AI and Data-Driven In-situ Sensing for Space Digital Twin

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Abstract—The formation and evolution of giant planets define the dominant characteristics of our planetary system. The giant-planet exploration can improve the understanding of heat flow, radiation balance, chemistry and can work as ground truth for exoplanets. Atmospheres of giant planets are larger and, in many respects, but simpler than that of Earth. Studying giant planets' atmospheres and environments can serve as laboratories for the Earth atmosphere's fundamental physical and dynamical processes. On the other hand, exploring the relevant environments that affect the Earth's atmosphere can help us develop a sound technical and scientific basis in giant planets. Particularly, climate change on Earth is central to the question of understanding the roles of physics, geology, and dynamics in driving atmospheres and climates on Jupiter.

While Juno Mission has significantly enhanced our understanding of the Jovian atmosphere in every orbit through remote sensing, in-situ observations are essential for validating the models, studying the composition, and capturing the dynamic processes of gas giants. The singular in-situ observation made by the Galileo Probe in 1995 has a major disagreement with standard Jovian atmospheric models, making scientists believe the entry site may happen to be one of the least cloudy areas on Jupiter. This suspicion exhibits a strong limitation of free-fall probing. A logical next step, then, would be a mission with actively controllable probes that stay in the atmosphere of a gas giant for an extended duration. The 2016 NIAC Phase I study on "WindBots" by Stoica et al. found that an adaptive wing glider and a lightweight, quasi-buoyant vehicle would be a viable option by obtaining a lift from updrafts, however, autonomously navigating in the highly uncertain and turbulent flow field remains a major challenge.

The closest terrestrial analog to Jupiter's atmosphere would be the tropical cyclones (TCs) on the Earth. Although the formation mechanism of a TC is very different from GRS on Jupiter, the resulting phenomenon, represented by highly turbulent and strong wind field as well as its localized and dynamic nature, are similar, hence providing a suitable test ground for future missions to Jupiter's atmosphere. This paper develops an autonomous small unmanned aircraft system (sUAS) in-situ TC sensing, through the simulated environment of cooperative control of distributed autonomous multiagent systems deployed into the eye of TC. The main objective is to test various observing systems from single and multiple sUAS platforms close to the eyewall of the storm to capture essential measurements to be used in explaining the Jovian environment. Preliminary results demonstrated successful sUAS flight optimization for maximizing improvement of the quality of key measurements (e.g., 3-dimensional wind velocity, pressure, temperature, and humidity). Simulated sUAS flight toward the inner core of the TC boundary layer made high-resolution meteorological observations and supplemented existing partial knowledge for a better estimate of the TC intensity. This was a great addition to the task of testing sUAS technology, but a few methods have focused on the critical region of the storm environment and no data-driven optimal system design was developed to gain more information through exploring target locations. Anticipatory sUAS routing lowered the overall energy usage and maximized the reduction of forecasting error by exploring and sampling unobserved cells along the path to a target location.

This paper analyzes how online updating from sUAS collected meteorological data would benefit hurricane intensity forecasting considering the temporal variation of the uncertainty. Unobserved heterogeneity and randomness of the data have shown multiple modes in probability distribution in each location. A huge collection of multiple sources of granular microscopic data in each location may result in the loss of multivariate information if not retrieved properly. It is important to quantify the uncertainty of prior belief and update posterior when critical observations are obtained. However, traditional entropy theory cannot handle i) sequential learning multimodal multivariate information; ii) dynamic spatiotemporal correlation; iii) importance of observation for posterior approximation. In this paper, we advance autonomous in-situ sensing under highly uncertain and turbulent flow through a multi-variate multi-modal learning by analyzing the similarities between the different types of mixture distributions of multiple variables and allocating a cluster to each group across high dimensional time and space. Specifically, this paper can track structural information flow of temporal multi-variate multi-modal correlation data and automatically update the posterior, with the weights to the new observations through an iterative process. Extensive experiments on hurricane ensemble forecasting data demonstrate the superior performance of our method over the state-of-the-art baselines across various settings.

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