ERCIM "ALAIN BENSOUSSAN" FELLOWSHIP PROGRAMME

ERCIM
European Research Consortium for Informatics and Mathematics

Scientific Report

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Period of the fellowship	01/10/2019 to 30/09/2020

I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

The research activity during the ERCIM fellowship focussed on the investigation of methods to sample spatial fields such as temperature, chlorophyll etc in the marine environments using robotic vehicles in an adaptive manner. The problem is known as the adaptive sampling problem in the literature. Specifically, the problem of sampling a hot-spot region in the spatial field was considered. A hot-spot is defined as a region in the survey area, where the value of the variable of interest (example, temperature) exceeds a predefined threshold. Such problems find significance in monitoring areas where the biological or environmental activity differs from the usual expected behavior and can be used to monitor toxic algal blooms as an example.

The problem of adaptive sampling consists of two main problems, namely i) development of machine learning methods to build a data-driven model of the ocean processes, and ii) exploitation of the data-driven models to plan informative robotic paths. The robotic paths need to be planned such that the relevant data, high in quality (in terms of

information conveyed) are chosen in order to further improve the accuracy of the data-driven ocean models. To this end, following are the details of the study undertaken.

Data-driven model of the ocean processes:

Gaussian Processes (GP) [1] have emerged as an attractive solution to obtain data-driven ocean models owing to their simplicity and their ability to characterize uncertainty associated with the models. Therefore, GP was used as a proxy model for the spatial field in the ocean environment. The GP needs to be trained a priori with observed data. In the context of robotic sampling, this requires robotic vehicles to collect measurements in the marine environment. A naive sampling strategy would be to discretize the sampling area into grids and sample each grid cell sequentially. Such a strategy while effective, results in operational costs that make such an approach impractical. Therefore, sampling locations needs to be chosen in an intelligent manner leading to an adaptive robotic sampling system.

Informative Path Planning:

The robotic path planner within the adaptive sampling system utilizes an information theoretic criterion that is optimized to make sampling decisions. The most common objective of informative path planners in the literature is to explore the environment. To this end, cost functions such as entropy, mutual information, posterior variance or combination of these metrics are used [2,3,4]. These metrics are however not suited for the task of monitoring and mapping the hot-spots in the spatial field, wherein the boundary regions that constitute the hot-spot form the potential sampling candidate locations. To this end, a new uncertainty metric based on the concepts of excursion sets and probabilities, used in the field of optimal experiment design [5] is studied for the adaptive sampling problem. The first result to use the excursion set based uncertainty metric for the adaptive sampling problem was presented in [6] wherein greedy approaches to optimize the uncertainty metric was used. It was shown that the computational costs become prohibitive for non-myopic, look-ahead strategies beyond two horizon steps. This motivates the development of non-myopic, lookahead strategies that optimizes the excursion set based uncertainty measure for the sampling of hot-spot regions in the spatial field.

Rapidly Exploring Random Trees (RRT) [7] and its optimal variants namely the RRT* [8] have emerged as a very useful tool for robotic path planning owing to their ability to rapidly expand a tree in the search area while optimizing a given cost function. Further, these algorithms enable inclusion of collision avoidance constraints within the tree building process. Consequently, they have also been used for Informative Path Planning [9,10]. However, all the RRT based methods in the literature use entropy and mutual information metric to explore the environment. In the research conducted during the

ERCIM fellowship, an online RRT based algorithm was developed that utilizes the excursion set based uncertainty metric to plan look-ahead paths in the environment. The use of RRT based methods in conjunction with excursion set based measure lead to sampling of boundary regions, thereby resulting in an interesting approach towards the sampling of hot-spot regions. Extensive simulation studies were conducted to assess the performance of the proposed adaptive sampling method. Two datasets, namely i) a synthetic gaussian scalar field, and ii) temperature data from the SINMOD ocean model were used to illustrate the performance of the proposed method. In addition, the performance comparisons were made against a benchmark method that uses the greedy informative path planning algorithm.

Note: The research work was conducted in collaboration with the Department of Mathematical Sciences at the Norwegian University of Science and Technology.

References

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2. Krause, Andreas, Ajit Singh, and Carlos Guestrin. "Near-optimal sensor placements in Gaussian processes: Theory, efficient algorithms and empirical studies." *Journal of Machine Learning Research* 9.Feb (2008): 235-284.
3. Low, Kian Hsiang, John M. Dolan, and Pradeep Khosla. "Information-theoretic approach to efficient adaptive path planning for mobile robotic environmental sensing." *arXiv preprint arXiv:1305.6129* (2013).
4. Kemna, Stephanie. *Multi-robot strategies for adaptive sampling with autonomous underwater vehicles*. PhD Thesis, University of Southern California, 2018.
5. Chevalier, Clément, et al. "Fast parallel kriging-based stepwise uncertainty reduction with application to the identification of an excursion set." *Technometrics* 56.4 (2014): 455-465.
6. Fossum, Trygve Olav, et al. "Learning excursion sets of vector-valued Gaussian random fields for autonomous ocean sampling." *arXiv preprint arXiv:2007.03722* (2020).
7. LaValle, Steven M. "Rapidly-exploring random trees: A new tool for path planning." (1998).
8. Karaman, Sertac, and Emilio Frazzoli. "Sampling-based algorithms for optimal motion planning." *The international journal of robotics research* 30.7 (2011): 846-894.
9. Schmid, Lukas, et al. "An Efficient Sampling-based Method for Online Informative Path Planning in Unknown Environments." *IEEE Robotics and Automation Letters* 5.2 (2020): 1500-1507.
10. Hollinger, Geoffrey A., and Gaurav S. Sukhatme. "Sampling-based Motion Planning for Robotic Information Gathering." *Robotics: Science and Systems*. Vol. 3. No. 5. 2013.

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

The research conducted during the fellowship led to the following publication:

Title: An Online RRT based method for Adaptive Robotic Sampling of Hot-spots in Spatial Field
Authors: R. Praveen Jain, Jo Eidsvik and Tor Arne Johansen.
Status: Under Preparation
Target Journal/Conference: IEEE Robotics and Automation Letters with International Conference on Robotics and Automation (ICRA) or International Conference on Intelligent Robots and Systems (IROS) option.
Abstract: This paper presents the problem of sampling a hot-spot area in a spatial field in an adaptive manner using a robotic vehicle. The boundary region that separates the hot-spot from the rest of the survey area forms the region of interest that needs to be sampled. To this end, an uncertainty measure based on the concepts of the excursion sets and probabilities are employed that leads to the sampling of boundary regions that constitutes the hot-spot. An online, non-myopic robot path planning method based on the Rapidly Exploring Random Tree (RRT) algorithm is developed that utilizes the aforementioned uncertainty measure. The performance of the proposed adaptive sampling method is illustrated using two datasets, namely i) a synthetic gaussian scalar field, and ii) temperature data from the SINMOD ocean model. In addition, the performance of the proposed method is compared with a benchmark method that uses the greedy informative path planning algorithm.

III – ATTENDED SEMINARS, WORKSHOPS, CONFERENCES

Attended an internal conference “AMOS Day”, organized by Center for Autonomous Marine Operations and Systems (AMOS), Norwegian University of Science and Technology on 29 October 2019, Trondheim.

IV – RESEARCH EXCHANGE PROGRAMME (REP)

Due to the situation with COVID-19, a REP could not be conducted.