Contents

Preface List of symbols 1 Introduction 1.1 Background 1.2 The complexity of the rendezvous process 1.3 Objective and scope			XV		
Lis	st of sy	mbols		xviii	
1	Introduction			1	
	1.1	Backg	ground	1	
	1.2	The co	omplexity of the rendezvous process	3	
	1.3	Objec	tive and scope	6	
2	The phases of a rendezvous mission				
	2.1	Launc	h and orbit injection	8	
		2.1.1	The launch window	8	
		2.1.2	Definition of orbit plane and other orbit parameters	9	
		2.1.3	Launch operations flexibility	10	
		2.1.4	Vehicle state at end of launch phase	11	
	2.2	Phasir	ng and transfer to near target orbit	12	
		2.2.1	Objective of phasing and state at end of phasing	12	
		2.2.2	Correction of time deviations and orbit parameters	12	
		2.2.3	Coordinate frames during rendezvous	13	
		2.2.4	Forward/backward phasing	13	
		2.2.5	Different phasing strategy for each mission	14	
		2.2.6	Location of the initial aim point	15	
		2.2.7	Strategy with entry gate instead of aim point	16	
		2.2.8	Final accuracy of open loop manoeuvres	16	
	2.3	Far ra	nge rendezvous operations	17	
		2.3.1	Objectives and goals of far range rendezvous	17	
		2.3.2		17	
		2.3.3		18	
		2.3.4	Communication with the target station	18	

x Contents

	2.4	Close	range rendezvous operations	19
		2.4.1	Closing	19
		2.4.2	Final approach to contact	21
	2.5	Mating	g: docking or berthing	24
		2.5.1	Objectives and end conditions of the mating phase	24
		2.5.2	Capture issues	25
	2.6	Depar	ture	26
		2.6.1	Objectives and end conditions of the departure phase	26
		2.6.2	Constraints and issues during departure	26
3	Orb	it dynai	mics and trajectory elements	29
	3.1	Refere	ence frames	29
		3.1.1	Earth-centred equatorial frame $F_{\rm eq}$	30
			Orbital plane frame $F_{\rm op}$	30
			Spacecraft local orbital frame F_{lo}	31
			Spacecraft attitude frame $F_{\rm a}$	32
			Spacecraft geometric frames $F_{\rm ge}$	33
	3.2		dynamics	34
			Orbital motion around a central body	34
		3.2.2	Orbit corrections	37
		3.2.3	The equations of motion in the target reference frame	40
	3.3			41
		3.3.1	Free drift motions	42
		3.3.2	Impulsive manoeuvres	48
		3.3.3	Continuous thrust manoeuvres	58
	3.4	Final 1	remark on the equations of motion	72
		3.4.1	Examples for combined cases	74
4	App	roach s	afety and collision avoidance	76
	4.1		tory safety – trajectory deviations	76
			Failure tolerance and trajectory design requirements	77
			Design rules for trajectory safety	78
			Causes of deviations from the planned trajectory	79
	4.2		tory disturbances	80
			Drag due to residual atmosphere	81
			Disturbances due to geopotential anomaly	85
			Solar pressure	87
		4.2.4	•	
			and target	89

Contents xi

	4.3	Trajectory deviations generated by the spacecraft systems	90		
		4.3.1 Trajectory deviations due to navigation errors	90		
		4.3.2 Trajectory deviations due to thrust errors	93		
		4.3.3 Trajectory deviations due to thruster failures	97		
	4.4	Protection against trajectory deviations	98		
		4.4.1 Active trajectory protection	98		
		4.4.2 Passive trajectory protection	101		
	4.5	Collision avoidance manoeuvres	107		
5	The	drivers for the approach strategy	112		
	5.1	Overview of constraints on the approach strategy	112		
	5.2	Launch and phasing constraints	114		
		5.2.1 The drift of nodes	114		
		5.2.2 Adjustment of arrival time	115		
	5.3	Geometrical and equipment constraints	116		
		5.3.1 Location and direction of target capture interfaces	116		
		5.3.2 Range of operation of rendezvous sensors	124		
	5.4	Synchronisation monitoring needs	126		
		5.4.1 Sun illumination	127		
		5.4.2 Communication windows	133		
		5.4.3 Crew activities	136		
		5.4.4 Time-flexible elements in phasing and approach	137		
	5.5	Onboard resources and operational reserves	140		
	5.6	Approach rules defined by the target	141		
	5.7	Examples of approach strategies	144		
		5.7.1 Approach strategy, example 1	144		
		5.7.2 Approach strategy, example 2	155		
		5.7.3 Approach strategy, example 3	164		
6	The	e onboard rendezvous control system			
	6.1	Tasks and functions	171		
	6.2	Guidance, navigation and control	173		
		6.2.1 The navigation filter	174		
		6.2.2 The guidance function	180		
		6.2.3 The control function	184		
	6.3	Mode sequencing and equipment engagement	203		
	6.4	Fault identification and recovery concepts	207		
	6.5	Remote interaction with the automatic system	212		
		6.5.1 Interaction with the GNC functions	213		

xii Contents

		650	Manual state and data familia automatic CNC anatom	21.4
			Manual state update for the automatic GNC system	214
		6.5.3	Automatic GNC system with man-in-the-loop	215
7	Sens	ors for	rendezvous navigation	218
	7.1	Basic	measurement requirements and concepts	219
		7.1.1	Measurement requirements	219
		7.1.2	Measurement principles	229
	7.2	RF-se	nsors	231
		7.2.1	Principles of range and range-rate measurement	231
		7.2.2	Principles of direction and relative attitude measurement	238
		7.2.3	Measurement environment, disturbances	242
		7.2.4	General assessment of RF-sensor application	243
		7.2.5	Example: the Russian Kurs system	245
	7.3	Absol	ute and relative satellite navigation	250
		7.3.1	Description of the navigation satellite system setup	250
		7.3.2	Navigation processing at the user segment	254
		7.3.3	Functional principle of differential GPS and relative GPS	260
		7.3.4	Measurement environment, disturbances	264
		7.3.5	General assessment of satellite navigation for RVD	266
	7.4	Optica	al rendezvous sensors	267
		7.4.1	Scanning laser range finder	267
		7.4.2	Camera type of rendezvous sensor	272
		7.4.3	Measurement environment, disturbances	277
		7.4.4	General assessment of optical sensors for rendezvous	279
8	Mat	ing syst	tems	283
•	8.1		concepts of docking and berthing	283
	0.1	8.1.1	Docking operations	284
		8.1.2	Berthing operations	286
		8.1.3	Commonalities and major differences between docking	
		01110	and berthing	288
	8.2	Types	of docking and berthing mechanisms	290
	0.2	8.2.1	Design driving requirements	291
		8.2.2		293
		8.2.3		295
		8.2.4	e .	296
		8.2.5	Examples of docking and berthing mechanisms	297
	8.3		ct dynamics/capture	305
			Momentum exchange at contact	305

Contents xiii

		8.3.2	Shock attenuation dynamics	307
		8.3.3	Example case for momentum exchange and shock attenuation	312
		8.3.4		316
		8.3.5		321
		8.3.6	The interface between the GNC and the mating system	327
	8.4		ents for final connection	329
	0.7	8.4.1	Structural latches	330
		8.4.2		333
9	Spac	ce and g	ground system setup	336
	9.1		ons and tasks of space and ground segments	337
		9.1.1	General system setup for a rendezvous mission	337
		9.1.2	Control responsibilities and control hierarchy	340
	9.2	Groun	d segment monitoring and control functions for RVD	344
		9.2.1		344
		9.2.2	The functions of a support tool for ground operators	346
		9.2.3	Monitoring and control functions for the target crew	350
	9.3	Comm	nunication constraints	353
		9.3.1	Data transfer reliability	354
		9.3.2	Data transmission constraints	356
10	Veri	fication	and validation	362
	10.1	Limita	ations of verification and validation	363
	10.2 RVD verification/validation during development		verification/validation during development	364
		10.2.1	Features particular to rendezvous and docking	365
		10.2.2	Verification stages in the development life-cycle	366
	10.3	Verific	eation methods and tools	369
		10.3.1	Mission definition and feasibility phase	370
		10.3.2	Design phase	371
		10.3.3	Development phase	375
		10.3.4	Verification methods for operations and tools for remote	
			operators	381
		10.3.5	Flight item manufacture phase	385
	10.4		lling of spacecraft items and orbital environment	387
		10.4.1	Modelling of environment simulation for RV-control	
			system test	388
		10.4.2	8	396
	10.5		tion of models, tools and facilities	398
		10.5.1	Validation of GNC environment simulation models	398

xiv Contents

	10.5.2	Validation of contact dynamics simulation models	402
	10.5.3	Validation of simulator programs and stimulation facilities	403
10.6	Major	simulators and facilities for RVD	404
	10.6.1	Verification facilities based on mathematical modelling	404
	10.6.2	Example of a stimulation facility for optical sensors	406
	10.6.3	Dynamic stimulation facilities for docking	408
10.7	Demo	nstration of RVD/B technology in orbit	411
	10.7.1	Purpose and limitations of in-orbit demonstrations	411
	10.7.2	Demonstration of critical features and equipment	412
	10.7.3	Demonstration of RV-system and operations in orbit	417
App	endix A	Motion dynamics, by Finn Ankersen	424
A.1		ions of relative motion for circular orbits	424
	A.1.1	General system of differential equations	424
	A.1.2	Homogeneous solution	429
	A.1.3	Particular solution	431
	A.1.4	Discrete time state space system	434
	A.1.5	Travelling ellipse formulation	435
A.2	Attitude dynamics and kinematics		
	A.2.1	Direction cosine matrix (DCM)	437
	A.2.2	Nonlinear dynamics	438
	A.2.3	Nonlinear kinematics	439
	A.2.4	Linear kinematics and dynamics attitude model	439
App	endix B	Rendezvous strategies of existing vehicles	441
B.1	Space	Shuttle Orbiter	441
B.2	Soyuz	/Progress	445
App	endix C	C Rendezvous vehicles of the ISS scenario	450
C .1	Intern	ational Space Station	451
C.2	Russia	an Space Station 'Mir'	456
C.3	Space	Shuttle Orbiter	459
C.4	Soyuz		461
C.5	Progre	ess	463
C.6	ATV		465
C.7	HTV		467
	Glossa	•	470
	Refere	nces	477
	Index		486