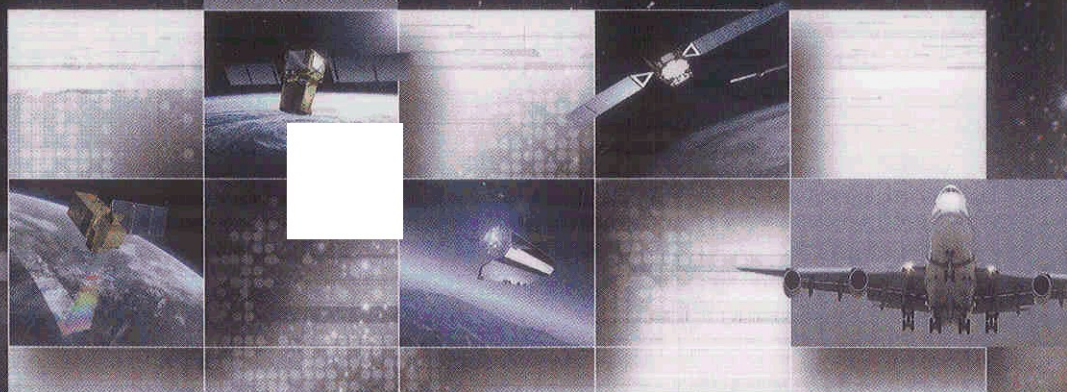
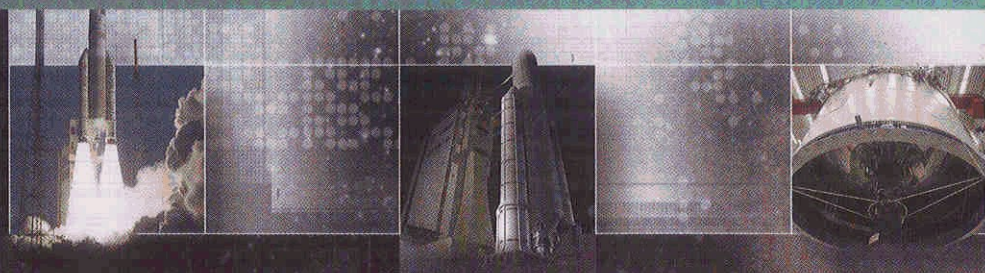




SPRINGER AEROSPACE TECHNOLOGY



Jens Eickhoff

# Simulating Spacecraft Systems

 Springer

# Contents

|                                        |     |
|----------------------------------------|-----|
| List of Abbreviations.....             | XV  |
| Notation of Variables and Symbols..... | XIX |
| Introduction.....                      | XXI |

## Part I Simulation Based System Development

|                                                                         |    |
|-------------------------------------------------------------------------|----|
| 1 Complex Systems in Spaceflight.....                                   | 3  |
| 2 System Simulation in System Engineering.....                          | 11 |
| 2.1 Development Process Phases for Spacecraft.....                      | 12 |
| 2.2 A System, its Control Functions and their Modeling.....             | 14 |
| 2.3 Algorithms, Software and Hardware Development and Verification..... | 16 |
| 2.4 Functional System Validation.....                                   | 19 |
| 3 Simulation Tools for System Analysis and Verification.....            | 23 |
| 3.1 Tools for System Design and Dimensioning.....                       | 26 |
| 3.1.1 Tools for System Predesign and Conception.....                    | 26 |
| 3.1.2 Functional System Analysis Tools for Phase B.....                 | 29 |
| 3.2 System Verification Tools.....                                      | 33 |
| 3.2.1 Functional Verification Bench (FVB).....                          | 35 |
| 3.2.2 Software Verification Facility (SVF).....                         | 36 |
| 3.2.3 Hybrid System Testbed (STB).....                                  | 42 |
| 3.2.4 Electrical Functional Model (EFM).....                            | 47 |
| 3.2.5 Spacecraft Simulator for Operations Support.....                  | 51 |
| 3.3 Infrastructure History.....                                         | 52 |
| 4 Testbench Components in Detail.....                                   | 55 |
| 4.1 Control Consoles.....                                               | 56 |
| 4.2 Test Procedure Editors and Interpreters.....                        | 61 |
| 4.3 Special Checkout Equipment.....                                     | 66 |
| 4.4 Simulator-Frontend Equipment.....                                   | 69 |
| 4.5 Spacecraft Simulators.....                                          | 72 |
| 4.6 Equipment and System Models.....                                    | 74 |
| 5 Spacecraft Functionality to be Modeled.....                           | 79 |
| 5.1 Functional Simulation Concept.....                                  | 80 |
| 5.2 Attitude, Orbit and Trajectory Modeling.....                        | 83 |
| 5.3 Aspects of Structural Mechanics.....                                | 85 |
| 5.4 Thermal Aspects.....                                                | 86 |
| 5.5 Equipment Modeling.....                                             | 87 |

## Part II Simulator Technology

|                                                              |     |
|--------------------------------------------------------------|-----|
| 6 Numerical Foundations of System Simulation.....            | 107 |
| 6.1 Introduction to Numerics.....                            | 108 |
| 6.2 Modeling of System Components as Transfer Functions..... | 109 |
| 6.3 Components with Time Response.....                       | 110 |

|                                                                             |     |
|-----------------------------------------------------------------------------|-----|
| 6.4 Balance Equations.....                                                  | 112 |
| 6.4.1 Equation Set for Fluid Systems.....                                   | 112 |
| 6.4.2 Equation Set for Spacecraft Dynamics.....                             | 116 |
| 6.4.3 Equation Set for Spacecraft Electrics.....                            | 117 |
| 6.5 Classification of Partial Differential Equations.....                   | 118 |
| 6.6 Transformation of PDEs into Systems of ODEs.....                        | 119 |
| 6.7 Numerical Integration Methods.....                                      | 121 |
| 6.8 Integration Methods Applied on System Level.....                        | 126 |
| 6.9 Boundary Value Problems in System Modeling.....                         | 135 |
| 6.10 Root Finding Methods for Boundary Value Problems.....                  | 140 |
| 6.11 Numerical Functionalities for Control Engineering.....                 | 143 |
| 6.11.1 Mathematical Building Blocks and their Transformation to RPN.....    | 143 |
| 6.11.2 Linearization of System State Equations.....                         | 146 |
| 6.11.3 Linearization by Algorithmic Differentiation.....                    | 148 |
| 6.12 Semi-Implicit Methods for Stiff DEQ Systems.....                       | 149 |
| 7 Aspects of Real-time Simulation.....                                      | 155 |
| 7.1 Time Definitions.....                                                   | 156 |
| 7.2 Time Synchronization.....                                               | 157 |
| 7.3 Modeling Time in a Simulator.....                                       | 159 |
| 7.4 Real-time Parallel Processing.....                                      | 163 |
| 8 Object Oriented Architecture of Simulators and System Models.....         | 167 |
| 8.1 Objectives of Simulator Software Design.....                            | 168 |
| 8.2 The Model Driven Architecture.....                                      | 170 |
| 8.3 Implementation Technologies - Programming Languages.....                | 173 |
| 8.4 Implementation Technologies - The Unified Modeling Language (UML).....  | 174 |
| 8.4.1 Code Generation from UML.....                                         | 182 |
| 8.4.2 Designing a Simulator Kernel using UML.....                           | 185 |
| 8.4.3 Designing Spacecraft Equipment Models with UML.....                   | 187 |
| 8.5 Implementation Technologies - The Extensible Markup Language (XML)..... | 190 |
| 8.6 Implementation Technologies - Modeling Frameworks.....                  | 198 |
| 8.7 From a Model Specification to the Simulation Run.....                   | 200 |
| 8.7.1 From Equipment Documentation to the Model Specification.....          | 200 |
| 8.7.2 Application Example - Fiber-optic Gyroscope.....                      | 202 |
| 8.7.3 Writing an Equipment Model Specification.....                         | 203 |
| 8.7.4 Translation of the Model Specification into UML Based Design.....     | 206 |
| 8.7.5 Code Generation and Code Instrumentation.....                         | 208 |
| 8.7.6 Integrating the Model into the Simulator.....                         | 213 |
| 8.7.7 Configuration Files for a Simulation Run.....                         | 216 |
| 8.7.8 Simulation Run.....                                                   | 221 |
| 9 Simulator Development Compliant to Software Standards.....                | 223 |
| 9.1 Software Engineering Standards - Overview.....                          | 224 |
| 9.2 Software Classification According to Criticality.....                   | 227 |
| 9.3 Software Standard Application Example.....                              | 228 |
| 9.4 Critical Path in Spacecraft Development.....                            | 240 |
| 9.5 Testbench Configuration Control vs. OBSW and TM / TC.....               | 243 |
| 9.6 Testbench Development Responsibilities.....                             | 245 |
| 9.7 Lessons Learned from Projects.....                                      | 246 |
| 10 Simulation Tools in a System Engineering Infrastructure.....             | 249 |
| 10.1 The System Modeling Language (SysML).....                              | 251 |

|                                                                 |     |
|-----------------------------------------------------------------|-----|
| 10.2 System Engineering Infrastructures.....                    | 257 |
| 10.3 Standards for Data Exchange Between Engineering Tools..... | 263 |

### **Part III    Advanced Technologies**

|                                                                         |     |
|-------------------------------------------------------------------------|-----|
| 11 Service Oriented Simulator Kernel Architectures.....                 | 271 |
| 11.1 SOA Implementation of Simulator Initialization.....                | 274 |
| 11.2 SOA Implementation of the Kernel Numerics.....                     | 277 |
| 11.3 Orchestration of the Computation and Function Distribution.....    | 280 |
| 12 Consistent Modeling Technology for all Development Phases.....       | 281 |
| 12.1 Requirements to a Cross-Phase Design Infrastructure.....           | 284 |
| 12.2 Cross-Phase Simulation Infrastructure and Engineering Steps.....   | 288 |
| 13 Knowledge-Based Simulation Applications.....                         | 295 |
| 13.1 Modeling of Information for Rule-Based Processing.....             | 297 |
| 13.2 Accumulation of Knowledge on a System's Behavior.....              | 300 |
| 13.3 Coupling of Knowledge-Processor and simulated / real System.....   | 301 |
| 13.4 Application of Expert Systems for User Training.....               | 314 |
| 13.5 Implementation Technology: Rules as Fact Filters.....              | 315 |
| 14 Simulation of Autonomous Systems.....                                | 319 |
| 14.1 Testing Conventional on-board Software Functions.....              | 320 |
| 14.2 Testing Failure Management Functions.....                          | 321 |
| 14.3 Testing Higher Levels of System Autonomy.....                      | 322 |
| 14.4 Implementations of Autonomy and their Focus.....                   | 324 |
| 14.4.1 Improvement Technology – on-board SW / HW Components.....        | 326 |
| 14.4.2 Improvement Technology – Optimizing the Mission Product.....     | 328 |
| 14.4.3 Enabling Technology – Autonomous OBSW for Deep Space Probes..... | 330 |
| 15 References.....                                                      | 333 |
| Index.....                                                              | 349 |