NASA Monographs in
Systems and Software Engineering

The **NASA Monographs in Systems and Software Engineering** series addresses cutting-edge and groundbreaking research in the fields of systems and software engineering. This includes in-depth descriptions of technologies currently being applied, as well as research areas of likely applicability to future NASA missions. Emphasis is placed on relevance to NASA missions and projects.

Walt Truszkowski, Harold L. Hallock,
Christopher Rouff, Jay Karlin, James Rash,
Mike Hinchey, and Roy Sterritt

Autonomous and Autonomic Systems: With Applications to NASA Intelligent Spacecraft Operations and Exploration Systems

With 56 Figures

Springer

Walt Truszkowski
NASA Goddard Space Flight Center
Mail Code 587
Greenbelt MD 20771, USA
Walt.Truszowski@nasa.gov

Harold L. Hallock
NASA Goddard Space Flight Center (GSFC)
Greenland MD 20771, USA
harold.l.hallock@nasa.gov

Christopher Rouff
Lockheed Martin, Advanced Technology Laboratories
Arlington, VA, USA
christopher.rouff@lmco.com

Jay Karlin
Viable Systems, Inc.
4710 Bethesda Ave. #516
Maryland MD 20814, USA
jkarlin1@comcast.net

James Rash
NASA Goddard Space Flight Center
Mail Code 585
Greenbelt MD 20771, USA
James.L.Rash@nasa.gov

Mike Hinchey
Lero-the Irish Software Engineering Research Centre
University of Limerick
Limerick
Ireland

Roy Sterritt
Computer Science Research Institute
University of Ulster
Newtownabbey, County Antrim
Northern Ireland
r.sterritt@ulster.ac.uk

ISSN 1860-0131
ISBN 978-1-84628-232-4 e-ISBN 978-1-84628-233-1
DOI 10.1007/978-1-84628-233-1
Springer Dordrecht Heidelberg London New York

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2009930628

Cover design: SPi Publisher Services

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

In the early 1990s, NASA Goddard Space Flight Center started researching and developing autonomous and autonomic ground and spacecraft control systems for future NASA missions. This research started by experimenting with and developing expert systems to automate ground station software and reduce the number of people needed to control a spacecraft. This was followed by research into agent-based technology to develop autonomous ground control and spacecraft. Research into this area has now evolved into using the concepts of autonomic systems to make future space missions self-managing and giving them a high degree of survivability in the harsh environments in which they operate.

This book describes much of the results of this research. In addition, it aims to discuss the needed software to make future NASA space missions more completely autonomous and autonomic. The core of the software for these new missions has been written for other applications or is being applied gradually in current missions, or is in current development. It is intended that this book should document how NASA missions are becoming more autonomous and autonomic and should point to the way of making future missions highly autonomous and autonomic. What is not covered is the supporting hardware of these missions or the intricate software that implements orbit and attitude determination, on-board resource allocation, or planning and scheduling (though we refer to these technologies and give references for the interested reader).

The book is divided into three parts. The first part gives an introduction to autonomous and autonomic systems and covers background material on spacecraft and ground systems, as well as early uses of autonomy in space and ground systems. The second part covers the technologies needed for developing autonomous systems, the use of software agents in developing autonomous flight systems, technology for cooperative space missions, and technology for adding autonomicity to future missions. The third and last part discusses applications of the technology introduced in the previous chapters to spacecraft constellations and swarms, and also future NASA missions that will need the

discussed technologies. The appendices cover some detailed information on spacecraft attitude and orbit determination and some operational scenarios of agents communicating between the ground and flight software. In addition, a list of acronyms and a glossary are given in the back before the list of references and index.

In Part One of the book, Chap. 1 gives an overview of autonomy and autonomic systems and why they are needed in future space missions. It also gives an introduction to autonomous and autonomic systems and how we define them in this book. Chapter 2 gives an overview of ground and flight software and the functions that each supports. Chapter 3 discusses the reasons for flight autonomy and its evolution over the past 30 plus years. Chapter 4 mirrors Chap. 3 for ground systems.

In Part Two, Chap. 5 covers the core technologies needed to develop autonomous and autonomic space missions, such as planners, collaborative languages, reasoners, learning technologies, perception technologies and verification and validation methods for these technologies. Chapter 6 covers designing autonomous spacecraft from an agent-oriented perspective. It covers the idea of a flight software backbone and the spacecraft functions that this backbone will need to support, subsumption concepts for including spacecraft functionality in an agent context, and the concept of designing a spacecraft as an interacting agent. Chapter 7 covers the technologies needed for cooperative spacecraft. It starts by discussing the need for cooperative spacecraft, a model of cooperative autonomy, mission management issues for cooperation, and core technologies for cooperative spacecraft. Chapter 8 covers autonomic systems and what makes a system autonomic, why autonomicity is needed for future autonomous systems, and what functions would be needed to make future missions autonomic.

Part Three starts with Chap. 9, which discusses spacecraft constellations, cooperation between or among the spacecraft in the constellation, difficulties in controlling multiple cooperative spacecraft, and a multiagent paradigm for constellations. Chapter 10 gives an overview of swarm technology, some example missions that are being proposed that use this technology, and issues in developing the software for swarm-based missions. Chapter 11 discusses some future missions that NASA is planning or developing conceptually. This chapter discusses how the technology discussed in the previous chapters would be applied to these missions, as well as additional technology that will need to be developed for these missions to be deployed.

The Appendix offers additional material for readers who want more information concerning attitude and orbit determination and control, or concerning operational scenarios of agents communicating between the ground and flight software. This is followed by a list of acronyms used in the book and a glossary of terms. All references are included in the back of the book.

There are three types of people who will benefit from reading this book. First are those who have an interest in spacecraft and desire an overview of ground and spaceflight systems and the direction of related technologies.

The second group comprises those who have a background in developing current flight or ground systems and desire an overview of the role that autonomy and autonomic systems may play in future missions. The third group comprises those who are familiar with autonomous and/or autonomic technologies and are interested in applying them to ground and space systems.

Different readers in each of the above groups may already have some of the background covered in this book and may choose to skip some of the chapters. Those in the first group will want to read the entire book. Those in the second group could skip Chap. 2 as well as Chaps. 3 and 4, though the latter two may be found interesting from an historical view. The third group of people could skip or skim Chap. 5, and though they may already be familiar with the technologies discussed in Chaps. 6–8, they may find the chapters of interest to see how AI technologies are applied in the space flight domain.

We hope that this book will not only give the reader background on some of the technologies needed to develop future autonomous and autonomic space missions, but also indicate technology gaps in the needed technology and stimulate new ideas and research into technologies that will enable future missions possible.

MD, USA — Walt Truszkowski
MD, USA — Lou Hallock
VA, USA — Christopher Rouff
MD, USA — Jay Karlin
MD, USA — James Rash
Limerick, Ireland — Mike Hinchey
Belfast, Northern Ireland — Roy Sterritt

Acknowledgements

There are a number of people who made this book possible. We would like to thank them for their contributions. We have made liberal use of their work and contributions to Agent-based research at NASA Goddard.

We would like to thank the following people from NASA Goddard Space Flight Center who have contributed information or some writings for material that covered flight software: Joe Hennessy, Elaine Shell, Dave McComas, Barbara Scott, Bruce Love, Gary Welter, Mike Tilley, Dan Berry, and Glenn Cammarata.

We are also grateful to Dr. George Hagerman (Virginia Tech) for information on Virginia Tech's Self Sustaining Planetary Exploration Concept, Dr. Walter Cedeño (Penn State University, Great Valley) for information on Swarm Intelligence, Steve Tompkins (NASA Goddard) for information on future NASA missions, Drs. Jonathan Sprinkle and Mike Eklund (University of California at Berkeley) for information on research into UUVs being conducted at that institution, Dr. Subrata Das and his colleagues at Charles River Analytics of Boston for their contribution of information concerning AI technologies, and to Dr. Jide Odubiyi for his support of Goddard's agent research, including his major contribution to the development of the AFLOAT system.

We would like to thank the NASA Goddard Agents Group for their work on the agent concept testbed (ACT) demonstration system and on spacecraft constellations and the NASA Space Operations Management Office (SOMO) Program for providing the funding. We would also like to thank Drs. Mike Riley, Steve Curtis, Pam Clark, and Cynthia Cheung of the ANTS project for their insights into multiagent systems.

The work on autonomic systems was partially supported at the University of Ulster by the Computer Science Research Institute (CSRI) and the Centre for Software Process Technologies (CSPT), which is funded by Invest NI through the Centres of Excellence Programme, under the EU Peace II initiative.

The work on swarms has been supported by the NASA Office of Systems and Mission Assurance (OSMA) through its Software Assurance Research Program (SARP) project, Formal Approaches to Swarm Technologies (FAST), administered by the NASA IV&V Facility and by NASA Goddard Space Flight Center, Software Engineering Laboratory (Code 581).

Contents