FROctomap: An Efficient Spatio-Temporal Environment Representation

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We present a novel software tool intended for mobile robot mapping in long-term scenarios. The method allows for efficient volumetric representation of dynamic three-dimensional environments over long periods of time. It's based on combination of a well-established 3D mapping framework called Octomaps [1] and an idea to model environment dynamics by its frequency spectrum [2]. The proposed method allows not only for efficient representation, but also reliable prediction of the future states of dynamic three-dimensional environments. Our spatio-temporal mapping framework is available as an open-source C++ library and a Robot Operating System (ROS) module [3] which allows its easy integration in robotic projects.

In order to act intelligently, an agent has to be able to reason about its surroundings and thus needs to model its environment. In mobile robotics, suitable world representation is an essential component that allows an intelligent robot to make decisions, plan future actions, estimate its location and cooperate with others. So far, the environment models used in mobile robotics have been tailored to represent static scenes and treat environment dynamics as unwanted noise. Thus, the research was aimed at efficient acquisition, representation and usage of static environment models.

One of the most popular environment representations is an occupancy grid [4], which allows for efficient probabilistic sensor fusion, motion planning, localization and exploration. The main drawback of occupancy grids is their low-memory efficiency because they represent large, empty areas of the environment by a large amount of empty cells. This is mitigated by the so-called Octomap [1] framework, that locally adapts the grid resolution to the level of detail required. The authors of the Octomap framework demonstrate that their method allows to represent large-scale environments with a fine level of detail on standard computational hardware.

In order to efficiently act in changing environments, the robots need to model the environment dynamics as well. Since it is infeasible to store all the observations a robot makes over long periods of time, one has to represent the temporal domain in an efficient way. The authors of [5, 2] propose to use an occupancy grid and model the dynamics of individual cells independently. While [5] represents the occupancy of each cell with a hidden Markov model, [2] assumes that the variations observed are caused by hidden processes that are naturally periodic and identifies these processes by means of a Fast Fourier Transform.

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The authors of [2] show that their method (called FREMen) achieves compression of the model's temporal domain by rates up to 10^6 while predicting the environment states with 90% accuracy.

We represent the occupancy of the cells stored in the Octomap by the spectral model proposed in FREMen. Thus, the efficiency of the Octomap to model large spatial scales and the efficiency of FREMen to represent long periods of the time are combined in an efficient spatio-temporal environment model.

We consider the occupancy of each cell (voxel) stored in an Octomap as a binary function of time, i.e. the occupancy of i^{th} cell is represented as $s_i(t)$. The approach in [2] considers the $s_i(t)$ as being influenced by a set of naturally periodic processes and proposes to represent $s_i(t)$ by a probabilistic function of time that is a combination of harmonic functions which reflect the most prominent periodic processes that constitute the environment dynamics. Technically speaking, FREMen represents each function $s_i(t)$ by a set of the n highest values of its frequency spectrum $S_i(\omega)$ obtained by Fast Fourier transform and a Δ-encoded set $\mathcal{O}$ that represents time intervals where the Inverse Fourier Transform of $S_i(\omega)$ does not equal the original function $s_i(t)$, i.e.

$$s_i(t) = (\mathcal{IFT}(\mathcal{S}(\omega)) > 0.5) \oplus (t \notin \mathcal{O}), \tag{1}$$

where $\oplus$ is a XOR operation. The FREMen model of each Octomap voxel is build iteratively; each time a state $s_i(t)$ is measured, Eq. (1) is calculated and if the observed occupancy does not equal (1), the time t is added to the outlier set $\mathcal{O}$. Whenever the set $\mathcal{O}$ grows too large, the spectrum S_i can be recalculated, which results in reduction of $\mathcal{O}$. Since Eq. (1) can be calculated for any value of t, (1) can be used to predict the state $s_i(t)$ as well.

Thus, our system takes a series of Octomaps observed over time and builds a temporal model of each observed voxel. After that, the system allows to calculate the state of the individual voxels and recover the Octomap for any given time.

We have applied the proposed approach to data collected in an office environment for a period of one week. The dataset consisted of 120960 Octomaps each representing 213192 spatial cells. The proposed system stored the spatio-temporal model in a 2MB file achieving a compression rate of 1:10000. Comparing the model's predictions to day-long measurements performed two weeks later showed that the model predicted the environment states with 98% accuracy.

References

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