SYSTEMS ENGINEERING RESEARCH CENTER

Theory-Grounded Guidelines for Solver-Aware System Architecting (SASA)

Athul Chakkithara Dharmarajan, Purdue University

achakkit@purdue.edu

Under

Prof. Jitesh Panchal, Design Engineering Lab Purdue

Prof. Zoe Szajnfarber, SzajnLab, GW

Prof. Taylan G. Topcu, Virginia Tech

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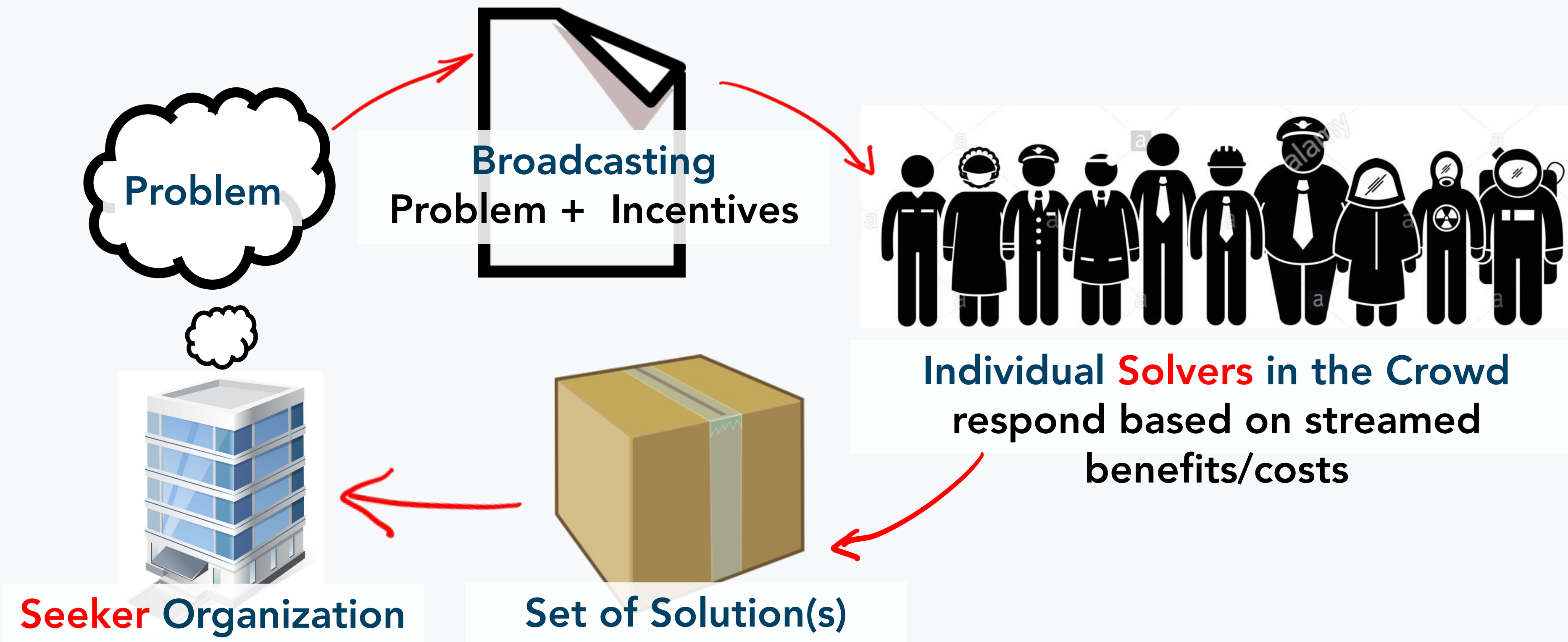
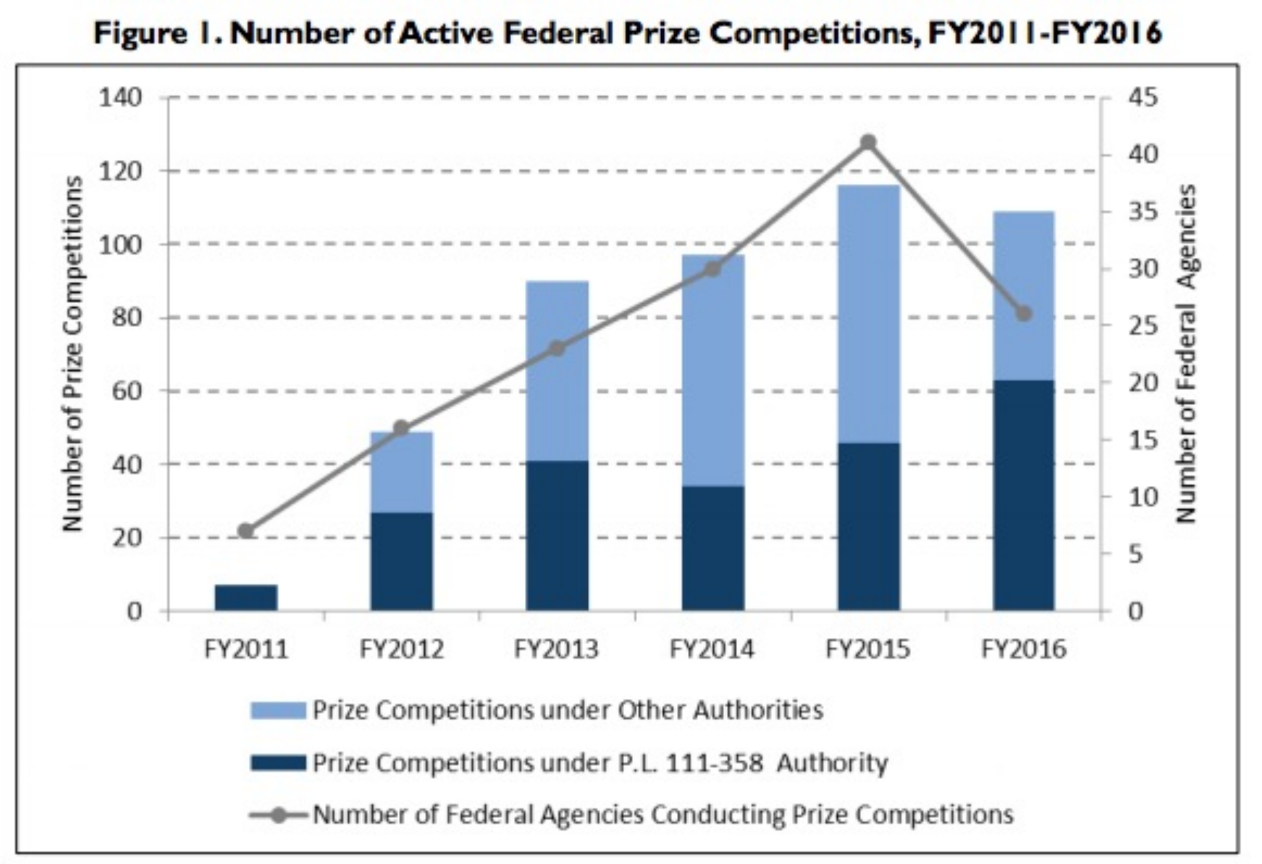
SERC DOCTORAL STUDENT FORUM 2022

Background - Open Innovation Crowdsourcing Mechanism

- STEM Agencies are increasingly using Open Innovation (OI), more specifically the Crowdsourcing Mechanism



Increased use of prizes, path to novelty?



Source: Gallo, M. 2018

'Prizes are great, but they can't actually solve *my* [complex] core problems…'
-- typical engineer

'You get a lot of unicorns… is it novel if they'll never work?'
-- experienced exec

Barrier: need better understanding of link among ***prize design***, ***novelty*** and ***quality***, before introducing strategies to drive novelty.

Theory: How prizes generate "better"

- General agreement that broadcasting yields quality, but nature and role of novelty in that process varies across theories.

Random draws: dist. over solution quality; *novelty* incidental.

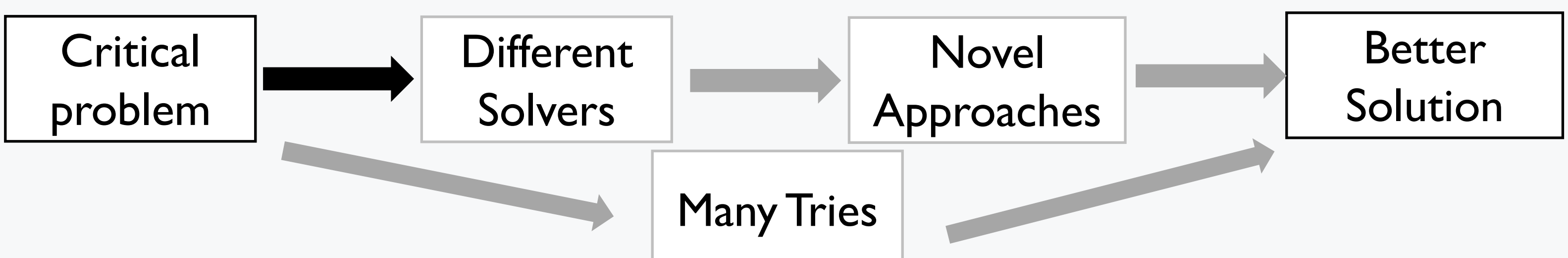
Wright 1983, Fullerton et al 1999, Che and Gale 2003, Terwiesch and Xu 2008

Talent search: dist. over *different* solvers; some yield high quality.

Terwiesch and Xu 2008, Afuah and Tucci 2012, Boudreau, Lacetera, & Lakhani 2011

New **perspective**: dist. over solving approaches; novel approaches yield quality.

Jeppesen and Lakhani 2010, Poetz and Schrier 2012, Franzoni and Sauermann 2014



Focus of my work

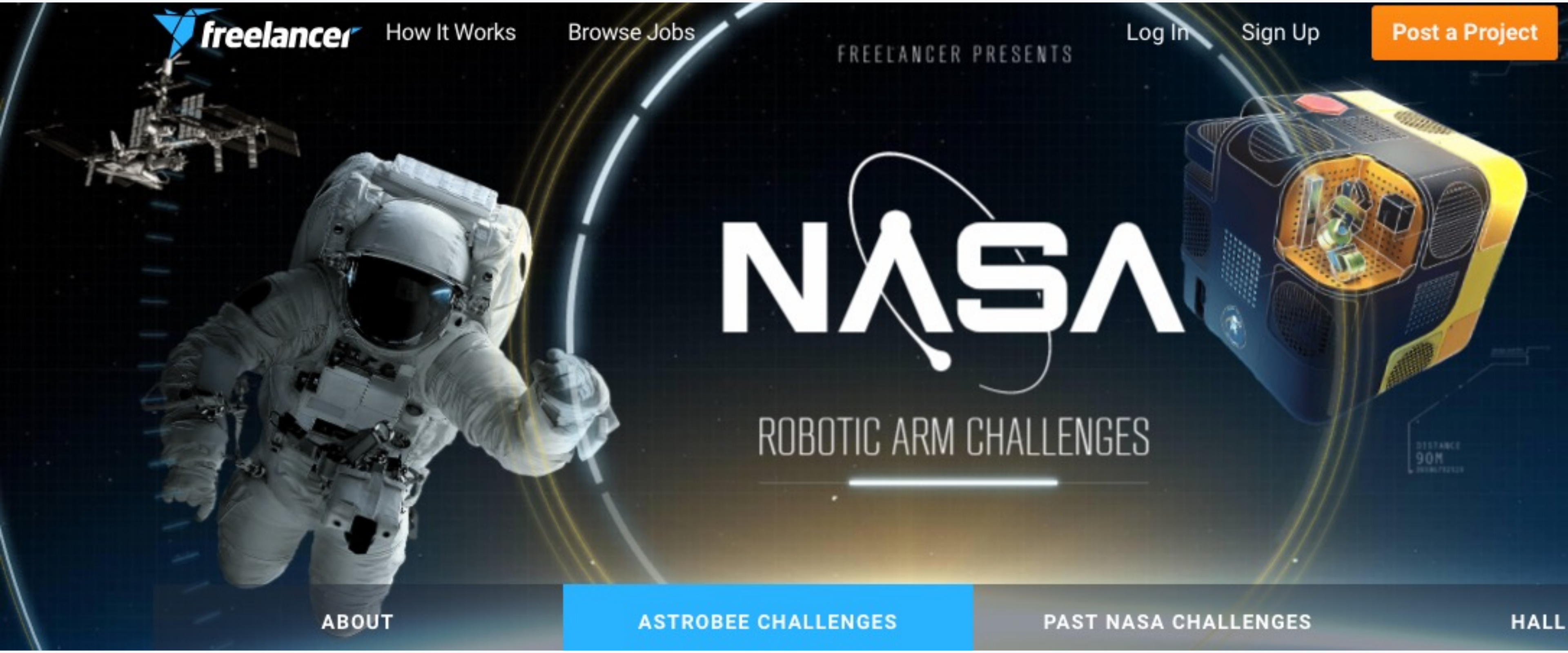
- Relationship between problem framing (decomposition) and solution novelty:
  1. How to characterize novelty distribution of solutions.
  2. What is the relationship between the scope of the problem and the resultant novelty distribution?

- Knowing this is important beyond prize competitions:
  - Affects how we build design teams and present challenges to them.

- Approach: leverage data from the OI experiment
  - data on problem -> solver -> solution chain

Experiment Overview

Robotic Arm Field Experiment

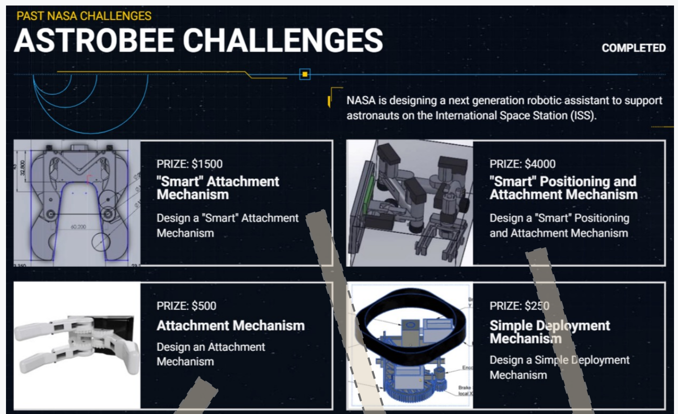


Data Summary

Registration Survey

16000+ registered Freelancers

Demographics, work and educational history, motivation, self-reported distance/expertise etc.



Interest Tracking Data

3900 interested Freelancers

Detailed design documentation, incl. drawings, flow charts, analysis

Submission

263 solutions

Exit Survey

143 solvers across 17 contests

Motivation, contest-specific effort and learning, past similar projects etc.

Solution Characterization

Functional coding of each solutions

- All challenges relate to the design of an autonomous robotic manipulator. Global functions include: reach, grasp, pack, orient, control etc.
- For each function, coded how a solution achieved that function, based on Shah et al. tree structure.

Architecture	Challenge	Description	Electronics	Planning	Control Free Space	Control Onto Handrail	Control Orient	Control Other	Contingency Loading	Packing/Unpack	Reaching	Grasping	Orient
D1	SRA	Autonomous deployment, attachment, and positioning systems	●	●	●	●	●		●	●	●	●	●
D2	SFA	Autonomous deployment and positioning system	○	●	●	○	●	●	●	○	●		●
	SAM	Autonomous attachment system	○			○			●	○		●	
D3	SCA	Autonomous deployment mechanism	○	○			●	●	●	○	○		●
	SPAM	Autonomous positioning and attachment system	○	○		●			●	○	○	●	
D4	EMA	Mechanical Elements of SRA							●	●	●	●	●
	CDPD	Electronics elements of SRA	●	○				●	●				
	RASA	Software Architecture of SRA		○			●		●				
	PSA	Positioning Function for RASA		○	●	●			●				
	HMSA	Health Monitoring Software Architecture		○					○			○	
D[illegible]	AM	Mechanical Elements of SAM								○		○	
	EDC	Electrically Driven Clamp								○		○	
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	○	
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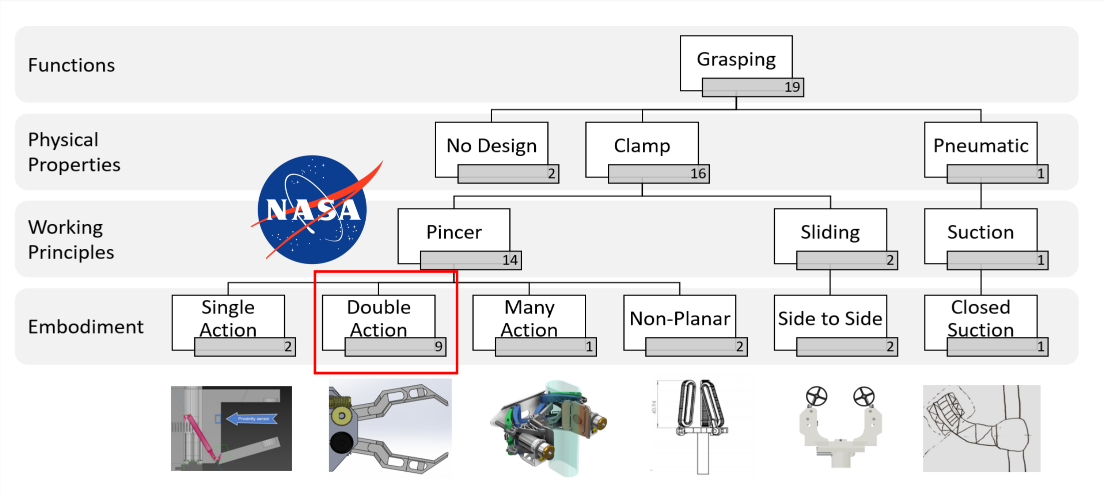
Mapping of challenges to functions



NASA reference approach

Functional coding of each solutions

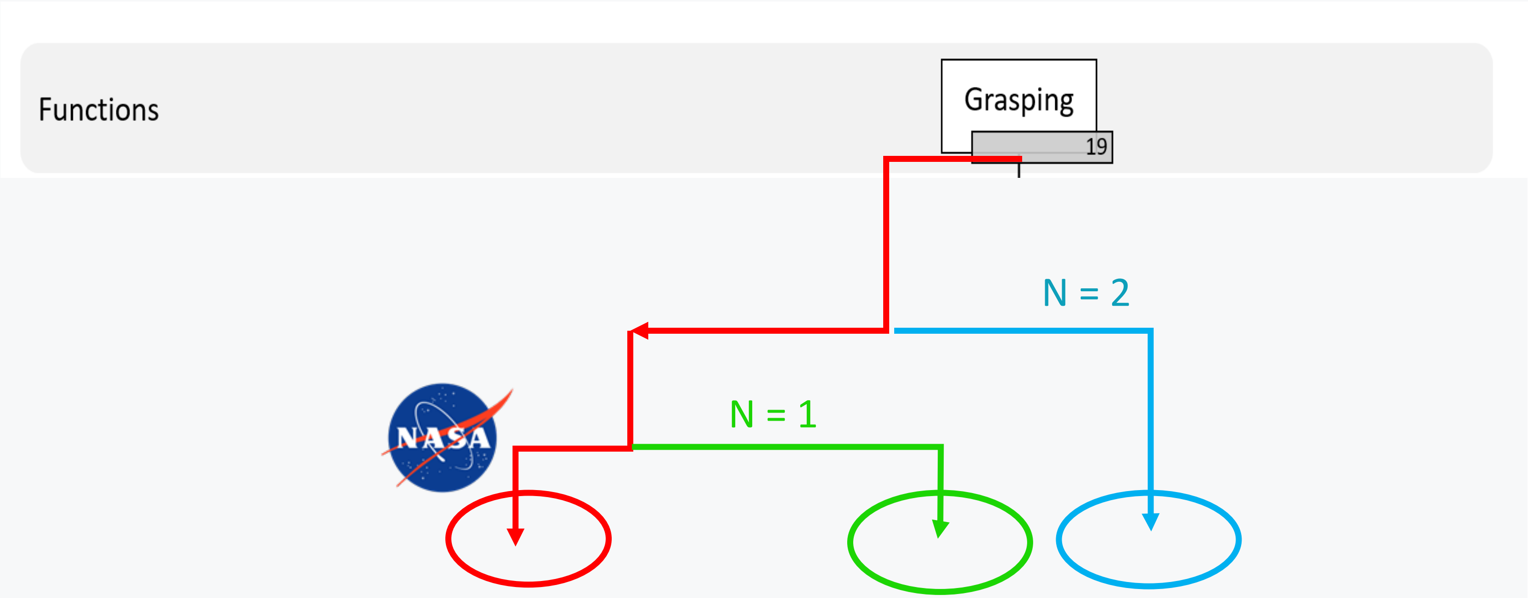
Architecture	Challenge	Description	Electronics	Planning	Control Free Space	Control Onto Handrail	Control Orient	Control Other	Contingency Loading	Packing/Unpack	Reaching	Grasping	Orient
D1	SRA	Autonomous deployment, attachment, and positioning systems	●	●	●	●	●		●	●	●	●	●
D2	SFA	Autonomous deployment and positioning system	○	●	●	○	●	●	●	○	●		●
	SAM	Autonomous attachment system	○			○			●	○		●	
D3	SCA	Autonomous deployment mechanism	○	○			●	●	●	○	○		●
	SPAM	Autonomous positioning and attachment system	○	○		●			●	○	○	●	
D4	EMA	Mechanical Elements of SRA							●	●	●	●	●
	CDPD	Electronics elements of SRA	●	○				●	●				
	RASA	Software Architecture of SRA		○			●		●				
	PSA	Positioning Function for RASA		○	●	●			●				
	HMSA	Health Monitoring Software Architecture		○					○			○	
D5	AM	Mechanical Elements of SAM								○		○	
	EDC	Electrically Driven Clamp								○		○	
	MDC	Mechanically Driven Clamp								○		○	
	MIS	Attachment Surface										○	
	SDM	Single Joint											
	EBD	CDPD Electronics Box Design		○									
	BMA	Mechanical analysis and optimizations of EBD		○									

Measures of Novelty

- Genealogical Categorization (Shah et al 2003)
- Ideas separated by physical principles used to satisfy each function

- NASA roboticists -> conventional solution (ground truth)
- How separated from the conventional solution is the user submission for each challenge
- Distance measured using generational distance
- function -> physical principles -> working principles sharing same physical principles -> embodiment -> detail

Generational Distance

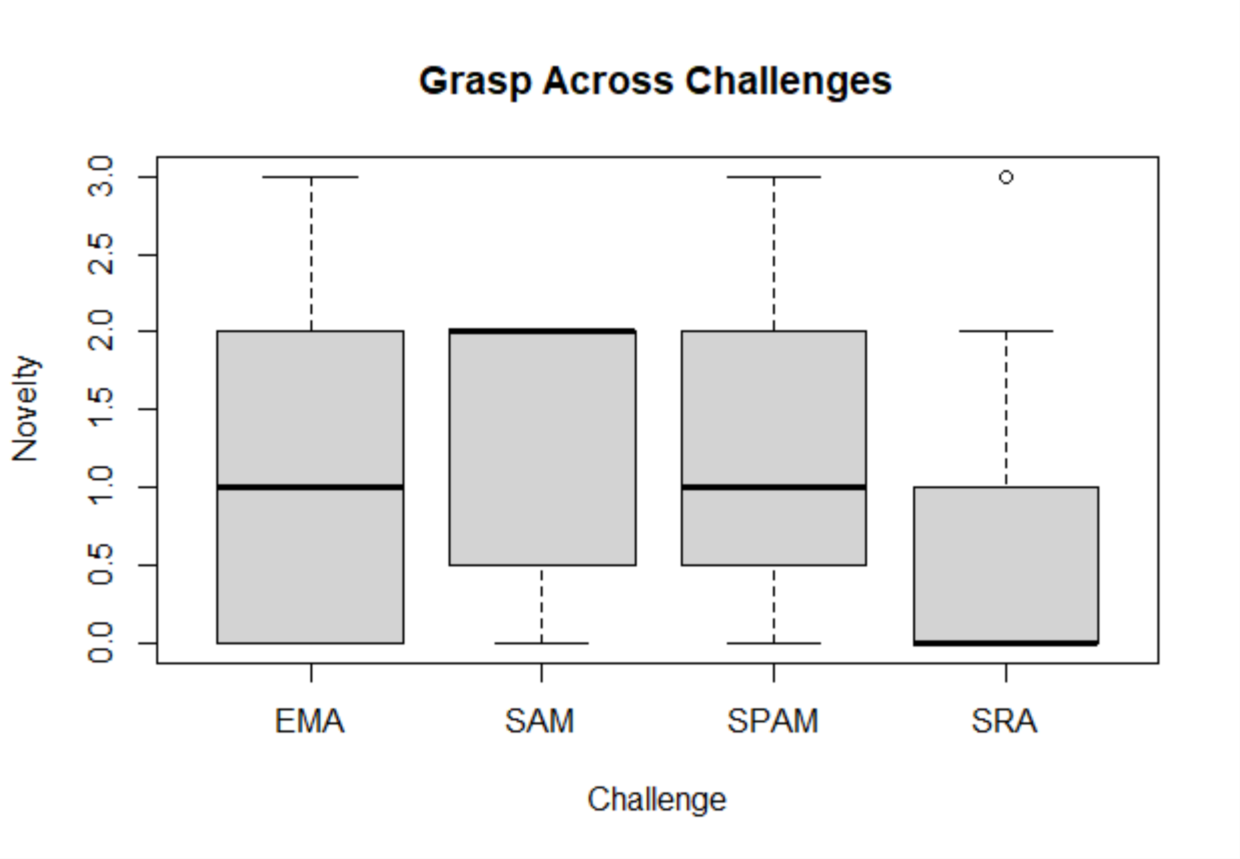


Aggregating at functional level

- Currently comparisons are made at a functional level across challenges
- We use an average novelty score to combine the individual scores
- Novelty score $= \frac{3*(\#) + 2*(\#) + 1*(\#) + 0*(\#)}{Total\ Solutions}$
- This is an average over the set which helps to aggregate and give a single value for each function
- Going ahead we need ways to aggregate for challenges with different functions – not addressed in literature
- Methods available rely on a subjective aggregation using arbitrary weights assigned by experts

Results

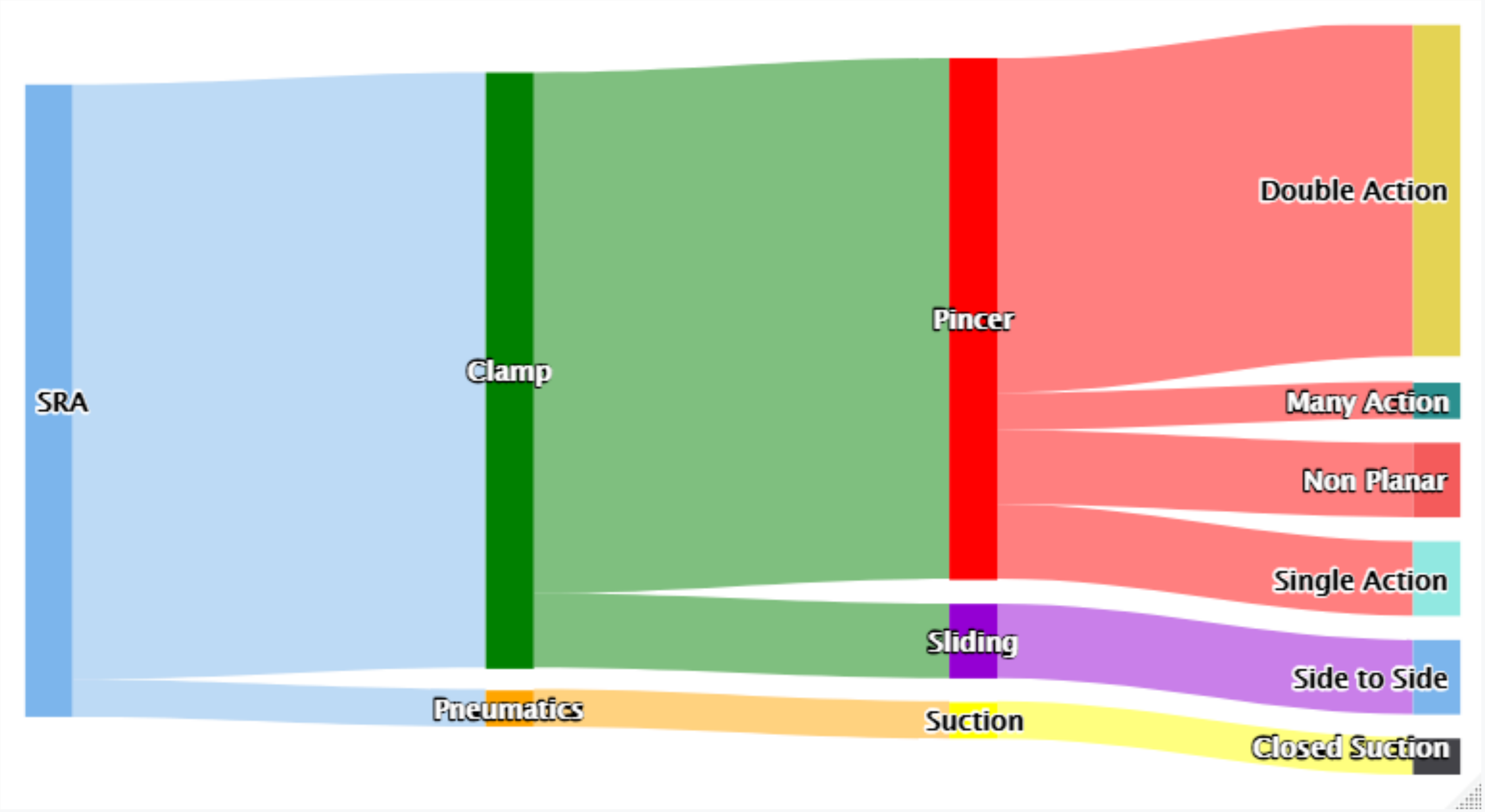
Distribution of Novelty scores



Increasing functional scope

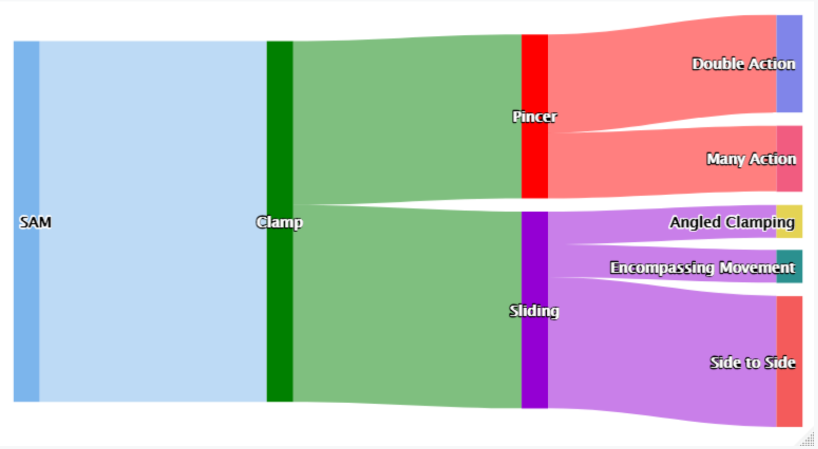
Solutions to Grasp across challenges

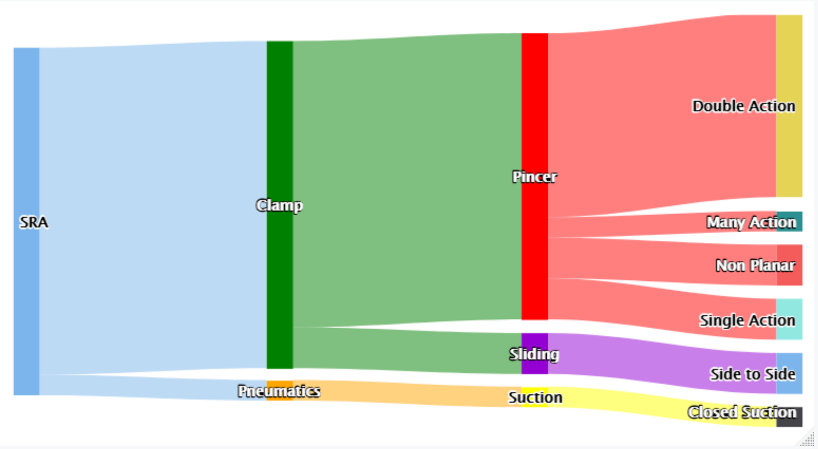
- Visualize with Sankeys – shows how different solvers attempted it in comparison to the NASA solution

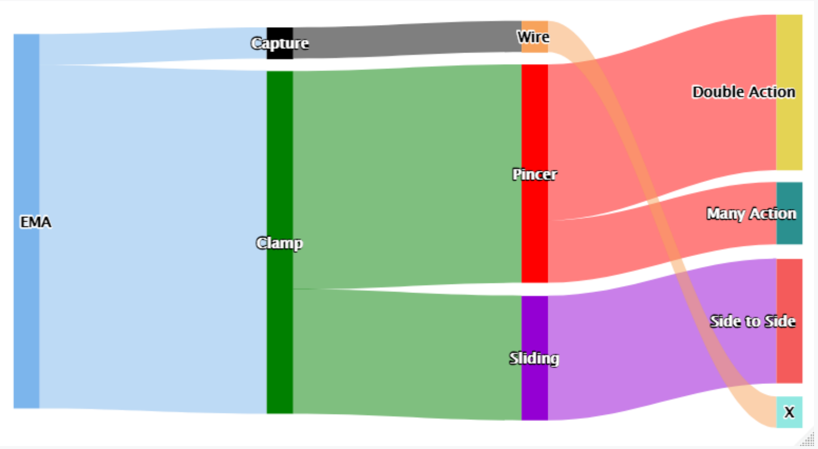


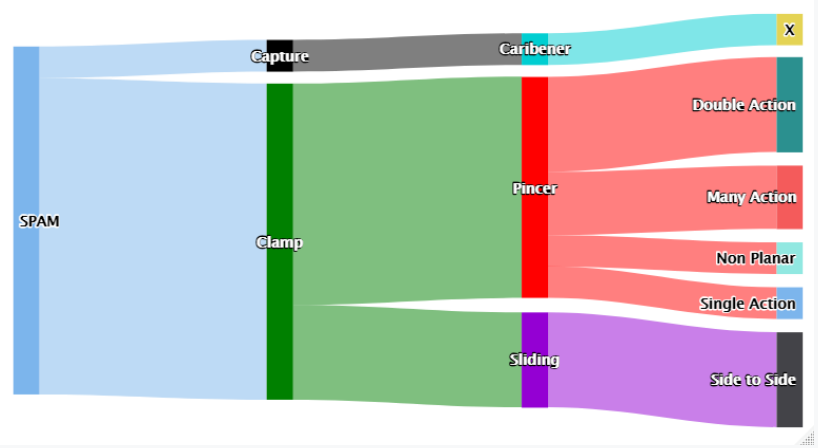
Solutions to Grasp across challenges

- Same function, different decompositions and framing









Explaining impact of decomposition

Less Novelty/Variety

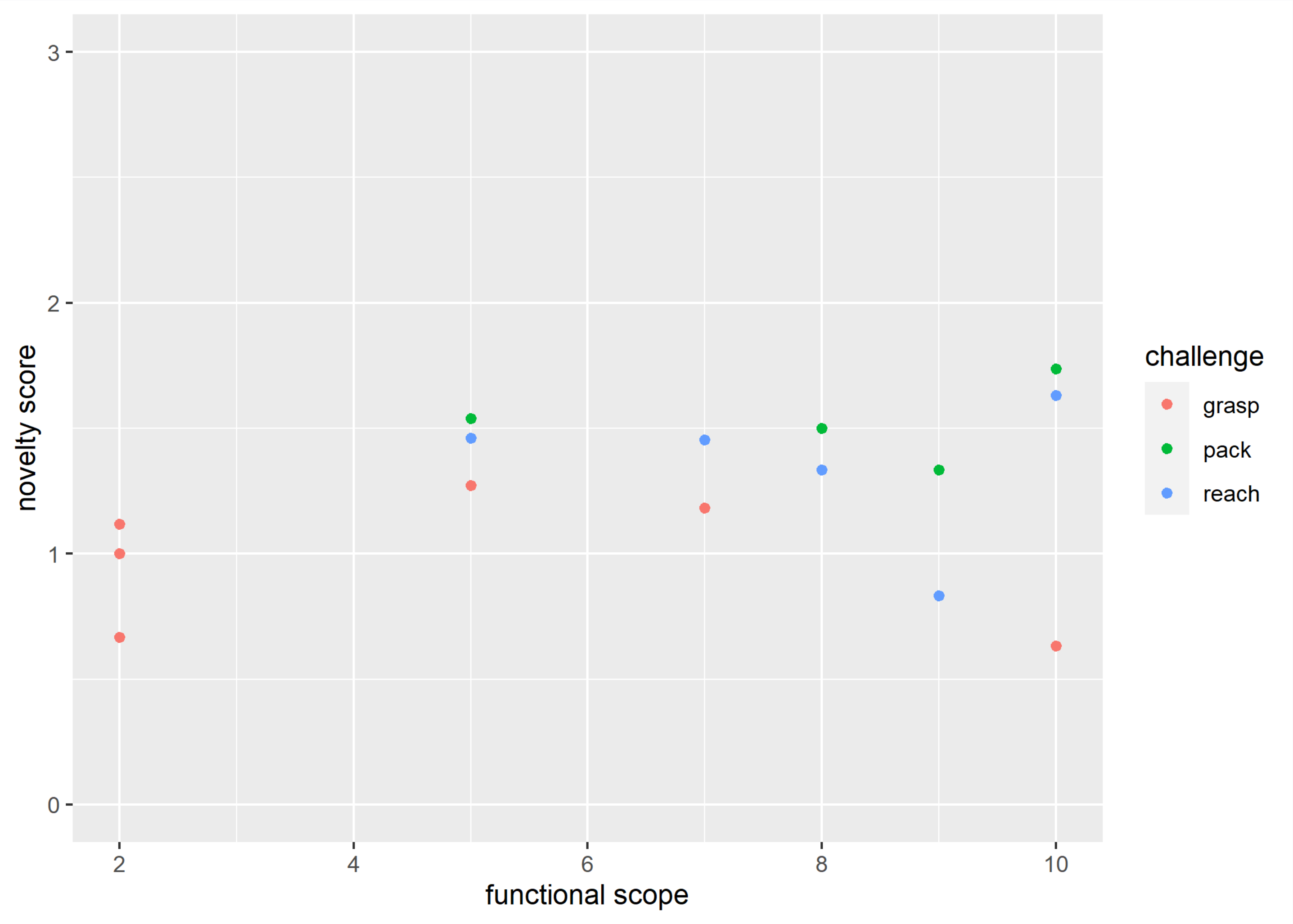
- Low complexity; limited possibility
- Very complex: people stick to traditional methods, attract experts

More Novelty/ Variety

- More complex: more possibilities
- Less complex: less distractions, can focus more on individual parts

Hypothesis: Bathtub curve in the novelty vs functional scope plot

Novelty Score vs Functional Scope



Summary of my work

- There seems to be a more nuanced relationship here
  - More work needs to done to fully characterize
  - Use of alternate methods for analysis
  - Better understanding the factors at play here
  - We need to understand relationship between novelty and quality

- Ongoing work, looking at aggregating beyond single function (not currently addressed in the literature)

Relationship to broader project

- Objective: Develop heuristics for how to architect systems to take advantage of the non-traditional contributions (e.g., from new contractors, or crowd actors)

Simple simulation proof-of-concept that “best” architecture depends on “who” solves

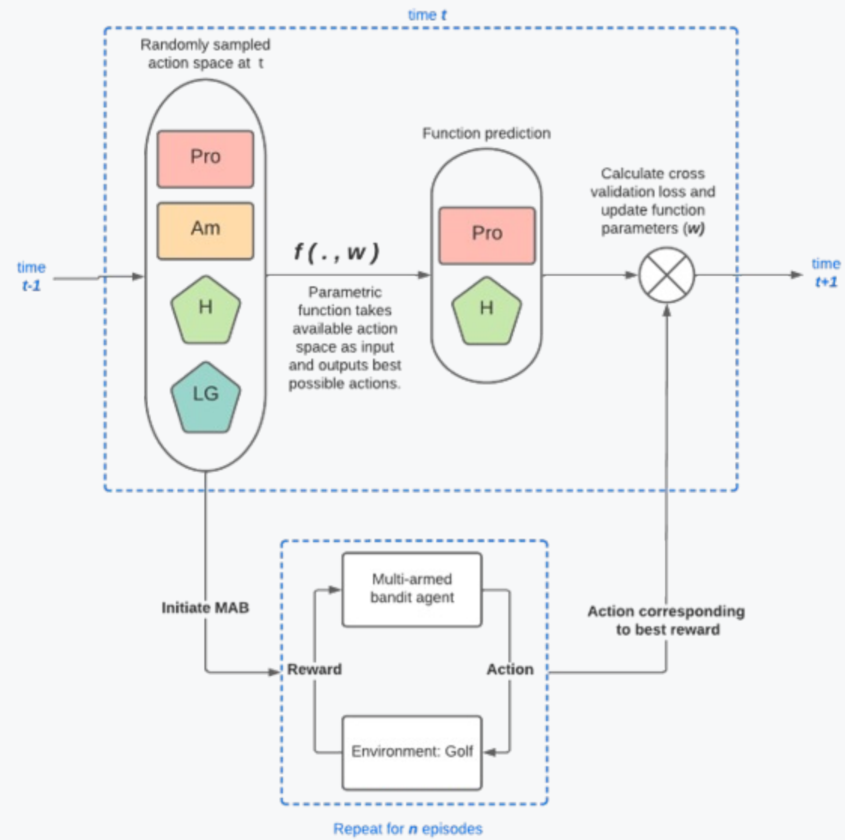
Extend modeling framework to address complex systems, like the manipulator presented here
(this feeds characterization)

Developing RL-based tools to extract heuristics from the complex tradespaces that we will need to explore

Relationship to broader project

Action Type	1. Choice of solver			2. Choice of decompositions			
Action Number	0	1	2	3	4	5	6
Action	Pro	Amatuer	Specialist	Hole	Long Green	Tee Fairway Green	Tee Short
Symbol	Pro	Am	Spec	H	LG	TFG	TS

The above table shows the complete action space



References

[1] Shah, J. J., Smith, S. M., & Vargas-Hernandez, N. (2003). Metrics for measuring ideation effectiveness. *Design studies*, *24*(2), 111-134.

[2] Z. Szajnfarber, L. Zhang, S. Mukherjee, J. Crusan, A. Hennig and A. Vrolijk, "Who Is in the Crowd? Characterizing the Capabilities of Prize Competition Competitors," in *IEEE Transactions on Engineering Management*, vol. 69, no. 4, pp. 1537-1551, Aug. 2022

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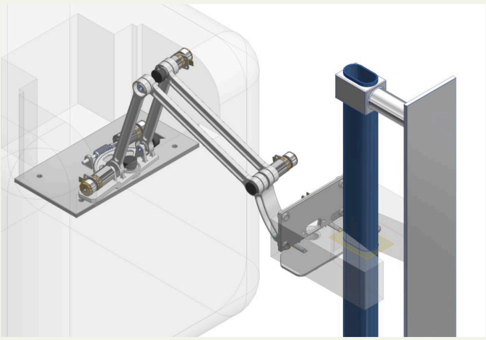
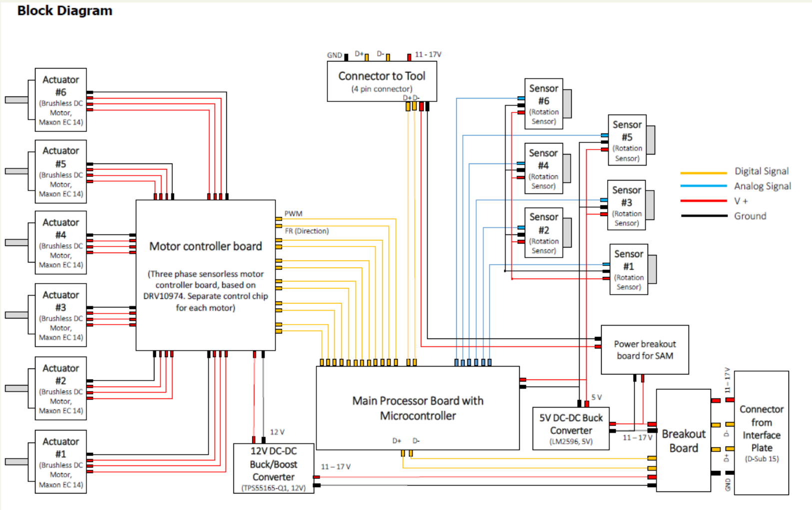
[4] Szajnfarber, Z., Topcu, T., & Lifshitz-Assaf, H. (2022). Towards a solver-aware systems architecting framework: Leveraging experts, specialists and the crowd to design innovative complex systems. Design Science, 8, E10.

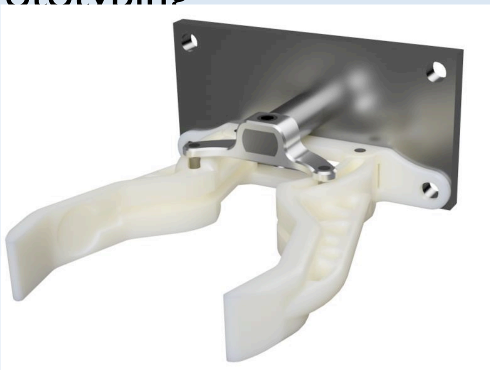
Athul Chakkithara Dharmarajan
achakkit@purdue.edu

Detailed Design Descriptions

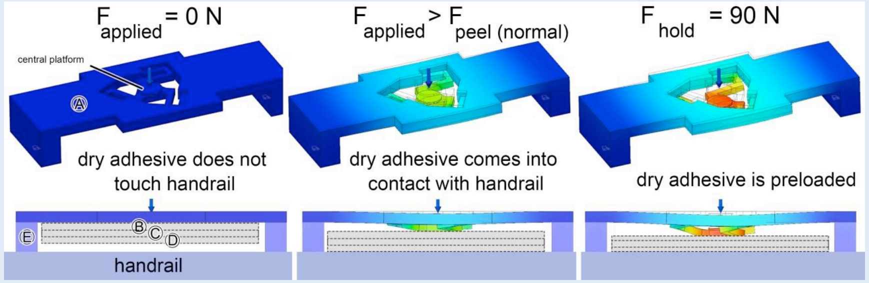




Design Concept Prototyping



Sophisticated Engineering Analyses



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THANK YOU

Stay connected with us online.

17 Astrobee Challenges

Manipulated functional scope and interdisciplinarity in fixed technology area

Arch	Challenge	Prize
1	SRA – whole arm	$5000
2	SFA – Arm, no hand	$4000
	SAM - hand	$1500
3	SCA - Shoulder	$1500
	SPAM – Elbow down	$4000
4	EMA – Arm mechanisms	$4000
	CDPD – Arm electronics	$1500
	RASA – Arm software arch	$1500
	PSA – Pointing architecture	$500

Challenge	Prize
AM – Hand mechanisms	$500
MDC – mech clamp	$250
EDC – elec clam	$250
SDM - joint	$250
MIS – finger surface	$500
HMSA – monitoring s/w	$250
EBD – Electronics box	$250
BMA – Box analysis	$250