Fundamental Limitations for Classes of Cooperative Multi-Agent Systems

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The rapid proliferation of embedded and networked microprocessors has created many new opportunities for control. One opportunity lies in the replacement of traditional mechanical linkages with cyber, or virtual connections. Another opportunity is the possibility for multiple independent agents to coordinate their activity through network communications in order to achieve a common goal. Applications arise in many domains, including vehicle platooning in transportation systems, consensus in formation control, and synchronization of networked coupled oscillators. Common to these applications is information exchange through virtual connections rather than physical linkages. While virtual connections allow greater flexibility in the information exchanged between agents, the lack of associated significant power exchange poses a set of issues not present when agents are connected physically. For example, the two-way information flow and power exchange that is inherent in most physical connections is generally stabilizing. Actions transmitted through virtual links need not be accompanied by reactions, and need not carry energy or power, and as such are more likely to give rise to stability issues. Two-way information flow may exist in a virtual connection, but this would be a consequence of design rather than physics. If the coupling is virtual there may be no physical intuition for the behavior of the system as a whole, especially when human and computers are cooperating to achieve a goal. Use of visual feedback by a human driver controlling headway to the preceding vehicle is an example of a virtual link that lacks a simple physical equivalent. We posit that whether a human is interfaced to a system through a virtual or a physical link has very important implications in achievable human/machine performance. Our goal is to describe relationships (capturing in particular the tradeoffs) between feedback properties and performance in systems that mix human and computer agents and that include physical and virtual links.

String instability is one example of a behavior that emerges from a multi-agent system with virtual links (e.g. vehicle platooning). Only very recently have infeasible specifications been delineated for agents using arbitrary control policies, using analysis from the theory of fundamental design limitations, but the agent models were limited to single or double integrators. Significant gaps remain in the determination of fundamental design limits for cyber-physical systems with more complex agent models such as harmonic oscillators. Our initial objective is to extend fundamental design limitations theory to cover systems with mixed cyber and physical links. Specifically, we will contribute tools that delineate tradeoffs between performance and feedback properties for control systems involving mixes of human and computer agents and classes of hardware dynamics, controllers, communication topology, and time delays. We will assess the contribution to system behavior (e.g. string stability) of each agent's realization in hardware (whose behavior is subject to the laws of Newton) as well as realization in software and communication (subject to the fundamental limitations of Shannon and Bode). Along with the development of fundamental design limitations theory, we are verifying our theory on real hardware in the Michigan Embedded Control Systems Laboratory. We are conducting experiments and analyses in string stability that combine system identification of the haptic devices and each human operator with systematic control design. The ability to express such relationships for classes of dynamics, controllers, and topologies will significantly extend the tools available to predict behaviors emerging within multi-agent systems.

In this first year of the project, we considered the problem of string instability in coupled harmonic oscillator strings. Although the string instability problem of vehicle platooning has been studied in the past few decades, the results cannot be directly applied to oscillator strings as the fundamental limitation theory developed for vehicle platooning is based on the single or double integrator model of the vehicle. We have developed extensions to accommodate the oscillator model with its two pure imaginary poles. We developed a new Bode-like integral relation that must be satisfied by the complementary sensitivity function in oscillator systems using the Cauchy integral theorem. We also derived relationships between time domain specifications (steady-state and transient errors) to track a ramp-enveloped sinusoidal signal and frequency domain constraint (bound in magnitude response). We can say that certain design specification will necessarily lead to string instability in oscillator systems based on our results. At present, we are considering more complex control and communication strategies, heterogeneous strings, and time delays.