Systems of Systems

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Introduction

The increasing scale and complexity of control applications have reached a point that imposes qualitatively new demands on control systems technology. Just as the transition from single-input, single-output systems to multivariable control required new theories, tools, and techniques, similarly, the new imperatives cannot be satisfied by evolutionary extensions of the state of the art.

Emerging applications are not just large-scale and complex; they are also characterized by decentralized, distributed, networked compositions of heterogeneous and (semi)autonomous elements. These new "systems" are, in fact, "systems of systems" (SoS) [1]. The term has arisen from the systems engineering community and reflects the interest in concepts and developments such as smart grids, integrated supply chains, collaborative enterprises, and next-generation air traffic management.

The challenges associated with designing, building, and operating systems of systems are not limited to control science and engineering. Yet the relevance of SoS to control, and vice versa, is apparent—as acknowledged by the frequent use of terms such as "systems and control" and "control systems." It can even be said that the importance of control increases as our conception of systems is broadened by encompassing consideration of multiscale and hybrid dynamics, cooperative and competitive architectures, multicriteria optimization, semiautonomous and autonomous systems, self-diagnosing and self-repairing systems, and so on. Systems of systems thus offer exciting opportunities for research in control (or systems and control) [2].

Below, we first note some properties of SoS. Next, we briefly compare and contrast SoS with another emerging research focus in the controls community, cyber-physical systems (CPS). We include a few examples to illustrate the increasing levels of interest in SoS. Before concluding, we discuss a few SoS-relevant research topics in control.

What Are Systems of Systems?

As the term implies, a system of systems is a composition; it consists of components that are themselves systems. But the term gains specificity with two properties that the whole must possess for it to be considered a system of systems [3]:

- *Operational independence of components.* The component systems fulfill valid purposes in their own right and continue to operate to fulfill those purposes if disassembled from the overall system; and
- *Managerial independence of components.* The component systems are managed (at least in part) for their own purposes rather than the purposes of the whole.

The "independence" aspect implies that autonomy is inherent in SoS—not just in the function of the SoS but also in the function of component systems. Autonomy in this context does not necessarily mean human-free operation; the human element may be part of the component system. But this subsystem must be able to function independently on occasion and yet be a cog in a larger machine on other occasions. Dynamics in the evolving structure is a peculiarity of SoS.

The prospect of developing large, functionally rich, behaviorally complex SoS *ab initio* is unrealistic, especially given the requirement that component systems be useful entities in their own right. Systems of systems tend to exhibit evolutionary development—intermediate systems are developed that perform useful functions and are then integrated into larger systems. SoS will typically evolve through stable intermediate forms [4].

Other characteristics of systems of systems can be highlighted as well:

- SoS will be heterogeneous. From components to subsystems to systems, different technologies and implementation media will be involved.
- SoS will exhibit emergent behavior. Given their architectural complexity, the interaction of the SoS component elements will inevitably result in behaviors that are not predictable in advance.
- SoS will be large-scale systems. "Scale" should be interpreted more in a logical than necessarily a geographical sense—a system of systems can be a local entity with collocated subsystems.

Although these defining properties and characteristics do not explicitly invoke control, the relevance of the technology to SoS is evident given the dynamics involved in the component systems and compounded by the meta-system. Individual components will require control applications within them, and these control applications will interact explicitly (e.g., through coordination signals) or implicitly (e.g., through physical influences). Information technologies will provide the integration infrastructure, which is an enabler for closing the loop and optimizing design and operations (Fig. 1).

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Dynamics and control aspects of SoS are also critical for nonfunctional properties; SoS requirements cannot be limited solely to their core performance-related functions. Systems of systems have to be designed so as to provide assurances for predictability, dependability, and safety. Verification at several levels of abstraction will be required given the safety- and mission-criticality of engineered systems of systems, and such verification will need to be informed by the dynamics of SoS.

Systems of Systems and Cyber-physical Systems

SoS and CPS both represent exciting new vistas for control, in the eyes of the controls community as well as its government and industry sponsors. The influence of the revolutionary advances in information technologies is prominent in both areas, and thus it is not surprising that overlap exists. However, there are significant differences between CPS and SoS as well—differences reflected in the semantics of the terms.

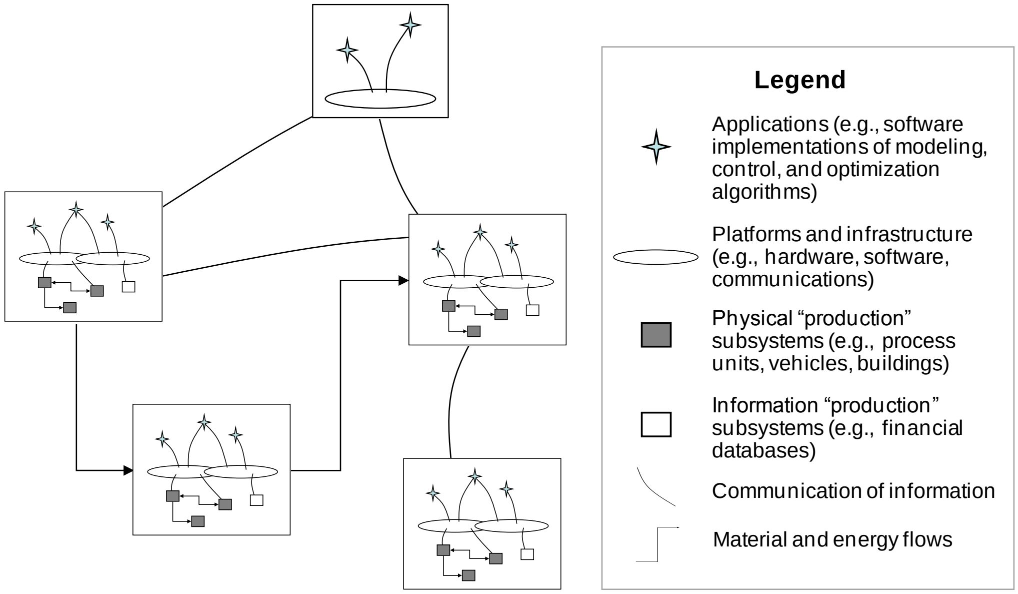

Figure 1. A schematic representation of a system of systems. Each component system may consist of applications, platforms, and “production” elements, the last of which can be physical systems or information systems—dynamics are very different in the two cases. Component systems may be integrated through information and/or material/energy interconnections. Additional component systems may be employed for coordination and control (the top system), and coordination can also occur among production systems.

First, the connection with physical systems is a defining feature of CPS. The interconnection of computer-based control algorithms and mechanical, chemical, or other processes governed by scientific laws has been exemplified by control systems since they became digital decades ago. With progress in computer science and related fields, new opportunities have arisen for control applications, and CPS research is attempting to capitalize on these opportunities.

Not all control applications are connected with the physical world, however. One point of divergence between CPS and SoS relates to applications that are purely in the information space. Control technologists are working in financial industries or otherwise developing applications to economic and market systems. Similarly, enterprise applications are a fertile target for control technology and do not necessarily require closing the loop in the “real” world. These applications are generally considered outside the CPS realm but not, at least necessarily, outside the SoS one. (It might be argued that even in these applications, the underlying processes are physical ones—what ultimately must be modeled is human psychology, for example. However, at least today this ultimate reduction is not being pursued.)

Second, many control applications, and many complex control applications, are not focused on distributed, hierarchical, and compositional mega-/meta-systems. Even a single-input, single-output PID controller, in a digital implementation, suggests opportunities for CPS research. Certainly the development of reconfigurable multivariable controllers running on sophisticated real-time platforms with adaptive scheduling would constitute significant progress in CPS. The connection with SoS is minimal at best.

These are definitional differences, and an obvious question is whether they lead to differences in research agendas and methodologies. This is a difficult question to answer at this stage of development of these fields, especially of SoS. Whereas the controls community has been instrumental in establishing

CPS (the field of more recent vintage) over the last several years, the engagement with SoS has only just begun. In any case, we do not expect significant qualitative contrasts, but rather variations in emphasis and prioritization. For example, topics such as verification and validation of real-time controller implementations or control over wireless links will likely be more prominent in CPS than in SoS. Conversely, game-theoretic negotiation algorithms strike us as more SoS territory.

SoS Examples

Examples of systems of systems, either existing or proposed, can be found in all societal sectors [5]: air and road transportation, power grids, healthcare, water management, industrial processes, building complexes, critical infrastructures, enterprise systems, smart homes and cities, and others. We discuss a few examples here, highlighting control connections.

Manufacturing Supply Chains

A large-scale manufacturing facility is a system of systems in itself, and today connectivity with upstream and downstream entities is being explored. The focus is largely on IT integration—platforms and communications that can, for example, automate ordering from suppliers based on inventory and production levels in a factory. Although the benefits of such automation are significant, the real value of the infrastructure is as a foundation for the optimization of the overall supply chain—enabling responsiveness to market conditions, maximizing energy efficiency, coordinating inventories with production plans dynamically, and the like.

Control loops exist within the entities in a supply chain (even suppliers and distributors that do not have manufacturing operations have feedback processes operating to service requests, accommodate inputs, and manage inventories; these are typically discrete-event processes, with simpler dynamics than a production operation). An interconnected supply chain establishes additional control structures with complicating factors. Different business entities are involved with their own, and often competing, priorities. Centralized or global optimization is not feasible. See Fig. 2 for an illustrative sketch.

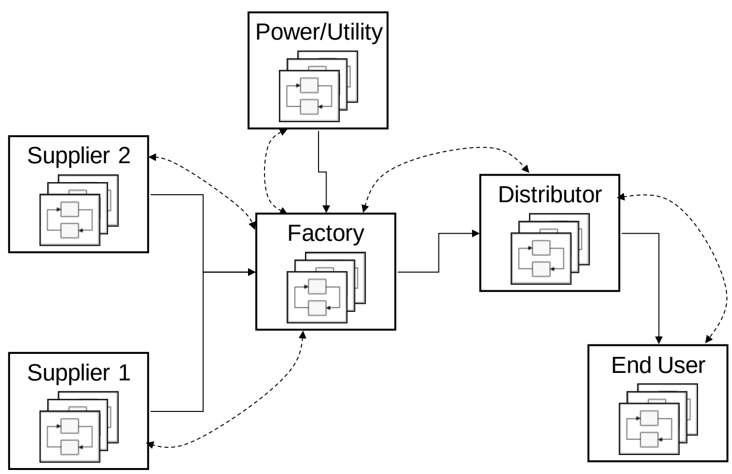

Figure 2. A control-centric view of an enterprise-level system of systems. Solid arrows show material and energy flows; dashed lines show information (including measurement, estimation, and command) flows. Individual systems contain optimization and control loops, and intersystem interactions realize higher-level control loops.

Embedded Automotive Systems

Today's cars are collections of embedded systems on wheels. Much of the innovation in the automotive industry in the last decade or two has been as a result of onboard computing, control, and communication, and this innovation has dramatically improved safety, fuel economy, emissions, and reliability. A number of separate embedded systems exist in a modern automobile—just those related to safety include collision impact warning, airbag deployment and seatbelt pre-tensioners, antilock and differential braking, intelligent cruise control, and traction and stability control. Often designed independently, these systems are nevertheless interdependent through the physics of the vehicle and the environment and the actions of the driver. Thus arose failure modes such as cars that locked themselves if the driver got out with the engine running and shut the door, or cars whose antitheft systems disengaged and doors unlocked if the cars were rocked side-to-side, triggering rollover detection.

The solution, evidently, is to adopt an SoS viewpoint when designing automotive systems (Fig. 3). Standard network protocols and buses have already been adopted in vehicles. Some level of algorithmic integration has also occurred—some systems coordinate traction control and antilock braking, for example. But much remains to be done, and with the continuing rollout of X-by-wire systems (e.g., active steering), more opportunities will arise.

With developments in intelligent road transportation systems, communication and coordination among vehicles and between vehicles and infrastructure elements (road signage, traffic lights, etc.) will further increase the SoS web. We have focused here specifically on intra-automobile systems to make the point that (unlike most examples that are discussed) the SoS vision, and its strong control connections, are also relevant in localized embedded electronic domains.

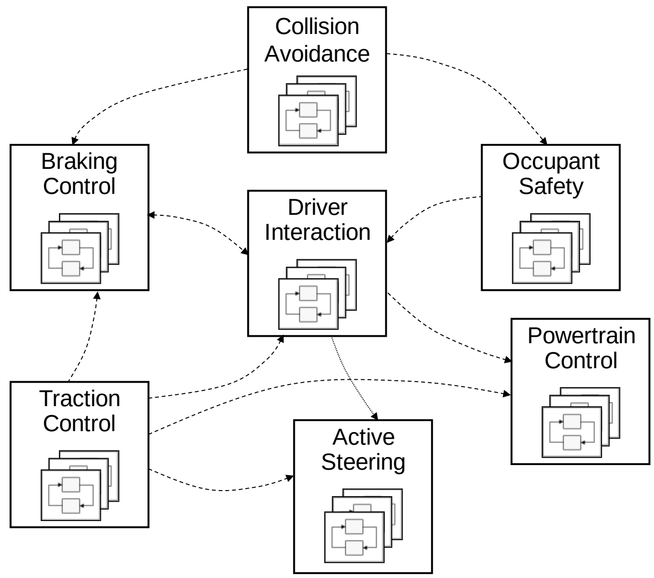

Figure 3. An “embedded” system-of-systems example (automotive) illustrating control applications and their dependencies. The dependencies can be realized through the physics of the vehicle-driver-environment SoS or through explicit control commands. (Not all control-related embedded systems are shown and not all possible interactions are depicted.)

Smart Grids

Smart grids are a topic of tremendous interest worldwide. They represent a revolutionary advance over today’s power grids enabled by two-way flow of both electricity and information. Smart grids incorporate an overlay of communication and control over a modernized power system infrastructure, resulting in a cyber-physical system extending from generation to consumption and facilitating the integration of distributed storage and generation (especially from renewable sources) and electric and plug-in hybrid vehicles.

Today, electricity consumption is, for the most part, independent of the exigencies of supply. Adjustment of consumption may be desired for several reasons—generation shortfalls, desires to ramp down use of polluting or expensive generation assets, better use of renewable generation, bottlenecks in the transmission system—but no systemwide infrastructure exists to realize such adjustment. Similarly, opportunities to effect optimized control of transmission and distribution grids, accurately monitor and communicate system state, closely connect power markets with power flows, and achieve other advanced power system capabilities are limited by the existing infrastructure.

A smart grid, as a system of systems, will enable such functions. One example is depicted in Fig. 4. Autonomous control units manage generation (including renewables and combined heat and power (CHP)), storage devices such as fuel cells, electric vehicles, and building loads—and the future may bring as-yet-unknown technologies. Utilities and system operators can interact with these master controllers and also with market entities. Individual control systems must satisfy local objectives, but they also need to cooperate to ensure the reliable and efficient operation of the power system. In the figure, the coordination is through a central node—this is closer to today's situation; in the future we can anticipate less hierarchical, more collaborative decision and control architectures.

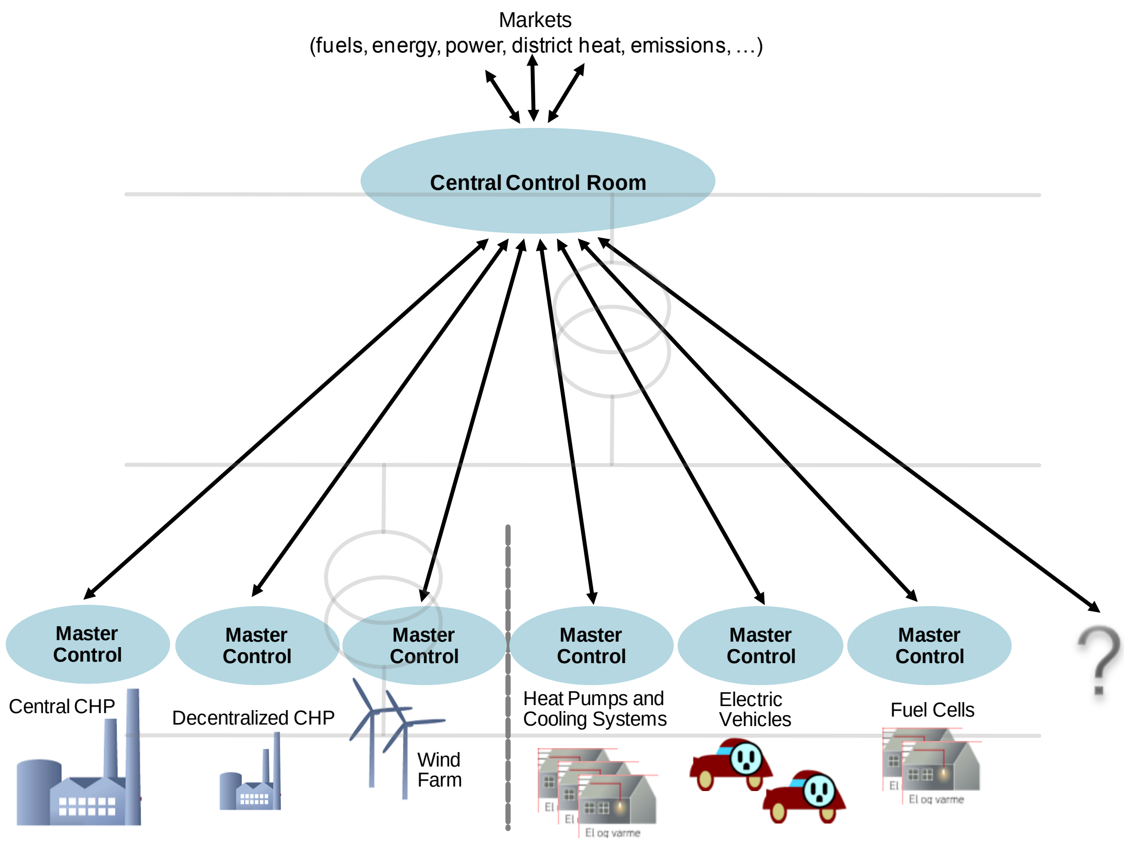

Figure courtesy of Dong Energy

Figure 4. Smart grid SoS example.

Research Opportunities for the Controls Community

Although systems of systems is not the research preserve of any one field—it is truly a multidisciplinary research frontier, as noted earlier—systems and controls constitutes a core enabling discipline. Here we discuss some of the SoS research implications for the controls community.

Cooperative/Coordinated/Collaborative Control

The adjectives overlap and are often used interchangeably, but altogether this is currently one of the most active topics of research in control systems. Formation flight and coordinated robot motions are the main application targets; the focus is on vehicular/mobile agents and geometric relationships. Notable theoretical results have been generated. A system-of-systems perspective can further enrich research in the area by broadening the space of applications.

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For agents that are capable of autonomous or semiautonomous operation, cooperation and collaboration imply task-level interactions. Indeed, in the SoS context, it should be expected that component systems have their imposed goals but might also generate (in an evolutionary way) their own goals—causing dynamic interactions with other component systems. The relevance for control becomes especially prominent when temporal aspects must be considered—whether at the level of individual tasks or of the interaction. Both continuous-time behaviors and discrete decisions can be involved, and the interactions between the two offer particular opportunities. Consider, for example, scenarios in which the usefulness, for one agent's objectives, of a task being undertaken by a second agent varies based on both the degree of completion of the task and the elapsed time; the first agent must continuously decide whether to wait or to incorporate partial results. Expanded over a large scale, the complexity can be overwhelming, and new approaches will be needed.

In general, richer formulations for cooperative/coordinated/collaborative control are needed for the potential of this area to be realized. Theoretical and algorithmic contributions to systems of systems will be spurred by such broadening of perspective.

Identification, Learning, and Adaptation

Embedded models are a prerequisite for advanced control. However, modeling for systems of systems brings complexities that are often not encountered at the subsystem level. Effective techniques are available for developing models in general, and control-relevant models in particular, at a component level, but these cannot straightforwardly be extended to SoS. In particular, a distributed assemblage of independent, heterogeneous elements renders the prospect of centralizing knowledge about it problematic. Thus, instead of modeling as we often know it, with its first-principles orientation, the emphasis with systems of systems is likely to shift toward more data-driven, empirical techniques such as identification, learning, and adaptation.

Empirical modeling is subject to theoretical limitations based on partial information—as is the use of derived models for decision-making and control. There is no gainsaying these limitations, but they can provide guidance for research. In this context, we offer a few suggestions below.

- Generic, prepackaged solutions for large-scale applications are not a realistic objective. The "one size fits all" model is not a scalable one. Knowledge of problem domains, even if it is heuristic in nature, must be incorporated in customized approaches and algorithms.

- Levels of uncertainty in modeling and control are likely to be significantly higher with SoS. Greater attention must be paid to the stochastic aspects of learning and identification. Uncertainty and risk must be rigorously managed. This challenge plays to the strengths of control science and engineering.

- Autonomy, in the sense of operator-free automation, is not a viable prospect for many systems of systems. Given the likelihood of model-reality mismatch and the safety- or performance-critical nature of systems of systems, ultimate decision authority is likely to lie with humans, not machines. The human-in-the-loop aspect must be considered—it lessens the responsibility that otherwise would rest with automation and at the same time opens new opportunities for research in learning and adaptation.

Monitoring, Fault Diagnosis, and Fault-Tolerant Control

Increased scope and scale can imply a proportionate increase in risk. Adverse impacts from a low-level component failure can be managed. Failures at the system-of-systems level can have truly catastrophic consequences—for individuals, societies, system owners and operators, and the environment. Extreme levels of safety, reliability, and dependability will be required of systems of systems. With the large numbers of components and interconnections, individual failures will be unavoidable. Instead, methodologies and tools will be needed that can ensure safe and reliable SoS operation even in the face of component faults.

These arguments suggest renewed emphasis on monitoring, fault detection and diagnosis, and fault-tolerant control. Recently, the controls community has made significant progress in these areas. Rigorous, scalable theoretical results are now available, and sophisticated algorithms have been developed. Yet the SoS perspective further raises the bar on requirements and will provide further motivation for continued research.

Automation and Control Architectures for Systems of Systems

"System of systems" refers not only to a physical application configuration, but also to the automation and control infrastructure required to support the coordinated operation of heterogeneous autonomous and semiautonomous elements. Large-scale complex physical systems exist today and are supported by large-scale complex automation systems. These latter, however, tend toward centralized command-and-control architectures. The strictly hierarchical approach is untenable for SoS; "cooperation and coordination" is the appropriate metaphor, not command and control (traditionally construed). New developments in platforms and architectures will be needed.

Middleware is one central infrastructure need. Flexibility and adaptation will be essential to SoS and will need to occur in real time. Plug-and-play features will also be increasingly important. Traditional real-time systems restrict online flexibility, a conservative strategy that ensures stability at the cost of agility. An open question for the controls research community is whether this conservative approach can be overcome—whether, based on advances in real-time systems, wireless networks, embedded intelligence, and componentized software (for example), new control architectures can be developed that are not static and hierarchical but are constituted by flexible, adaptive, dynamic networks of cooperating objects.

The envisioned features for SoS automation and control must be attained without compromising safety, reliability, or security. Of especially critical importance is cyber security. The autonomy and heterogeneity of SoS imply a lack of centralized control. Multiple platforms and communication protocols will be involved, software and hardware components will be dynamically updated, and greater system responsiveness will be demanded. These are desirable, even revolutionary, benefits, but diligence must be exercised in building security features into the devices, software, protocols, and operational procedures.

Conclusions

Systems of systems are an exciting vision for the engineering community in general and for controls researchers in particular. The concept represents the culmination of developments in complex systems engineering over the last few decades, with obvious and broad-based advantages to society and industry. At the same time, SoS also represents a set of fresh research challenges. The multidisciplinary nature of SoS will require close collaboration between control researchers and researchers from several other fields—a positive development from several perspectives.

The control-related research required for systems of systems covers the basic-to-applied spectrum: advances are needed in areas ranging from fundamental systems science to the development of specific applications. What is crucial, however, is for basic research to be informed by application prospects and, conversely and at least at this early and immature state of the field, for application-oriented explorations to be conducted with awareness of the broader scientific issues.

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Selected recommendations for research in aerospace control:

- For SoS visions to be realized, robust, scalable algorithms for cooperation and coordination among heterogeneous autonomous and semiautonomous components—that can effectively balance local and global objectives—must be developed.
- Given their scale, systems of systems will always be faced with component-level faults; fault-tolerant and fault-adaptive methods are needed to ensure safe and reliable operation nonetheless.
- New automation and control architectures, hierarchical and heterarchical, are required that are based on dynamic networks of cooperating, flexible, and adaptive objects.

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