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Collaborative control theory for e-Work, e-Production, and e-Service

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Abstract

Recent developments in collaborative control theory and e-Work influence the emergence of e-Production and e-Service. The influence includes impacts of e-Work on enterprises, and proliferation of applications of robotics and agents' services. Our concern is the effective design and implementation of such e-systems. The purpose of this article is to review design principles and collaborative control theory guiding these new developments. The ''four wheels'' of e-Work, their 15 e-dimensions and their role in e-Production and e-Service are explained and illustrated. Network models and their bio-inspired redesign counterparts are explained with implications to the future of production and service systems.

Keywords: Bio-inspired control; Collaborative control; Collaborative networked organizations; e-Work design principles; Networked enterprise; Task administration protocols

1. The nature of e-Work and collaborative control

Those of us who share the passion for production realize that fundamental transformations are emerging. From the levels of nano and micro systems and devices all the way to the level of global enterprise networks, productive work is reshaped by e-Work. What is e-Work and how can it be optimized? It has been defined as any collaborative, computer-supported and communication-enabled productive activities in highly distributed organizations of humans and/or robots and autonomous systems. The transformative influence of e-Work can be described by this quote: ''As power fields, such as magnetic fields and gravitation, influence bodies to organize and stabilize, so does the sphere of computing and information technologies. It envelops us and influences us to organize our work systems in a different way, and purposefully, to stabilize work while effectively producing the desired outcomes'' (Nof, 2003).

A survey of e-Work applications (Nof, 2005, 2006a) covers examples from human–agent–robotic machine cells; multi-nanosensor arrays and networks; multi-robot search, security, remote maintenance, and service teams; RFID-based active information monitoring and sharing to improve customer service; end-to-end product life-cycle design and management; supply, logistics and distribution of physical and digital products by networked enterprises; to collaborative, virtual, networked organizations indicates several common characteristics of emerging production and delivery of goods and services:

a. e-X is *not* the same as X. e-Work and e-Production/e-Business are not the same as work, production, and business. Similarly, e-Services are not the same as service. What is the difference? A traditional operation *cannot* be copied as-is to an e-Activity, there must be certain changes. For a simple, useful example, compare a search for information by three generations of workers: a. Search through manual (usually, paper) records; b. Search of a database by a query; c. Search of the Web by a browser (and this search can be by regular browser, or by a bot). Think: How are the three similar? In what are they different? Why are they different?
b. e-Work and e-Production/e-Business are tightly coupled, but the e-relations are not the same as the traditional relations between them. In general, e-Work enables e-Production/e-Business, and the latter require e-Work.
c. The design objectives and benefits of emerging production and service must respond to the increasing needs of sustainability and dependability with a growing world population, while satisfying customer-centered objectives.

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These needs include 24×7 customizable service, availability, accessibility and supply with minimal waiting (and minimal parking); personalization by variety and by comparison; customization of product, process, service, and interactions; better quality-of-service (QoS) by following ‘‘best practices’’; better coordination, e.g., of suppliers; better collaboration, teamwork, community interactions, and other criteria and benefits.

d. Emerging production and service involve networks of demand and supply. They are enabled by smart teams and workflow interactions, which require decentralized decisions and automation, and collaborative control and management with timely planning and timely response.

Challenges, including growing inter-dependence, communication, diversity and cultural obstacles, safety and security threats, and design mismatch are well (or at least better) understood by now. Enablers to overcome these challenges have been developed and are tested against new constraints and demands (see Figs. 1 and 2).

It has been generally recognized that computer and communication science and technologies have revolutionized our ability to provide significantly better levels of quality and customization. Particularly, collaborative e-Work is fundamentally transforming our ability to improve e-Production and e-Services. One of the most significant realizations is that we can leverage the excellence developed for traditional manufacturing, production and supply by the ‘‘e’’ in e-Manufacturing, e-Production, and e-Supply to increasingly focus on and satisfy the customers’ needs in those areas, and also in e-Service.

Emerging production and service are generally enabled by the ‘‘four wheels’’ of (1) *e-Work*; (2) *integration, coordination, and collaboration*; (3) *distributed decision support; and* (4) *active middleware*. The 15 e-dimensions of e-Work and their role in production and service are as follows.

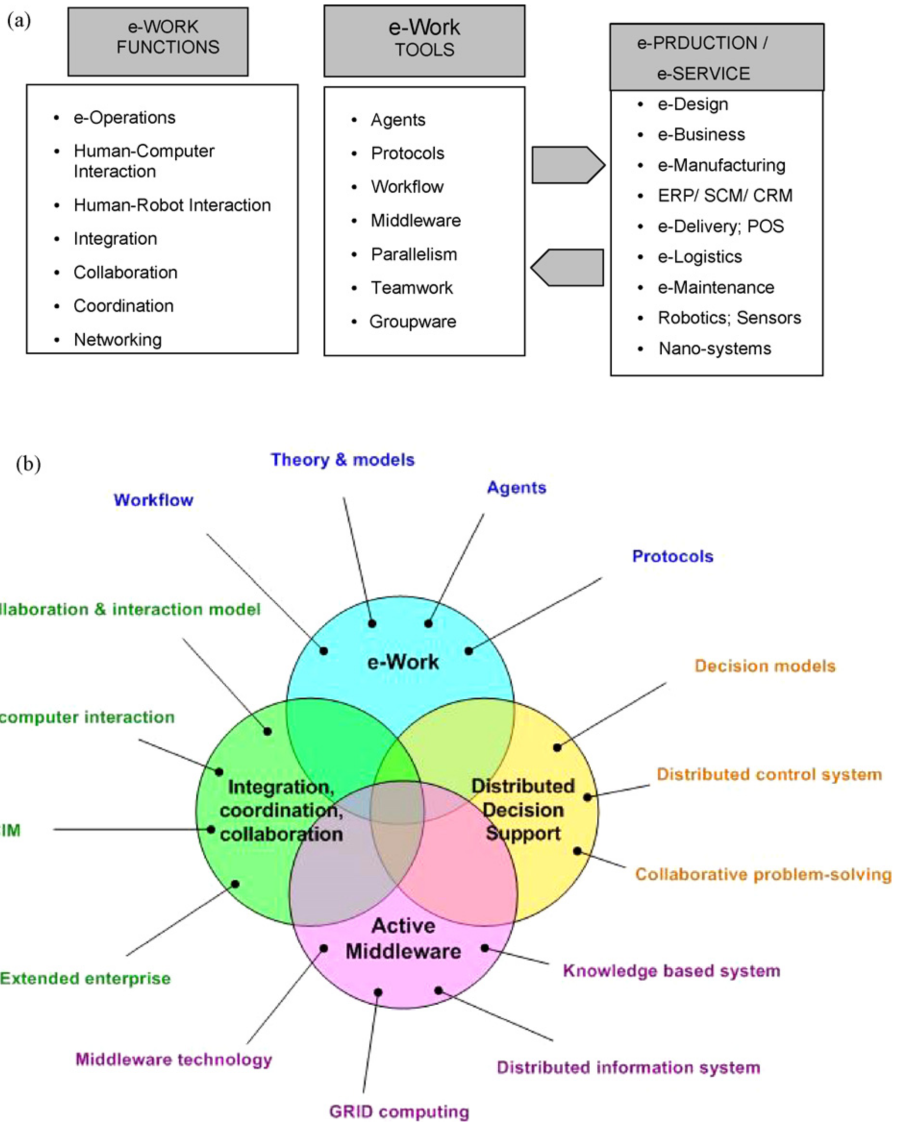


Fig. 1. e-Work, e-Production, e-Service: (a) functions and tools; (b) the four wheels of e-Work (Nof, 2003).

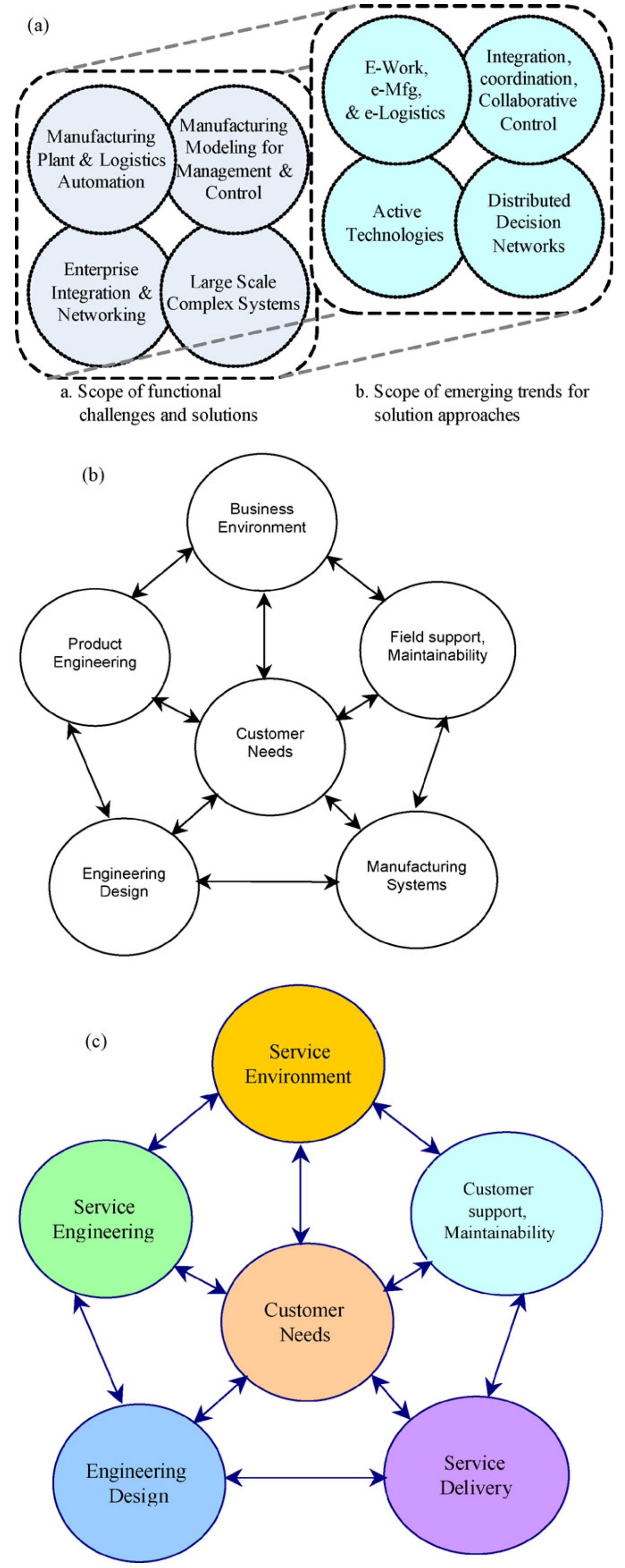


Fig. 2. Scope of e-Production and e-Service: design and engineering concerns: (a) scope of e-Production challenges and solutions (Nof, Morel, Monostori, Molina, & Filip, 2006); (b) concurrent engineering framework—manufacturing oriented (after Sanchez, Priest, & Burnell, 1994, Chap. 4) and (c) collaborative engineering framework—service oriented.

A. e-Work
  - **A1.** *e-Work theory and models*: Augment human abilities at work and organizations abilities to accomplish their goals.
  - A2. *Agents*: Function to automate flexible, adaptive activities and integration of heterogeneous components and tasks.
  - A3. *Coordination protocols*: Administer and synchronize distributed processes for coherency and integrity; also known as Task Administration Protocols (TAP).
  - A4. *Workflow:* Enables systematic procedures, process improvement and scalability, availability, and performance dependability.

B. Integration, coordination, and collaboration (ICC)
  - B1. *ICC theory and models*: Identify links between information resources and processing entities, and improve performance of collaborative activities.
  - B2. *Human–computer interaction (HCI)*: Develop systems that support people in their role as learners, explorers, and workers.
  - B3. *Computer integrated manufacturing (CIM)*: Integrate and manage the entire product life cycle.
  - B4. *Extended enterprises:* Integrate upstream and downstream business processes and workflow beyond a single enterprise, including end-to-end functions, internal operations, and entire supply chains.

C. Distributed decision support (DSS)
  - C1. *Decision models:* Contribute to effective, better quality decisions with on-line support.
  - C2. *Distributed control systems:* Allow associated parties to negotiate for their tasks and rewards with some degree of autonomy.
  - C3. *Collaborative problem-solving*: Exchange information to influence parties' local decisions for coherent and better overall results.

D. Active middleware (including web services)
  - D1. *Middleware technology:* Facilitate distributed, remote applications between heterogeneous, legacy, and advanced environments.
  - D2. *GRID computing:* Developing services by grid architecture and management for computational economy.
  - D3. *Distributed knowledge systems*: Maintain high reliability, integrity, and quality of services over large-scale distributed networks.
  - D4. *Knowledge based systems (KBS)*: Mine, refine, construct and extract knowledge for a variety of information needs.

2. Emerging principles of collaborative control theory

As mentioned in the previous section, important features of emerging production and service are the networks of collaborative teams and participating organizations, at many levels of implementation. For instance, these features (and the 15 e-dimensions of e-Work) serve well in answering the questions raised earlier about the three generations of search. Collaborative control theory has been developed to support the

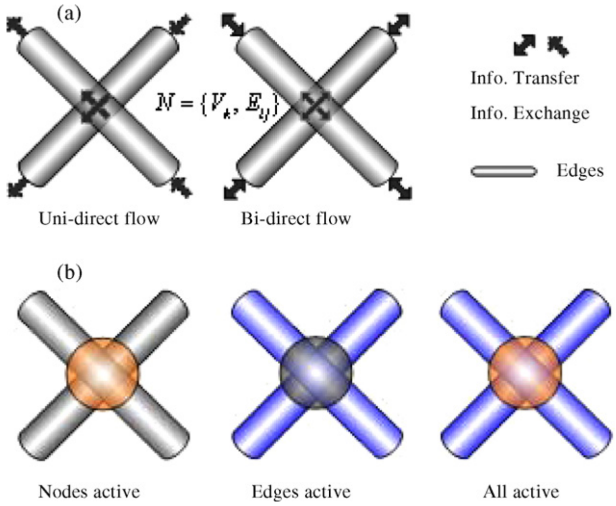


Fig. 3. Basic network models: (a) flow through edges; (b) activation of edges and/or vertices.

effective design of e-Work, e-Production and e-Service systems, including several design principles. Network models have been applied to analyze and optimize collaborative organization, and are illustrated below for each principle. A network model is defined as $N = \{V_k, E_{ij}\}$ where V is a vertex, or node; E is an edge, or channel. Flow through a network can be uni-directional or bi-directional; Nodes and/or edges can be active or non-active (Fig. 3). For instance, an edge describing a transition or transfer is non-active when no changes occur during the transition between states, or during transfer between two locations. The edge can be active when it specifies changes occurring during transition, e.g., quality testing during shipping, or optimization by an active protocol as support during collaborative communications. The following six principles of collaborative control theory have been defined, analyzed, verified and validated through various research and discovery projects. Their common purpose is to augment the work and achievements of humans, and enable organizations to accomplish their goals.

2.1. The principle of cooperation requirement planning, CRP (by Rajan and Nof)

Collaboration is one of the most powerful augmentations of work abilities by e-Work. Collaboration varies from minimal information sharing and exchange (which is a certain level of cooperation), to fully collaborative enterprises. Effective collaboration requires advanced planning, as stated in this principle. The *Principle of Cooperation Requirement Planning*, CRP, includes two phases (Rajan & Nof, 1996a, 1996b; Fig. 4a). In the first phase, CRP-I, a plan of ‘‘who does what, how, and when’’ is generated based on the work objectives and available facility resources. In the second Phase, CRP-II, during execution, the plan is revised in real time, adapted to temporal and spatial changes and constraints. The adaptation responds to changes and new constraints both in the internal facility and its components, and in the external design, logistics and market interactions.

A recent effort in robotic assembly and disassembly has been to integrate CRP with error diagnostics, recovery, and conflict resolution (Nof & Chen, 2003). The principle indicates that effective e-Work requires both advanced planning and adaptive, real-time planning of the necessary cooperation and collaboration.

2.2. The principle of collaborative e-Work parallelism (by Ceroni and Nof)

All e-Work models entail interactions among parallel software workspaces and human workspaces. The principle of e-Work Parallelism (Ceroni & Nof, 2003, 2005) is concerned with how to optimally exploit the fact that work in these respective spaces can, and must be allowed to advance in parallel (Fig. 4b). In other words, to be effective, e-Work systems cannot be constrained by linear (sequential) precedence of tasks. A simple example: tasks can be performed in parallel by software agents preparing information for human decision makers, while the latter are busy with other tasks, away, or asleep. In e-Work, workflow parallelism has a deeper meaning, since work activities can be widely distributed, locationally and over human- and software-workspaces; there can be widely distributed human–human interactions; human–machine and human–computer interactions; and machine–machine, computer–computer interactions.

2.2.1. ‘‘KISS’’: keep it simple, system!

A central design consideration of effective e-Work is ‘‘KISS’’, meaning that the computer and communication support system can be designed to be as complex as necessary, as long as it can work autonomously, in parallel to and supportive of humans, subject to their inputs and instructions. At the same time, for human users, the e-Workers, working with this support system must be simple. ‘‘KISS’’ is associated with the principle of e-Work parallelism by the notion that new versions and advanced functions of software systems must minimize the need for repeated human retraining, by using internal, parallel e-functions to simplify the transition to the evolving system's interfaces and logic.

2.2.2. DPIEM: distributed planning of integrated execution method

DPIEM is a method for planning how to satisfy a CRP-based plan (Ceroni, 1999). A key issue in this planning is the ability to determine the optimal Degree of Parallelism (DOP). DOP is defined as the maximum level of resource and task parallelism, which will balance the trade-off between increased communication, transportation, and equipment costs incurred with a higher DOP (wider parallelism), and the increased yield (productivity) gained by that level of parallelism.

In addition to the issue of DOP, there are several basic concerns in the design and implementation of any coordinated problem solving and decision support system for e-Work, which can also be considered as key concerns in active middleware development. The principle of e-Work parallelism includes five guidelines, seeking to let the e-Work Support

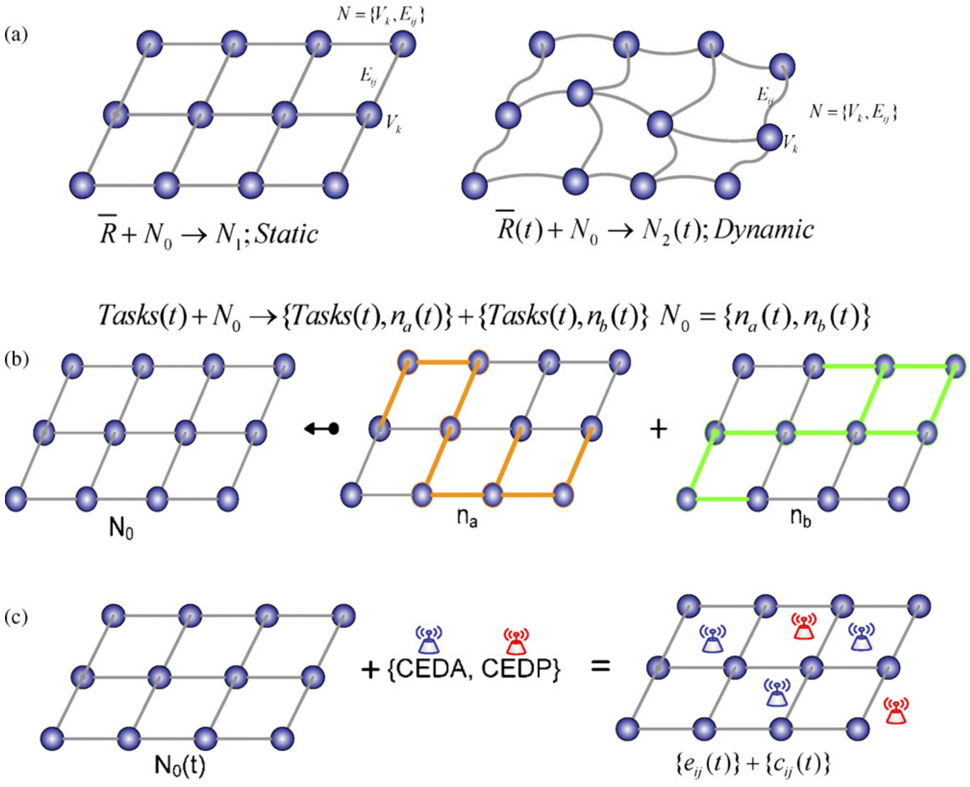


Fig. 4. Network models for: (a) CRP on initial network N_0: static requirements R; dynamic $R(t)$. (b) Assignment of tasks to parallel sub-networks $\vec{N}_a$ and $\vec{N}_b$. (c) Conflict and error detection agents (CEDA) and protocols (CEDP) are assigned to Network $N_0(t)$.

System (EWSS): (1) formulate, decompose, and allocate problems; (2) enable applications to communicate and interact under task administration protocols; (3) trigger and re-synchronize independent entities to act coherently in making decisions and taking action; (4) enable entities to reason about actions, plans, and knowledge of other agents and coordinate with them; (5) develop conflict resolution, error recovery, diagnostics and prevention.

For instance, PIEM (with centralized optimization algorithms) and DPIEM (optimization with distributed protocols) were developed for evaluating and planning the communication and coordination trade-offs in e-Work with parallelism in design, manufacturing, supply, and sales functions by Japanese, North American and South American companies; for planning outsourcing strategies; information systems middleware development; and for robotic cells design.

2.3. *The principle of conflict resolution in collaborative e-Work (by Huang and Nof)*

This principle addresses the cost of resolving conflicts among collaborating e-Workers. It has been observed and recognized that with a greater rate of interactions, which increases with the number of collaborating parties, there is also a greater rate of conflicts and errors. This problem is critical in terms of scalability. It means that beyond the information and task overloads, e-Work must be designed to overcome quickly and inexpensively as many errors and conflicts as required to be effective. Huang and Nof (1999; Fig. 4c) showed that for practical values of the probability to resolve a conflict in one of several iterations of negotiations, the total resolution cost would depend on the relative portion of human intervention in the resolution process, as follows:

(a) With more errors and conflicts, the cost of resolution grows exponentially and it is unbounded. Implication: Under these design conditions, the e-Work system will collapse because of ineffectiveness.
(b) With less human involvement in the detection and resolution, approaching zero, meaning IT services are designed and applied in parallel for detection and resolution-support by automating functions (active task administration protocols) of negotiations for corrections or compromises, then the total cost of resolution reaches an upper bound. Implication: In this case, e-Work systems can be effective and scalable.

The design objective, following this principle, is to develop better and more powerful IT support for detection, prevention, and resolution or recovery of errors and conflicts in e-Production and e-Service, leading to lower overall costs, better quality results, and more effective e-Work. A relevant example is the recent work by Chen and Nof (2007a, 2007b) developing computer-supported CEDM, conflict and error detection management, prognostics and diagnostics methods aiming to

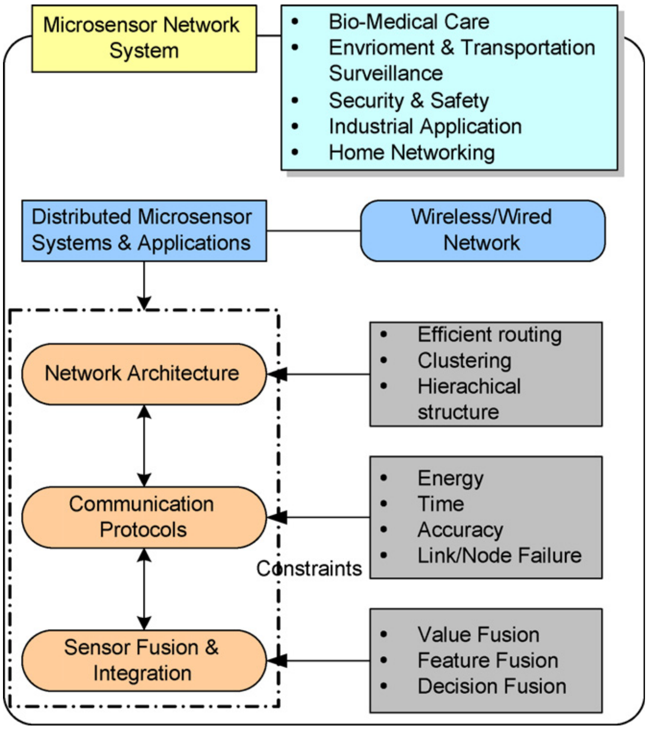


Fig. 5. Applications and development of distributed microsensor networks (Jeong & Nof, 2005a).

eliminate errors and conflicts in robotic systems and in supply networks.

2.4. *The principle of collaborative fault-tolerance (by Jeong and Nof)*

Feed-forward collaborative control protocols combined with fault-tolerant collaborative control can yield better, more effective results from a team of weak agents, such as nano- and micro-robots and sensors, relative to a single optimized and even faultless agent (Jeong & Nof, 2005a, 2005b, 2007a, 2007b; Figs. 5–7). Beyond the synergy lesson, well known from ancient history, that a collaborative team is better than the sum of the individuals, this principle addresses *how* to achieve this advantage by smart automation (e.g., Ghiasi, Srivastava, Yang, & Sarrafzadeh, 2002), even with some faulty (or temporarily faulty) agents.

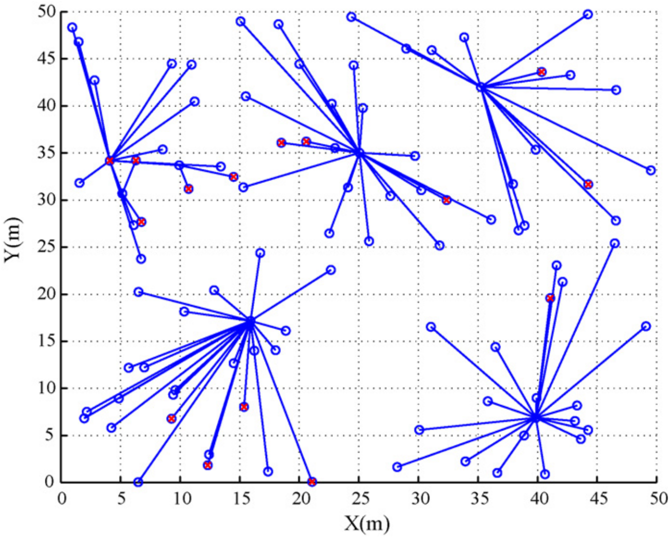


Fig. 6. Faulty sensor routed communication by a time-based control (Jeong & Nof, 2005b).

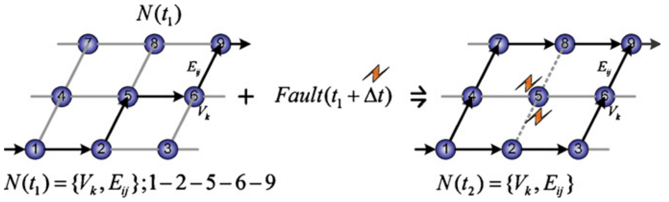
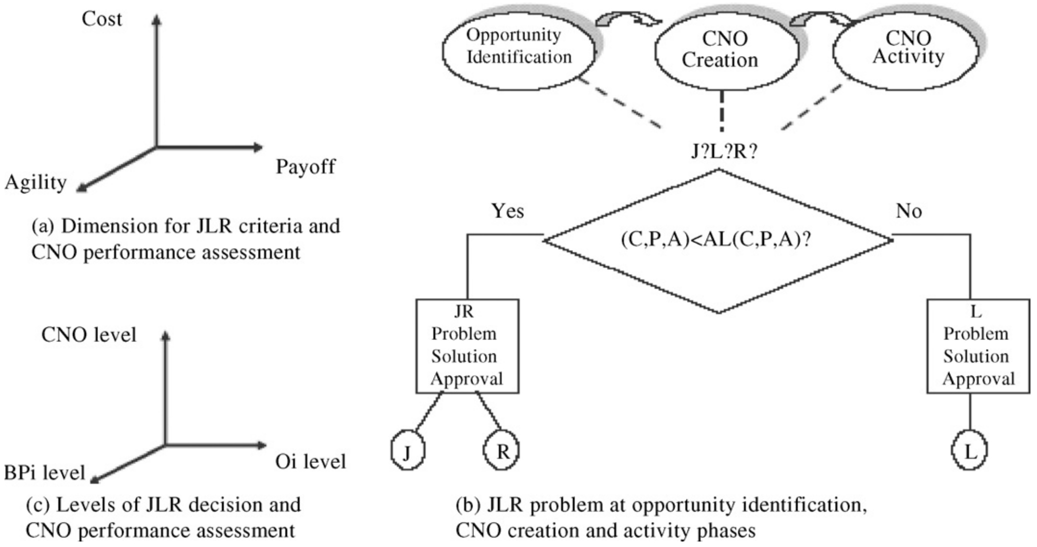


Fig. 7. Collaborative fault tolerance: original network with flow 1-2-5-6-9 adapts to link or node failures and converts to backup flow 1-4-7-8-9 or 1-2-3-6-9, depending on energy and response-time constraints.



(a) Dimension for JLR criteria and CNO performance assessment

(c) Levels of JLR decision and CNO performance assessment

(b) JLR problem at opportunity identification, CNO creation and activity phases

Fig. 8. The JLR decision in collaborative enterprises (Chituc & Nof, 2005).

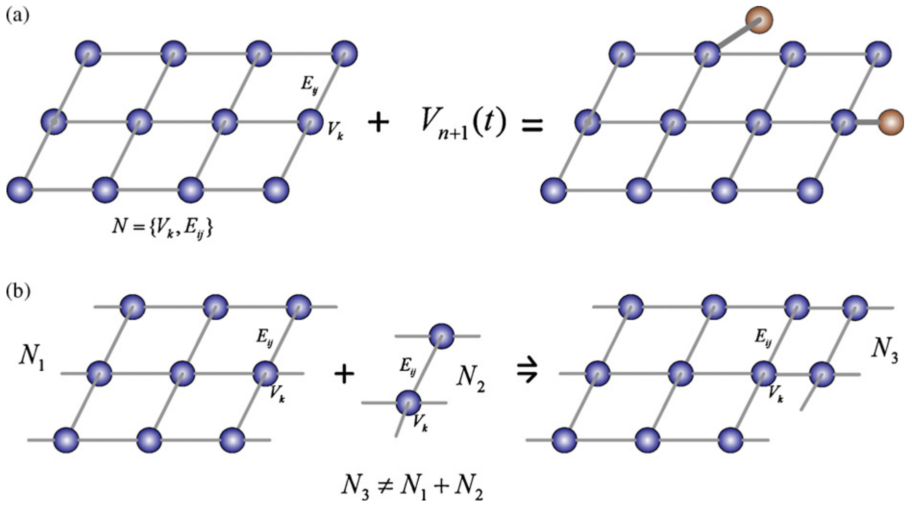


Fig. 9. The JLR model: (a) Original network is joined by two individual vertices. (b) Larger and smaller networked organizations unite, transforming the original structure.

Conflict resolution and error detection in collaborative design of products and facilities, and knowledge-based diagnostics and recovery of robotic work have been developed. Control Protocols for such diagnostics, prevention, resolution, and recovery are important design issues. Collaborative e-Work has to depend on cheaper, redundant groups, arrays, networks, and grids of interacting peers, e.g., groups of disposable service micro-robots, human designer teams, and DNA-sensor arrays. Enabling effective e-Work in each of these examples requires effective handling of errors and conflicts.

2.5. The join/leave/remain (JLR) principle in collaborative organizations (by Chituc and Nof)

This principle is associated with the increasingly virtual and dynamic nature of enterprise alliances (Camarinha & Afsarmanesh, 2005; Hou & Su, 2006; Seth, Deshmukh, & Vrat, 2006; Wu & Su, 2005; Yigin, Taskin, Cedimoglu, & Topal, 2007). It can also be valid for self-organizing agent-teams, sensor-clusters, and modular services. It addresses the conditions and timing for individual parties or organizations to join, leave, or remain in a collaborative networked organization, CNO (Chituc & Nof, 2005; Figs. 8 and 9). The JLR decision for individual e-organizations (or v-organization) ponders, when and why would this organization join a given CNO? What are the specific benefits this particular organization would gain by participating in a given CNO? How much would it cost to participate in the given CNO? And why would a particular organization wish to remain in a given CNO? Similar JLR decisions have to be pondered repeatedly also by every CNO: Is there a significant positive balance between total potential benefits and the costs incurred (including increased coordination) relative to each of the member organizations? Which are the key dimensions to most succinctly characterize and assess the whole CNO and its performance?

The JLR problem can be analyzed at different levels: CNO level, individual organization's level (Oi), and inter-organizational business processes (BPi) level. There can also be interest in sub-grouping of some organizations within the CNO, which is termed sub-CNO, and in multi-CNOs. Each level can be analyzed for each phase of the CNO life: CNO creation, CNO activity, CNO dissolution, and CNO support. It can be noted, however, that such performance analysis is phase- and multi-phase correlated.

2.6. The principle of emergent lines of collaboration and command, LOCC (by Velasquez and Nof)

Another abundantly evident challenge of modern enterprises is the highly dynamic, often volatile nature of formal and informal communications among participants, both within and between organizations, and with suppliers and customers. Interdependence among participants increases, and so does mobility. While telecommunication, internetworking, and wireless mobility are rapidly impacting production and services, questions under time constraints of whom to contact, which channel to use, and details of the message are often challenging. The LOCC problems are particularly critical under severe natural and security hazards (Velasquez, Yoon, Partridge, & Nof, 2005; Velasquez & Nof, 2007; Fig. 10). This principle focuses on the impact of Lines of Collaboration and Command within an organization to enable better collaborative decision making under the complex and dynamic nature of requirements, the cost of information and its timely delivery, and the development of emergent networks. Emergent networks are defined as evolutionary mechanisms of interac-

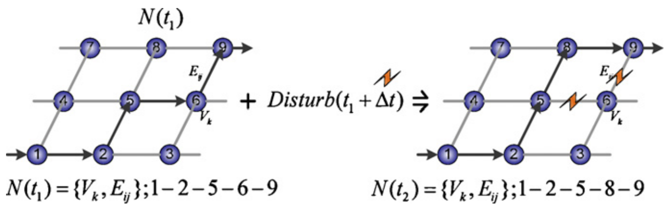


Fig. 10. LOCC model: Line 1-2-5-6-9 evolves after disturbance (emergency) to 1-2-5-8-9.

tion, developed by organizational learning. They are characterized by the need for ad-hoc decisions, handling effective improvisation, on-the-spot contact creation, and best matching protocols for pairing information alerts and decisions, decision makers and executors. Examples of system that can benefit from an LOCC design based on this collaborative e-Work principle: PHERIS for surveillance, collection and reporting of information, command center for detection, decision making, order issuing, resource planning and allocation (Liang & Xue, 2004); SACHEM, which is a large scale real-time KBS for monitoring and diagnosing dynamic processes for blast furnaces (Le Goc & Frydman, 2004).

2.7. e-Measures, e-Criteria

New measures and performance evaluation criteria are required for collaborative control, as mentioned in the above principles. In the emerging e-Production and e-Service, these new measures are considered in addition to traditional measures of effectiveness. Certain measures have already emerged with the advent of CIM and networked enterprises: Flexibility, agility, connectivity, integration-ability, scalability, reachability, and so on. Two recent measures developed for e-Work design and collaborative control are level of autonomy, and viability (e.g., Huang, 1999). The autonomy level implies the delegation of authority, decentralization, and how active (i.e., provide their own intelligent decisions) the agents, protocols, and other e-Work system participants can be. Viability in the context of e-Work has been defined as a relative measure of the ratio between the cost of operating and sustaining agents, and the rewards from their services. Theories of agent design and interaction have been developed using measures of autonomy and viability. Anussornnitisarn (2003) discovered that collaborative e-Work rationalized by viability-based protocols performs significantly better than by protocols ignoring viability.

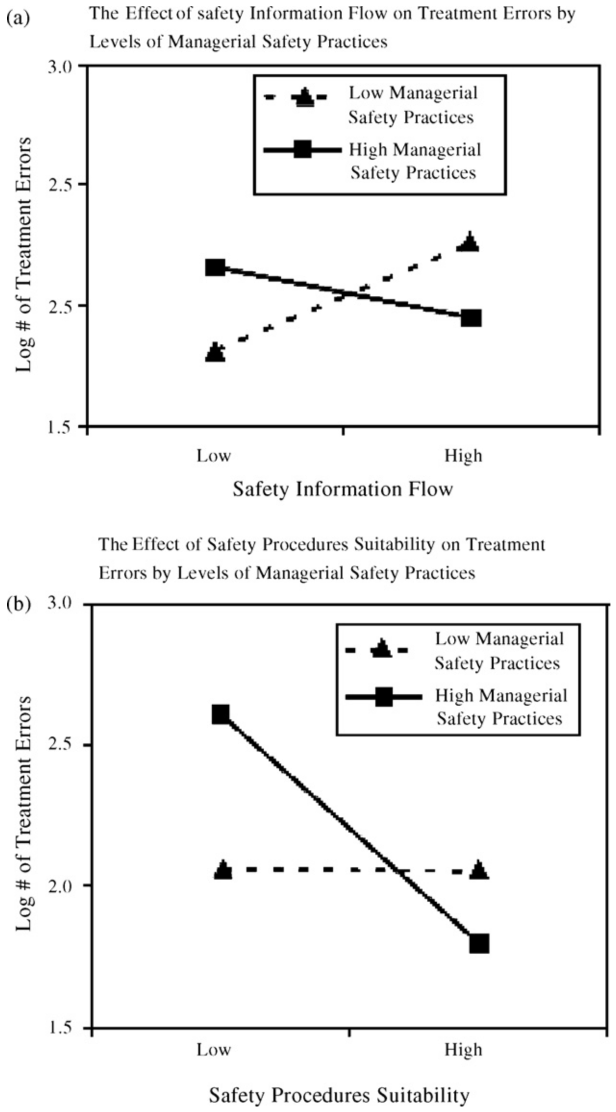


Fig. 11. Collaborative control performance in the form of managerial safety practice sharing, in terms of (a) reduction in errors and (b) procedure suitability (*Source*: Naveh, Katz-Navon, & Stern, 2005).

An interesting example of collaborative control performance enhancement can be illustrated in health-care service delivery (Fig. 11). Improvements are indicated in quality-of-service (significant reduction in treatment errors) when managerial safety practices are shared. Examples of other emerging collaborative control measures for e-Work design are: learning-ability, collaboration-ability; Integration-ability, errors- and conflicts-severity, errors and conflicts prevention-ability, detect-ability, diagnosis-ability, and recovery-ability. Measures related to information assurance: measures of security, integrity, and information significance (Bellocci, 2001).

3. Bio-inspired design and collaborative control principles

3.1. Bio-inspired collaborative control

The development of collaborative control in e-Production and e-Service by multi-agent theories and techniques has also been inspired by biological control. For instance, in ant colonies, collaborative hints are made available locally by pheromones. Such efficient animal–animal interactions have been adapted for coordinating agents and holons. The principle is to reduce overloads on individual insects' (and agents') decisions, by eliminating the complexity and details locally, sharing instead minimal useful traces (for instance, Hadeli, Valckenaers, Kollingbaum, & Van Brussel, 2004). Hence, their communication efforts and task overloads can be minimized, while their actions are effective. Bio-inspired applications have included virtual ants as mobile software agents (bots); message-based interactions among agents and robots; and control-measures, such as the viability and autonomy of agents, analogous to living creatures' survivability and independence. Negotiation-based and bio-inspired techniques are two useful approaches for multi-agent collaborative control, especially in complex organizations and enterprise networks.

3.2. Adaptation and learning in collaborative control

Learning and other adaptive mechanisms are essential in production/enterprise control and automation, and can be categorized as:

- *Centralized learning*—approaches executed entirely by individual, autonomous agents, excluding any interaction with other agents.
- *Decentralized, interactive learning*—approaches executed by joint and coordinated interaction among several agents/ learners.

Adaptation is effective in market-based resource allocation processes to satisfy customer orders. The adaptation can be a centralized approach by which each resource agent locally adapts its behavior to achieve a more rewarding position relative to other agents. Feedbacks include measures of utilization and bid awarding, or rejection by order agents, e.g., the ratio between won and lost bids.

Simulation studies at different labs repeatedly demonstrate that the major advantage of adaptation-by-agents is a significantly more rational allocation of tasks and more balanced use of resources. Specifically, economic performance measures have proven to be better for agent-base adaptation protocols.

3.3. Bio-inspired network models

Recent research in neurology (e.g., Mysore, 2006; Shultz, Mysore, & Quartz, 2006) and bio-membranes (e.g., Ho, 2006; Ho, Chu, Lee, & Montemagno, 2004) reveals enabling bio-mechanisms of adaptation and collaborative control. For instance, millions of synapses and spines collaborate to achieve survival and competitive animal behaviors. Similarly, human-made enablers of collaborative control, such as adaptivity, dependability, interoperability, discovery by data mining, decision support, active middleware and web-services, etc., can also be modeled by bio-inspired networks, as depicted in Figs. 12 and 13. It is anticipated that further investigation of such bio-inspired brain models will increase our understanding of how to optimize e-Work for e-Production and e-Service.

Further research is carried out to understand how biological collaborative control may be useful. It is expected that learning from nature's design and control, discoveries will inspire significant progress in understanding how to model optimal automation for human benefits.

4. Implications and open questions

The emerging future of production and service enterprises depends on the understanding of how effective e-Work can be designed and integrated into their design. Collaborative control principles, models and techniques, as explained in this article, provide useful insight to design guidelines. Design to achieve the benefits enabled by e-Work and optimized e-Activities will lead to the needed levels of delivery, integrity, quality, performance, and QoS. In this article, the nature of e-Work, e-Production and e-Service, their respective roles and functions have been explained. Clearly, e-Work methods, systems and protocols cannot and should not duplicate non-e traditions (e-Work $\not\approx$ Work). Traditional economic measures of produc-

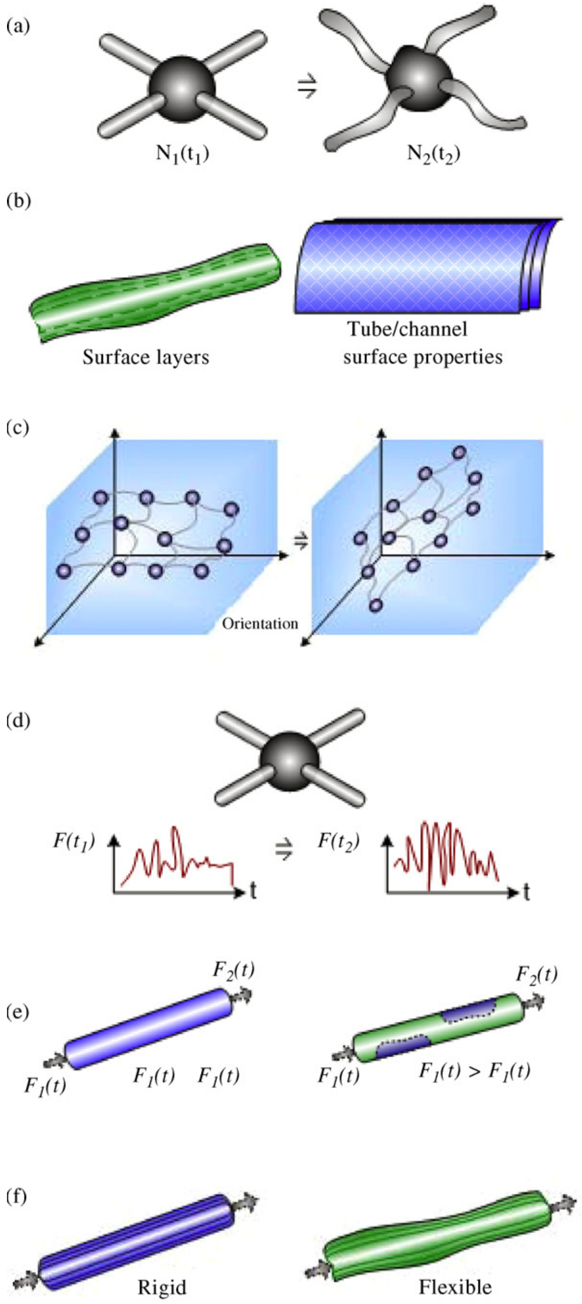


Fig. 12. Physical, electrical, and bio-chemical dynamic changes in neural and brain activities enable collaborative control and interactions (e.g., experiments with mice and barn owls, Mysore, 2006; and bio-membranes, Ho, 2006). Bio-inspired network models of e-Work, e-Service, and e-Production are developed: (a) channels (arteries) modify their shape and plasticity over time; (b) the surface of channels changes dynamically; channels may have multiple internal layers; (c) changes over time in network spatial orientation; (d) time-variable electromagnetic channels waves ("sound") as observed via nano-wires in mice; (e) network learning: structural plasticity has role in behavior—channel rigidity allows free flow, vs. channel blockages which constrict flow; (f) network learning: rigid vs. flexible channels (arteries).

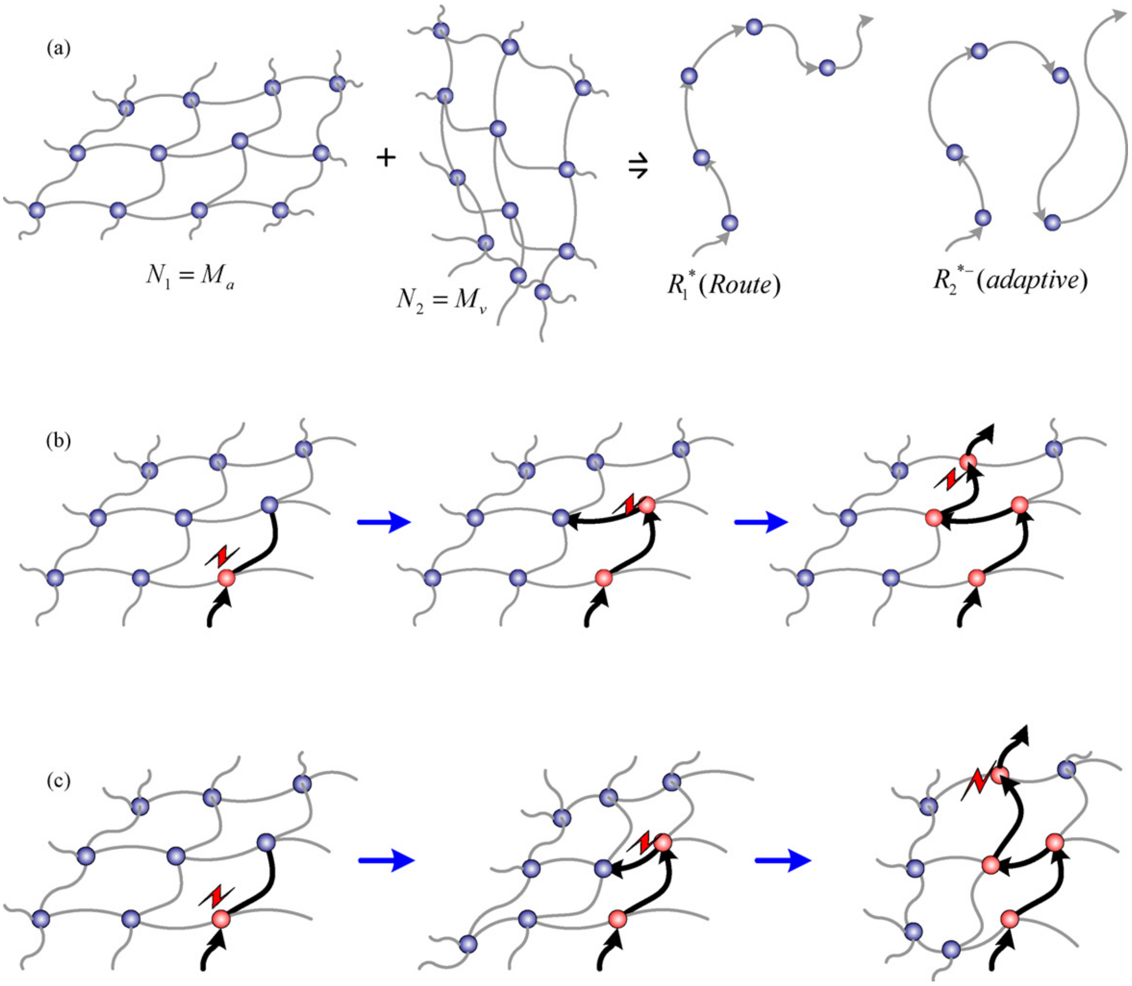


Fig. 13. Bio-inspired network models: (a) survival mechanisms of escape and prey hunting—calibrating by alignment of two topographic maps (left), one auditory (network N_1) and one visual (N_2) the barn owl can optimize a route R_1^* and dynamically adapt to route R_2^* (rightmost); (b) cascading causality (propagation) consecutively leading to changes in certain affected arteries; (c) same, but changes are affected in both arteries and network structure.

tion, services, and productivity continue to be valid and important. Performance measures, such as functionality and usability, have to be augmented by trustworthiness and e-advantages, e.g., ease of human navigation and communication through complex, highly distributed interactive environments. Other measures, related to errors and conflicts, information assurance and responsiveness are receiving increased attention because of the emerging challenges. New measures reflect analogies to bio-inspired control, e.g., viability, collaboration-ability, and survivability.

Network models have been applied successfully to describe the nature and design of smart networked teams in the context of e-Work, e-Production and e-Service. These models are applicable at organizational network levels form nano-sensors and micro-robots, to multi-agents and extended enterprise networks. Further study is needed to understand the limits of these network models in highly complex environments. Several other interesting questions remain open:

1. Which organization to join? When several organizations are relevant and available for a given party (mobile sensor, robot, agent, or enterprise) looking to join, which of them would be preferred?
2. Organizations joining each other: When a networked organization wishes to expand by collaborating with one or more other organizations, thus organizing a ‘‘super-network’’, which organizations or their sub-sets would be the best candidates? Can optimal modules (or clusters) of networks be effectively and rationally combined to increase scalability of service?
3. Joining (combining) two or more organizations by a given organization, which is becoming the link that combines them for a ‘‘multi-network’’—How can economic, quality, and functional measures be useful for this decision?
4. Clustering optimization: With dynamic changes occurring frequently, how can a networked team, e.g., of robots or sensors, reorganize itself to optimally shrink or expand by clustering?
5. Profitability versus sustainability: In economic survival terms, can measures of rewards be balanced by sustainability measures, especially for public sector and non-profit enterprises?

6. Penalties: Agreements, contracts, and legal binding protocols with their associated penalties are common in corporate life-cycles. They are also applicable in agent-based networked systems of agents, robots and sensors. How do contractual penalties figure in addressing the above decision questions?
7. Topology-based performance: Does an organization's productive performance depend on its network topology in terms of looseness, redundancy, and contract-binding terms over time?
8. Bio-inspired network behavior: Can theory and principles of collaborative control be further investigated following inspiration from brain models?

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