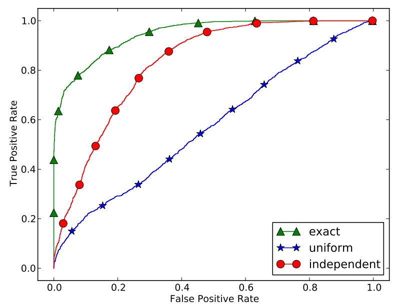

Fig. 1 – Comparison of the proposed models using samples from a synthetic dataset with variable number of sensed features.

6. Conclusions

This thesis studied the problem of detection of novel semantic categories of rooms in the context of semantic mapping with mobile robots. To that purpose, a semantic mapping process [2] was studied and a novelty detection scheme based on a conceptual map was proposed. Initial tests where performed on synthetic data showing benefit of using unlabelled data to increase the detection performance. Additionally, all the assumptions behind novelty detection were presented and several directions on how to create a generalized framework for novelty detection were discussed.

References

[1] Andrzej Pronobis. *Semantic Mapping with Mobile Robots*. PhD thesis, Royal Institute of Technology (KTH), Stockholm, Sweden, June 2011.

[2] Andrzej Pronobis and Patric Jensfelt. Understanding the real world: Combining objects, appearance, geometry and topology for semantic mapping. Technical Report TRITA-CSC-CV 2011:1 CVAP319, Kungliga Tekniska Högskolan, CVAP/CAS, May 2011.

[3] M. Markou and S. Singh. Novelty detection: a review–part 1: statistical approaches. *Signal Processing*, 83(12):2481–2497, 2003.

[4] C. Chow. On optimum recognition error and reject tradeoff. *Information Theory, IEEE Transactions on*, 16(1):41–46, 1970.