Cross-layer Paradigms in the Convergence of Computing, Communication and Control (C^3)

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***Abstract*—A closer insight into the design of existing embedded systems suggests that *computation, communication* and *control* (C^3) are indivisible research fields. C^3 convergence is broadly considered as the research agenda in information technology for the next decades. The paper review preliminary results and future perspectives on new ways of thinking C^3 convergence. The starting point of the analysis is the wireless technology. The technology is seen as the communication infrastructure of a *team* of artificial agents cooperating to realize specific tasks in *tactical* environments. The term tactical defines a family of applications related to hazardous and challenging scenarios as in military and civil protection worlds. The envisaged research issues provide effective technological improvements for tactical teams and, more ambitiously, attractive theoretical insights into the foundation of C^3 convergence.**

Keywords- *actor-sensor networks, cross-layer paradigms*

I. Introduction

THE LAST half of the twentieth century was the age of the building of *computation*, *communication* and *control* (C^3) disciplines. Recent research trends [An04, Js08] suggest that the convergence of these disciplines opens great possibilities for interaction with the physical world [Ku04].

The paper outlines research ideas on the investigation of *new way of thinking the design of C^3 convergence*. The main issue is extending cross-layer paradigms of communication engineering to the entire C^3 chain. More specifically, the present approach takes origin from recent research fields of wireless technology (e.g., mobile ad hoc, sensor networks). The technology is seen as the communication infrastructure of a team of artificial agents cooperating to realize specific tasks in tactical environments. The document is organized as follows. Application scenarios and social impacts of the C^3 research are highlighted in the next section. Section III proposes an insight into scientific motivations and challenges. Section IV finally outlines some new ideas.

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II. Application Scenarios and Social Impacts

A. Technological trends

Embedded systems of particular interest in this paper are devices interconnected through ad hoc wireless infrastructures ([La05, Ku04]) and acting together towards the accomplishment of a common mission. Each device communicates with each other by exchanging information and acting over the environment. Such kind of systems are identified here as *mission teams*. Each component of the team is called *agent*.

B. Application scenarios

The mission of the team is interaction with the environment in tactical situations. *Interaction* means sensing variables of interest from the environment and actuation over the environment. The term *tactical* defines a family of applications related to hazardous and challenging scenarios as in military and civil protection worlds.

Possible examples are: **i)** vehicle exploration of inaccessible (planets), dangerous (volcanoes) or hostile (behind enemy lines) environments or **ii)** expert systems to coordinate effective emergency operations (e.g., rescue) and disaster relief efforts. The *Global Information Grid* (GIG) project of the United States Department of Defense recently activates research studies in these fields. In GIG environments, action theatre is composed of a huge amount of agents, spread over large regions through different vehicles and interconnected through heterogeneous communications means. Agents possess autonomous decision making capabilities and receive controls from remote headquarters. Decision making is continuously supported by information captured on the field. In the GIG viewpoint, providing effective support to the entire decision chain involves the development of techniques covering the spectrum of all C^3 activities [Ja06].

C. *Sensing*

Recent network infrastructures enforcing the concept of environmental sensing are *sensor networks*. Sensor networks are receiving great attention from the scientific community because they seem representing the ultimate wave moving towards C^3 convergence. In these infrastructures, nodes with variety of sensors (acoustic, sismic, infrared, videocamera) have wireless communication capabilities and some level of intelligence for signal processing and networking of the data. Some applications are: **i)** detection and tracking phenomena (e.g., movement, explosions) or parameters (temperature, atmospheric pressure, amount of sunlight, humidity) of interest at a given number of locations; **ii)** characterization of (chemical, biological, radiological, nuclear and explosive) material; **iii)** monitoring environmental changes (in plains, forests, oceans); **iv)** surveillance (e.g., monitoring vehicle traffic, assisting alertness to potential threats).

The list suggests that sensor networks enforce capabilities of a mission team to feedback information from the environment. Then, proper actions may be provided by agents in dependence of the specific targets of the mission. Example may be: **i)** exploration, **ii)** triggering alarms, **iii)** transportation, disposal or release of some specific objects or material, **iv)** track or destroy specific targets.

D. *Action*

In the mere communication viewpoint, sensor networks are engineered to support reliable communication in the presence of constrained (bandwidth and computational) resources. Data acquisition is based on the "data mule" principle (i.e., a single entity, often human, periodically visit each sensor site and collect last measurements) or on routing information towards a single information centre (called sink node). In the C^3 viewpoint, such data acquisition procedures are too limited. Endowing agents with both sensors and decision capabilities to influence external environment drastically expands the spectrum of team capabilities. For instance, sensors (or at least sinks) could move around the environment to maximize probability of capturing events of interest [Ca05].

E. *Technological and environmental constraints*

Mission accomplishment over tactical environments means the assurance of resource control to guarantee specific degrees of *Quality of Service* (QoS) at both communication and control application levels. That means command-and-control information exchange must support the right decision at the right moment in any traffic condition, even in the presence of unexpected congestion, network failures or external manipulations of the environment (e.g., due to the presence of hostile entities). Topology of the team may be: **i)** *heterogeneous* (different computational and network technologies may compose agents structure), **ii)** *hierarchical* (team organization may be based on different levels of responsibilities) and **iii)** *dynamic* (connectivity among the agents varies with time due to mobility, agents arrivals or departures, network failures).

III. Scientific and Technological Aims

Mission team involves open research issues in all C^3 disciplines.

A. *The communication perspective*

In the communication perspective, network infrastructure of mission team is designed according to cross layer methodologies [Fa05]. *Cross layer* design is an emerging research field in changing conventional design of communications protocols. Traditionally, network protocol design has been based on a layered approach in which each layer in the protocol stack is designed and operated independently, with interfaces between layers that are static and independent of the individual layer constraints and applications. The approach exploits the advantage of modularity in system design. However, the system dynamics representing the interactions among the protocols at the different layers is fairly complex because of the existence of numerous parameters and the nonlinear nature of the protocol state machines at the different layers. Careful exploitation of some cross layer interactions leads to more efficient network performance and hence better application performance. As such, the concept of cross layer design can be generalized for the entire C^3 chain. This topic is detailed in the next section.

B. *The control perspective*

In the control perspective, team theory has a long tradition. Networked control systems more recently receive great attention [An07]. Heuristics and optimization approaches exist for team control design, especially in case of exploration of a given set of targets in unknown environments [Li06]. From the mere control perspective, however, many topics of research are still open. One of these is related to the hierarchical structure of teams. The presence of different kind of agents, each of which having different level of responsibilities (from sensing to actions), implies more general cooperative control approaches [Ak04].

C. *The C^3 perspective*

More fundamental issues of much broader long-term impact must be highlighted [Cs05]. They can be reasonably considered as the agenda in information technology for the next decades [Fr07, Gr05].

1) *Time-driven versus event-driven systems*. While the gathering of data is inherently asynchronous, the processes of data fusion and control are traditionally synchronized. Some sort of matching between state machine design (of computational processes) and differential equation engineering (of control theory) is needed. This idea introduces the study of new design patterns of programming languages [Ga95], aimed at building a middleware "bridge" [Ba04, Ku04] between time driven and event driven procedures.

2) *Sensor-poor versus data-rich systems*. A second research issue of particular importance is the shift from sensor-poor to data-rich control systems. Before the sensor network age, control system were designed in the presence of limited state information. After that, control systems should be studied in order to comply with the presence of a huge amount of (sometimes redundant) information.

In overall, while times seem mature for C^3 convergence, curiously, such a convergence seems turning back scientific community to the original concept of *cybernetics* of the mid of last century. Even before the advent of C^3 disciplines and their complete independence, cybernetics was a debated [Mi03] school of thought that looked at information theory as a "meta-theory" capable to abstract "natural laws" of information processing, thus giving unified foundation of dialectical description of C^3 languages, and simultaneously to extend it beyond technology into biology, economics, social systems, human language, and hence a broad array of human activities [Wi48].

IV. Cross Layer Paradigm up to Control

A. Key idea

The current proposal is not so ambitious. Some original ideas are outlined specifically for mission team management, by planning original techniques where C^3 disciplines can converge.

To summarize the concepts outlined in previous sections, it must be noticed that building a mission accomplishment control system, supported by a wireless ad hoc network, is a challenging task that requires a new design approach [Ak04]. The design objective is mission accomplishment. There is a tradeoff between communication and controller performance. Traditional control design faces the problem of noisy feedback from the environment. Increasing the number of sensors may help control performance, but this is not so straigthforward because that also means increasing network congestion and thus eventually leading to lossy and delayed control feedback. Communication and control should be therefore designed jointly (see, e.g., [Xi03]).

B. Joint protocol stack

The idea here is to study the effects of control actions on the communication environment and viceversa (communication actions on control applications). The new concept of *joint protocol stack* is introduced. Joint protocol stack defines the addition of the application layer to regular communication protocol stack so that cross layer design can be applied to the communication and control chain. In the eyes of the communication protocol stack, application is team control to accomplish the mission. Generalizing the example above, actions of the agents are considered influencing the entire C^3 chain. That means their effects must be considered at both application and network levels. Actions at application level are those actuations that directly influence the environment (e.g., firing over specific targets). In the regular *Open System interconnection* terminology, actions at network level may independently involve: modulation and error correction techniques at physical layer, access scheme at link layer, routing at network layer, congestion control at transport layer, middleware translations and socket classification at presentation and session layers. Those schemes should be designed all together to optimize protocol stack performance. Ultimately, action at network level means control of network resource to support QoS communication. In turn, QoS supports reliable information exchange within the team, thus eventually mission accomplishment. A reciprocal influence between network actions and application actions exists. Team cooperation can be therefore extended from the application layer towards all layers of the agent computational and communication structure.

C. Cross layer variables and costs

An engineering approach to the mission team problem means formulating and solving an optimization problem involving joint protocol stack design. That means introducing a proper mathematical formulation of involved cost and control variables. Roughly speaking, the cost of the mission usually measures the distance between the current state of the team and the final one, where the mission can be considered "accomplished". Study the reciprocal influence of the actions according to cross layer design means formulating the mission accomplishment problem in terms of cross layer cost and cross layer variables. *Cross layer cost* means modelling the distance in terms of all the performance measures of the joint protocol stack. The cross layer cost takes into account communication costs (e.g., delay and loss of information, energy consumption, call priority, fault tolerance guarantees) together with mission costs seen by the application layer (e.g., distance from the target to be reached). Cross layer cost is formulated using cross layer variables. *Cross layer variables* describe control decisions at communication level (modulation scheme, bandwidth allocation, scheduling times and so on) and application layer (movements, material release, sensing).

D. The way ahead

Investigation on modelling cross layer variables and optimizing cross layer cost constitutes a frontier research line. The formulation is made explicitly (whenever possible) or implicitly. At this stage of research, the problem of analytically intractability of the formulation is disregarded. Methodologies to face such intractability are outcomes of the research.

1) *Heuristic approaches*. Analytical models and optimization of cross layer costs are hard tasks. The analytical description of performance measures is sometimes impossible even for single layers; numerical approaches should be investigated (see, e.g., [Ma07] and references therein). Some preliminary approaches of joint communication and control designs are recently proposed in the literature. Even if they are dedicated to specific cases, they can be considered as preliminary steps towards joint protocol stack design. More specifically, some examples for simple control applications are reported in [Go04, Li04, Xi03]. Some theoretical results on the effect of communication losses in linear control systems are envisaged in [Li04, Xi03]. In [Ca05], the composition of communication and control costs is provided to highlight the effect of limited communication resources on the movement capabilities of a sensor team. The empirical iterative method of [Go04], used for layers parameters tuning, is of great interest. It is suboptimal because it is based on just a few protocol parameters. Reciprocal effects between layers are not explicitly considered. Even though it is a suboptimal algorithm, it still yields significant performance gains and insight. So, generalizing such heuristic approach for mission teams seems promising and deserves further analysis.

2) *Theoretical approaches*. It is common opinion that there is a lack of theory in evaluating cross layer design. Some emergent theoretical approaches are base on the adoption of: Markov Jump Linear System modelling [Go04], static optimization approaches [Cu07] or extensions to regular Kalman filtering theory [Li04]. Without entering in the details, these models may allow capturing the effect of cross layer variables and driving resource allocation at each layer of the joint protocol stack. Several limitations affect these approaches. Lack of: practical experience, non linear state modelling, distributed computation together with unrealistic certainty equivalent assumptions on the stochastic environment and severe notational and computational burden significantly affect joint protocol stack engineering. Notational burden is motivated by the need of letting cross layer variables playing their effects on the cross layer costs. Some sort of cross layer "synthesizing parameters" should be investigated. Computational burden arises if limited computational resources are not explicitly considered. Thus, cross layer solutions should approximate optimality with a small computational effort.

3) *Mission accomplishment optimality*. Again regarding theoretical aspects, it must be noted that mathematical approaches in [Ca05, Cu07] exploit joint protocol stack formulations by considering a simple weighted summation of a limited set of C^3 performance measures. The approach allows capturing the reciprocal influence of C^3 measures in terms of Pareto optimality. That means a curve of operational points of the system is found as a function of available resources. No performance measure of that curve can be improved without decreasing another one. Pareto optimality curve leaves open the choice of implementing a specific behaviour of the agents, since an infinite set of operational points can be extracted from the curve. The main question is: *does a Pareto optimal point exist to assure the highest probability of mission accomplishment with the minimum quantity of resources?* Such a problem involves some form of search criterion within the set of Pareto optimal points. The search criterion must capture the concept of mission accomplishment.

4) *Cross layer protocols.* Cross layer methodologies are not consolidated. Different approaches [Sr05] may be applied in dependence of the specific applications and network deployments. Appropriate procedures for cross layer information exchange and optimization are far away from being well discussed and standardized. Extending cross layer principles to control application is an original idea. As such, the study deserves much more attention than it has received for cross layer in communications. A cautionary perspective on cross layer design [Ka05] suggests that an important question to answer is what parameters must be shared among different layers and how each layer can be made robust to changing system conditions. In this view, a generalization of the regular concept of inter-layers *Service Access Point* (SAP) (especially taking as reference QoS environments [Et06]) may help interface control application requirements with network and computational infrastructure.

5) *Middleware*. The SAP principle may also lead to the study of novel middleware architectures, specifically designed to support portability of mission accomplishment solutions across different technological platforms. Since operating systems, drivers and network devices may not be common across all platforms, a useful solution is to insert a layer before the application stack. Such a common interface is known as *middleware*. The idea is to hide the unnecessary details on how specific functionalities are provided by lower layers. Reliable communication (using, e.g., TCP), energy aware routing, fading counteraction and other specific network functionalities may be activated by middleware primitives only when needed and without entering in details on how network functionalities are guaranteed. A good example is "etherware" [Ba04], recently developed to abstract communication functionalities in networked controlled systems. Developing appropriate techniques (as the ones mentioned at points **1)-3)** above) at middleware level introduces a generalizing degree of abstraction so that solutions can be slightly modified when changing operating systems or hardware devices. The challenge is to let solutions easily portable over other network environments (when changing physical communication supports) or applicable for other control purposes (when changing mission requirements). It is worth noting that middleware solutions in this context are not required to interface with the other SAPs components of the system. That means if other SAPs are developed at different layers of the protocol stack, they do not interfere with the higher SAP positioned at the middleware level, namely closest to the application layer.

Specific laboratory instrumentations is necessary to constitute hardware prototypes of the C3 solutions. The aim of the instrumentations is to create a system of sensors, controllers and actuators that communicate and function over a network of computational nodes. A good reference in this context is [Gr03]. The testbed of [Gr03] is dedicated to action coordination for autonomous vehicles. However, as also state in [Gr03], the idea is going beyond centralized coordination of autonomous vehicles and improving their independent processing, cognitive and observational capabilities. Applications to be emulated must be detection and tracking of specific phenomena using agents coordination at both communication and control level. The adoption of cognitive radio capabilities may be of great help in this context.

All mentioned issues deserve further study. The theoretical analysis outlined above in particular is left open for future research. As to specific experimental results on some families of C^3 networked controlled systems, the interested reader is referred to [Js08].

V. Conclusions

While it may be too early to be definitive about C^3 research potentiality on the long run, it may be argued that the envisaged research lines constitute real challenges that can contribute to the study of C^3 convergence. Despite the level of challenge, being based on the referenced emerging research lines, they are capable to drive research towards C^3 solutions on the mid term. On the other hand, lying on the frontier sides of C^3 disciplines, the proposed research lines can provide effective outcomes and attractive insights into the foundation of C^3 convergence.

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