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RASS: Resilient Autonomic Software Systems

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Final Report

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RASS: Resilient Autonomic Software Systems
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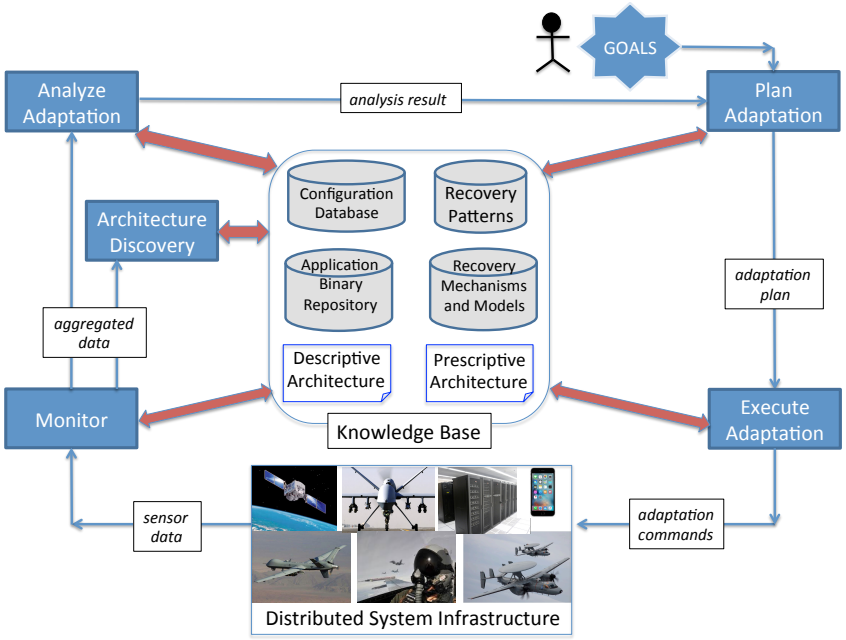
Overview. USAF missions are generally supported by software systems that may become unexpectedly unavailable or degraded due to hostile activity or forces of nature. Under such occurrences, these systems need to dynamically self-adapt to continuously operate in the best possible manner. The systems that support the USAF missions are generally highly dynamic, distributed, very complex, heterogeneous, and need to be extremely resilient and dependable.



Thus, the *objective of this research* is to conceptualize, implement, and evaluate a framework called Resilient Autonomic Software Systems (RASS) inspired by the MAPE-K (i.e., **M**onitor, **A**nalyze, **P**lan, and **E**xecute based on **K**nowledge) paradigm for autonomic systems (aka self-managing systems).

As shown in the figure above, sensor data is obtained from a variety of systems (e.g., airplanes, UAVs, cloud systems, and cell-phones) by the Monitor component of RASS.

These data are aggregated and sent to the Analyze Adaptation component that determines whether self-adaptation is needed and why. The results of this analysis are passed to the Plan Adaptation component, which determines an optimal or near-optimal plan to automatically adapt the system. This plan is received by the Execution Adaptation component, which sends adaptation commands to the parts of the system that need to be adapted and/or recovered, and orchestrates the adaptation to ensure an appropriate and consistent recovery. Because the adaptation plan is driven by the system's software architecture, an Architecture Discovery module recovers the descriptive architecture (i.e., the one that reflects the actual system) or supplements the prescriptive architecture (i.e., the one used to guide the development) when one is not available or has been eroded by system evolution.

The Knowledge Base of RASS includes recovery methods and models that capture their performance overhead, failure recovery software patterns, adaptation patterns, a configuration database, an application binary repository to assist in recovering the software architecture of mobile applications, and the descriptive and prescriptive software architectures.

A significant challenge of our research is that all the activities described above need to be carried out in a completely decentralized fashion. This is essential for achieving high-resiliency and high-dependability.

Project Accomplishments.

Students. The RASS project recruited the four doctoral students listed below:

- Mahmoud Hammad, University of California at Irvine, received his PhD degree in August 2018 with the dissertation *Self-Protection of Android Systems from Inter-Component Communication Attacks*. PhD advisor: Prof. Sam Malek.
- Jason Porter, George Mason University, received his PhD degree in May 2018 with the dissertation *Decentralized Runtime Architecture Discovery and Testbed for Adaptation and Failure Recovery of Large Dynamic Distributed Systems.* PhD advisors: Profs. Daniel A. Menascé and Hassan Gomaa.
- Emad Albassam[1], George Mason University, received his PhD degree in May 2017 with the dissertation *A Model-Based Approach for Self-Healing and Self-Configuration in Component-Based Software Systems.* PhD advisor: Prof. Hassan Gomaa.
- Noor Bajunaid, George Mason University, advanced to candidacy with the dissertation proposal *Modeling and Optimization of Performance and Reliability of Distributed Autonomic Systems*. PhD advisor: Prof. Daniel A. Menascé.

The entire RASS Research Group met once a week for two hours with the Mason and UC Irvine members (i.e., Prof. Sam Malek and Mr. Mahmoud Hammad) participating over Skype. During these meetings we discussed research ideas and members of the group gave presentations regarding their progress. Additionally, Profs. Menascé and Gomaa met once a week with Mason members of the project and each individual student met individually at least once a week with his/her PhD advisor.

[1] Dr. Albassam was not supported as a GRA by the AFOSR grant. However, he was a full-fledged member of the RASS research group.

The RASS group worked on the following interrelated research areas:

Automatic generation of architectural models of mobile applications. Autonomic software systems leverage an abstract representation of the software, often in the form of an architectural model, to manage and adapt the system at runtime. Prior research assumes that these models are developed manually by software engineers. Manual construction of such models is difficult and labor-intensive, hence error prone [26]. Moreover, models used for runtime adaptation of software quickly become obsolete due to changes in the software. In this research, we developed novel static program analysis and dynamic monitoring techniques for the Android system to automatically obtain and maintain a precise architectural model without human intervention [30,35-36,39,41]. Static analysis techniques are used to extract the static architectural model of the Android app from its byte-code [25], whereas dynamic monitoring is used to update the runtime model and keep it synchronized with the running system [21-22]. Due to Android's commercial success as well as the fact that it is an open-source platform, Android is increasingly adopted in many mobile military systems. Our research shows that Android systems are also vulnerable to a variety of security attacks [10,19]. The techniques developed in this thrust of the RASS research facilitates construction of autonomic Android systems that are resilient to changes in system resources (e.g., available battery) as well as unexpected dynamic conditions (e.g., security attacks). We demonstrated how architectural models obtained in this way can be used to improve the security posture of an Android device by reducing the unnecessary privileges granted to its applications [5,28,42].

Robust Decentralized Discovery of Software Architectures of Distributed Systems. As indicated above, autonomic systems typically rely on the knowledge of a software architectural model to plan for adaptation. This thrust of the research considers highly dynamic distributed software systems for which the software architecture is not known in advance because it either suffered erosion (i.e., the software changed over time and architecture prescriptive documents were not updated) or no prescriptive documents were ever produced. We designed and implemented a system called DeSARM (Decentralized Software Architecture DiscoveRy Method) that uses a gossip-like mechanism based on propagation of aggregated message traces to uncover the structural view of the distributed architecture [33]. We conducted experiments to assess the convergence of the process, its termination under stable conditions, its accuracy in discovering the architecture, and its overhead relative to a centralized approach. The experiments were successful and determined the robustness of the method with respect to component and node failures [33].

Analysis and Optimization of Resiliency Mechanisms. Distributed systems can be made more dependable by replacing software components by other components or composite components that implement one or more fault-tolerant mechanisms or add security to the communication between components. Examples of such fault-tolerant mechanisms include checkpointing, replication with or without replica diversity, replication with diversity and voting, consensus building protocols in the presence of byzantine failures. Fault-tolerant mechanisms typically add some level of performance overhead in terms of added computational requirements and/or added communication requirements and latency. We derived and validated a comprehensive analytic model for checkpointing of

concurrent software systems [9, 29]. Our models are the first to consider components that are heterogeneous in terms of (1) resource demands and (2) failure probability distribution. Our first models were based on Markov Chains [29]. While fully automated, their computational complexity was very high for a large number of heterogeneous components. We then developed a novel model based on Queuing Networks [9]; this model is several orders of magnitude faster than the model based on Markov Chains and produces the same results. Because of its speed, the new model can be used at run-time to autonomically determine the optimal checkpointing rate of each component as the environmental conditions change. We implemented such an optimizer based on hill-climbing and showed that it can find the optimal solution by visiting a very small fraction of the solution space [9].

We also developed policies and models for redundant submission of requests to multiple servers [12]. The first replica to finish cancels its identical requests in other servers. We carried out an extensive analytic and simulation analysis to determine the benefits of each policy and the optimal number of replicas in each case.

Decentralized Recovery Patterns and Connectors. This research investigated how recovery patterns, recovery and adaptation connectors, and a decentralized MAPE manager (as shown in the above figure) can be designed and integrated to provide self-healing and self-configuration in distributed software architectures. A distributed software architecture is composed of several interconnected architectural structure patterns (such as client/server, hierarchical, decentralized control, hierarchical control) and distributed communication patterns (such as asynchronous, synchronous with reply, subscription/notification, brokered). A recovery pattern defines how components in an architectural pattern can be dynamically relocated and recovered to a consistent state after a component has failed. Connectors in component-based software architectures interconnect components and encapsulate a communication protocol. In this research, we extend connectors with adaptation and recovery capabilities to assist with component recovery and adaptation [17, 18, 23, 37]. All communication with a component passes through one or more recovery and adaptation connectors, which maintain a copy of messages sent to the component. When a component failure occurs, a decentralized MAPE manager works with the relevant recovery connectors, using the appropriate recovery pattern(s), to analyze the cause of component failure, plan for component recovery, and execute the plan by reconfiguring the system, assigning the recovered component to a different node, and re-establishing its communication with neighboring components to ensure a consistent system state. We also designed reusable secure connectors for secure architectures [16, 40]. Our project researched Software Product Lines for IoT applications [6], recovery and adaptation connectors [23], secure connectors [7], and applications for smart environments [38].

We designed and built a middleware called DARE (**D**istributed **A**daptation and **Re**covery) [24] that uses the services of DeSARM [33] to implement failure recovery and adaptation. DARE is a decentralized, integrated adaptation and recovery framework for providing both self-healing and self-configuration properties to complex and highly dynamic component-based software architectures. DARE was deployed and evaluated in a computer cluster with 30 nodes. The experimental results demonstrated DARE's

capability of dynamically adapting and recovering components in a decentralized environment.

Automated Evaluation of Recovery and Adaptation Frameworks. Evaluating the performance of distributed software systems is very challenging especially in the presence of failures and adaptation. Of particular interest to us is self-healing and self-adaptation middleware such as DARE [24] that detects failures of distributed software systems, analyzes their root causes, devises plans to recover from these failures, and executes these plans. Recovery plans may trigger software architecture adaptations, which may be also initiated by the need to maintain performance and availability goals. In order to provide a comprehensive and scientific evaluation of recovery and adaptation middleware such as DARE, we developed TESS [11], a testbed for automatically generating distributed software architectures and their corresponding runtime applications, deploying them to the nodes of a cluster, running many different types of experiments involving failures and adaptation, and collecting in a database the values of a variety of failure recovery and adaptation metrics. Queries can then be run against the database to provide a thorough and scientific analysis of the efficiency and/or effectiveness of a recovery and adaptation framework.

Autonomic Fog and Cloud Resource Management and Elasticity Control. Many computer systems, such as Internet datacenters and cloud computing environments, consist of a multitude of servers that process user requests. Incoming requests that find all servers busy have to wait until a server becomes idle. This type of queuing system is known as a G/G/c system and has been extensively studied in the queuing literature under steady state conditions. We derived closed-form analytic models for non steady-state G/G/c systems [8] and used these models to design autonomic controllers for multi-server systems subject to *workload surges* of generic shapes during which the average arrival rate of requests exceeds the system's capacity. We performed an extensive evaluation of the these controllers using a G/G/c simulator that we developed (see https://cs.gmu.edu/~menasce/ggc-sim/). We used both synthetic arrival streams and traces from a Google cluster as inputs to the simulator. The results showed that our autonomic controllers are able to successfully vary the number of servers to mitigate the impact of the workload surges [4, 20].

We also studied the problem of job partitioning between fog and cloud servers and developed a performance and cost analytic model [3] and corresponding tool (see https://cs.gmu.edu/~menasce/fogqn/) that we are now using in the design of an autonomic controller that dynamically decides the optimal fraction of processing that should be allocated to a fog server and to the cloud. In [15] we derived analytic models that can be used for capacity planning of IaaS clouds that offer multiple service classes.

Analytic Modeling of Distributed Systems. One of the methods used to design autonomic controllers is to use analytic performance models, typically based on queuing networks, of the system to be controlled. These models are used to compute the values of utility functions to be optimized by the controller. One of the drawbacks of this approach is that it requires expertise from performance engineers. The RASS project developed a framework that automatically derives analytic performance models from relationships

between inputs (e.g., arrival rates) and outputs (e.g., response time and throughput values) [27, 32, 34]. Other modeling activities carried out under the RASS project include the derivation of TDQN, a trace-driven queuing network algorithm [2], and an analytic queuing model for multi-tiered software servers [31] along with an autonomic controller that determines the optimal number of servers in each tier.

Moving Target Defenses. Moving Target Defense (MTD) has recently emerged as a game changer in the security landscape due to its proven potential to introduce asymmetric uncertainty that gives the defender a tactical advantage over the attacker. Many different MTD techniques have been developed, but, despite the huge progress made in this area, critical gaps still exist with respect to the problem of studying and quantifying the cost and benefits of deploying MTDs. In fact, all existing techniques address a very narrow set of attack vectors, and, due to the lack of shared metrics, it is difficult to quantify and compare multiple techniques. We proposed a quantitative analytic model for assessing the resource availability and performance of MTDs, and a method for maximizing a utility function that captures the tradeoffs between security and performance. The proposed model can be applied to a wider range of MTDs and operational scenarios that allow limits to be imposed on the maximum number of resources that can be reconfigured to improve availability and performance. The analytic results were validated by simulation and experimentation, confirming the accuracy of our model [1, 14].

Publications: the RASS project generated 42 publications, all of them acknowledging AFOSR funding. There are two additional publications under review that also acknowledge AFOSR funding.

1. W. Connell, D.A. Menasce, M. Albanese, Performance Modeling of Moving Target Defenses with Reconfiguration Limits, IEEE Tr. Dependable and Secure Computing, accepted for publication on November 15, 2018.
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4. V. Tadakamalla and D.A. Menasce, Model-Driven Elasticity Control for Multi-Server Queues Under Traffic Surges in Cloud Environments, Proc. 2018 Intl. Conf. Autonomic Computing, Trento, Italy, September 3-7, 2018.
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6. V. Tzeremes and H. Gomaa, A Software Product Line Approach to Designing End User Applications for the Internet of Things, Proc. 13th Intl. Joint Conf. Software Technologies (ICSOFT 2018), Porto, Portugal, July 2018.

7. M. Shin, H. Gomaa, and D. Pathirage, A Software Product Line Approach for Feature Modeling and Design of Secure Connectors, Proc. 13th Intl. Joint Conf. Software Technologies (ICSOFT 2018), Porto, Portugal, July 2018 (**best paper award**, invited to submit an extended version to a Spring LNCS publication).
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12. D.A. Menasce and Noor Bajunaid, Performance Evaluation of Heterogeneous Multi-Queues with Job Replication 2017 Computer Measurement Group Conf. (imPACt 2017), New Orleans, LA, November 6-9, 2017.
13. Joshua Garcia, Mahmoud Hammad, and Sam Malek. Lightweight, Obfuscation-Resilient Detection and Family Identification of Android Malware ACM Transactions on Software Engineering and Methodology (TOSEM), November 2017 (Accepted)
14. W. Connell, D.A. Menasce, M. Albanese, Performance Modeling of Moving Target Defenses, 2017 Moving Target Defense (MTD) Workshop, Oct 30th - Nov 3rd, 2017, Dallas, Texas.
15. M. Carvalho, D.A. Menasce, and F. Brasileiro, Capacity Planning for IaaS Cloud Providers Offering Multiple Service Classes, Future Generation Computer Systems, Elsevier, 77 (2017), pp. 97–111.
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29. Noor Bajunaid and Daniel A. Menasce, Analytic Models of Checkpointing for Concurrent Component-Based Software Systems, 8th ACM/SPEC Intl. Conf. Performance Engineering, L'Aquila, Italy, April 22--26, 2017.
30. Hamid Bagheri, Joshua Garcia, Alireza Sadeghi, Sam Malek, Nenad Medvidovic, "Software Architectural Principles in Contemporary Mobile Software: from Conception to Practice," J. Systems and Software 119, 2016, pp. 31-44.

31. Daniel A. Menasce and Noor Bajunaid, "Modeling and Optimization of Multitiered Server-based Systems," 2016 Computer Measurement Group Conference (imPACT 2016), La Jolla, CA, November 7-10, 2016.
32. Mahmoud Awad and Daniel A. Menasce, "A Knowledge Base to Support the Automatic Derivation of Performance Models of Operational Systems," 2016 Computer Measurement Group Conference (imPACT 2016), La Jolla, CA, November 7-10, 2016.
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14. ABSTRACT

The objective of this research is to conceptualize, implement, and evaluate a framework called Resilient Autonomic Software Systems (RASS) inspired by the MAPE-K (i.e., Monitor, Analyze, Plan, and Execute based on Knowledge) paradigm for autonomic systems (aka self-managing systems). Sensor data is obtained from a variety of systems (e.g., airplanes, UAVs, cloud systems, and cell-phones) by the Monitor component of RASS. These data are aggregated and sent to the Analyze Adaptation component that determines whether self-adaptation is needed and why. The results of this

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Abstract

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Because the adaptation plan is driven by the system's software architecture, an architecture discovery system called DeSARM recovers the descriptive architecture (i.e., the one that reflects the actual system) or supplements the prescriptive architecture (i.e., the one used to guide the development) when one is not available or has been eroded by system evolution. The Knowledge Base of RASS includes recovery methods and models that capture their performance overhead, failure recovery software patterns, adaptation patterns, a configuration database, an application binary repository to assist in recovering the software architecture of mobile applications, and the descriptive and prescriptive software architectures. A significant challenge of our research is that all the activities described above need to be carried out in a completely decentralized fashion. This is essential for achieving high-resiliency and high-dependability. The RASS group published 42 papers covering the areas of automatic generation of architectural models of mobile applications, robust decentralized discovery of software architectures of distributed systems, analysis and optimization of resiliency mechanisms, decentralized recovery patterns and connectors, automated evaluation of recovery and adaptation frameworks, autonomic fog and cloud resource management and elasticity control, analytic modeling of distributed systems, and moving target defenses. Additionally, we graduated 3 PhD students plus another expected to graduate in May 2019.

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1. W. Connell, D.A. Menasce, M. Albanese, Performance Modeling of Moving Target Defenses with Reconfiguration Limits, IEEE Tr. Dependable and Secure Computing, accepted for publication on November 15, 2018.
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New discoveries, inventions, or patent disclosures:

Do you have any discoveries, inventions, or patent disclosures to report for this period?

No

Please describe and include any notable dates

Do you plan to pursue a claim for personal or organizational intellectual property?

Changes in research objectives (if any):

None

Change in AFOSR Program Officer, if any:

We started with Dr. Kathleen Kaplan as PO. Then Dr. James Lawton became the PO. Finally, Dr. Tristan Nguyen became the PO.

Extensions granted or milestones slipped, if any:

none

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

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