Keynote at the

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Not Just Data, Catalytic Operators are Needed for Converting Data to Causal Embodiments:

Koopman Operators Provide a General Framework for Solving Robotics

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Abstract

Data are crucial in today's robotics, but it is equally important to address, as a general methodology, how data can be converted to causal, actionable embodiments. This keynote talk introduces Koopman operators as a foundational modeling architecture and an underpinning theory for making good use of data and machine learning techniques to construct a special system representation amenable for estimation, reasoning, and real-time control. In Koopman, a given process is lifted to a high-dimensional space of embeddings, which are constructed from data and domain knowledge, and its nonlinear dynamics of state transition is reduced to a globally linear relationship in the high-dimensional space. Koopman's theory guarantees the existence of such globally linear models and has been applied to both AI and robotics. In Large Language Model (LLM), words are projected onto a high-dimensional vector space, and causal and meaningful relationships are captured for prediction and reasoning. Transformers in LLM represent the dynamics of a language using nonlinear embeddings and linear transitions, which can be viewed as a Koopman operator. In robotics, complex, nonlinear dynamics can be globally linearized with a Koopman operator, where an effective set of embeddings, called observables, are obtained based on machine learning techniques. Such globally linear models facilitate real-time control and prediction. Model Predictive Control (MPC), for example, can be computed as a convex optimization, allowing for real-time implementation. Furthermore, the Koopman global linearization empowers us to tackle challenging robotics problems. Legged locomotion and non-prehensile manipulation, for example, are complex due to switching of segmented dynamics, as the robot makes and breaks contact with the environment. Koopman operators, however, can subsume segmented dynamics within a globally linear, unified model in a high-dimensional space. The model can predict the robot behavior beyond switching boundaries, where the robot transverses multiple domains. These exemplify that the Koopman operators serve as a catalyst that converts the nonlinear switched system to a globally linear system, completely changing the difficult dynamic properties to benign dynamics. The talk is concluded by addressing the role of foundational modeling architecture for general robotics in the AI and data-dominating era.