Autonomic Computing in the First Decade: Trends and Direction

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Abstract **— The Autonomic Computing (AC) concept has received strong interest amongst the academic and industrial research communities since its introduction exactly a decade ago. It is important, after the first decade, to evaluate the actual work done in achieving the original vision of this concept. In this short paper we present a brief report of our work in this direction. We have analyzed all the proceedings (2004 – 2011) of two leading AC conferences (ICAC and ICAS) to show the trends in and direction of AC research and to identify current and future research challenges.**

Keywords- autonomic computing; trends and direction

I. INTRODUCTION

The International Conference on Autonomic Computing (ICAC) and the International Conference on Autonomic and Autonomous Systems (ICAS) are two leading AC conferences and have together published about 647 high quality research papers in eight years of the first ten years of AC research. We believe that the two conferences give a true representation of the distribution of interest, work done, and trends in AC research. Papers used in this work are sourced from [1]. AC research is widely viewed to have started with the publication of [46] in 2001 introducing the concept of AC and [47] elucidating further the AC vision. However, only high level analysis, requirements and challenges of AC were presented.

Jeffrey Kephart in a keynote during ICAC 2011 presented an excellent analysis of the extent to which the original AC vision has been realized, and some discussion and speculation about the remaining research challenges [2]. While Kephart concentrated more on the various technological threads, their origins and how they have progressed, our focus is mainly on the level of maturity in terms of the types of, and scale of, problems targeted at the various stages. This enables us to reflect on the overall progress in the field, and to be able to identify current and future challenges. Our work is not just a review but also a validation of our earlier proposed roadmap (pathway) to achieving the goal of autonomic computing [21].

We reviewed a total of 647 research publications including keynotes (336 of which are from ICAC and 311 from ICAS) using webometrics and direct analysis techniques. These are analyzed in terms of main application domain, emphasis, and technical approach as well as author distribution. Our result is an empirical evaluation of the overall impact, trends and state-of-the-art of AC research activity.

An analysis-by-problem approach reveals a particular pattern (problem definition to issues of scale) in tackling the AC vision. On the horizon there is the challenge of coexistence and interoperability between Autonomic Managers and yet beyond the current state-of-the-art, and even further beyond state-of-practice are issues of validation, trustworthiness and certification, requiring solutions specifically tailored for run-time self-adaptive systems.

Overall, very impressive progress has been made in the first decade, and this has been driven by the interest of the main sponsors – industry leaders such as IBM, Sun, Motorola, Google, Microsoft and Hewlet Packard, amongst others.

The remainder of this paper is organised as follows: Section II gives a high level and general analysis of all conference proceedings. Section III discuses trends and direction, showing the pattern of how the research challenge is being tackled by the AC research community while Section IV concludes the work.

II. HIGH LEVEL AND GENERAL ANALYSIS

Tables I and II are high level analysis of conference proceedings mainly taken from IEEE Computer Society Digital Library [1]. A select few areas have been chosen and some of these are discussed in this first report. In terms of authoring, the academic community has the most publications. While ICAS is academic dominant, ICAC has been predominantly industry driven until recently. This explains why on the average even though ICAS has more publications ICAC has a far greater number of datacenter-oriented papers and has been somewhat dominated by this application domain. In terms of emphasis, contrary to popular assumption that self-optimization takes the top shot, our investigation actually shows that the predominance of work in the field continues to focus on self-healing followed by self-configuration, self-optimization and then self-protection. Both conferences maintain the same trend. Out of all the self-CHOP (self-configuration, self-healing, self-optimization and self-protection) based publications in Tables I and II put together, 35% focus on self-healing while 27% on self-configuration, 22% are on self-optimization and 16% on self-protection (Figure 1). In terms of technical approaches, good progress has been made in using specific techniques including machine learning [3, 4, 5], fuzzy logic [6, 7], utility functions [8, 9] and policies [10, 11, 12] to define and achieve self-managing capabilities. Alternative autonomic architectures (e.g., Intelligent Machine Design [13]) have also been proposed.

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Figure 1: Self-CHOP analysis in terms of emphasis of work in the community.

In terms of application domain, the datacentre clearly tops the ranking in terms of interest to the community. This is partly because the AC vision is industry-borne and has continued to be driven by the industry. This is evidenced by the number of papers (including on datacentre) that are authoured, co-authoured or sponsored by the industry partners. Datacentres are very complex; in fact have many dimensions of complexity; which arise from their scale, necessary speed of operation, and large number of tuning parameters. In addition they have high power costs, including a significant cost component for the cooling systems. Autonomic Computing arose because of the need for automatic management of such complexity and successful autonomic techniques in this domain translate into significant financial reward for the owners and users of such systems. This high complexity is also attractive to academic researchers as it provides a rich domain in which to evaluate a wide range of techniques, tools and frameworks for AC.

With the vested interest, it is clear why the industry takes the lead in datacentre related research when the industry led ICAC is compared with the academic led ICAS (Figure 2). While the influence is understandably obvious for ICAC, the academic community, in ICAS, has diversified the research to cover other areas more evenly.

TABLE I. ICAC PROCEEDINGS DISTRIBUTION

Distribution	icac 04	icac 05	icac 06	icac 07	icac 08	icac 09	icac 10	icac 11	Tot al
Authouring									
Academic	39	30	20	15	15	18	18	32	187
Industry	17	18	09	06	05	10	04	01	70
Joint	08	16	14	11	06	06	05	13	79
Total	64	64	43	32	26	34	27	46	336
Main Application Domain									
Datacentre	03	11	11	11	09	10	09	12	**76**
Distributed Systems	17	06	05	04	00	01	02	04	**39**
Networks	08	02	00	01	00	00	01	03	**15**
Robotics	01	00	00	00	00	00	00	02	**03**
Storage & Dbase Mgt	05	05	04	02	00	00	01	04	**21**
Others									
Design/ Architecture	07	12	01	02	04	03	03	03	**35**
Learning/ knowledge	08	04	03	01	06	03	01	03	**29**
Performance Mgt	09	05	05	03	01	06	03	08	**40**
Policy	02	06	03	02	02	00	01	00	**16**
Self-CHOP	11	09	04	05	07	06	04	02	**48**
Survey	00	00	00	00	00	00	00	01	**01**
VTC	04	03	03	04	02	03	00	00	**19**
Actual VTC proposal	01	01	01	03	01	01	00	00	**08**

TABLE II. ICAS PROCEEDINGS DISTRIBUTION

Distribution	icas 05	icas 06	icas 07	icas 08	icas 09	icas 10	icas 11	Total
Authouring								
Academic	20	39	53	34	48	27	23	244
Industry	01	10	13	00	04	01	01	30
Joint	02	09	03	09	05	02	07	37
Total	23	58	69	43	57	30	31	311
Main Application Domain								
Datacentre	01	06	04	03	03	04	02	23
Distributed Systems	05	12	07	01	05	01	02	33
Networks	04	07	06	02	05	03	01	28
Robotics	01	03	01	04	04	01	03	17
Storage & Dbase Mgt	00	04	03	01	03	00	01	12
Others								
Design & Architecture	03	15	07	02	09	03	07	46
Learning & knowledge	00	01	04	06	04	00	01	16
Performance Mgt	01	05	07	03	06	02	00	24
Policy	00	02	02	03	03	02	00	12
Self-CHOP	00	01	01	01	03	03	01	10
Survey	00	01	02	01	03	00	01	08
VTC	01	03	01	00	00	01	03	09
Actual VTC proposal	00	00	01	00	00	00	00	01

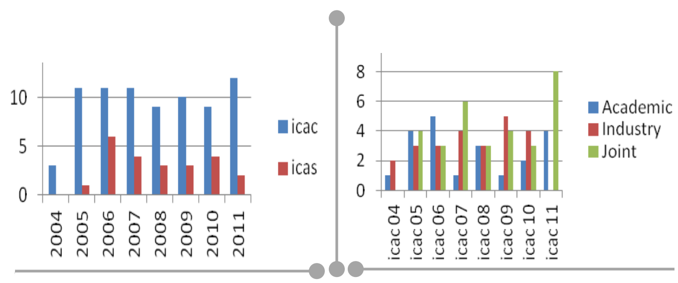

Figure 2: Distribution of datacentre related publications.

But, there is also a noticeable industry influence on ICAS; In the first year (2005) of ICAS there was only one datacentre related paper but the second year saw a jump and at the same time the industry participation on ICAS also saw a jump almost with the same margin. This could be arguably one other reason why the academic community's interest has significantly drifted towards datacentre (Figure 3).

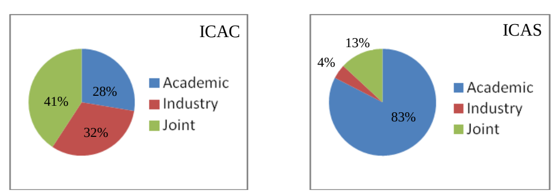

Figure 3: Authour distribution of datacentre related publications.

In general, good progress has been recorded in achieving the AC vision with growing inter-disciplinary collaborations as well as industry and academic partnerships. The industry has a visible influence over the research direction notwithstanding the lead by the academia (in terms of number of publications –Tables I and II). This is a key factor in why datacentre is the most addressed application domain. Figure 3 shows how the academic community is responding to this influence. Industry inspired and driven ICAC is one of the first conferences to address the AC vision while ICAS is a leading academia response to the challenge. Kephart [2] also concludes that in terms of application domain, the datacentre has emerged as the primary area of interest to the AC research community. With this fact we draw, in Section III, the AC research trends, direction and remaining challenges using datacentre as case study.

III. TRENDS AND DIRECTION

We believe that trends in datacentre research will reflect similar patterns in other application domains. So the analysis in this section will mainly focus on datacentre. We use analysis-by-problem approach (Figure 4) to show the pattern (in terms of maturity stages) of how the research challenge is being tackled by the AC research community.

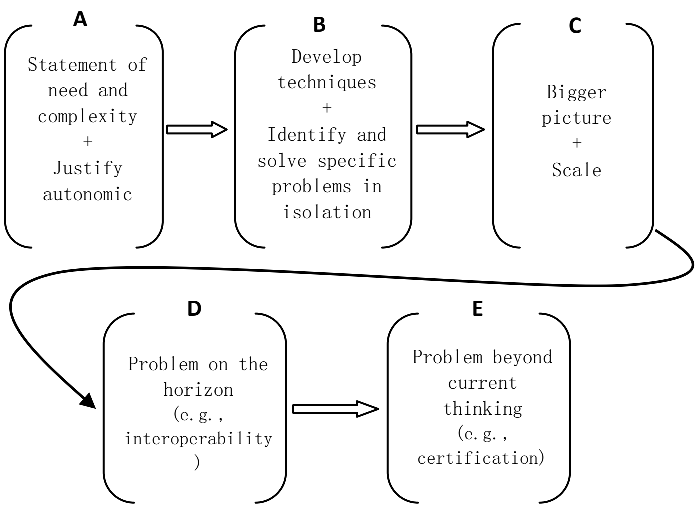

Figure 4: Observed trend and direction of AC research.

Figure 4 shows the stages (A - C) the community has adopted in addressing autonomic computing and our view of the future challenges (D and E) towards achieving the goal of autonomic computing. We keep this to a high level, but appreciate that finer-grained sub stages exist. We classify the stages against a maturity timeline, as shown in Table III.

TABLE III. STAGE CLASSIFICATION FOR ALL PROCEEDINGS

	early stage (A)	middle stage (B)	current stage (C)
ICAC	2004 - 2005	2006 - 2008	2009 - 2011
ICAS	2005 - 2006	2007 - 2008	2009 - 2011

Our investigation reveals that in the early stage research focused mainly on stating the problem and challenge of ever growing system complexity [14, 15], the need for solution and justifying autonomicity as that solution [16, 17]. Majority of work in this area are hinged on dynamic resource allocation [18, 19, 20] and are industry (e.g., IBM, HP, Sun, etc) dominant (Table III). Towards the middle stage the community intensified effort in developing and applying techniques which have now been established and are increasingly used in today's research e.g., policy-driven autonomics [11, 41], utility functions [42, 43], fuzzy logic [6, 44] etc. Also progress was made in identifying and solving specific problems in isolation. A significant number of papers offered specific solutions to specific problems, e.g., [23, 24, 25, 26, and 27]. Some examples of the variety of these include; [27] proposes a control scheme for dynamic resource provisioning in a virtualized datacentre environment to address issues of power management without trading performance. Experiments report that the controller, while still maintaining QoS goals, is able to conserve power by 26%. [25 and 26] investigate thermal load management to address heating in datacenters. While Justin *et al* [25] concentrated on predicting the effects of workload distribution and cooling configurations on temperature (deducing heat profile), Saeed *et al* [26] based their work on workload scaling. Radu Calinescu in [24] implemented an earlier proposed generic autonomic framework (based on service-oriented architecture) and demonstrated the effectiveness of his framework in resource allocation while [23] presents an automatic diagnosis framework to dynamically identify bottlenecks in large systems. Virtualisation and power management [27, 28] are also of interest in this area. Work in this stage largely comprise of implementations, demonstrations and presentation of experimented results of proposed ideas. Towards the end of our list of reviewed papers we discover that the community is now addressing the bigger picture with concern now more to do with scale [29, 30, 31], and generalisation of techniques so as to make re-usable solutions. At this stage issues of heterogeneity of services and platforms [32, 33] began to arise. The community is now addressing large scale datacentres with diverse heterogeneous platforms. The increase in scale and size of datacentres coupled with heterogeneity of services and platforms means that more Autonomic Managers could be integrated to achieve a particular goal. This has led to the need for interoperability between Autonomic Managers.

Interoperability has been somewhat neglected as a challenge to date. Earlier work was fundamentally concerned with getting autonomic computing to work and establishing fundamental concepts and demonstrating viability. Many mechanisms and techniques have been explored. Now that the concept of autonomic computing is well understood and widely accepted the focus can shift to the next level; - i.e. how to manage multi-manager scenarios, to govern interactions between managers and to arbitrate when conflicts arise. These are the kind of problems on the horizon. For example, when more than one autonomic manager is needed to coordinate a system, there may be situations where one manager counters the decision of another. There have been a few mentions and general discussion around this problem [34, 35, 37] lately. The community has not yet made good progress on this though there are efforts on the way. For example Richard *et al* [36] evaluates the nature and scope of the interoperability challenges for AC systems, identifies a set of requirements for a universal solution and proposes a service-based approach to interoperability to handle both direct and indirect conflicts in a multi-manager scenario. In this approach, an Interoperability Service interacts with autonomic managers through a dedicated interface and is able to detect possible conflicts of management interest. In this way the Interoperability Service manages all interoperability activities by granting or withholding management rights to different autonomic managers as appropriate.

On the other hand, beyond current mainstream thinking are problems of validation, trustworthiness and certification. A lot of questions have not been considered or fully answered. For example, 'what are the processes to ensure that component upgrades that are tested and confirmed in isolation will not cause harm in a multi-system environment?', 'how can certified autonomic systems be achieved?' and 'how can users be confident that a system does what it says?' [38]. In Tables I and II a number of Validation, Trustworthiness and Certification (VTC) related papers have been published but only a few are actual VTC methodologies and only one of these [39] considers datacentre. The number for VTC includes mainly those papers that incorporated validation, testing and reliability into their architectures, frameworks or implementations and not necessarily as a core or critical feature. For example, in seven years of ICAS only one paper [37] proposes a method. The work in [37] presents a framework (based on model checking) for verifying and detecting constraint violation when two or more workflows are executed on the same system as a way of ensuring system trustworthiness. The few in ICAC include [38], [39] and [40]. Hoi *et al* [38] asks the critical question of "How can we trust an autonomic system to make the best decision?" and proposes a 'trust' architecture to win the trust of AC system users. Shinji *et al* [39] proposes a policy verification and validation framework that is based on model checking to verify the validity of administrator's specified policies in a policy-based system. Because a known performing policy may lead to erroneous behaviour if the system (in any aspect) is changed slightly, the framework is based on checking the consistency of the policy and the system's defined model or characteristics. In all the reviewed papers, this is the only VTC method implemented with datacentre case study. Heo and Abdelzaher [40] presented '*AdaptGuard*', a software designed to guard adaptive systems from instability resulting from system disruptions. The software is able to infer and detect instability and then intervenes (to restore the system) without actually understanding the root cause of the problem –root-cause-agnostic recovery.

Our research group has been working on this problem for some time and in ICAS 2011 we presented several works [13, 21, and 22] identifying the problems of robust design, validation and related issues on trustworthiness leading to certification. In [21], we outline the challenges in current autonomic system validation methods and propose a strategy leading to the achievement of autonomic systems certification. This strategy is a roadmap defining the stages or processes in the journey towards full autonomic computing. We posit that there are significant limitations to the way in which AC systems are validated, with heavy reliance on traditional design-time techniques, despite the highly dynamic behaviour of these systems in dealing with run-time configuration changes and environmental and context changes. These limitations ultimately undermine the trustability of these systems and are barriers to eventual certification. Haffiz, Richard and Mariusz [13] proposed a framework that will allow for proper certification of AC systems. Central to this framework is an alternative autonomic architecture based of Intelligent Machine Design which draws from the human autonomic nervous system. James, Richard and Miltos [22] demonstrated Teleo-Reactive (T-R) programming approach to autonomic software systems and shows how T-R technique can be used to detect validation issues at design time and thus reducing the cost of validation issues. We strongly believe that certification is critical to achieving the full goal of AC. We have a longer term vision to develop trustworthy and certifiable autonomic systems and hope to progress towards this through defining validation techniques. We propose that one vital step in this chain is to introduce robust techniques by which the systems can be described in universal language, starting with a description of, and means to measure the type and extent of autonomicity (autonomic functionalities) they provide [45]. Another of our current focus area is interoperability [36] where we are evaluating the nature and scope of the interoperability challenges for AC systems, identifying a set of requirements for a universal solution and proposing a service-based approach to interoperability to handle both direct and indirect conflicts in a multi-manager scenario.

IV. CONCLUSION

We have presented a review and analysis of the actual work done in achieving the original vision of autonomic computing (AC) after the first decade. We reviewed all ICAC and ICAS proceedings (2004 – 2011) and have shown what the trends and directions there are in the AC research. Our investigation transcends technologies and how they have progressed to include areas, origins and scale of maturity. Our results also show the current and future (or remaining) challenges facing the AC research community. Beyond being a review, this work also illustrates a pathway to achieving the goal of AC and validates our earlier proposed roadmap [21].

The community has made good progress in terms of autonomic technologies and in terms of collaboration or partnership between the industry and academia. Though the research is driven by the industry (the major sponsors) the academia has also woken to the challenge. In terms of application domain, the datacentre appears to dominate the interest of the community. This is chiefly because AC is industry borne and also the datacentre provides the academia a rich and complex environment for diverse implementations and testing. As systems grow in complexity and scale, the community must now deal with addressing issues of interoperability in multi-manager scenarios. This is one of the critical issues on the horizon. Beyond current thinking, the community will need to provide answers to issues of validation, trustworthiness, standardisation and certification of autonomic computing systems.

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