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A Position Paper Titled:

**Networked Control Systems Research
A Brief Discussion of Challenges and Opportunities**

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Control systems with spatially distributed components have existed for several decades. Examples include chemical process plants, refineries, power plants, and airplanes. In the past, in such systems typically the components were connected via hardwired connections and the systems were designed to bring all the information from the sensors to a central location where the conditions were being monitored and decisions were taken on how to act. The control policies then were implemented via the actuators, which could be valves, motors etc.

What is different today is that technology can put low cost processing power at remote locations via microprocessors and that information can be transmitted reliably via shared digital networks or even wireless connections. These technology driven changes are fueled primarily by the high costs of wiring and the difficulty in introducing additional components into the systems as the needs change.

The changes in the scope and implementation of control systems have caused two main changes in the emphasis in control system analysis and design. The first has to do with the explicit consideration of the interconnections; the network now must be considered explicitly as it affects the dynamic behavior of the control system. The second change has to do with a renewed emphasis on distributed control systems.

Regarding the network, control systems are redefined in the sense that there is an additional component to the plant, controller, sensor and actuator components, namely the network that represents the interconnections among components. The network has become a factor because of the use of digital communication networks shared by other applications. There, media access by the sensor that needs to transmit data may not be immediate and communication delays and packet losses may occur. Furthermore the increasing use of wireless communications introduces new issues such as fading and time varying throughput in communication channels. As a result of these changes the effect of the interconnections needs to be explicitly addressed in networked control systems.

The second area of change is the change of emphasis from centralized to distributed control systems. The fact that there is ample processing power available at low cost that can be embedded almost anywhere opens a vast array of exciting possibilities. Sensor data can be processed locally and control policies can be implemented again locally, without the need for a central decision maker. The remote units act locally but they must coordinate their actions to serve global goals. In this way there is no need for large amounts of data being exchanged over the network. The common wisdom is that distributed control can never be as good and effective as centralized control. Is this assumption correct? Intuitively it is true assuming that there are no delays when data are sent to and from the central processing unit. When delays are present, and this is unavoidable under current technology trends of shared digital networks and wireless connections, distributed control has the potential of being superior to centralized control, since sharing local information and acting upon it may be relatively delay free. The distributed control systems can then be seen as consisting of clusters of sensor, actuators processing units and communication devices that are rather loosely interconnected, sharing perhaps only supervisory information. An illustrating example of a distributed control system is a group of UAVs that coordinate their flight directions and velocities to fly in formation.

Because of these changes in control systems, several new concerns need to be addressed. Several areas such as communication protocols for scheduling and routing have become important in control when considering for example stability, performance and reliability. Algorithms and software that are capable of dealing with hard and soft time constraints are very important in control implementation and design and so areas such as real-time systems from computer science are becoming increasingly important. There is also some re-ordering of control concepts due to changes in importance to control applications. Control concepts that were of interest before have been brought to the forefront and assumed new importance because of the changing circumstances. An example is actuator saturation or constraints, which plays an even more important role today, since networked systems are expected to run intermittently open loop. The fact that there are actuator constraints implies that unstable systems are much more restricted from running open loop for extended periods of time as there may not be possible to reverse direction in an unstable trajectory if the system has departed significantly from an equilibrium point.

At a more fundamental level, control theorists have been led to re-examine the open (feed-forward) versus closed loop (feedback) control issues. The desire to do better than holding the control input value constant during open loop intervals, as is the case in zero-order hold, has led to the introduction of increased explicit knowledge about the plant in the controller, and to model based control architectures in certain studies.

There had also been renewed emphasis on increased autonomy that allows the system to run without feedback information for extended periods of time. This has brought forth the area of autonomous intelligent control and consideration of approaches and methodologies on how to build such systems.

Distributed control is related to the areas of decentralized control and of large-scale systems, which were studied extensively in the 70s. In the case of large-scale systems several results were derived, primarily on the stability of such systems. Typically it would be assumed that the interconnections had certain strength and then some form of Lyapunov theory would be applied. Other results were also derived. About 30 years ago decentralized control was studied, where the controller had special structure; for example, the controller could be a diagonal matrix, so that measurements from the first output were used to decide only the first control input. These (block) diagonal special structures introduced restrictions conveniently expressed by the notion of fixed modes in decentralized control. Note however that the plant in decentralized control was still a single tightly connected unit, and not a rather loosely interconnected group of complete systems, which is the typical case in distributed control. Currently, there is on-going related work on decentralized supervisory control of discrete event systems using finite automata or Petri net models.

The whole area of sensor networks is very relevant, although the networks we are primarily interested in are sensor and actuator networks. In networked control systems data are not only gathered and processed as in sensor networks, but are used in decision algorithms to derive control policies implemented via the actuators. There are many similarities and also significant differences. For example routing algorithms for networked control systems must satisfy much more severe delay requirements than in sensor networks, where even a few seconds delay in receiving data may be totally acceptable.

It should be noted that there are several research areas in other disciplines that deal with topics relevant to networked control systems. Optimization is one such relevant area. Of particular interest are distributed optimization algorithms. The area of complex systems studied by physicists using statistical methods is relevant. They are interested in modeling systems ranging from the internet to protein metabolic networks in biological organisms. Tools used are graph theory and power distribution laws, and scale free networks together with phenomena such as the small world phenomenon are observed.

What is the status of theoretical in networked control systems? So far, researchers have focused primarily on a single loop and stability. Some fundamental results have been derived that involve the minimum average bit rate necessary to stabilize a linear, time-invariant system. Although progress has been made, there is a lot of work to be done. In the case of a digital network where information is typically sent in packets, the minimum average rate is not perhaps a good guide to control design. When a packet is sent typically contains a payload of tens of bytes and so it does not make a lot of sense to send only a few bits at a time as we can send more at no real cost. Keep also in mind that one can send 1 bit per second or 1000

bits every 1000 seconds for the same average. In view of the typical actuator constraints an unstable system may not be able to recover after 1000 seconds.

An alternative measure is to see how infrequent feedback information is needed so to guarantee that the system remains stable. This scheme has been combined with model-based ideas for significant increases in the periods where the system is operating in an open loop fashion. Intermittent feedback is another way to avoid taxing the networks for sensor information. In this case every so often the loop is closed for certain-fixed or time varying-period of time. This may correspond to opportunistic, bursty situations where the sensor sends up bursts of information when the network is available. The original idea of intermittent feedback was motivated by human motor control considerations.

There are strong connections with cooperative control. There, researchers have used spatial invariance ideas to describe results on stability and performance. If spatial invariance is not present then one may use graphs and graph theory to describe the interaction of systems/units to study problems such as flying in formation, foraging, cooperation in search of targets or food etc. A more realistic formulation especially in the wireless case is to consider channels that vary with time, fade, disappear and re-appear. The problem of course in this case becomes significantly more challenging. There is ongoing fundamental work in this area. Consensus approaches have also been used, which however typically assume rather simple dynamics for the agents and focus on the topology considering fixed or time-varying links in synchronous or asynchronous settings.

Hybrid systems is an area of significant importance to networked control systems with potential for significant impact on greater understanding of such systems. Networked control systems run over digital networks may involve synchronous and asynchronous processes and be governed by both time-driven and event-driven inputs. Such cyber-physical systems are becoming increasingly important. There are attempts to use hybrid and switched systems results to derive stability results for networked control systems with multiple possible delays. Much more work is needed.

Implementation issues in both hardware and software are in the center of successful deployment of networked control systems. Data integrity and security are also very important and may lead to special considerations in control system design even at early stages.

What then are areas that have been or are being studied and what are research areas where the community needs to pay more attention?

Overall, single loop and stability have been emphasized and studied under quantization of the sensor measurements. The research should move to multiple interconnected systems over realistic channels that work together in a distributed fashion towards common goals. Performance is key in making such systems attractive to practitioners.

Limits to performance in networked control systems appear to be caused primarily by delays and dropped packets. Need to have ways to cope with actuator constraints, understand better the feedback mechanisms, need to build into our systems increased degree of autonomy, so to be able to use open loop control more often. Need to talk about reliability, fault detection and isolation, graceful degradation under failure and reconfigurable control. We should not forget that our control systems have now an additional component, the network.