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Robotic Satellite Servicing Tool Down Selection

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Which Kitchen Tools Do I Need?

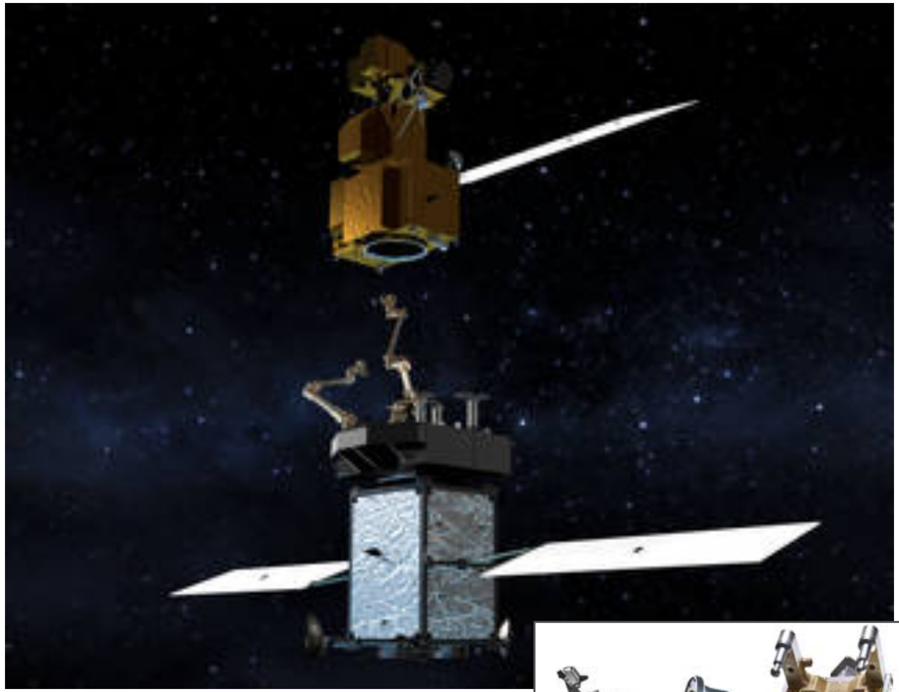
Boil Pasta

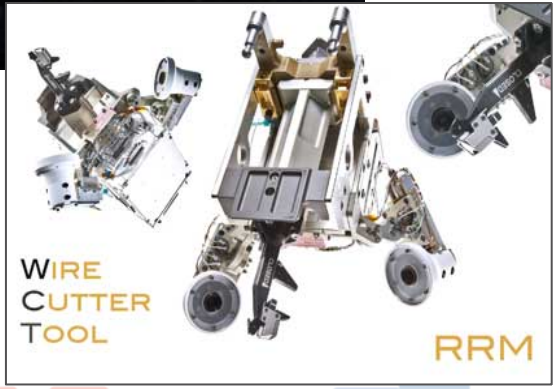
Remove Pasta

Place Pasta in Bowl

Robotic Satellite Servicing

- Robotic servicer satellites can be cheaper and safer than astronauts
- Robots are mass, power and time limited, so which tools and arms are the best to fly with?

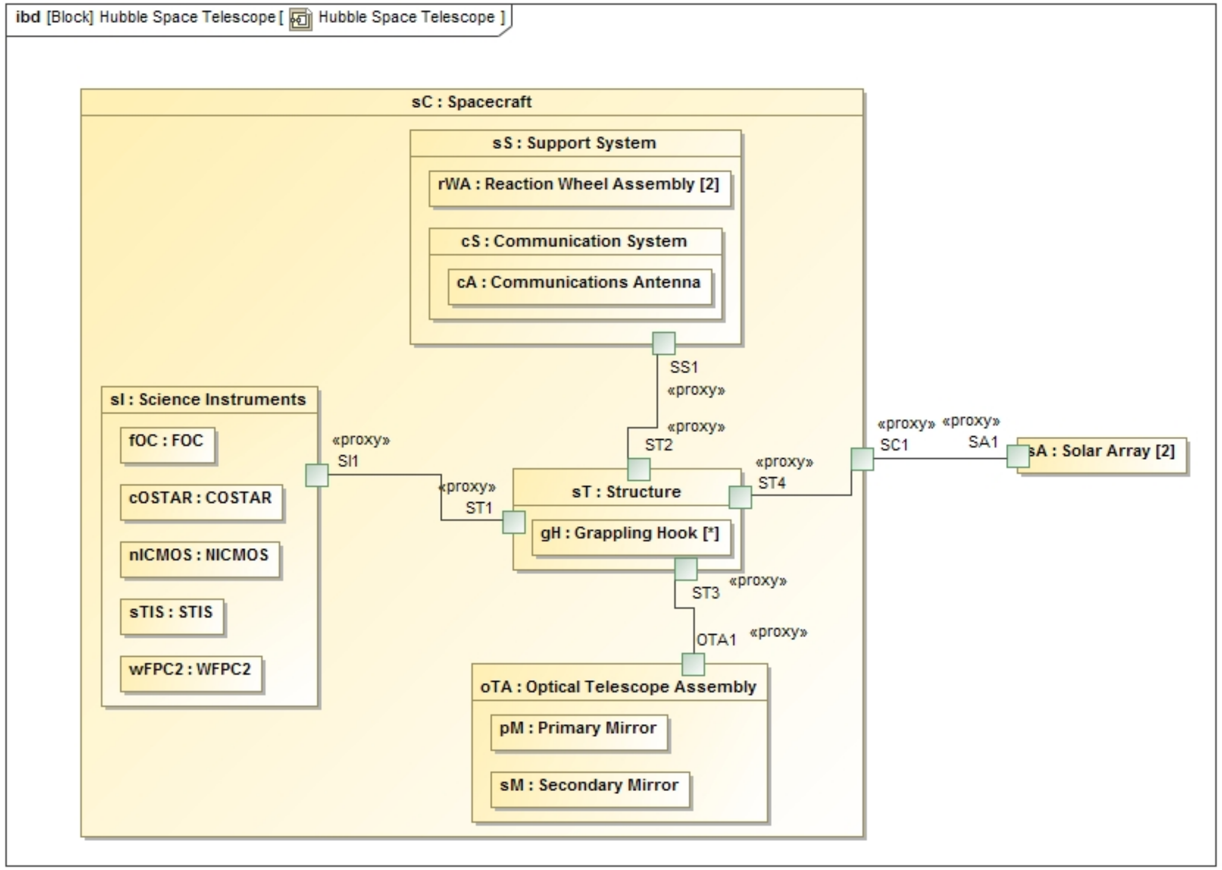


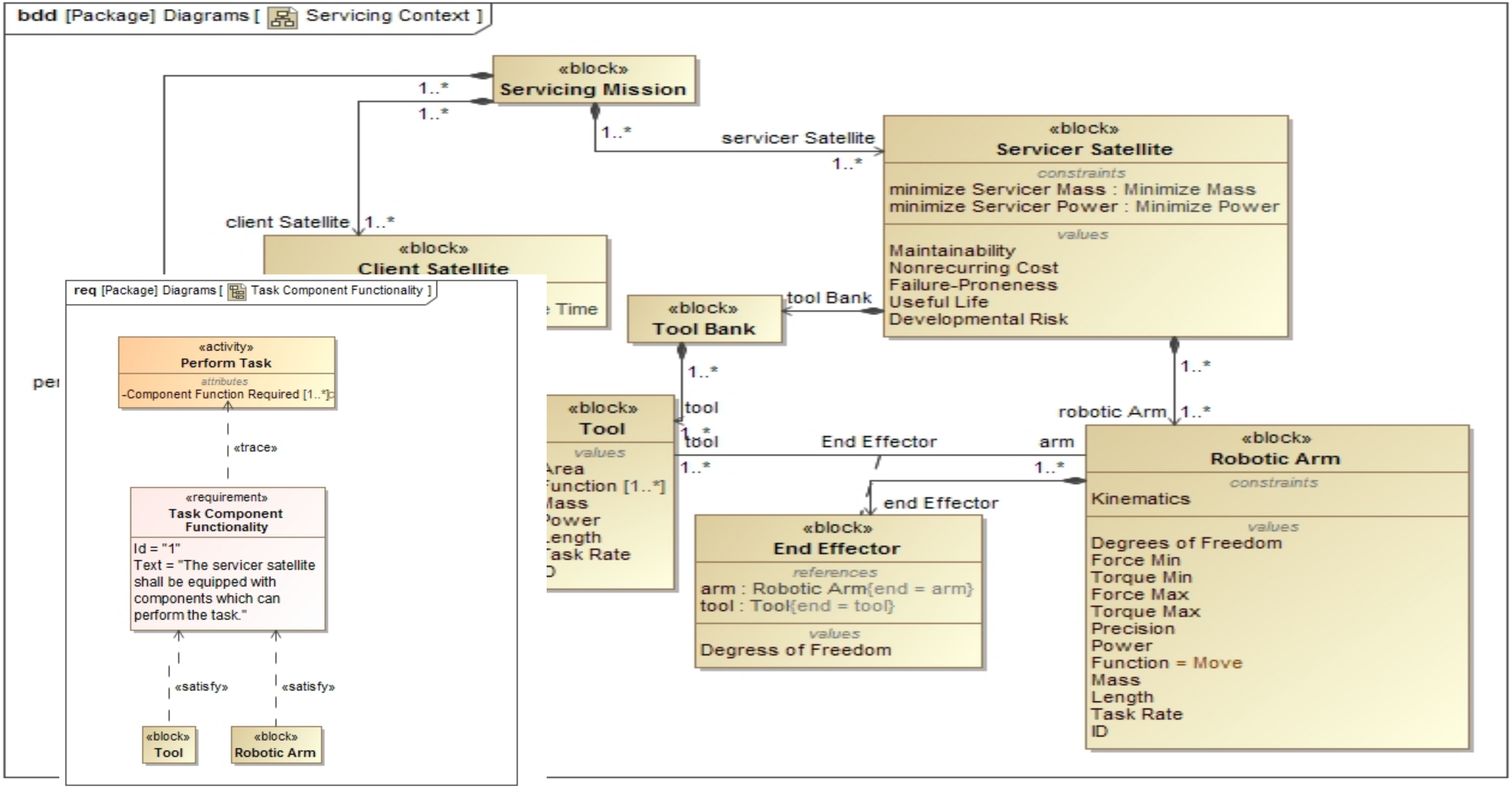


99.996%

Design Options Removed

Hubble Space Telescope Architecture



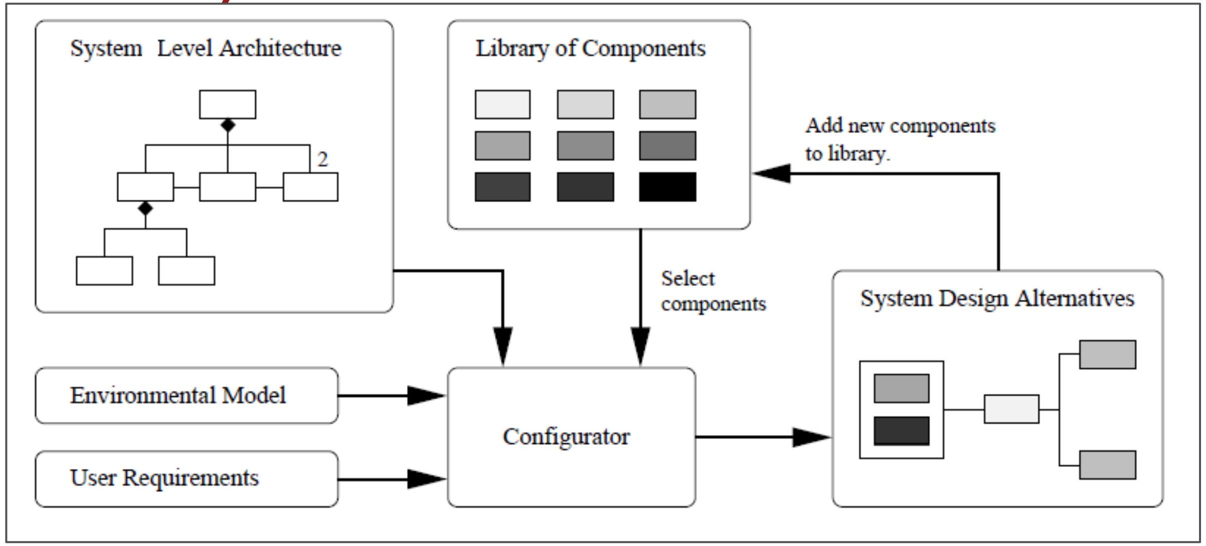

bdd [Package] Diagrams [Servicing Context]
«block»
Servicing Mission
1..*
1..*
1..*
servicer Satellite
1..*
«block»
Servicer Satellite
constraints
minimize Servicer Mass : Minimize Mass
minimize Servicer Power : Minimize Power
values
Maintainability
Nonrecurring Cost
Failure-Proneness
Useful Life
Developmental Risk
client Satellite
1..*
«block»
Client Satellite
Time
tool Bank
«block»
Tool Bank
1..*
tool
1..*
robotic Arm
1..*
«block»
Tool
values
Area
Function [1..*]
Mass
Power
Length
Task Rate
ID
tool
1..*
End Effector
arm
1..*
end Effector
«block»
Robotic Arm
constraints
Kinematics
values
Degrees of Freedom
Force Min
Torque Min
Force Max
Torque Max
Precision
Power
Function = Move
Mass
Length
Task Rate
ID
«block»
End Effector
references
arm : Robotic Arm{end = arm}
tool : Tool{end = tool}
values
Degress of Freedom
req [Package] Diagrams [Task Component Functionality]
«activity»
Perform Task
attributes
-Component Function Required [1..*]
«trace»
«requirement»
Task Component Functionality
Id = "1"
Text = "The servicer satellite shall be equipped with components which can perform the task."
«satisfy»
«satisfy»
«block»
Tool
«block»
Robotic Arm

Past Work – Hubble Servicing (Pilotte 2004)

Identified robotic tasks and tools necessary to perform Hubble Space Telescope (HST) Astronaut Servicing Mission 3B (SM3B)

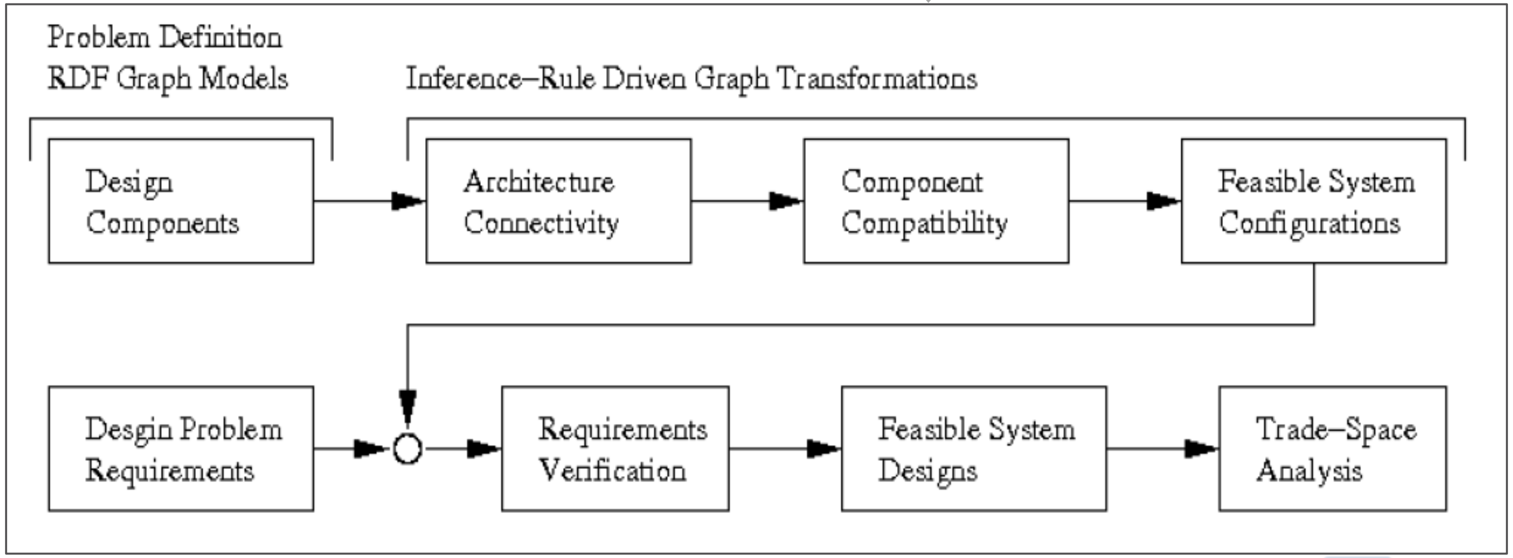
Ref #	EV	Primitive	Task Name	Need?	Broad Prim	1st EE	Inst #	2nd EE	Inst #
3|11		**PCU-R Mate**							
3226	R MS	Mate connectors (2-bottom PCU-R)	PCU-R Mate	Yes	mate/demate PCU connector	Pinch on retainer	2	HT Pinch	2
3227	R MS	Mate connectors (34-left PCU-R)	PCU-R Mate	Yes	mate/demate PCU connector	Pinch on retainer	34	HT Pinch	34
3228	R MS	Stow J13/J14 saver caps in trash bag	PCU-R Mate	Yes	stow connector cap	Pinch	2		
3|12		**V2 Aft Shroud Handrail Covers**							
3230	FF	inspect +/- V2 handrails used for ACS and NCS	V2 Aft Shroud Handrail Covers	Yes	inspect worksite	Camera	1		
3231	FF	retrieve handrail covers from ASIPE	V2 Aft Shroud Handrail Covers	Yes	retrieve handrail covers	Unknown	1		
3232	FF	install handrail covers	V2 Aft Shroud Handrail Covers	Yes	install handrail covers	Unknown	1		
3233	FF	config. HST PFR (aft ASIPE) for ACS	V2 Aft Shroud Handrail Covers	No		Unknown	1		

Past Work – Down Selection (Nassar and Austin, CSER 2013)



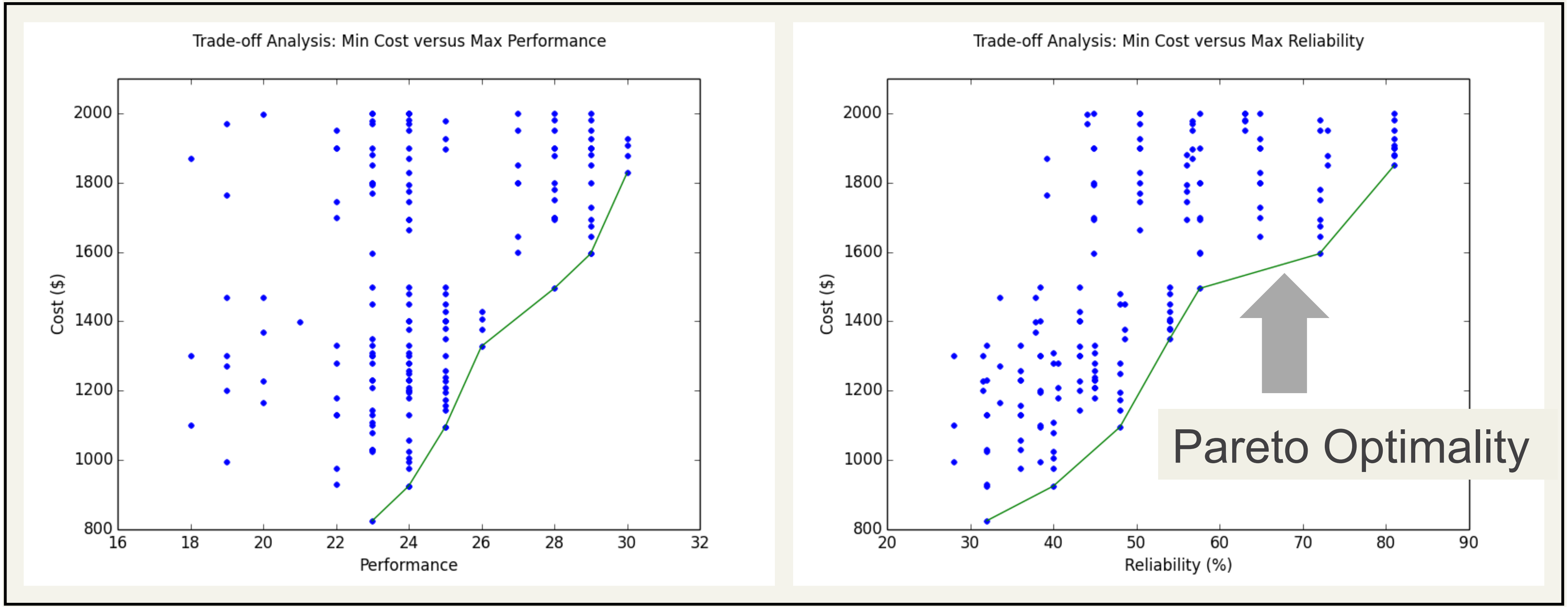
Modeling: Requirements, Components and Architectures represented with RDF.

Processing Pipeline: Component Selection corresponds to sequence of RDF graph transformations.



Past Work – Demonstrate Down Selection Process

Pipeline: Down selection from a space of 1,000 ``potentially good'' design options.
Result: Tradeoff curves of: 1. Cost versus Performance, 2. Cost versus Reliability, 3. Performance versus Reliability.



Work Thus Far

- Manual Application
  - Simplified
  - Proof of concept
- Automated Application
  - Full problem
  - Decision tool

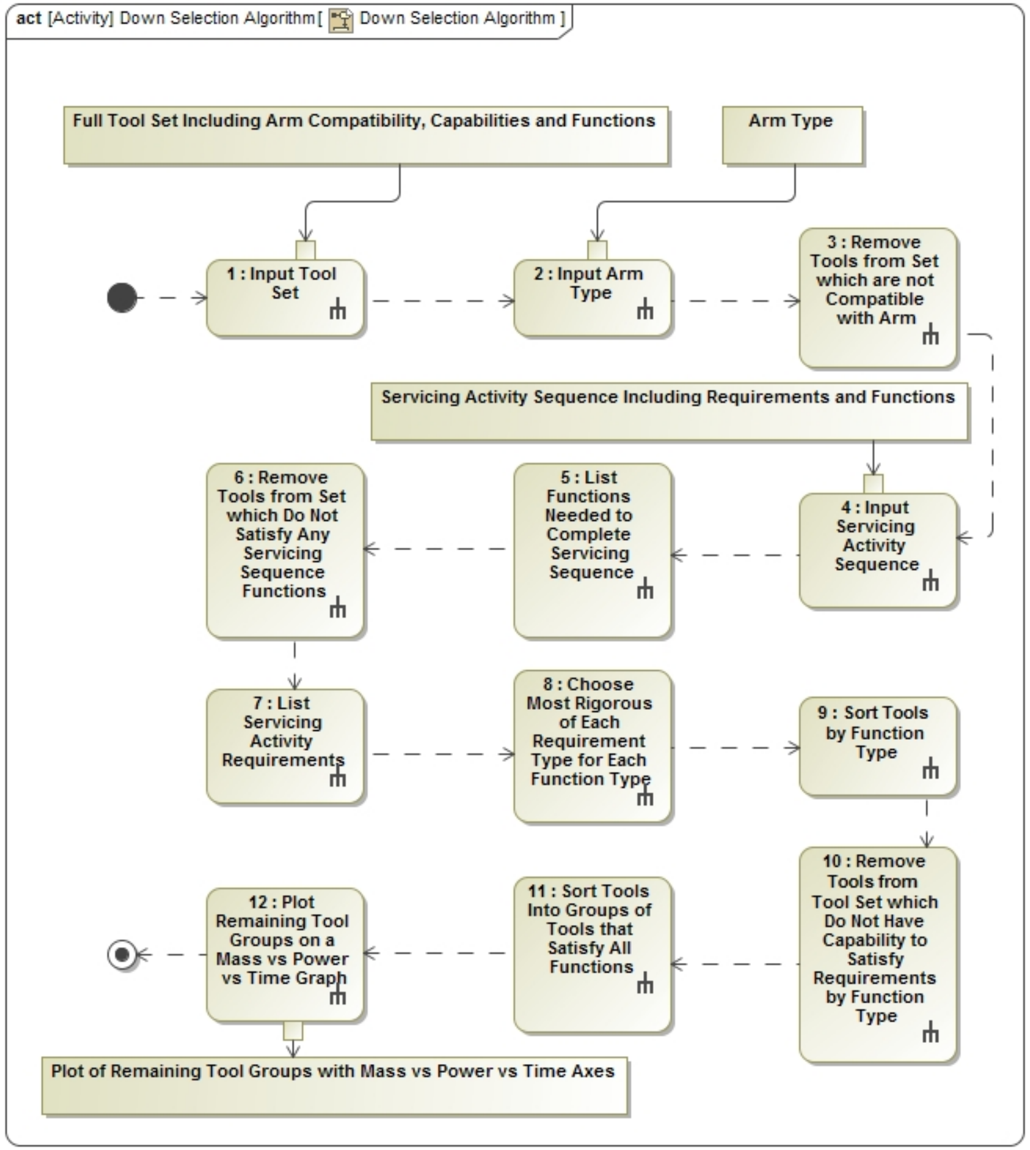
Manual Problem Set Up

- Which tools can perform four representative servicing tasks?
  - Removed arm selection to simply problem

ID	Activity	Tool Function	Force	Resolution	Size
1	Stow groundstrap (SA-3)	Delicate pinch	<5		<10
2	Remove PIP pin (fwd latch)	PIP (pinch)	4<x<10		9<x<20
3	Remove BAPS post	Small handrail (grip)	>10		<5
4	Inspect p105 and p106 covers	Camera		>20	<10

Manual Down Selection Process

ID	Tool	Functions	Arm	Force	Resolution	Size	Step Rem
1	Delicate Pinch	Delicate Pinch	RESTORE	1		10	
2	Delicate Pinch	Delicate Pinch	RESTORE	2		9	
3	Delicate Pinch	Delicate Pinch	RESTORE	20		15	10
4	Delicate Pinch	Delicate Pinch	DEXTRE	10		20	3
5	Welder	Welder	RESTORE	5		12	6
6	Cutter	Cutter	RESTORE	13		13	6
7	Pinch	Pinch	DEXTRE	1		8	3
8	Pinch	Pinch	RESTORE	6		12	
9	Pinch	Pinch	RESTORE	7		13	
10	Bolt Driver	Bolt Driver	RESTORE	5		18	
11	Bolt Driver	Bolt Driver	RESTORE	4		30	6
12	Multi Tool	Delicate Pinch, Pinch and Camera	RESTORE	5	22	10	
13	Grip	Grip	DEXTRE	1		1	3
14	Grip	Grip	DEXTRE	2		2	3
15	Grip	Grip	RESTORE	5		5	10
16	Grip	Grip	RESTORE	20		4	
17	Camera	Camera	RESTORE	0	30	5	
18	Camera	Camera	RESTORE	0	21	11	10
19	Camera	Camera	DEXTRE	0	20	10	3

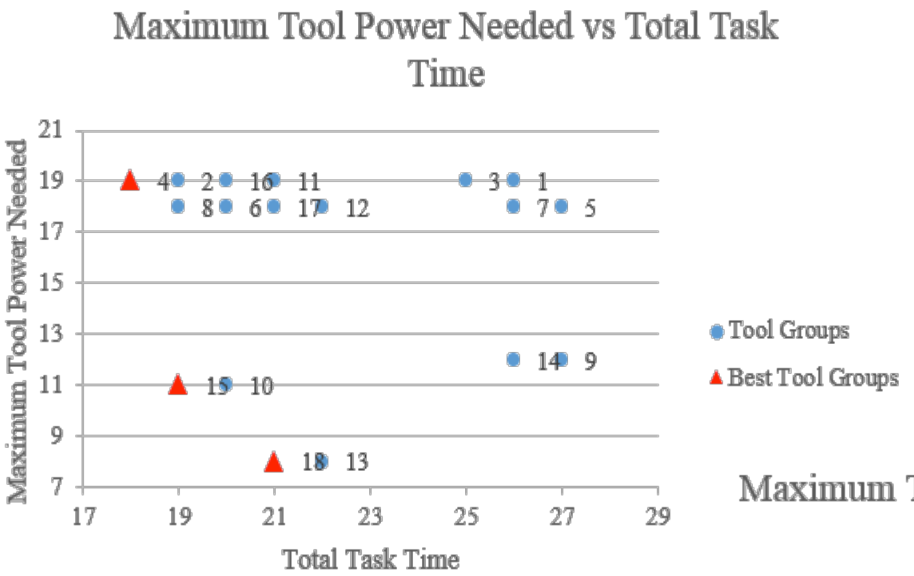


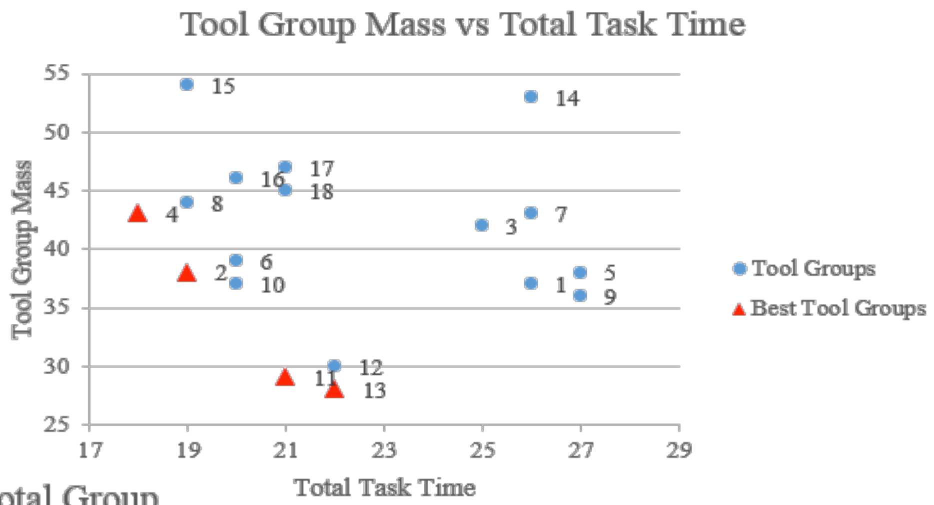
Creating Tool Groups

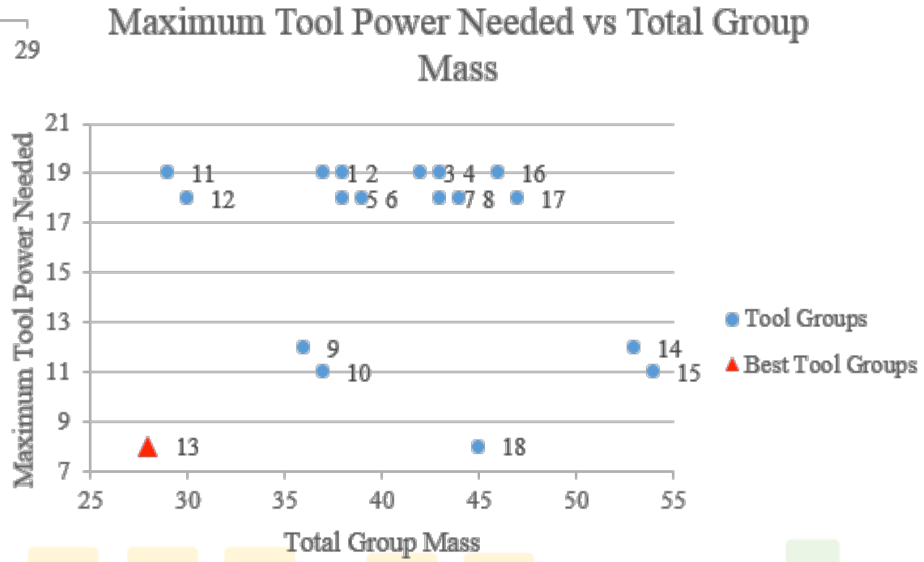
ID	Tool	Functions	Mass	Power	Time to Complete Task 1	Time to Complete Task 2	Time to Complete Task 3	Time to Complete Task 4
1	Delicate Pinch	Delicate Pinch	1	19	1			
2	Delicate Pinch	Delicate Pinch	2	18	2			
8	Pinch	Pinch	8	12		8		
9	Pinch	Pinch	9	11		1		
12	Multi Tool	Delicate Pinch, Pinch and Camera	12	8	2	3		7
16	Grip	Grip	16	4			10	
17	Camera	Camera	17	3				6

Group ID	Tool IDs
1	1, 8, 12, 16
2	1, 9, 12, 16
3	1, 8, 16, 17
4	1, 9, 16, 17
5	2, 8, 12, 16
6	2, 9, 12, 16
7	2, 8, 16, 17
8	2, 9, 16, 17
9	8, 12, 16
10	9, 12, 16
11	1, 12, 16
12	2, 12, 16
13	12, 16
14	8, 12, 16, 17
15	9, 12, 16, 17
16	1, 12, 16, 17
17	2, 12, 16, 17
18	12, 16, 17

Manual Results







Best Design Options

Group 2

ID	Tool	Functions
1	Delicate Pinch	Delicate Pinch
9	Pinch	Pinch
12	Multi Tool	Delicate Pinch, Pinch and Camera
16	Grip	Grip

Group 11

ID	Tool	Functions
1	Delicate Pinch	Delicate Pinch
12	Multi Tool	Delicate Pinch, Pinch and Camera
16	Grip	Grip

Group 15

ID	Tool	Functions
9	Pinch	Pinch
12	Multi Tool	Delicate Pinch, Pinch and Camera
16	Grip	Grip
17	Camera	Camera

Group 4

ID	Tool	Functions
1	Delicate Pinch	Delicate Pinch
9	Pinch	Pinch
16	Grip	Grip
17	Camera	Camera

Group 13

ID	Tool	Functions
12	Multi Tool	Delicate Pinch, Pinch and Camera
16	Grip	Grip

Group 18

ID	Tool	Functions
12	Multi Tool	Delicate Pinch, Pinch and Camera
16	Grip	Grip
17	Camera	Camera

Expanded Automated Problem

4 arbitrary task primitives

8 requirements

→

35 Solar Array 3 (SA-3) Removal task primitives

55 requirements

21 components

2 arms

19 tools

→

162 components

5 arms

157 tools

Selected SA-3 Removal Task Primitives

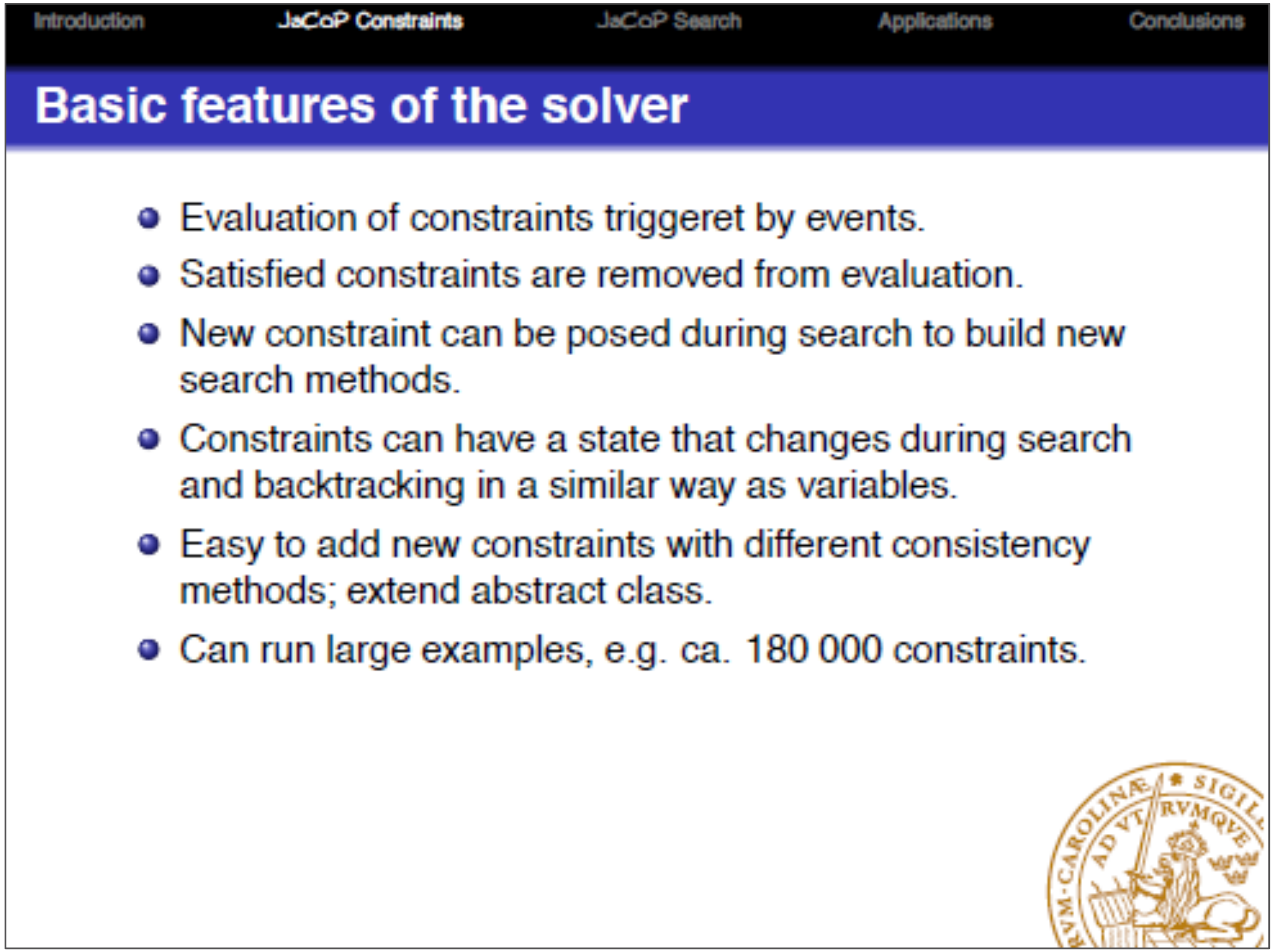
Ref #	EV	Primitive	Task Name	Need?	Broad Prim	1st EE	Inst #	2nd EE	Inst #
1207	FF	drive latch 3 until clamp clears tang, 7-9 turns (release)	SA-3 Removal	Yes	drive bolt	Bolt drive	1		
1208	FF	pivot latch 3 to clear tang	SA-3 Removal	Yes	pivot latch	Small handrail	1		
1209	FF	tether to tang	SA-3 Removal	No		Tether tool	1		
1210	FF	PGT: A2, CCW 2, 5.5	SA-3 Removal	Yes	set bolt drive	COMPUTER	1		
1211	FF	drive tang bolts 9-10 turns (2-disengage)	SA-3 Removal	Yes	drive bolt	Bolt drive	2		
1212	FF	stow tang on CSS	SA-3 Removal	Yes	stow tang	Bolt drive	1	Small handrail	1
1213	FF	PGT: A2, CW 2, 5.5	SA-3 Removal	Yes	set bolt drive	COMPUTER	1		

Selected SA-3 Removal Requirements

Ref #	EV	Primitive	Task Name	Need?	Broad Prim	1st EE	Inst #	2nd EE	Inst #	Tool + Arm			Tool		Arm	
										Force	Torque	Length	Resolution	Area	Precision	DoF
1207	FF	drive latch 3 until clamp clears tang, 7-9 turns (release)	SA-3 Removal	Yes	drive bolt	Bolt drive	1				12.0			<70	<17	
1208	FF	pivot latch 3 to clear tang	SA-3 Removal	Yes	pivot latch	Small Handrail	1			-1.37 - 1.37				<150	<37	
1209	FF	tether to tang	SA-3 Removal	No		Tether tool	1									
1210	FF	PGT: A2, CCW 2, 5.5	SA-3 Removal	Yes	set bolt drive	Computer	1									
1211	FF	drive tang bolts 9-10 turns (2-disengage	SA-3 Removal	Yes	drive bolt	Bolt drive	2				5.5			<70	<17	
1212	FF	stow to tang on CSS	SA-3 Removal	Yes	stow tang	Bolt drive	1	Small handrail	1							
1213	FF	PGT: A2, CW 2, 5.5	SA-3 Removal	Yes	set bolt drive	Computer	1									

Semantic vs Numeric Logic

- Previous work used Jena semantic rule solver
- JaCoP mathematical constraint solver has potential to evaluate larger problems



Selected SA-3 Removal Mathematical Constraints

ID	Mathematical Constraint	Component Function Constraint	Which components in the group must meet it?	ROIN
63	toolTorqueMin <= 12.0 ft-lb	Drive Bolt	at least one tool	1207-TAT
64	toolTorqueMax >= 12.0 ft-lb	Drive Bolt	tool which meets ID 63 constraints	1207-TAT
65	armTorqueMin <= 12.0 ft-lb	Move	at least one arm	1207-TAT
66	armTorqueMax >= 12.0 ft-lb	Move	arm which meets ID 65 constraints	1207-TAT
67	toolArea >= 0 in^2	Drive Bolt	same tool as ROIN 1207-TAT	1207-TA
68	toolArea <= 70 in^2	Drive Bolt	same tool as ROIN 1207-TAT	1207-TA
69	armPrecision >= 0 in	Move	same arm as ROIN 1207-TAT	1207-AP
70	armPrecision <= 0.17 in	Move	same arm as ROIN 1207-TAT	1207-AP
71	toolForceMin <= 1.37 * 1000 lbs OR toolForceMax <=1.37 *1000 lbs	Grip Small Object	at least one tool	1208-TAF
72	toolForceMin >= -1.37 * 1000 lbs OR toolForceMax >= -1.37 *1000 lbs	Grip Small Object	tool which meets ID 71 constraints	1208-TAF
73	armForceMin <= 1.37 * 1000 lbs OR armForceMax <=1.37 *1000 lbs	Move	at least one arm	1208-TAF
74	armForceMin >= -1.37 * 1000 lbs OR armForceMax >= -1.37 *1000 lbs	Move	arm which meets ID 73 constraints	1208-TAF
75	toolArea >= 0 in^2	Grip Small Object	same tool as ROIN 1208-TAF	1208-TA
76	toolArea <= 150 in^2	Grip Small Object	same tool as ROIN 1208-TAF	1208-TA
77	armPrecision >= 0 in	Move	same arm as ROIN 1208-TAF	1208-AP
78	armPrecision <= 0.37 in	Move	same arm as ROIN 1208-TAF	1208-AP
79	toolTorqueMin <= 5.5 ft-lb	Drive Bolt	at least one tool	1211-TAT
80	toolTorqueMax >= 5.5 ft-lb	Drive Bolt	tool which meets ID 79 constraints	1211-TAT
81	armTorqueMin <= 5.5 ft-lb	Move	at least one arm	1211-TAT
82	armTorqueMax >= 5.5 ft-lb	Move	arm which meets ID 81 constraints	1211-TAT
83	toolArea >= 0 in^2	Drive Bolt	same tool as ROIN 1211-TAT	1211-TA
84	toolArea <= 70 in^2	Drive Bolt	same tool as ROIN 1211-TAT	1211-TA
85	armPrecision >= 0 in	Move	same arm as ROIN 1211-TAT	1211-AP
86	armPrecision <= 0.17 in	Move	same arm as ROIN 1211-TAT	1211-AP

Selected Components from Library

Component #	Type	Function(s)	Force Min	Force Max	Torque Min	Torque Max	Length	Resolution	Area	Precision	DoF	Mass	Power	Time
A2	Arm	move	0.0005	0.001	-50	20	15			0.15	7	60	9	0.5
MT1	Multi Tool	Drive Bolt, Inspect, pinch, delicately pinch, cut	0.0005	0.0015	-6	30	2	3	70			30	4	3
C1	Camera	Inspect					0.5	4	130			21	7	2.5
BD1	Drive Bolt	Drive Bolt			0	17	2		50			15	7	4.5
SH12	Small Hand rail	grip small object	-0.9	-0.38			1		100			20	10	5

Group Selection

Each group will have **two arms** and no more than **four tools**

Group 1

Component #	Mass	Power	Time
A2	60	9	0.5
A2	60	9	0.5
MT1	30	4	3
SH12	20	10	5
Total	170	32	9

Group 2

Component #	Mass	Power	Time
A2	60	9	0.5
A2	60	9	0.5
BD1	15	7	4.5
SH12	20	10	5
Total	155	35	10.5

Lower power allocation

Lower down time allocation

Lower mass allocation

Numerical Approach: Constraint Satisfaction Problem

JaCoP: Java Constraint Programming Library (Open Source)

JaCoP Constraints

- primitive
  - $X + Y = Z$,
  - $X >= Y$,
  - $X \times Y = Z$,
  - etc.
- conditional
  - IF $(X = Y)$ THEN $B > 10$ ELSE $C <= 7$
  - $X = Y \Leftrightarrow A > C$
- reified
  - $X = Y \Leftrightarrow B$
- logical
  - $(X = Y) \vee (X = Z)$
  - $\neg(A = B)$

JaCoP Search

- JaCoP offers a number of search methods
  - search for a single solution,
  - find all solutions, and
  - find a solution that minimizes/maximizes a given cost function.
- Search is achieved using depth-first-search together with consistency checking.
- Search is parametrized (different classes for labeling, delete, and indomain).
- There are complete search methods and heuristics
  - depth-first-search and branch-and-bound,
  - credit search,
  - "limited discrepancy search",
  - hierarchical search.

Preliminary Assessment: Support for many types of constraints. Algorithms for design space search and pruning are powerful. But, various forms of problem data need to be converted to a common numerical format.

99.996%

Design Options Removed

160000 options → 6 options

99.99999998%

Design Options Removed

3116006480 options → 6 options

Future Work

- Link with SysML
- Sensitivity analysis
- Expand to other problems

Sources

- Hubble Space Telescope. See: http://hubblesite.org/, 2016.
- Kuchcinski, K., 'JaCoP: Java Constraint Programming library and its applications', See: http://www.gecode.org/~schulte/events/SweConsNet/kuchcinski.pdf.
- Nassar, N. and Austin, M., 2013, 'Model-Based Systems Engineering Design and Trade-Off Analysis with RDF Graphs', Conference on Systems Engineering Research, Atlanta, GA, US.
- Pilotte, K. J., 2004, 'Analysis of Grasp Requirements for Telerobotic Satellite Servicing', Master of Science Thesis, University of Maryland, College Park, MD, US.
- RESTORE-L Mission. See: http://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat- 7-demonstrate-crosscutting-technologies, 2016.
- Robotic Refueling Mission. See: https://ssco.gsfc.nasa.gov/rrm_tools.html and https://ssco.gsfc.nasa.gov/rrm_tasks.html, 2016.

Questions?