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14. ABSTRACT
The ARO-supported AWARE project addressed the design and performance of adaptive software technologies for highly trusted software systems. A dynamically adaptive system (DAS) monitors itself and its execution environment at run time. This monitoring enables a DAS not only to detect conditions warranting a reconfiguration, but also to determine when and how to safely reconfigure itself in order to deliver acceptable behavior before, during, and after adaptation. Using this technology, existing systems can be hardened against adverse conditions and cyber attacks that were unforeseen at the time of deployment. The project produced several important

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Report Title

Final Report: AWARE: Adaptive Software Monitoring and Dynamic Reconfiguration for Critical Infrastructure Protection

ABSTRACT

The ARO-supported AWARE project addressed the design and performance of adaptive software technologies for highly trusted software systems. A dynamically adaptive system (DAS) monitors itself and its execution environment at run time. This monitoring enables a DAS not only to detect conditions warranting a reconfiguration, but also to determine when and how to safely reconfigure itself in order to deliver acceptable behavior before, during, and after adaptation. Using this technology, existing systems can be hardened against adverse conditions and cyber-attacks that were unforeseen at the time of deployment. The project produced several important advances in several aspects of self-adaptive systems, including: novel methods for modeling dynamically adaptive software; (2) adaptive monitoring software through code generation and verification, both at development time and run time; (3) real-time decision-making algorithms that enable the system to respond effectively to changing conditions and threats; and (4) application of evolutionary computation to software assurance, self-organizing protocols for distributed systems, and the design of autonomous robots.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/29/2014	1.00	David B. Knoester, Philip K. McKinley. Evolution of Synchronization and Desynchronization in Digital Organisms, Artificial Life, (01 2011): 0. doi: 10.1162/artl_a_00014
08/09/2014	17.00	S. Masoud Sadjadi, Philip K. McKinley. Transparent autonomization in CORBA, Computer Networks, (07 2009): 0. doi: 10.1016/j.comnet.2008.12.012
08/11/2014	5.00	Pete Sawyer, Nelly Bencomo, Betty H. C. Cheng, Jean-Michel Bruel, Jon Whittle. RELAX: a language to address uncertainty in self-adaptive systems requirement, Requirements Engineering, (03 2010): 177. doi: 10.1007/s00766-010-0101-0
08/11/2014	27.00	Benjamin E. Beckmann, David B. Knoester, Brian D. Connelly, Christopher M. Waters, Philip K. McKinley. Evolution of Resistance to Quorum Quenching in Digital Organisms, Artificial Life, (07 2012): 291. doi: 10.1162/artl_a_00066
08/11/2014	29.00	Philip K. McKinley, Betty H. C. Cheng, Andres J. Ramirez, Adam C. Jensen. Applying evolutionary computation to mitigate uncertainty in dynamically-adaptive, high-assurance middleware, Journal of Internet Services and Applications, (12 2011): 51. doi: 10.1007/s13174-011-0049-4
08/11/2014	24.00	David B. Knoester, Heather J. Goldsby, Philip K. McKinley. Genetic Variation and the Evolution of Consensus in Digital Organisms, IEEE Transactions on Evolutionary Computation, (06 2013): 403. doi: 10.1109/TEVC.2012.2201725
08/11/2014	36.00	Andres J. Ramirez, David B. Knoester, Betty H. C. Cheng, Philip K. McKinley. Plato: a genetic algorithm approach to run-time reconfiguration in autonomic computing systems, Cluster Computing, (03 2010): 229. doi: 10.1007/s10586-010-0122-y
TOTAL:		**7**

Number of Papers published in peer-reviewed journals:

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Received Paper

TOTAL:

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
07/29/2014	2.00	David B. Knoester, Philip K. McKinley. Constructing Communication Networks with Evolved Digital Organisms, 2012 IEEE 6th International Conference on Self-Adaptive and Self-Organizing Systems (SASO). 10-SEP-12, Lyon, France. : ,
08/03/2014	4.00	Brian D. Connelly, Benjamin E. Beckmann, Philip K. McKinley. Resource abundance promotes the evolution of public goods cooperation, ACM Genetic and Evolutionary Computation Conference. 07-JUL-10, Portland, Oregon, USA. : ,
08/03/2014	22.00	Brian D. Connelly, Philip K. McKinley, Benjamin E. Beckmann. Evolving cooperative pheromone usage in digital organisms, 2009 IEEE Symposium on Artificial Life (ALife). 03-MAR-09, Nashville, TN, USA. : ,
08/09/2014	8.00	David B. Knoester, Heather J. Goldsby, Philip K. McKinley. Neuroevolution of mobile ad hoc networks, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 07-JUL-10, Portland, Oregon, USA. : ,
08/09/2014	23.00	Benjamin E. Beckmann, Laura M. Grabowski, Philip K. McKinley, Charles Ofria. Applying digital evolution to the design of self-adaptive software, 2009 IEEE Symposium on Artificial Life (ALife). 03-MAR-09, Nashville, TN, USA. : ,
08/09/2014	20.00	Ji Zhang, Heather J. Goldsby, Betty H.C. Cheng. Modular verification of dynamically adaptive systems, the 8th ACM international conference. 02-MAR-09, Charlottesville, Virginia, USA. : ,
08/09/2014	19.00	Andres J. Ramirez, Betty H. C. Cheng. Design patterns for developing dynamically adaptive systems, the 2010 ICSE Workshop. 03-MAY-10, Cape Town, South Africa. : ,
08/09/2014	18.00	Andres J. Ramirez, David B. Knoester, Betty H.C. Cheng, Philip K. McKinley. Applying genetic algorithms to decision making in autonomic computing systems, the 6th international conference. 15-JUN-09, Barcelona, Spain. : ,
08/09/2014	16.00	David B. Knoester, Andres J. Ramirez, Philip K. McKinley, Betty H.C. Cheng. Evolution of robust data distribution among digital organisms, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 08-JUL-09, Montreal, Québec, Canada. : ,
08/09/2014	15.00	Benjamin E. Beckmann, Philip K. McKinley. Evolving quorum sensing in digital organisms, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 08-JUL-09, Montreal, Québec, Canada. : ,
08/09/2014	14.00	Jon Whittle, Pete Sawyer, Nelly Bencomo, Betty H.C. Cheng, Jean-Michel Bruel. RELAX: Incorporating Uncertainty into the Specification of Self-Adaptive Systems, 17th IEEE International Requirements Engineering Conference. 31-AUG-09, Atlanta, Georgia, USA. : ,
08/09/2014	13.00	Benjamin E. Beckmann, Philip K. McKinley, David B. Knoester. Effects of Communication Impairments on Quorum Sensing, 2009 Third IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO). 14-SEP-09, San Francisco, California, USA. : ,

08/09/2014 12.00 David B. Knoester, Philip K. McKinley. Evolution of Probabilistic Consensus in Digital Organisms, 2009 Third IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO). 14-SEP-09, San Francisco, California, USA. : ,

08/09/2014 10.00 Andres J. Ramirez, Betty H.C. Cheng, Philip K. McKinley, Benjamin E. Beckmann. Automatically generating adaptive logic to balance non-functional tradeoffs during reconfiguration, Proceedings of the 7th International Conference on Autonomic Computing. 07-JUN-10, Washington, DC, USA. : ,

08/09/2014 9.00 Jeff Clune, Benjamin E. Beckmann, Philip K. McKinley, Charles Ofria. Investigating whether HyperNEAT produces modular neural networks, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 07-JUL-10, Portland, Oregon, USA. : ,

08/11/2014 3.00 Jared M. Moore, Jianxun Wang, Xiaobo Tan, Anthony J. Clark, Philip K. McKinley. Evolutionary Design and Experimental Validation of a Flexible Caudal Fin for Robotic Fish, International Conference on the Simulation and Synthesis of Living Systems. 02-JUL-12, . : ,

08/11/2014 6.00 A J Ramirez, B H C Cheng, P K McKinley. Adaptive monitoring of software requirements, 2010 First International Workshop on Requirements at Run Time (RE@RunTime). 28-SEP-10, Sydney, NSW. : ,

08/11/2014 7.00 Adam C. Jensen, Betty H.C. Cheng. On the use of genetic programming for automated refactoring and the introduction of design patterns, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 07-JUL-10, Portland, Oregon, USA. : ,

08/11/2014 25.00 Philip K. McKinley, Jared M. Moore. Evolving flexible joint morphologies, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 07-JUL-12, Philadelphia, Pennsylvania, USA. : ,

08/11/2014 26.00 Chad Byers, Betty Cheng, Philip McKinley. Exploring the evolution of internal control structure using digital enzymes, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 07-JUL-12, Philadelphia, Pennsylvania, USA. : ,

08/11/2014 28.00 Andres J. Ramirez, Adam C. Jensen, Betty H. C. Cheng. A taxonomy of uncertainty for dynamically adaptive systems, 7th International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS). 04-JUN-12, Zurich, Switzerland. : ,

08/11/2014 30.00 Andres J. Ramirez, Adam C. Jensen, Betty H. C. Cheng, David B. Knoester. Automatically exploring how uncertainty impacts behavior of dynamically adaptive systems, 26th IEEE/ACM International Conference on Automated Software Engineering (ASE). 06-NOV-11, Lawrence, KS, USA. : ,

08/11/2014 31.00 David B. Knoester, Philip K. McKinley. Neuroevolution of Controllers for Self-Organizing Mobile Ad Hoc Networks, 5th IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO). 03-OCT-11, Ann Arbor, MI, USA. : ,

08/11/2014 32.00 Andres J. Ramirez, Betty H.C. Cheng, Philip K. McKinley. An Evolutionary Approach to Network Self-Organization and Resilient Data Diffusion, 5th IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO). 03-OCT-11, Ann Arbor, MI, USA. : ,

08/11/2014 33.00 Chad M. Byers, Betty H.C. Cheng, Philip K. McKinley. Digital Enzymes: Agents of Reaction Inside Robotic Controll\ers for the Foraging Problem, Proceedings of the ACM Genetic and Evolutionary Computation Conference. 12-JUL-11, Dublin, Ireland. : ,

08/11/2014 34.00 Daniel J. Couvertier, Philip K. McKinley. Effects of biased group selection on cooperative predation in digital organisms (poster summary),
Proceedings of the ACM Genetic and Evolutionary Computation Conference (companion) . 12-JUL-11, Dublin, Ireland. : ,

08/11/2014 35.00 Andres J. Ramirez, Adam C. Jensen, Betty H.C. Cheng. An aspect-oriented approach for implementing evolutionary computation applications,
Proceedings of the 10th International Conference on Aspect-Oriented Software Development. 21-MAR-11, Porto de Galinhas, Brazil. : ,

08/11/2014 37.00 David Knoester, Philip McKinley. Evolving Virtual Fireflies,
Proceedings of the 10th European Conference on Artificial Life. 13-SEP-09, . : ,

08/12/2014 39.00 Heather Goldsby, Betty Cheng. Automatically Discovering Properties That Specify the Latent Behavior of UML Models,
Proceedings of the ACM/IEEE International Conference on Model Driven Engineering Languages and Systems. 10-MAY-10, . : ,

08/12/2014 40.00 Betty H. C. Cheng, Pete Sawyer, Nelly Bencomo, Jon Whittle. A Goal-Based Modeling Approach to Develop Requirements of an Adaptive System with Environmental Uncertainty,
Proceedings of the ACM/IEEE 12th International Conference on Model Driven Engineering Languages and Systems. 04-OCT-09, . : ,

08/12/2014 41.00 Andres J. Ramirez, Erik M. Fredericks, Adam C. Jensen, Betty H. C. Cheng. Automatically RELAXing a goal model to cope with uncertainty,
Proceedings of the 4th International Conference on Search Based Software Engineering. 28-SEP-12, . : ,

08/12/2014 42.00 Andres J. Ramirez, Betty H. C. Cheng, Nelly Bencomo, Pete Sawyer. Relaxing Claims: Coping with Uncertainty While Evaluating Assumptions at Run Time,
Proceedings of the 15th International Conference on Model Driven Engineering Languages and Systems. 30-SEP-12, . : ,

08/12/2014 43.00 Andres J. Ramirez, Betty H. C. Cheng. Automatic Derivation of Utility Functions for Monitoring Software Requirements,
Proceedings of the 15th International Conference on Model Driven Engineering Languages and Systems. 16-OCT-11, . : ,

08/12/2014 38.00 Brian Connelly, Philip McKinley. Evolving Social Behavior in Adverse Environments,
Proceedings of the 10th European Conference on Artificial Life. 13-SEP-09, . : ,

TOTAL: **34**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Best Paper Award for, "Evolutionary design and experimental validation of a flexible caudal fin for robotic fish," by A. Clark, J. Moore, J. Wang, X. Tan and P. McKinley, Proceedings of the Thirteenth International Conference on the Synthesis and Simulation of Living Systems, pp. 325-332, East Lansing, Michigan, July 2012.

Best Paper Nomination for, "A Toolchain for the Detection of Structural and Behavioral Latent System Properties," by A. Jensen, B.H.C. Cheng, H.J. Goldsby, E. Nelson, Proceedings of the ACM/IEEE International Conference on Model Driven Engineering Languages and Systems (MODELS 2011). pp. 683--698. Wellington, New Zealand, October 2011.

Best Paper Nomination for, "Digital Enzymes: Agents of Reaction Inside Robotic Controllers for the Foraging Problem," by C. M. Byers, B. H. C. Cheng and P. K. McKinley, Proceedings of the ACM Genetic and Evolutionary Computation Conference, Dublin, Ireland, July 2011.

Best Paper Award for, "Resource Abundance Promotes the Evolution of Public Goods Cooperation," by B. D. Connelly, B. E. Beckmann and P. K. McKinley, Proceedings of the ACM Genetic and Evolutionary Computation Conference, Portland, Oregon, July 2010.

Best Paper Award for, "Applying Genetic Algorithms to Decision Making in Autonomic Computing Systems," by A. Ramirez, D. B. Knoester, B. H. C. Cheng and P. K. McKinley, Proceedings of the 6th IEEE International Conference on Autonomic Computing and Communications, Barcelona, Spain, June 2009.

Best Paper nomination for, "Evolution of Robust Data Distribution Among Digital Organisms," by D. B. Knoester, A. Ramirez, P. K. McKinley and Betty H.C. Cheng, Proceedings of the ACM Genetic and Evolutionary Computation Conference (GECCO-2009), Montreal, Canada, July, 2009.

Distinguished Paper, invited for journal submission, 17th IEEE International Requirements Engineering Conference Atlanta, Georgia, September 2009. Title: RELAX: Incorporating Uncertainty into the Specification of Self-Adaptive Systems Authors: Jon Whittle, Pete Sawyer, Nelly Bencomo, Betty H.C. Cheng, Jean-Michel Bruel.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Andres Ramirez	0.90	
FTE Equivalent:	**0.90**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Philip K. McKinley	0.08	
Betty H.C. Cheng	0.08	
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Malcolm Doering	0.00	Computer Science
Anthony Curley	0.00	Computer Science
Joseph Meleca	0.00	Computer Science
Hanquing Hu	0.00	Computer Science
James Gung	0.00	Computer Science
FTE Equivalent:	**0.00**	
Total Number:	**5**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 5.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 5.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 2.00

Names of Personnel receiving masters degrees

NAME
Chad Byers
Total Number: 1

Names of personnel receiving PHDs

NAME
Andres Ramirez
David Knoester
Heather Goldsby
Brian Connelly
Jeff Clune
Adam Jensen
Chad Byers
Benjamin Beckmann
Total Number: 8

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The AWARE project has advanced the state-of-the-art in several aspects of dynamically adaptive systems, including the design and performance of adaptive monitoring technologies for highly trusted software systems. Many of the proposed methods leverage evolutionary computation to automatically generate new system configurations and adaptive logic to transition a system from one configuration to another in a safe and consistent fashion, as well as how to help the system respond effectively to adverse situations. These contributions have been well-received by the research community, as AWARE-based papers have received several best paper awards and nominations (listed elsewhere in this report). The main activities (and research progress) address three key elements of such systems: model-driven engineering of adaptive systems, assurance of adaptive systems, and decision-making of adaptive systems. See attached discussion of each.

Technology Transfer

Throughout the course of the AWARE project, we have collaborated with industrial organizations in order to obtain industrial-strength data to guide our research and to validate the research techniques. To ensure broader applicability while maximizing impact, we explicitly sought applications from a range of domains, all of which involve the need for high-assurance in the face of uncertain environmental conditions.

Northrop Grumman Corporation: We collaborated with two groups of researchers and developers at Northrop Grumman Corporation (NGC). This collaboration was initiated when a researcher at NGC approached us after reading about our research applying digital evolution to produce robust, collective behavior in software agents. One NGC group (at Fort Wayne, IN) applied these technologies to problems in the area of cyber-security and multi-agent systems. Subsequent meetings between MSU and NGC personnel has led to collaboration with a second NGC group (at Linthicum, MD), interested in applying our evolutionary computation methods to enhance the robustness of autonomous systems such as Large Displacement Unmanned Underwater Vehicle (LDUUVs), These systems are expected to survive without human control for months at a time.

Continental Automotive: We collaborated with Continental Automotive on applying evolutionary computation to future onboard automotive systems. Continental provided descriptions of a steer-by-wire system for an undergraduate course, and the students created detailed requirements specifications and prototypes for this emerging onboard system. The detailed specifications were essential to exploring how the system should adapt as it undergoes changing (and possibly unexpected) environmental conditions.

Ford Motor Company: One of the Best Paper nominations involved our collaborations with Ford Motor Company, where we used our techniques to analyze industrial-strength (but proprietary-free) models provided by Ford. Our objective was to use a tool chain, involving several of our tools, including an extended version of Marple, to look for errors in the models. With our toolchain, we were able to look for syntactic and semantic errors that would not be detectable using existing tools. Ultimately, we were looking for feature interactions with multiple automotive subsystems. This tool chain can be applied to other systems that have been modeled with state-based models and domain models. Ford also served as customers for an upper-level undergraduate software engineering course, where they again provided high-level requirements for two advanced automotive systems (cooperative, adaptive cruise control and onboard diagnostics systems).

BAE Systems: We were approached by researchers at BAE Systems to collaborate on applying evolutionary computation to the design and maintenance of software that needs to adapt to changing requirements and new threats. In an ongoing project, we are exploring how evolutionary computation can be used to enable automated composition strategies for reusing existing software components.

HP/Google: One of our studies, which won a Best Paper Award, involved the use of evolutionary computation to enhance reliability of a remote data mirroring system (RDM). The case study was provided to us by an industrial collaborator who initially worked at HP and then moved to Google, where he continued to provide industrial-strength data and feedback on our research results.

The AWARE project has advanced the state-of-the-art in several aspects of dynamically adaptive systems, including the design and performance of adaptive monitoring technologies for highly trusted software systems. Many of the proposed methods leverage evolutionary computation to automatically generate new system configurations and adaptive logic to transition a system from one configuration to another in a safe and consistent fashion, as well as how to help the system respond effectively to adverse situations. These contributions have been well-received by the research community, as AWARE-based papers have received several best paper awards and nominations (listed elsewhere in this report). The main activities (and research progress) address three key elements of such systems: model-driven engineering of adaptive systems, assurance of adaptive systems, and decision-making of adaptive systems. Each is discussed in turn.

1. MODEL DRIVEN ENGINEERING OF SELF-MODELING SOFTWARE

In the early part of the project, we developed and extended a set of design patterns intended to capture the subtleties found in the monitoring portion of an autonomic computing system. These design patterns were harvested from numerous existing frameworks for monitoring in distributed applications. We extended the design pattern template with additional fields specific to adaptation concerns. In addition to providing guidance for constructing design models for implementation, these design patterns explicitly address the assurance concerns of the resulting models, using the A-LTL specification language (adapt-operator extended linear temporal logic) previously developed by Zhang and Cheng. We conducted a case study in which we applied these adaptation patterns to an adaptive news web server intended to tolerate extremely heavy, unexpected loads. To address assurance concerns, we applied automated formal verification techniques (Hydra) to ensure instantiated pattern models satisfy invariant properties specified in each adaptation pattern. By verifying the instantiated patterns satisfy specific safety and liveness properties, we can assure this system cannot reach an inconsistent state as a result of a reconfiguration.

We also investigated the use of evolutionary computation for automatically refactoring object-oriented (OO) designs to improve OO metrics and introduce new design patterns. This technique, called REMODEL, was applied to collection of existing models used as benchmarks for OO-based refactoring and an existing web-based repository called REMODD to provide users with model-driven development artifacts. REMODEL uses a genetic algorithm (GA) to apply different combinations of mini-transformations to existing designs. These transformations are intended to be semantics-preserving. We developed a number of fitness criteria to drive the evolutionary process to identify viable refactored designs. The resulting capability provides a means to automate the refactoring of designs to include design patterns and improve the overall design metrics for the system. This work was the first to support this type of design refactoring.

2. ASSURANCE IN DYNAMICALLY ADAPTIVE SYSTEMS

Three key aspects of assurance were investigated as part of the AWARE project: specification languages, analysis support, and model generation. The assurance investigations take advantage of A-LTL, an adapt-operator extension to Linear Temporal Logic developed previously by Zhang and Cheng (ICSE 2006, Distinguished Paper Award). A-LTL enables specification and verification of invariant properties that must be satisfied before, during, and after adaptation. Specifically, we model a dynamically adaptive program as a collection of (non-adaptive) steady-state programs and a set of adaptations that realize transitions among steady state programs in response to environmental changes.

Three lines of investigation were pursued to support the specification of adaptive systems. First, we developed adaptation semantics in terms of the A-LTL specification language. As part of this work, we developed adaptation patterns as well as specification patterns that describe properties to be satisfied before, during, and after adaptation. These specification patterns involve the use of LTL and A-LTL properties describing invariant properties of the non-adaptive and the adaptive portions of a system. Second, we developed the RELAX specification language to enable developers to explicitly identify sources of uncertainty when specifying the requirements of a given system. This capability enables systems designers to build in flexibility into a system to account for the uncertainty, thus making systems less brittle. RELAX has been formalized in terms of fuzzy logic semantics. Finally, we developed a goal-based modeling approach to modeling adaptive systems that makes use of the RELAXation of goals, which is supported by our AutoRELAX tool that harnesses evolutionary computation to automatically generate RELAXed goal models.

The second dimension of assurance is the development and use of a modular model checking approach to verifying that a formal model of an adaptive program satisfies its requirements specified in LTL and A-LTL, respectively. We leveraged the extended version of the assume/guarantee paradigm to develop three modular model checking algorithms that are used to verify global invariants and transitional properties, where local properties are verified as part of the transitional property model checking algorithm. Our approach, called AMOebA (Adaptive program MOdular Analyzer), enables developers to verify that adaptive programs adhere to requirements specified in LTL and ALTL, including transitional properties. Additionally, it reduces the complexity of verifying an adaptive program by a factor of n, where n is the number of steady-state programs. Moreover, additional or modified steady-state programs can be verified in isolation without repeating the verification of the entire adaptive program. As such, we apply the separation of concerns strategy both in the modeling and in the verification process, thereby simplifying both steps.

Third, we applied evolutionary computation to the problem of generating models of target systems that satisfy invariant properties. Specifically, we developed Avida-MDE (based on the Avida digital evolution platform) to support the automatic generation of software models (i.e., state-based models) representing the target systems of an adaptive system. Avida-MDE generates models that satisfy invariant requirements (specified as LTL properties) user-provided scenarios, and software engineering metrics. As an extension to this work, we developed Avida-Marple, which automatically identifies latent properties within models. These are properties that were not intended to be satisfied (as specified by requirements). We use Avida-Marple to identify the "latent properties" satisfied by the target system models to identify the distinguishing characteristics thus enabling us to match the target systems to the appropriate set of environmental conditions. Avida-Marple can also be used to identify unwanted feature interactions and undesirable latent properties. We later improved the Avida-Marple work by incorporating a technique called Novelty Search, which significantly decreases the number of properties identified. We applied Marple to find unwanted properties in an automotive application obtained from one of our industrial collaborators. Finally, we developed Loki, an automated technique for identifying combinations of system and environmental conditions that cause requirements violations. Experimental results with an intelligent vehicle application show Loki is able to discover combinations of system and environmental conditions that lead to latent behaviors and requirements violations. We also developed Plato to automatically generate software configurations in response to adverse environmental changes, where the software configurations are able to balance competing tradeoffs -- the results greatly improve the state of art technique for generating run-time configurations. This work received a Best Paper Award at the IEEE International Conference on Autonomic Computing (ICAC). We also developed Hermes, a technique for automatically generating the adaptive logic that moves the system from one adaptive configuration to another while ensuring that the system remains consistent as defined by the A-LTL specifications.

3. DECISION MAKING IN AUTONOMIC SYSTEMS

The third major part of the AWARE project addresses run-time decision making in autonomic systems, which produce actions or dynamic reconfigurations intended to improve performance, conserve energy, or thwart an attack. A key challenge to be addressed is how such a system deals with incomplete information and uncertainty in the environment as new situations are encountered.

The AWARE project has produced several novel methods for decision making. First, we developed Plato, a genetic algorithm-based decision-making process that searches the vast and complex space of possible reconfigurations with the objective of identifying suitable target reconfigurations in response to changing requirements and environmental conditions. A key benefit of Plato is that developers need not prescribe reconfiguration plans in advance to address specific situations warranting reconfiguration. Instead, Plato evolves suitable reconfiguration plans at run time. Plato-MDE is an extension of the Plato system that generates architectural models of target system configurations and enables developers to indirectly control the degree of change between the current and target system configurations. We later developed Hermes, a genetic programming-based decision-making process that accepts as input a starting and target system configuration and produces a series of reconfiguration steps, or an adaptation path, as output. A key benefit of Hermes is that it is capable of automatically evolving adaptation paths that safely transition an executing system from its current configuration to its desired target configuration while balancing tradeoffs between functional and non-functional requirements. Plato-RE is another extension specifically intended for adaptive monitoring of software requirements. Combined, these systems enable the system to adapt in ways that were perhaps unforeseen or even considered relevant at design time.

In the AWARE project, we have also applied evolutionary computation to realize robust and adaptive behavior. Evolutionary computation can be leveraged to explore and apply a richer set of behaviors that can withstand such adverse conditions while remaining mission-effective. Hence, these studies are relevant to sensor networks, autonomous robots and other cyber-physical systems. Such systems need to remain operational under highly adverse conditions. In early studies, we applied digital evolution and neuroevolution (evolution of artificial neural networks) to evolve energy-efficient algorithms for group communication protocols such as distributed consensus, synchronization, and quorum sensing. Later, we applied neuroevolution to the design of controllers for simulated robots, evaluating the effectiveness of different types of encodings. We also conducted experiments on fundamental issues in the evolution of cooperation, and we have demonstrated the ability of digital organisms to self-organize and build communication networks as well as physical structures reminiscent of bacterial biofilms. Such behaviors are critical to the overall safety of distributed adaptive systems, since remote components are typically monitored across unreliable networks and are at risk of cyber-attack. Finally, we have explored the joint-evolution of robot control and physical components, potentially enabling artificial systems to approach the capabilities of animals in terms of mobility and agility.

LEVERAGED FUNDING

Although the budget for the AWARE project supported only one graduate research assistant, the AWARE project leveraged

funding from other resources in order to accomplish more than could be done with single graduate research assistant. Results on evolutionary computation from the NSF-sponsored TEAMS project (led by P. McKinley) and the Orchid project (led by B. Cheng) fed directly into techniques and algorithms developed in the AWARE project. The AWARE project has also made use of the Evolution Park testbed, containing terrestrial and aquatic robots, a high-end 3D printer, and extensive computing facilities. Michigan State University provided $370K of funding for research and education in High-Assurance Systems (HAS). The AWARE project has directly benefitted from research and facilities supported by the HAS initiative. Finally, the NSF-sponsored BEACON Center for the Study of Evolution in Action provided fellowships and infrastructure leveraged in the AWARE project.

Andres Ramirez was the primary graduate student supported on the AWARE project. However several other students, supported by the other grants or working full-time, contributed to the project as part of their doctoral research. These students are: David Knoester, Benjamin Beckmann, Heather Goldsby, Brian Connelly, Erik Fredericks, Adam Jensen, Chad Byers, Jared Moore, Anthony Clark, Jeff Clune). In addition, five undergraduate research assistants (Malcolm Doering, Anthony Curley, Joseph Meleca, Hanqing Hu, and James Gung) contributed to the AWARE project but were partially or fully supported by Michigan State University.

CONCLUSIONS

In summary, the AWARE project addressed the design of adaptive monitoring software and, more generally, high-assurance adaptive systems that need to deal with uncertainty. Designing dynamically adaptive computing systems, especially those that interact with the physical world, is challenging because such systems need to operate with assurance, yet somehow accommodate the uncertainty of the environment. Our approach integrated rigorous software engineering with the open-ended search capabilities of evolutionary computation. In particular, We incorporated environmental uncertainty explicitly into the modeling of the behavior of the adaptive system and the monitoring infrastructure. The resulting systems are resilient and robust to changing environmental conditions and better able to deliver acceptable behavior even in the face of adverse conditions. The innovations produced by the AWARE project have been recognized through best papers awards at conferences. The technologies produced by this project facilitate development of software systems that exhibit adaptability and survival capabilities analogous to those found in natural organisms. Collaboration with industrial partners (described elsewhere in this report) helps to ensure these methods will benefit real-world systems.

Technology Transfer

Throughout the course of the AWARE project, we have collaborated with industrial organizations in order to obtain industrial-strength data to guide our research and to validate the research techniques. To ensure broader applicability while maximizing impact, we explicitly sought applications from a range of domains, all of which involve the need for high-assurance in the face of uncertain environmental conditions.

Northrop Grumman Corporation: We collaborated with two groups of researchers and developers at Northrop Grumman Corporation (NGC). This collaboration was initiated when a researcher at NGC approached us after reading about our research applying digital evolution to produce robust, collective behavior in software agents. One NGC group (at Fort Wayne, IN) applied these technologies to problems in the area of cyber-security and multi-agent systems. Subsequent meetings between MSU and NGC personnel has led to collaboration with a second NGC group (at Linthicum, MD), interested in applying our evolutionary computation methods to enhance the robustness of autonomous systems such as Large Displacement Unmanned Underwater Vehicle (LDUUVs), These systems are expected to survive without human control for months at a time.

Continental Automotive: We collaborated with Continental Automotive on applying evolutionary computation to future onboard automotive systems. Continental provided descriptions of a steer-by-wire system for an undergraduate course, and the students created detailed requirements specifications and prototypes for this emerging onboard system. The detailed specifications were essential to exploring how the system should adapt as it undergoes changing (and possibly unexpected) environmental conditions.

Ford Motor Company: One of the Best Paper nominations involved our collaborations with Ford Motor Company, where we used our techniques to analyze industrial-strength (but proprietary-free) models provided by Ford. Our objective was to use a tool chain, involving several of our tools, including an extended version of Marple, to look for errors in the models. With our toolchain, we were able to look for syntactic and semantic errors that would not be detectable using existing tools. Ultimately, we were looking for feature interactions with multiple automotive subsystems. This tool chain can be applied to other systems that have been modeled with state-based models and domain models. Ford also served as customers for an upper-level undergraduate software engineering course, where they again provided high-level requirements for two advanced automotive systems (cooperative, adaptive cruise control and onboard diagnostics systems).

BAE Systems: We were approached by researchers at BAE Systems to collaborate on applying evolutionary computation to the design and maintenance of software that needs to adapt to changing requirements and new threats. In an ongoing project, we are exploring how evolutionary computation can be used to enable automated composition strategies for reusing existing software components.

HP/Google: One of our studies, which won a Best Paper Award, involved the use of evolutionary computation to enhance reliability of a remote data mirroring system (RDM). The case study was provided to us by an industrial collaborator who initially worked at HP and then moved to Google, where he continued to provide industrial-strength data and feedback on our research results.