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Request for Information on the National Cyber-Physical Systems Resilience Plan

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Research Directions for Resilient Control of Cyber-Physical Systems

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Feedback control and uncertainty

Feedback control mitigates uncertainty. As an autonomous car drives or an autonomous aircraft flies, the control system uses data from sensors to compensate for myriad unknown effects that would otherwise prevent successful operation. Feedback control is essential for a vast number of technologies, but its presence and function are largely invisible.

Despite innumerable successes, many control applications are beyond the reach of existing techniques. These applications involve dynamics that change in unknown and unpredictable ways. Examples include the electric power grid, which changes as loads and sources are connected and disconnected; autonomous vehicles on roads whose coefficient of friction changes due to weather; and aircraft whose dynamics change due to payloads and damage. *In these and many other applications, it is extremely difficult to ensure that the control system will be resilient to unknown and unpredictable changes.*

Research Direction #1: Fast, targeted learning.

Machine-learning techniques use data-intensive methods to model the dynamics of a system, and the identified model is used to synthesize a feedback controller. Unfortunately, pre-training based on a system model produces a controller that is tuned for the model, which is invariably an imperfect representation of the true system. In addition, *machine-learning techniques are ineffective in the face of unknown and unpredictable changes, especially changes that have not occurred before and therefore cannot be anticipated by any amount of prior training.*

To address these challenges, resilient control of cyber-physical systems requires methods that can learn rapidly as the system changes. This can be done by *fast, targeted learning*, which rapidly updates system details that are crucial for closed-loop performance. Fast, targeted learning is an essential technology for resilient control of cyber-physical systems.

Research Direction #2: Adaptively cooperative decentralized control.

Systems such as the electric power grid are spatially distributed. This means that sensor data may not be available to a central processor. Instead, separate controllers must operate without direct communication. By operating in a decentralized fashion, the only "communication" among controllers is through the locally observed behavior of the system. To ensure resilient operation, decentralized controllers must learn to cooperate as the global system changes in unknown and unpredictable ways. Adaptively cooperative decentralized control is an essential technology for resilient control of cyber-physical systems.

Research Direction #3: Scientifically meaningful control experiments.

The foundation of control research is built on mathematics, as it should be. In cyber-physical systems, however, control algorithms interact with physical systems, and thus sensor data are generated by the full complexity of the physical system. Since no model can fully capture this complexity, *the challenge is to ensure that a cyber-physical system is resilient to unknown and unmodelable effects.* The ubiquity of control technology suggests that real-world control systems are inherently resilient. Many are, but the need for resilient control of cyber-physical systems demands a new paradigm for assessing the challenges of interacting with complex physical systems. The missing paradigm is *control experimentation*.

Physical experiments are essential for advancing all branches of science, but this has not been the case for feedback control. The lack of a culture of feedback-control experiments reflects the fact that the goal of feedback control is not to attain a deeper understanding of physical reality, but rather is to mitigate uncertainty in that understanding. Feedback control is thus unique among all branches of science.

It is tempting to view a control "experiment" as a physical construction whose features resemble the hypotheses of a theorem, in which case it may be expected that the conclusions of the theorem (such as stability and robustness) are ensured. The importance of neglected effects, however, can only be assessed by trial and error, engineering judgment, and experience. Unfortunately, learning from failure is often expensive.

A fundamental understanding of scientifically meaningful control experiments is needed. This question is deep and nontrivial, especially since the goal of feedback control is not to understand reality, but rather is to mitigate uncertainty. How does one ensure that feedback control mitigates uncertainty when the full complexity of physical reality cannot be fully known? These and related questions are not philosophical; rather, they get to the heart of resilient control of cyber-physical systems [1].

[1] Bernstein, D. S., "Facing Future Challenges in Feedback Control of Aerospace Systems Through Scientific Experimentation," *AIAA J. Guid. Contr.*, Vol. 45, 2022, pp. 2202–2210.