Autonomic Computing in the Cloud: An Overview of Past, Present and Future Trends

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***Abstract* - The use of cloud computing has grown at an exceptional rate, with offerings from major cloud providers removing the requirement for organisations to acquire and maintain their own infrastructure. However, the complexity of computer-based systems deployed to the cloud means that efficient and effective management of resources is difficult for humans to achieve. The application of autonomic computing to this environment has solved the problem of complexity and management by creating systems that can self-manage through self- and environmental awareness. This work aims to investigate how the application of autonomic computing has advanced the field of cloud computing with an overview of historical developments, current state-of-the-art solutions, and expected future trends. Investigation shows that optimisation of cloud services with respect to operational costs, energy consumption, Service Level Agreements (SLAs), and Quality of Service (QoS) has, and remains to be, an active area of research. With the protection of data and services in the cloud being a priority for users, we discuss advancements in the application of security-aware components for autonomic cloud computing. Ethical implications of cloud computing are discussed, principally the energy consumption of data centres, highlighting the growing research in the field of energy efficient computation and resource management. The contribution of this paper is Systematization of Knowledge (SoK).**

***Keywords – Cloud Computing; Autonomic Computing; Autonomous Systems; Service Oriented Architecture*.**

I. INTRODUCTION

Cloud computing has dramatically changed the way businesses approach creating, deploying, maintaining, scaling, and financing their information technology services. Small to Medium-sized Enterprises (SMEs) can benefit from accessing vast computational resource without the unaffordable upfront costs of provisioning and maintaining their own hardware or data centres [1][2]. Additionally, the diverse offerings from cloud computing providers today appeals to a range of consumers, from SMEs to large multinational corporations. The adoption rate of cloud technologies over the last few decades has been high and it is expected that organisations will continue to embrace cloud computing, with adoption of public cloud services accelerating [3][4].

Simultaneously, organisations have been working on improving the dependability of their systems. In an increasingly technological world, the reliance on computing systems is more important than ever. The criticality of computing systems is such that unplanned application downtime and critical IT failures can have massive business impact – potentially costing large organisations hundreds of thousands of dollars per hour [5]. Autonomic computing is an area that emerged to help address the challenge of creating reliable, fault tolerant, self-managing systems. The principles of autonomic computing are now commonplace, having already been incorporated into many computing systems. Work in the area has proposed that *all* computer-based systems should indeed be autonomic [6].

The aim of this paper is to detail how the principles of Autonomic Computing have been applied throughout the emergence of Cloud Computing. This section continues with "what is Cloud Computing?" and "what is Autonomic Computing?", followed by a history of the areas in Section 2. Section 3 then looks at the current state of the art, and Section 4 describe potential future trends before the paper concludes.

A. *What is Cloud Computing?*

Cloud computing is a method of utilising remote computing resource and capacity provided by means of an Internet service [7]. It has become customary in the field of cloud computing to describe cloud service models with the "as a Service" (aaS) phrase – prepended by the technology on offer [8]. Although there have been many takes on this "as a Service" approach – the major cloud service providers have generally adopted a three-tier approach, each tier representing a distinct level of resource abstraction and control. They include:

1. Software as a Service (SaaS)
2. Platform as a Service (PaaS)
3. Infrastructure as a Service (IaaS)

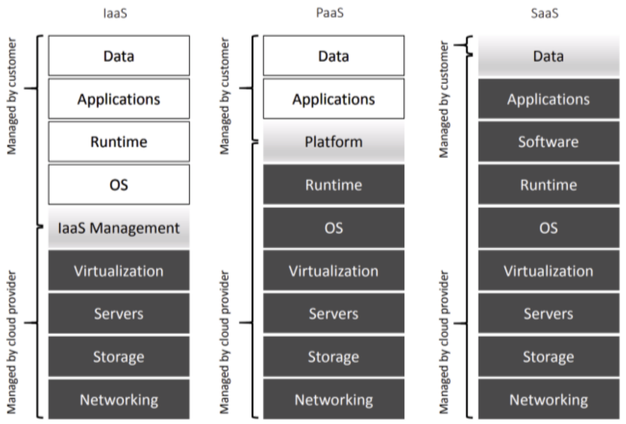

Figure 1. Representation of resource abstraction and level of control for the three main service models [9].

Figure 1 shows an example of how the level of control between the cloud provider and the customer varies between service models.

B. *What is Autonomic Computing?*

Inspired by the autonomic nervous system where bodily functions are unconsciously regulated, autonomic computing is a design model that aims to create computer-based systems that, through self- and environmental awareness, act to self-Configure, self-Heal, self-Optimise, and self-Protect (self-CHOP) [6][10].

An established method for achieving self- and environmental awareness in computing systems is by use of autonomic managers [11]. An autonomic manager cycles through a four-step control loop entailing Monitoring, Analysing, Planning, and Executing (MAPE) managed elements in a system, while consulting Knowledge (MAPE-K). Sensors collect information from the autonomic element and from its environment, with effectors able to complete executable tasks to accomplish system adaptation [12]. Figure 2 shows the high-level design of an autonomic manager.

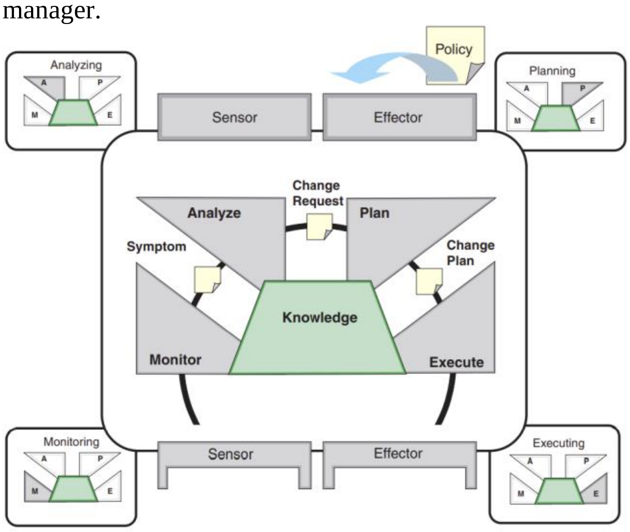

Figure 2. Autonomic manager utilising a MAPE-K control loop [11].

The *monitoring* stage collects information from the managed resource and prepares this data for analysis. Information collected may include data, such as performance metrics, capacity utilisation, response times, and health status of other managed elements in the environment. Communication between autonomic managers, including reporting of their health status, can facilitate self-healing and self-protecting mechanisms [13][14].

The *analysis* stage is responsible for determining if self-adjustment is necessary based on the data presented by the monitoring process. Comparison between the current state of the system and the ideal state of the system, dictated by policy, supports decision making at this stage of the control loop. Predictive forecasting techniques can also be utilised to determine the likelihood of self-adjustment in the future, allowing for pre-emptive change in the system to facilitate self-CHOP behaviour.

The *planning* stage naturally follows the analysis stage. If analysis determines that change is necessary, the plan acts on the change request to structure the workflow.

Execution puts the change workflow into action to update the state of the system through effector interfaces with managed resources.

Knowledge extends the standard MAPE control loop, allowing data to be shared between each of the four stages and between multiple autonomic managers in a system. Knowledge in an autonomic system may include information, such as decision-making governance policies, symptom diagnostics, and solutions.

II. HISTORY OF THE AREA

The emergence of cloud computing has provided many benefits to users including increased flexibility and scalability of resources, reduced time to market for applications, and financial savings on infrastructure cost and maintenance. However, the growth of this field has increased the complexity of computer-based systems making it harder for humans to manage, further emphasising the importance of autonomic computing to create self-managing systems [15][16].

A. *Runtime Management*

Large-scale distributed applications deployed to the cloud are adaptive and evolve throughout the lifetime of their execution. Early research identified the benefit of non-static techniques, which continually assess the demands and priorities of systems at runtime. One such proposed architecture was the Autonomic Runtime Manager (ARM), which used MAPE techniques to self-optimise the system. Experiments using wildfire simulation showed that the use of dynamic ARM optimisation improved performance by up to 45% compared with static techniques [17].

B. *Service Level Agreements*

Autonomic computing as a concept showed great promise for the management of infrastructure, however some outstanding issues meant that application within a cloud environment was not a simple task. Notably, existing frameworks did not account for virtualisation layers, and conflicts could arise between SLA and other targets, such as energy efficiency. This led to research proposals, such as extending the traditional MAPE-K loop to include an Adaption phase to balance virtualisation in the cloud. The adaptation phase of the suggested A-MAPE-K loop could establish SLA contracts, tailor monitoring processes, or handle attribute inconsistencies prior to application deployment [18]. The result being that cloud providers and consumers could create SLAs on demand, with self-management of infrastructure considering multiple goals simultaneously. Other work included flexible and reliable management of SLAs, with improved monitoring to prevent SLA violations [19].

C. *Scaling Optimisation*

The ability for cloud consumers to scale up their resources when required, and decommission or scale down when demand is reduced, has been one the greatest benefits of cloud computing. This elastic quality reduces the need for vast resource redundancy in preparation for peak demand – the infrastructure can simply scale up its capacity during peak times. This has the benefit of reducing the running costs for cloud providers, with cloud consumers only paying for the resources that are needed to maintain QoS. However, the processes involved with scaling resources up and down take time and have associated costs and therefore research has aimed to optimise this autonomic process. One such paper utilises machine learning techniques to classify Virtual Machines (VM) in a system during the analysis stage of the MAPE-K loop [20]. The VMs are labelled with a status of "Normal", "Underutilized", or "Overutilized" at each layer of the system based on their workload.

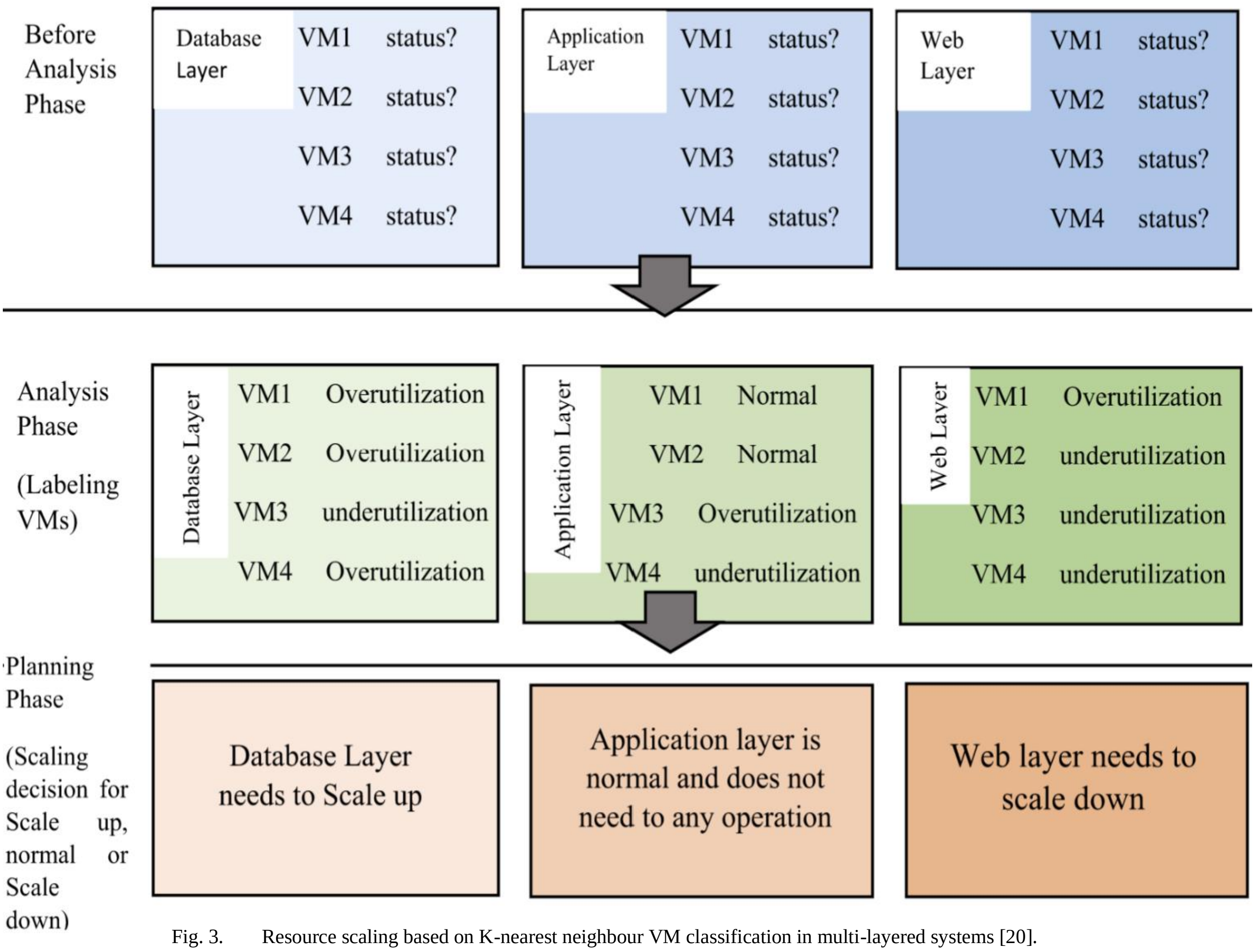

Fig. 3. Resource scaling based on K-nearest neighbour VM classification in multi-layered systems [20].

Figure 3 shows how labelling the VMs can inform the autoscaling decision process at each layer. Experimental results of simulations using this method discovered benefits including improved VM utilisation, shorter response times for customer requests, and lower operating costs for the cloud consumer.

III. CURRENT STATE OF THE ART

Work in the field of autonomic cloud solutions is well established [43]. Indeed, Cloud Computing was Autonomic Computing's major impact success during its 2nd decade [43].

Figure 4 shows a proposed taxonomy of the field, based on literature review, showing existing solutions categorised as either feature or parameter based [21]. The taxonomy is further divided into autonomic management, performance management, security-aware, and QoS-aware solutions.

A. *Autonomic Management*

Service, workload, and resource management are all types of autonomic management methodologies actively studied in research.

Service management concerns the ability to effectively manage the autonomic processes to abide by SLA and QoS agreements between cloud consumers and cloud providers. The efficiency of this process has been actively studied, with research revealing innovative solutions to improve on the existing methods. One such solution used a game theory approach to manage capacity of IaaS services [22]. Using simulations and real deployments to Amazon EC2, they report efficiency improvements of up to 70% when compared with other state of the art solutions. Other research has shown how an unsupervised machine learning approach can improve the performance of autonomic cloud managers, reporting reduction of SLA violations by up to 62% [23].

Workload management is important for adapting to the heterogenous demand throughout the system lifecycle. The trade-off between the benefit of auto-scaling and the cost of addition resources on the cloud has been an area of interest in industry and an active research topic. In the context of cloud web applications, one paper proposed an autonomic approach to optimise profits through consideration of revenue and costs models alongside performance objectives [24]. Although the scalability of the cloud is one of its greatest selling points, this research highlights the need to assess the business requirements to ascertain if the revenue generated by the additional resources will justify the costs of those additional resources. Their autonomic solution, implemented in a hybrid cloud setting, showed considerable profit improvement compared with other baseline methodologies.

Resource management is concerned with the availability and optimisation of resources at system runtime. It is important that resources are highly available to meet QoS demands, and that they are adequately utilised for greater cost benefit to the cloud consumer. An autonomic approach to resource provisioning has been presented, which uses Bayesian learning techniques and time series prediction models for scaling decisions in fog computing environments [25].

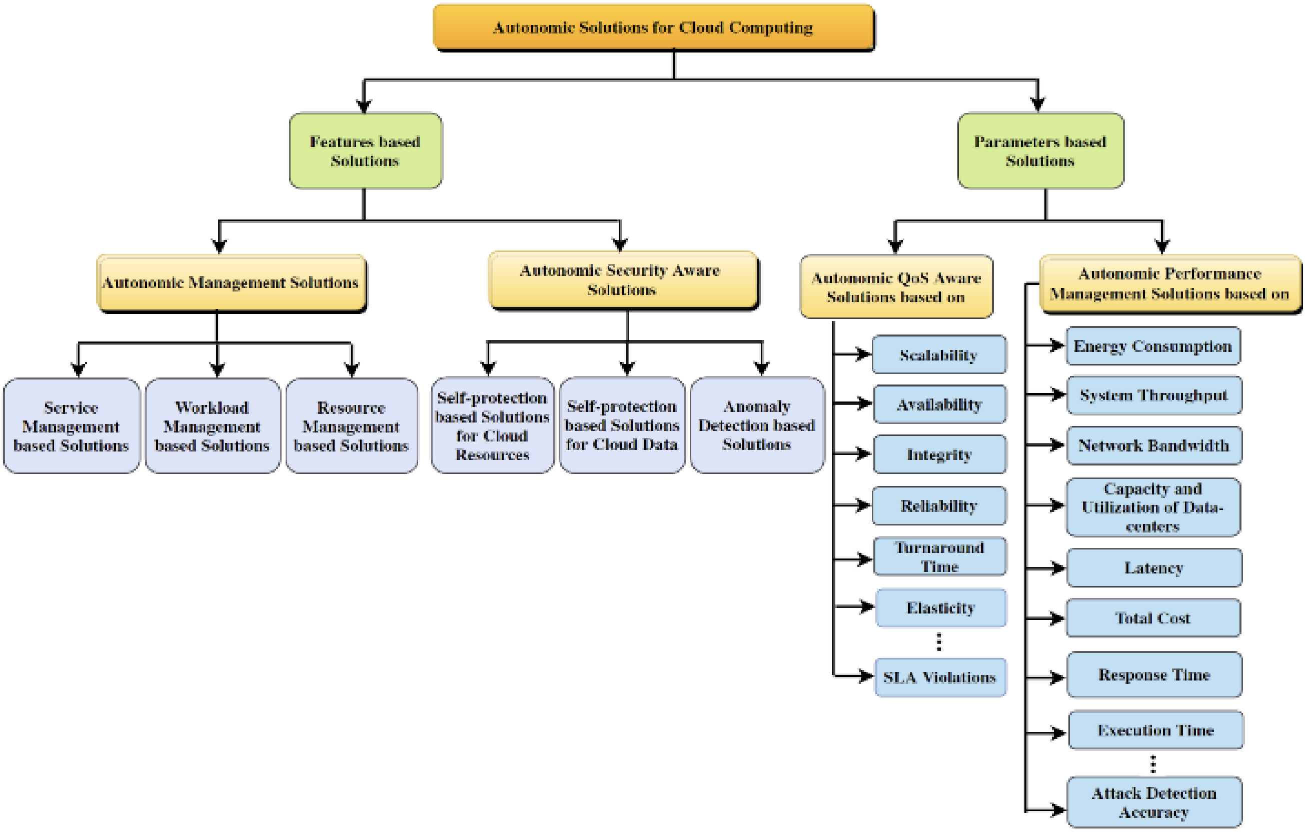

Figure 4. Overview showing the taxonomy of existing autonomic cloud solutions based on review of literature [21].

Simulation results of this novel approach shows benefits, such as decreased operating costs, decreased delays, and higher resource utilisation. Another approach that uses Reinforced Learning (RL) combined with autonomic computing benefitted from cost reductions of up to 50% whilst increasing resource utilisation by up to 12% [26].

B. Security-Awareness

The increased interest in cloud computing has necessitated consideration of how to protect systems deployed on such infrastructure. In the spirit of autonomic computing, self-protection is a key requirement of any system. Predominantly, self-protection of cloud resources and cloud data have been of significance in research.

It is important that sensitive data used in the cloud is protected in storage and during transmission to and from the cloud. There have been encouraging proposals to improve existing systems in this area [27]. Furthermore, existing security techniques have been evolving to better protect resources on the cloud. One of the latest proposals in this area, a system called SECURE [28], has shown promising improvements over other techniques, emphasising better QoS during security attacks.

C. QoS-Awareness

It is obvious that computing systems that can achieve higher QoS ratings will deliver greater benefit to organisations. The ability for autonomic systems to have QoS-awareness [29] is therefore another area of interest in research. An example of this research is a proposed "Agriculture as a Service" [30] using a QoS-aware autonomic information system. The system gathers information from Internet of Things (IoT) devices and, through analysis of QoS objectives with the use of fuzzy logic, makes appropriate decisions that are autonomically implemented. Simulations have shown resource management benefits of the system including lower execution costs, lower latency, and shorter execution times when compared with existing systems in the area.

D. Performance Management

The amount of computing power necessary to facilitate the scale of cloud computing today creates an ethical conundrum. The greater demand for processing capacity is causing energy consumption of cloud technologies to continuously grow. As mentioned, the adoption of cloud computing is likely to continue accelerating therefore it has become important to investigate other methods of addressing energy consumption in the cloud. This is where performance management plays a role, aiming to improve performance efficiency of cloud systems (getting better performance for the same energy usage). A proposed system called DREAM [31] tackles the issue of high energy consumption in mobile cloud systems. Their system specifically addresses high energy consumption related to cloud CPU and network usage by smartphones. Through optimisation techniques they were able to show energy reductions of up to 35% compared with other methods with similar performance.

IV. POTENTIAL FUTURE TRENDS

We have already seen many examples of successful implementation of autonomic cloud solutions and improvements. However, some areas will benefit from continued research and innovation.

A. *Cloud Privacy and Security*

Relinquishing control of system and user data to the cloud provider will be a concern for many cloud consumers, therefore, work in the field of security-aware solutions will continue [32]. It has been speculated that the emergent field of "confidential computing" is the future of the cloud [33]. Confidential computing gives cloud consumers full control over their sensitive workloads. It explicitly details the computing components that they must trust, whilst providing strong protection from other components, and preventing attacks from other cloud users. Although still in its initial stages, it is expected that the field will grow rapidly to become as popular as some of the most prevalent privacy mechanisms of today.

B. *IoT Ecosystems*

Although seemingly two independent fields, the IoT and cloud computing are closely linked. IoT "generally refers to scenarios where network connectivity and computing capability extends to objects, sensors and everyday items not normally considered computers, allowing these devices to generate, exchange and consume data with minimal human intervention" [34]. Quite often, it is cloud computing services that are facilitating IoT devices, but as the number of connected devices increases, cloud technologies are struggling to sustain real-time demand [35]. It is expected that research will continue to investigate autonomic processes to handle the complexity and demands of IoT systems [36]-[39].

C. *Energy Consumption and Sustainability*

As mentioned, the enormous demand for computational processing and data storage on the cloud means that energy efficiency is a high priority topic. Data centres consume huge amounts of energy with high utilisation of resources, large operating costs, and substantial carbon footprints. In addition to using cleaner energy sources to power data centres, it is paramount that progress continues in the field of computational energy efficiency. We have already described some of the successes in this endeavour, but it is expected that research and development into energy-efficient computation will continue to improve as energy consumption of the cloud grows [40]-[42].

V. CONCLUSIONS

Autonomic computing has been a key facilitator in the advancement of cloud computing. With the scale and complexity of cloud computing systems growing, autonomic computing has helped deal with the difficulty of managing these systems. Autonomic computing has shown great advantages, including improved dependability of systems, through the ability to self-configure, self-heal, self-optimise, and self-protect.

Historically, we have seen the challenges and successes of applying autonomic principles to a cloud infrastructure. The ability to manage autonomic elements at runtime in a heterogenous environment was achieved with innovations on the topic of ARM. SLA violations drove advancements in autonomic techniques to create a tailored approach for cloud applications, for example the proposal of an A-MAPE-K control loop within autonomic managers. Furthermore, identifying that the process of resource scaling could be optimised with respect to time and cost saw the introduction of other technologies, such as those used in machine learning, to support decision making.

Evaluation of the current state of the art highlighted new innovative solutions alongside considerable improvements to existing autonomic techniques in the cloud. Autonomic management solutions have been able to drastically reduce SLA violation occurrence rates, increase resource utilisation, and reduce operational costs of resources resulting in increased profit. Development of self-protecting security-aware solutions has expanded on existing security techniques whilst improving the QoS of systems under attack. QoS-aware systems have shown resource management benefits including lower costs, improved latency, and shorter execution times. Performance management research is extremely important for both cloud providers and cloud users, with the aim being to improve energy efficiency of computation. Innovation in this field has shown promise with proposed solutions achieving considerable energy reductions whilst maintaining performance.

The current state of the art in autonomic cloud computing is promising. Further work in the area will likely see optimisations with respect to self-CHOP and MAPE mechanisms in cloud-based computing systems. As the digital age continues, with more and more data generated every day, the importance for cloud providers to handle data in an efficient and secure manner will increase. It is expected that optimisation of cloud security will continue to be an active research topic in the future. Additionally, in the interest of sustainable ethical practices and Corporate Social Responsibility (CSR), cloud providers are becoming increasingly pressured to address the scale of their operational energy consumption. With the vast energy demands of data centres used to provide cloud computing services continually growing, it is expected that research into energy efficient computation will long continue.

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