Self-Organized Critical Networks

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We present a multi-scale physics-based framework to distill robust and sustainable distributed management schemes for self-organization of complex networks, which comprise collaborating distributed ICT systems, organizations and multi-agent systems. Our framework is based on a dynamic scale-space paradigm, which assumes that appropriate network management structures manifest themselves as intrinsic network connections, metrics and evolutions at critical scales. This self-organization of complex networks is grounded by the continuous interaction and co-evolution of the network entities being aware to a certain extent of their own and others resource capabilities and constraints. All this is exemplified for mobile surveillance security networks.

1 Introduction

Distributed ICT systems should meet ever more intricate end-to-end quality of service (QoS) requirements of organizations. These ICT system requirements involve real-time operation, scalability or sustainability under complex network dynamics and evolution, where complex networks comprise hybrids of collaborating ICT systems and organizations. In the future, however, ICT systems should not only adapt to its own dynamics and evolution, but also to those of organizations. As organizations have hardly any time to adapt themselves to ICT systems, the ICT systems have to provide appropriate means for bridging the gap between them. Instead of integrating such adaptive features into ICT systems themselves, such concerns are assigned to other systems, like multi-agent system(s) (MAS), These systems trigger those ICT systems or organizations to adjust to the changing circumstances on the basis of e.g. the monitored human system interaction and context information. This lack of real-time management support of dynamic and evolving ICT systems and organizations severely obstructs the growth of small as well as large businesses.

This paper shows how self-organizing complex networks can sustain and even improve the performance of time-critical ICT and organizational management by adopting a multi-scale physics based approach, coined a dynamic scale-space paradigm [2]. This paradigm in a distributed way enables robust complex network management by breeding MAS that dynamically plan, coordinate and chain ICT system components and team members of organizations at particular moments in time, such that the ICT system and organizational performance requirements are not affected by operational incidents or evolutionary changes. Through self-organization of MAS at shorter evolutionary time-scales than those of ICT systems and organizations, novel context-induced hierarchies of monitoring, decision-making and planning, coordination and chaining strategies emerge in a natural and intuitive way.

Our paper is organized as follows. In section 2, we explain why we advocate our dynamic scale-space paradigm above state-of-the-art optimal control theories applied to network management. In section 3, instead of presenting a thorough exposition on our paradigm we show how self-organization of mobile surveillance security networks can be corroborated following our paradigm.

2 Adopting a Dynamic Scale-Space Paradigm

A centralistic Operational Research (OR), workflow management or service oriented grid computing approach to self-organization of complex networks is possible. End-to-end network performance management can be effectuated on the basis of amalgamated QoS measures, such as availability, timing, expertise, flexibility, robustness, financial costs and mean-time-before-failure. However, fixed and centrally controlled solutions are hardly robust enough to handle dynamic and evolving complex networks: they do not form viable solutions in case of e.g. detrimental network failures or defects.

A distributed multi-scale agent-based solution that supports the orchestration and coordination of collectives of ICT systems, organizations and MASs at appropriate (operational and evolutionary) critical scales appears to be scientifically and technically a more viable and commercially more attractive solution to handle above-mentioned complexity issues. Furthermore, self-organization of such complex networks on the basis of e.g. bio-inspired AI approaches, e.g. swarm intelligence, appears to boost both the service grid, agent and business world. However, the shortcoming of most of the existing AI approaches is that most are based on phenomenological or heuristic descriptions rather than empirically grounded theories.

Although there are no explanatory and grounded social network theories yet for self-organization principles that small- or large-scale social networks display, condensed matter physics has paved roads towards them. In particular, multi-scale physics provides grounded accounts for the laws and principles involved in achieving self-organized criticalities. These criticalities manifest themselves as universality classes, i.e. self-similarity and scaling laws typical for the dynamics or evolution of complex networks. These criticalities correspond to either phase transitions or phases of such networks. At critical scales networks may run into in- and meta-stabilities which may cause persisting network performance degradation. However, such self-organized network criticalities can also serve as robust control measures to prevent such degradation.

For embedding and embodying self-organization into cybernetic systems as a collective of intelligent heterogeneous MAS a dynamic scale-space paradigm was proposed [2], providing a solid mathematical-physical basis for coarse graining. This paradigm provides a network consistent solution to data reduction, invariance, degradation, renormalization, real-time operation, robustness, scalability and sustainability issues. Contrary to the above mentioned control theories a dynamic scale-space paradigm does not merely address control issues; it integrally handles full cycles of networks interactions and co-evolution that should not be disentangled. Upon interaction and co-evolution with ICT systems an, MAS explore and distil the right self-organization mechanisms after adopting a network-consistent dynamic scale-space paradigm. Doing so, MAS can master in a distributed, orchestrated and coordinated way at different critical scales those issues related to robustly in-time formation, planning, chaining and re-configuration (in case of incidents) and sustainable handling evolutionary changes of complex networks. MAS control measures prevent such networks running into deadlock situations. In addition, the paradigm lets emerge consistent MAS fitness, utility, and sustainability (scalability including evolutionary issues, and robustness) measures that they may use as metrics to select through filtration the ‘best’ alternative network (re-) configurations or phases. Last but not least, such a paradigm can be used to define performance metrics for how well collaboration amongst networks is automated or supported. Moreover, the paradigm allows intelligently growing complex networks through propagation and diversification of MAS mechanisms for e.g. sustainable and robust context-awareness and discovery, advertising, personalization and dynamic composition of services with dependable quality of service and reliability properties in different application domains.

3 Mobile surveillance security networks

In the following we show how to achieve self-organization of MAS in mobile security networks through formal agent modeling and empirical modeling of collective intelligent agents by adopting a dynamic scale-space paradigm.

3.1 Towards a formal model

For any coalition formation problem in networks, we say that elements belong to a coalition formation environment of MAS [1]. We make a distinction between two types of elements. The first type of elements is of active type A, (e.g. an employee). The second type of elements is of passive type B (e.g. tasks or security objects). Typically, past, current and future contexts are considered passive elements; they may also constitute control variables.

If we study a mobile surveillance security network scenario, we identify active elements such as Mobile Surveillants $MS=\{MS_i\}$; Team-leaders, $TL=\{TL_j\}$; Dispatch Centralists, $DPC=\{DPC_k\}$, Private Alarm Centers, $PAC=\{PAC_l\}$; and coalition formation support system, ASK-ASSIST, $ASK=\{ASK_m\}$. Besides these active elements we identify passive elements such as the set of all tasks $\mathcal{T}=\{\tau_i\}$, that of all security objects by $Obj=\{obj_j\}$, that of patrol vehicles $V=\{v_k\}$, that of keys for accessing or locking security objects $K=\{k_l\}$, that of security object specific alarms $S=\{s_m\}$, that of routes $R=\{r_o\}$, and that of discrete times $t=\{t_p\}$.

Having a coalition formation environment M at its disposal, the goal is not only to generate a configuration of elements, so-called coalitions, that can handle common mobile surveillance circumstances, but also that can handle unexpected security incidents by providing improvisation support to humans with the advent of newly added elements, e.g. ASK-ASSIST, $ASK=\{ASK_m\}$.

In order to further structure a configuration we distinguish role groups. A group role is a subset of A that performs a collection of tasks, i.e., subset of $\mathcal{T}$, in a specific group context, i.e., a subset of B. This implies that an agent coalition having a certain group role in a given group context is assigned to a corresponding collection of tasks. We represent this assignment in terms of a function $\gamma:2^A\times 2^B\rightarrow 2^{\mathcal{T}}$. Thus a coalition of agents A_i in context B_i at discrete time t_i perform a collection of tasks $\gamma_{t_i}^{A_i,B_i}$. Here the time-points correspond to the procedural time constraints of the schedules, i.e., the time at which, ultimately, the tasks have to be completed.

For our mobile surveillance domain we formally denote a configuration as:

Definition 1 (Configuration) *Given a coalition formation environment M with agents in $\mathcal{A}$, the roles agents can fulfill A and passive elements B, a configuration is defined by a collection of coalitions, in which each coalition is represented by the time-ordered composite task assignment to roles in a context, labeled by a route number, as* $\gamma^{r\in R}=\gamma_{t_n}^{A_n,B_n}\circ\ldots\circ\gamma_{t_0}^{A_0,B_0}|_r$. *Here* $\circ$ *is a composition rule consistent with a non-commutative operator or task algebra.*

In general, there may be various security performance measures associated to a configuration. In order formalize let us for each coalition in a configuration consider a so-called *M*-value:

Definition 2 (*M*-value) *Let M be an environment. An M-value is a pair* $(\mathcal{V},v)$ *where* $\mathcal{V}\subseteq\Gamma$ *and a value function* $v:\mathcal{V}\rightarrow R$.

Now, to identify the different value schemes that individual agents may apply to coalitions, we define an *M*-evaluation as a family of *M*-values where the index set, represented by the set of agents, of the family is used to identify the different schemes

Definition 3 (*M*-Evaluation) *Let M be a coalition formation environment. An M-evaluation is a finite family* $V=\{(\mathcal{V}_a,v_a)\}_{a\in\mathcal{A}}$ *of M-values.*

Analogously, we have to perform an *M*-Evaluation of the possible reconfiguration functions ***f***: $\Gamma\times t\rightarrow\Gamma$, when security incidents, like alarms, occur at a certain point in time that require assistance and gathering of security guards active on other routes, or that require a coalition formation support system, like ASK-ASSIST, to be introduced.

This ranking feature of an *M*-Evaluation operator can be formally captured by inducing context-dependent hierarchies of reconfigurations:

Definition 4 (CMH on a Reconfiguration Function *f*) *Let M be a coalition formation environment and* $V=\{(\mathcal{V}_a,v_a)\}_{a\in\mathcal{A}}$ *an M-evaluation in terms of M-value pairs* $(\mathcal{V},v)$ *where* $\mathcal{V}\subseteq\Gamma$ *and generalized value function* $v:\mathcal{V}\times\ldots\times\mathcal{V}\rightarrow R$ *describing the value for consecutive reconfigurations coinciding with (unexpected) context changes over time. Assuming that reconfigurations occur at* $t_0,\ldots,t_n$ *, corresponding to time-points at which incidents occur, a Context-dependent M-Evaluation Hierarchy, CMH, of reconfiguration function f is defined by:*

$$CMH(f)=\left\{(\Gamma_q^{opt}(t_0^r),\ldots,\Gamma_q^{opt}(t_n^r))\,|q,n,r\in\mathbb{N}|\right\}$$

where $\Gamma_q^{opt}(t_i^r)$ *is valid from* t_i *to* t_{i+1} *and where r is denotes the route number and q denotes the index set of the ordering on the set of possible (re)configurations. Note that the time points carry route-specific annotations. Labeling* Γ *by opt expresses the optimality or acceptability of the (re)configuration in terms of the M-evaluation associated with it, such that the following holds:*

$$(\Gamma_q^{opt}(t_0), \ldots, \Gamma_q^{opt}(t_n)) = arg_{(\Gamma,\ldots,\Gamma)/(\Gamma_{q-1}^{opt}(t_0),\ldots,\Gamma_{q-1}^{opt}(t_n))}\,[ext\ v(\Gamma(t_0), \ldots, \Gamma(t_n))]$$

where ext $v(\Gamma^n)$ *denotes an extreme value configurations, this could be either a maximum (for profits) or a minimum (for costs) depending on the type of value function used.*

Herewith our formal model of our mobile surveillance domain is complete but not yet readily made operational. Grounding or empirical modeling of context-dependent *CMH*-hierarchies of reconfiguration function *f* and ASK-ASSIST functionalities are needed in order to really support improvisation by humans in setting up communications or taking decisions.

3.2 Towards an empirical model

In order to arrive at robust grounded coalition formation alternatives we elaborate on how to apply our dynamic scale-space paradigm [2]. Thereto, it is necessary first to define notions of a reconfiguration image, a gauge and a dynamic scale-space of a reconfiguration image.

Definition 5 (Reconfiguration Image) *A reconfiguration image* $I{:}M \rightarrow N$ *is a mapping of the external vector-valued energy-density field M of an actual reconfiguration* ***f***: $\Gamma \times t \rightarrow \Gamma$ *on a vector-valued density field of the induced one N.*

Note that the vector-valued density field of the induced reconfiguration is a member of the set of all context-dependent reconfigurations that can be made operational or are stored in e.g. the ASK-ASSIST database.

To properly analyze such an image in terms of a complete and irreducible set of equivalences, it is mandatory to know how the reconfiguration image changes whenever they are subjected to a particular class of so-called gauge groups:

Definition 6 (Gauge) *A gauge group G consistent with reconfiguration image (Definition 5) is a group or set of transformations leaving properties of (Definition 5) invariant.*

Such gauge groups could cover spatio-temporal deformations and even morphological transformations including spatio-temporal reordering, cutting, pasting, insertion and deletion of a reconfiguration image. For example, introducing ASK-ASSIST causes non-trivial image reconfigurations whenever unexpected alarms occur and an incentive to reduce the workload or to increase operational performance.

A set of equivalences *F* of a reconfiguration image (Definition 5) comes about after setting up a (co)-frame field, metric and/or connection invariant under a particular class of gauge group (Definition 6). As alluded some of the gauge groups can generate active transformations, such as introducing ASK-ASSIST. However, these transformations can be undone by means of similarity operations inducing robust monitoring, deliberation and control schemes on the reconfiguration image. Thus a categorization problem with respect to reconfiguration images involves besides the problem of invariance under gauge groups also the problem of robustness under similarity operations.

In order to ensure robust reconfiguration a gauge group consistent dynamic scale-space of reconfiguration images is generated. Such a dynamic scale-space is obtained by a gauge group consistent context dependent coarse-graining of reconfiguration images. Such a coarse-graining or self-similarity operation removes microscopic aspects of the images and yields universality classes across the critical context-dependent length scales.

Definition 7 (Dynamic Scale-Space) *A dynamic scale space of the context-dependent free energy F of a set of reconfiguration images, that is invariant under gauge group G, is governed by*

$$\delta_\tau F = -j^F,$$

$$j^F = -\frac{\nabla^{\Pi}_{v_s} F}{\kappa^2(\sqrt{g(\nabla^{\Pi}_{v_s} F, \nabla^{\Pi}_{v_s} F)}}$$

$$Z = \exp\left[-F\left[V_i(x)\right]\right]$$

$$F\left[V_i(x)\right] = \sum_{i,k,p} dv^p \left(\tilde{V}_{i;\pi_k(g_1\ldots g_k)}(x, \tau_{i;\pi_k(g_1\ldots g_k)})\right)$$

with κ *a monotonic increasing function, suitable initial-boundary conditions,* v_s *connecting free equivalence states* $F(p_i)$ *and* $F(p_j)$ *, and free energy F is related to statistical partition function Z. Here x labels any context complex,* π_k *a permutation of a sequence of* $k \geq 0$ *integers* $(g_1 \ldots g_k)$ *with* $k=0$ *for labeling frame vector fields* v_{g_k}

and τ*'s for dynamic scales consistent with the gauge group G and equivalences* $\tilde{V}_{i;\pi_k(g_1 \ldots g_k)}$.

Similarly, self-organized critical MAS and their associated reconfiguration schemes $\boldsymbol{f}$: $\Gamma \times t \rightarrow \Gamma$ for monitoring and controlling networks manifest themselves as typical universality classes across context-specific length scales.

For example, the multi-scale context dependent reconfiguration schemes needed for finding a suitable guard with expertise about an object in a security network can retrieved by coarse graining and renormalizing the history of the reconfigurations. Herein the associated M-evaluation functions are parts of a general cost function or Lagrangian involved in the nonlinear stochastic control or geometric control problem for the considered security domain.

4 Conclusions

Upon formal modeling a mobile security network domain a dynamic scale-space paradigm is proposed to generate robust multi-scale distributed context-dependent reconfiguration schemes to be applied by MAS in case of incidents or the introduction of new technology like ASK-ASSIST. These reconfiguration schemes are consistent with the universality classes existing across the different spatio-temporal and dynamic critical scales.

Bibliography

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