

Sequential Deep Learning for Mars Autonomous Navigation

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Index Terms—Path planning and navigation, Multirobot systems, Sensor and information fusion, Uncertainty reduction, Machine vision

Abstract—Recent advances in computer vision for space exploration have handled prediction uncertainties well by approximating multimodal output distribution rather than averaging the distribution. While those advanced multimodal deep learning models could enhance the scientific and engineering value of autonomous systems by making the optimal decisions in uncertain environments, sequential learning of those approximated information has depended on unimodal or bimodal probability distribution. In a sequence of information learning and transfer decisions, the traditional reinforcement learning cannot accommodate the noise in the data that could be useful for gaining information from other locations, thus cannot handle multimodal and multivariate gains in their transition function. Still, there is a lack of interest in learning and transferring multimodal space information effectively to maximally remove the uncertainty. In this study, a new information theory overcomes the traditional entropy approach by actively sensing and learning information in a sequence. Particularly, the autonomous navigation of a team of heterogeneous unmanned ground and aerial vehicle systems in Mars outperforms benchmarks through indirect learning.

Formulating a cost function with an appropriate valuation of information is necessary when knowledge of the information in one time and/or space gives conditional attributes of information in another time and/or space. This model, Sequential Multimodal Multivariate Learning (SMML) outputs informed decisions, conditioned on the cost of exploration and benefit of uncertainty removal. For instance, given an observable input, SMML is trained to infer posterior from samples taken from the same multimodal and multivariate distribution, approximate gains, and make optimal decisions. The utility is the usual metric to be optimized based on the difference between prior and posterior tasks, and it tells us how well the model is improving the data distribution after observation. Recall that, in general, it does not suffice to learn from average values like in the standard reinforcement learning problem to solve this kind of task, for this reason, SMML extends the capabilities of deep learning models for reinforcement learning whose reward for each action is restricted to unimodal or univariate

distributions. In highly uncertain conditions, this reduction of entropy is vital to any optimization platform employed in the robust, efficient, autonomous exploration of the search space. To overcome Shannon’s limitation in multimodal learning, we consider both standard deviation and entropy. We target cells with the highest importance of information distinguishing two cells with identical entropy, but different values of information.

Predictive routing is effective in knowledge transfer, however, ignore information gained from probability distributions with more than one peak. Consider a network with a grid laid on top, where each cell represents a small geographical region. To find an optimal route from an origin cell to a destination, forecasting the condition of intermediate cells is critical. Routing literature did not use a location’s observed data to forecast conditions at distant non-contiguous locations’ unobserved data. We aggregate the data from all the grid cells and cluster cells that have similar combinations of probability distributions. When one cell of a cluster is explored, the information gained from the explored cell can partially remove uncertainty about the conditions in distant non-contiguous unexplored cells of the same cluster. With this new framework, we explore the best options to travel with partial, sequential, and mixture of information gain.

We use observations obtained en route to infer the most likely conditions in unobserved locations. While distant unobserved locations may not share any inherent correlation with locally observed locations, classification errors by the image classifier may be correlated with certain image features found in different locations on the Martian surface. By clustering pixels with similar classifications, we gather evidence en-route that either supports or fails to support the hypothesis that the image classifier is making correct classification of the different terrain types. The two-step process (clustering - posterior) updates the state estimation of un-observed locations when navigating Jezero region of Mars environments in which prior belief is provided but contains high uncertainty. During 55 out of 100 runs in the Monte Carlo simulation the optimal expected travel time path based on the prior SPOC map resulted in the rover becoming stuck due to misclassification. Real-world misclassifications are expected to be lower compared with the ground truth map used in this research. Without considering runs in which the rover would have been stuck using the prior map, the median travel time was improved by 1 hour using the posterior. Travel time in the worst case outlier performance is improved by 2.32 hours and 75% quantile performance is improved by 1.61 hours. Over a mission spanning many months, this saving adds significant additional time for scientific experiments.

Part of the research work was carried out at the NASA Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA) [80NM0018D0004]. Funding for this research was provided by NSF RI [1910397] and NASA JPL [RSA 1625294, 1646362, 1659540]. The authors thank JPL Education Office for providing internships and faculty visiting opportunities to conduct this research