Rethinking Structural Properties in Large-Scale Hierarchical Control Systems via a hybrid system approach

The increasing complexity of modern infrastructures, particularly in energy systems, motivates the development of new theoretical frameworks for the analysis and control of large-scale dynamical systems composed of many interacting heterogeneous subsystems. In such contexts, classical notions such as observability and controllability must be revisited to account for structural constraints, partial information, and multi-level representations.

A first fundamental challenge concerns observability under partial and structured measurements. Consider a large-scale system composed of interconnected agents, where only a subset of these agents is directly measurable. The evolution of this measurable subset is influenced not only by its internal dynamics but also by interactions with external agents that are not observed. As a result, the available measurements provide only indirect and incomplete information about the system's evolution. The key question is not merely whether the full system is observable, but rather what information about the unobserved part is necessary and sufficient to control or monitor the observed subsystem. This shifts the focus from classical full-state observability to task-oriented and structured observability, where the objective is to reconstruct specific latent variables or aggregated effects induced by the unobserved agents. A central theoretical challenge is therefore to define and characterize reduced-order representations or observers that capture the influence of unmeasured components on the measured subsystem, without requiring full reconstruction of the global state. This may be achieved by extending the observed subsystem model with a black-box component, obtained from experimental steady-state data, that accounts for the external influences exerted by the unobserved agents. In other words, the observed subsystem model may be augmented with an unknown component derived from matching the steady-state response of the extended model with the steady-state response obtained from experimental data. This amounts to the well-known moment matching procedure. Then, based on the obtained system, the design of a corresponding observer will be addressed, whose stability will be analyzed using Lyapunov tools.

A second challenge lies in understanding how controllability properties evolve under changes of system representation**,** particularly in the presence of hierarchical or multi-level structures. Large-scale systems are often described at different levels of abstraction: a detailed representation capturing individual agent dynamics, and higher-level models describing aggregated or collective behavior. While such abstractions are essential for scalability, they may alter the system's structural properties. This raises fundamental questions: how does controllability propagate across representations? Under what conditions can control objectives defined at an aggregated level be realized through actuation at the lower level? More generally, how do mappings between representations affect the reachable sets of the system? Addressing these questions requires extending controllability theory to account for interconnected models linked by aggregation and abstraction operators**.**

The interaction between partial observability and multi-level controllability naturally leads to the consideration of hybrid dynamical systems**.** In many settings, the influence of unobserved components on a given subsystem can be interpreted as inducing switching behaviors or regime-dependent dynamics**,** resulting in systems whose evolution depends on both continuous states and discrete modes. Hybrid system theory provides a suitable framework to capture these phenomena, enabling the modeling of systems where different configurations correspond to different interaction patterns or external conditions. From an observability perspective, this raises the problem of reconstructing the relevant latent dynamics in the presence of mode-dependent behaviors. From a controllability perspective, the presence of multiple configurations leads to a combinatorial structure, where controllability must be analyzed not only within each mode but also across sequences of modes and abstraction levels**.**

The overarching theoretical challenge is therefore to develop a unified framework for observability and controllability in large-scale systems with partial information, hierarchical representations, and hybrid dynamics**.** This framework should enable the characterization of which information is necessary for control, how it can be reconstructed efficiently, and how control actions can be consistently designed across multiple levels of abstraction.

Such advances are expected to provide a rigorous foundation for the analysis and control of complex infrastructures, with direct implications for future energy systems, where scalability, partial information, and multi-level coordination are inherent features.

Expected Outcomes

The project is expected to deliver:

- New theoretical insights into observability and controllability in large-scale systems
- Scalable observer and control design methodologies
- Publications in high-impact journals and conferences
- Contributions to applications in energy systems, transportation, or networked infrastructures

Candidate Profile

Applicants should have:

- A PhD in control systems, applied mathematics, or a related field
- Strong background in control theory (nonlinear, distributed, or networked systems)
- Experience with modeling and simulation tools (e.g., MATLAB/Simulink, Python)
- Ability to work independently and in an interdisciplinary environment
- Strong communication and publication skills

References

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