Demystifying Self-awareness of Autonomic Systems

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Abstract: Self-awareness is a much discussed property of autonomic and self-managed networks. Attempting to demystify this property we show that it can be captured by a Self Awareness Function (SAF) that stems from the assessment of process correctness of autonomic and cognitive networks. Based on multiple position papers that were written in isolation we are able to identify various SAFs (for trust, security, dynamics control, service deployment), as well as associated research issues (information modelling, higher contextualisation, convergence, etc.). We show that multiple issues of self-management that create a tangled hierarchy of control loops can be systematically addressed with SAF in mind.

Keywords: Self-awareness, Autonomic Networking Systems, Context, Learning, Assessment, Trust, Control, Research Challenges

1. Introduction

There need for telecommunications technology to manage itself is critical. The reasons are multiple however the growing complexity of the traditional systems management is perhaps the most important one. In this multi-author position paper we collect self-management research challenges, as seen by different stakeholders (network operators, vendors, research institutions) in Europe and in Asia and attempt to put those in a hierarchy, which is inevitably tangled. Based on the available research results we are able to claim that *self-awareness of autonomic systems* [1] is the only challenge that helps to rigorously and systematically address the rest of this tangled hierarchy. The body of this paper is structured as follows: we use this section to introduce the three key factors of understanding and of eventual standardisation of self-awareness: common components, common rules, and the process correctness. The next section presents important results in the assessment of autonomic systems, which makes our background; these results clearly show that self-awareness as the next research target; this is followed by the section, where selected self-management functions forming the tangled hierarchy are presented in their relation to self-awareness; we conclude the paper with a summary of findings and with the acknowledgements.

Talking about management one naturally recalls classical FCAPS [2]. In transition to self-management these classical tasks can evolve separately; for example security can become self-managed earlier than other tasks; we refer here to systems that are secured by distributed peer validation of each and every action [3]. Feature evolution in isolation however would be dangerous since a common integrated platform (management plane or middleware) is promising not only to reduce the complexity of the platform but also to make it itself a self-aware infrastructure. Following this reasoning we define as the first factor shaping the understanding and potentially the standardisation in the area of self-aware autonomic communications systems the following one.

Common components: the need to define common components within the traditional telecommunications management architecture that can be re-designed to support self-x properties, and can be re-used in different facets of then would be self-management platform.

There are multiple roads leading to self management networking infrastructure - the ultimate goal of the future Internet. At the same time there is growing understanding of a new dimension that novel communication infrastructure needs to support - this new dimension is *semantic orchestration of multiple communication realms*, which sometimes are termed as various Internets. Most important are: Internet of Communities: the network of people by people and for people; Internet of Services: the network connecting service providers and service consumers at various levels spanning from business - ultimately the entire economy, down to software and hardware components; Internet of Media: the network that is optimised for handling of various and ever growing types of media formats, seamlessly integrating meta-data to facilitate ever sophisticated discovery, location and search - building blocks of multimedia service composition; Internet of Things: multiple and increasingly heterogeneous networks that interconnect sensors, RFIDs, etc. with any of the above Internets.

Leaving aside major properties and the associated challenges of these communication realms but following the reasoning of the seamless networking through and via these multiple realms we define the second factor urging for the standardisation action.

Common rules: the need to define common rules for semantic mapping between the realms with a very careful split between the placement of such mappings within specific realms (domain- specific placement) and within the common self-management platform.

There is yet another factor that underpins the urgent need for standardisation in autonomics; this factor stems from the human fear of selfish and uncontrolled behaviours that potentially might emerge inside self-managed networks, hence the below factor.

Process correctness: the need to continuously evaluate the process correctness [4] of self- managed components and networks.

While engineering of such future networks requires the creation of novel type of algorithms that will sense in the timely manner *relevant* changes in the operational context and shall invoke (generate, adapt, modify, etc.) the *relevant* behaviours, the continuous evaluation of the resulting adaptations shall answer the above relevance concerns. The relevance here is understood as the relevance to the externally given purpose achieved through the continuous self-evaluation.

2. Assessment as the Background

Two important aspects for understanding the autonomic operation of a system are the operation of its control loop[s], and the information management. After quick introduction of both topics we can start using the new evaluation methodology –assessment - to test and to describe this class of systems.

2.1 Control Loops

A self-managed system is based on different control loops with many models found in the literature. Self-management research can be traced back to the "Sense-Think-Act" model from the beginning of Artificial Intelligence (AI) and robotics; it led to different models used today, like the "Monitor-Analyze-Plan-Execute" (MAPE) model by IBM targeting autonomic computing [5], and the "Collect-Analyze-Decide-Act" one proposed by S. Dobson for Autonomic Communication [6], and various cognitions cycles from the area of cognitive radio. For a more detailed understanding of the operation of a self-managed system we want to point out the borders of autonomic systems including such control loops.

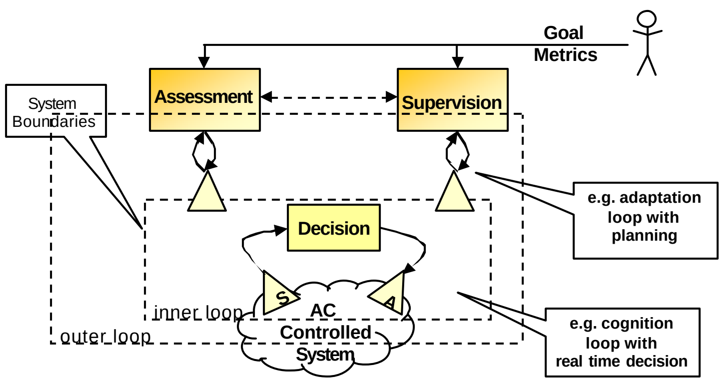

Fig. 1 Control Loops in autonomic system

The outer boundary of a system on Fig. 1 denotes the interface between the user and the system. The user presents at this outer boundary his/her goal or purpose to the system as a metric. This information will be evaluated by the system to offer a service to the user (Supervision in Fig. 1). A more sophisticated system also will include some checks of internal errors or contradictions; this can be seen as the first step towards the self-awareness. To test whether the system behaves correctly and performs as expected, the Assessment can be applied as *external* function.

A further boundary can be found inside the system itself. Since some parts of the system need to be fast they should run undisturbed and autonomously, deciding within a limited scope and in the real-time. Other parts of the system cannot run in real-time, because their control loops include decisions based on uncertain information or on communications with other, external devices. Even more, these control loops include the more sophisticated cognitive functions of a system (such as planning and learning).

As a simple example consider a router consisting of a high-speed packet forwarding process (probably hardware implemented) with a limited scope; the routing process, at least is aware of surrounding topology (environment) and is deploying protocols to communicate with other devices. Or, think of a multi-RAT interface, low-level air interface will be handled by fast protocol modules but the overall control with resource planning and handover mechanisms will require non-real-time tasks, such as communication with external devices and planning.

As a consequence an autonomic system will not consist of a single or global control loop. On the contrary it will consist of different nested and linked control loops, partly already known in cognitive radio research. These loops also support the new paradigm of functional composition for communication systems (composition replaces layering).

Fig. 1 can also be seen as a roadmap – function by function (or better topic by topic) we can start to in-source from the user into the system itself complex functionalities, such as perceiving a situation, deciding with multi-purpose optimization and learning (and forgetting) from experience.

2.2 Information Management

Context is any information that can be used for decisions inside a system. A single context information is rarely useful for complex systems, so we aggregate or combine different contexts into (a description of) situation.

These situations are described along their natural realms, meaning that information relevant for a special situation is included in the description of the situation. Of course, the main challenge here is in information aggregation, it needs to be solved with the existing approaches from AI, but we can start by using human expertise to build up first approaches for typical and well-known situations. We can follow this information aggregation to a final point where the decision is evident. This methodology can be seen as a bottom-up approach, aggregating existing information as a part of the decision itself, ideally replacing one global decision (or one inference module) by a sequence of descriptions of spatial and logically distributed situations formed by the information aggregation. In practice the system needs to cope with uncertain and incomplete, even erroneous information; the right decision might not be evident, but can be taken after collecting a fair amount of information and considering the lowest risk for system operation under these circumstances.

Given the importance of information management, self-managed systems can be defined purely based on their ability for context information handling and evaluation:

- Self-adapting systems are systems that timely detect relevant changes in relevant contexts, and timely adapt their behaviour to those changes.
- Cognitive systems are self-adapting ones, and in addition they learn to adapt, which means that they are able to discover new relevant contexts and to bind them to needed behaviours adaptations, including also new (composed) behaviours..

2.3 *Assessment*

The understanding of self-ware systems heavily depends on the internal structure (which can be decomposed into various control loops) and their information management. For the description of system's properties and for the testing of system characteristics (of an implementation) we need an additional method for this new class of systems. If a system has the ability to adapt we need methods to show the process correctness [4] and show the influence of gaining knowledge.

To characterise a system by an Assessment will require more than a single metric. While the results of a conformance test depend primarily on the specification and the implementation, the results of a performance analyses additionally depend on the environment of the system (e.g. the throughput of a system might depend on packet length of traffic). The result of the Assessment will depend supplementary on the internal knowledge of the system. So there is a hierarchy in these methods for testing communication equipment – the results are dependent on more and more prerequisites and a later (more sophisticated) test depends on simpler ones.

While self-managed systems can be defined by their information handling (see section 2.2), we can base the Assessment method also on context. Assessment is first of all based on external observation of a system - how it reacts on context changes and how it incorporates context in later decisions, e.g. by learning. In practical test of communication equipment one will use external context/traffic generators to artificially prepare a series of situations for such a test.

But Assessment also helps to understand the interaction between the environment (represented via context) and self-managed systems in general, beyond testing and assigning a test result to a commercially available device. Parts of the assessment can be integrated into the system itself and be the foundation of self-awareness.

3. The Way Out of Tangled Hierarchy of Self-Management

3.1 *Self-Awareness Function*

Since we have explained our definitions of self-organising and cognitive systems as behavioural reactive property to timely detected changes in relevant context it is natural, based on the achievements in our assessment work to further define Self-Awareness Function (SAF) through the context as well. Though this is the *common* approach as defined in the Introduction, we claim that SAF is specific for each network feature under adaptation. The co- authors contributed nine self-awareness position papers on wide range of potentially adapting features, ranging from adaptive trust to adaptive mobility management; these papers have expressed respective opinions on the common components, which opinions are mapped to different SAFs. In this respect, we find very illuminating that the definition of adaptability in [7] is done as Fitness for Evolution, rightfully noting that "Designing an architecture that could adapt to non-predicted changes is quite difficult."
The Table below introduces the SAF as the next step after cognition. With this definition in mind we present inevitably shortly but with references to full texts of position papers the nine SAFs with associated research challenges.

	Operation on Context	Reactive Behaviour
Self-adaptive	timely detect relevant changes	select required behaviour
Cognitive	timely detect relevant changes	select/compose required behaviour
Self-Aware	evaluate timeliness and relevance	evaluate the behaviour

3.2 Trust Establishment and Assessment SAF

Following the [8] that addresses the trust establishment and assessment operations between autonomic systems we conclude that “Malicious nodes may exploit lack of cooperation to intelligently attack legitimate nodes individually, or they may exploit cooperation capabilities in order to fake identities and create various types of exploitations." The framework that prevents this can be based on the concept of a role, modelled in social-like environments, and allow “evolution of the trustworthiness”. Moreover, the [8] outlines the need for “a coherent, mathematical, self-contained framework for trust that is required to quantify all the aforementioned and allow the accurate design and analysis of trusted systems "; for example such framework can be designed as a dynamic iterative trust vector based on Markov Random Field method. In this respect trust assessment is defined as "quickly respond to the question of whether the correct trust values have been assigned to the correct nodes", which clearly conforms to the specific *SAF for trust*. The challenge is however is in that "until now the interdependencies between the context and trust have not been sufficiently addressed, but as various threats are related to context awareness, the context information (anonymous if personal) whenever available can offer opportunities to establish and manage the trust relationships more efficiently" [8]. This challenge is accompanied by more traditional questions, like: How paradigms and solutions already applied in social networking, either web based or application based P2P overlay networks, can be utilized into a pure autonomic environment? Could trust models already developed by social science be infused into autonomic networking bringing such networks and infrastructures closer to the end user? Could user interfaces techniques regarding human machine interaction developed and largely adopted by web users be utilized by autonomic networking in order to make these systems more trusted by the end users?

3.3 Security, as a built-in feature in Autonomic Systems

This position paper [9] is conceptually very close to [8], however it goes a step further in the direction of relating the security levels to the levels of context awareness: “Self-protection in autonomic networks can be achieved only through self-reconfiguration, which, in turn, heavily relies on the data collected from monitoring (context-awareness). Being aware of service requirements and potential threats, the system can adjust itself in a timely manner according to the network policies. In this case, the system will be able to provide the right service at the right time to the right user detects attacks and misuse and takes actions to protect the network.” Thus the imaginary *Security SAF* allows [9] to define the following: “Autonomic security is an advanced step comparing to "reconfigurable" security. The former means adding more automation in the entire reconfiguration process and make the security system self-responsive. Similarly to autonomic systems, this can be achieved only through a control loop that monitors, analyzes and reacts.”

3.4 Engineering control levels in an Autonomic Network

The ubiquitous control loops forming the tangled hierarchy of self-management must be seen as a separate engineering concern [10]. When much of the network functionality belongs to a hierarchy of control loops, then the system constantly monitors for misbehaviour or a change in the operational environment, then, after thorough analysis, a management decision is made in order to respond to the shift in network state based on aggregated system information, and finally the adjustment of the system is performed accordingly. “A fundamental task is to determine the optimal level at which control decisions should be made - different problems require control loops of different "extent". On one hand, a certain amount of information is needed to make a decision, which pushes the decision making upwards in the hierarchy. On the other hand, resource efficiency or timeliness requires making decisions as fast as possible, which requires quick, low level decisions" [10]. The above evaluation of the adaptive behaviour and the relating its quality back to the information (context) used quality (timeliness, relevance) allows us to identify a *SAF that controls the dynamics* of particular decision process with respect to its placement in the self-management hierarchy. The authors of [10] suggest the following decision processes that can be equipped with the above SAF: addressing (the structure and distribution of the address space); routing and search (based on structured vs unstructured addressing schemes); scheduling time scales (packet, connection, process); trust-based forwarding (following the trust evolution); self-defence as a function of recognised timing constraints; self-healing and fault-tolerance as a function of system performance.

3.5 Self-management for cooperative transmission

It appears that the above control dynamics SAF suits the issue of cooperative transmission in infrastructure-less network outlined in [11]. "In the case of multi-tier set-ups is seems rather difficult for one node to take care of the overall control. What is more - there would be an additional control overhead to be handled which could affect the system performance. The idea behind the concept of self-management for cooperative transmission would be then to make it feasible for the different groups of nodes to employ some relevant self-management techniques. As a consequence each node would know which group to attach to, which resources to use and what transmission technique(s) to apply. For this reason the nodes would have to be aware of their contexts in the network and they would have to exchange all the relevant information" [11]. We see the control dynamics SAF as an example of the above relevant self-management technique, in which decision process is relocated between control groups rather than between levels of a single hierarchy.

3.6 Self-management in service deployment by autonomic systems

The [11] states that "context awareness in networks and services remains a key prerequisite for the realization of autonomics communication vision. Its ultimate factor of success depends highly on the self-awareness capability that in the case of service awareness requires a re-consideration of existing framework in order to incorporate service /application relevant features and parameters as well". This translates into the "need to define a semantic-based framework for the description, composition and orchestration of autonomic enabled services", which "framework should be enhanced with new/updated performance indicators or metrics to feedback the latest service generation quality requirements". Thus, a *service deployment SAF* can be articulated in the research agenda, which should act on the contexts of service life cycle, composition and orchestration.

3.7 Information Modelling and Meta-Modelling Challenges

The [12] states that "further investigation is required in a number of supporting areas such as Information Modelling and Ontological Engineering. To assist the development of advanced autonomic control algorithms, further investigation is also required in the application of bio-inspired autonomic systems to various scenarios such as traffic engineering and traffic management; anomaly, fault detection and diagnosis, intrusion detection, traffic classification and characterisation". There is a clear opportunity to structure the above information modelling along various SAFs, attempting to identify common and domain- or feature- specific models. The promise here is to find common information modelling framework for a particular SAF, to which a technology specific driving model

shall appear as an embedded specific control. Another promise in this respect is to achieve control plane self- similarity assuring scale free properties of SAF controlled networks.
Additionally to [12] the authors believe that the role of Design (Meta-) Models and Information Models as "enablers" for implementing Self-Awareness cannot be underestimated.

3.8 Issues in Future Autonomic Networks

The [13] states that "...the current designs of control loop only provide primary autonomic functions: the policy-based autonomic control loop lacks for learning ability, which restricts the autonomic capability of the network. Optimized decision is often difficult to achieve ... in the heterogeneous wireless environments, the different characteristics of the heterogeneous access technologies, together with the time-varying feature of wireless channels, result in a vibration during the information collection for the control-loops. In other words, the convergence rate of the control-loop in the autonomic networks can be low." As the needed research the [13] highlights the following

- Introducing the cognitive technology into autonomic networking architectures;
- Generalized context aware technologies,
- Autonomic mobility management with different granularity support;
- Fast control-loop convergence method for mobility management.

We see these agenda items as dedicated to the design of mathematical driving models that will in timely manner assist the generic SAF information modelling. At the same time, we believe in the critical importance for future autonomic networks to be compliant, meaning that "Business-Awareness", "Goal-Awareness (for *injectable* goals)" and "Application-Awareness" are to be essential properties of Self-Managed Networks.

3.9 Increasing Context Awareness in Autonomic Networks

The [14] says that "… by increasing the context-awareness of monitoring data exchanged by autonomic nodes it is possible to efficiently sense network conditions and the level of provided services and proceed to corrective actions (self-healing). Also, context-aware information is easily used in order to take decisions according to the specified administrators' policies (self- optimization)…". This statement clearly satisfies the requirement of having multiple SAFs. The [14] however articulates the need for a "generic monitoring framework based on autonomic principles", which will itself exhibit learning and reasoning capabilities and support intelligent interactions between other cognitive network elements and services.

4. Conclusions

In an attempt to demystify the self-awareness of future autonomic systems we propose a systematic approach to the design and the engineering of multiple self-x and cognitive functions, which will comprise inevitably tangled hierarchy of control loops in autonomic network. The major unit of our design is Self Assessment Function, which semantic is defined for both self-adaptive and for cognitive systems, moreover it is the same. With SAF in mind the design of particular self-adaptable or cognitive network feature gets solid foundation since the degrees of autonomic adaptation and/or cognition are being known to the feature designer.

We present a number of different SAFs, their associated challenges and generic issues such as network contextualisation and modelling. Repeating the [1] we believe in the benefits of "... computing and communication systems that are able to optimise overall performance and resource usage in response to changing conditions... This requires breaking through the tradition of fixing abstraction layers at design time, which hide issues at lower layers". The challenge quoted above is nicely met by our proposed unit of design; the proposed SAF is essentially a cross-layer and a multi-faceted decision process, which is an outcome of the work on assessment framework of autonomic and cognitive networks.

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