RASPBERRY SI: Resource Adaptive Software Purpose-Built for Extraordinary Robotic Research Yields

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https://nasa-raspberry-si.github.io/raspberry-si/

Target: Ocean worlds subsurface---Europa & Enceladus.

Science:

- Enhance autonomy by handling unexpected situations through causal learning
- Increasing the timeliness of scientific explorations by recovering from failures resulting from environmental and system dynamic changes

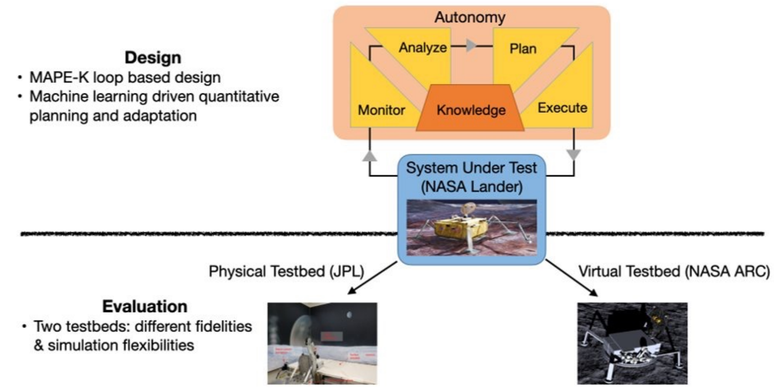
Objectives:

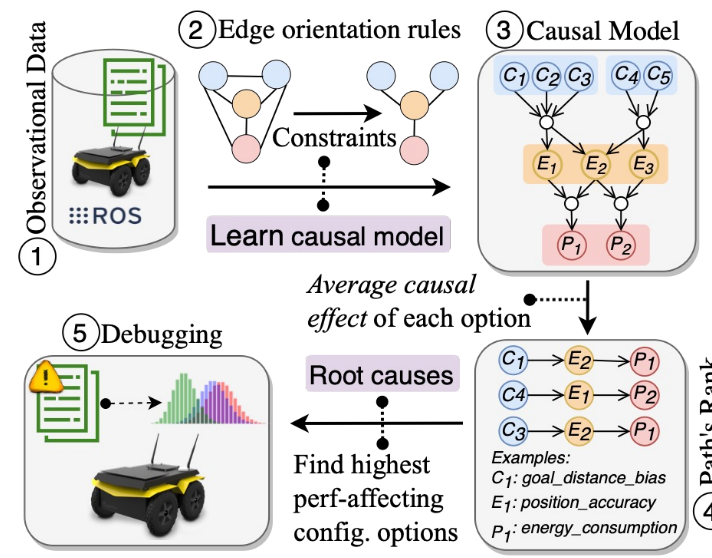
- Develop causal learning models to discover mission intent and enable transfer learning and online learning during a mission.
- Develop a probabilistic planner by integrating causal models to enable run-time adaptation based on the spacecraft's state, environment assumption, and resource availability.

Technology Accomplishments:

- CaRE: Finding Root Causes of Configuration Issues in Highly-Configurable Robots
- CURE: Simulation-Augmented Auto-Tuning in Robotics
- Casual MAPE-K for Fault-Tolerant Autonomy
- Causal MDPs for Probabilistic Model Checking

Autonomy Module





10/01/2020 - 09/30/2022
09/30/2022 - 09/30/2024
(no cost extension)

TRL (2) to (6)

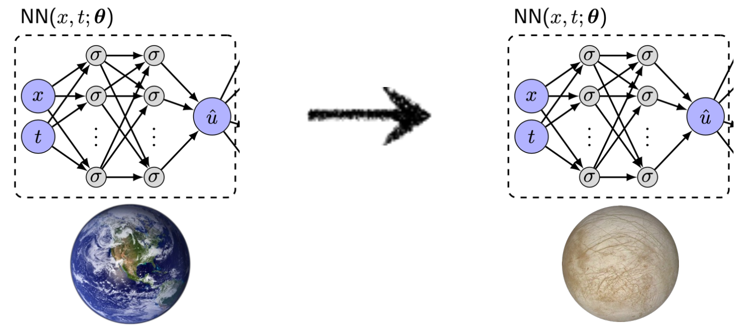
Concepts for Ocean worlds Life Detection Technology (COLDTech)

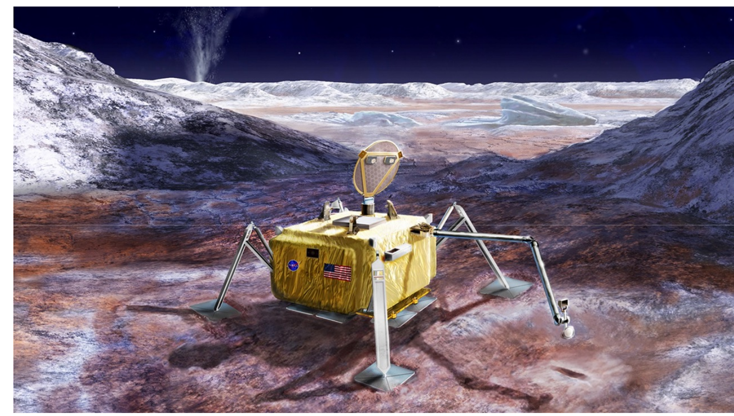
AISR: Autonomous Robotics Research for Ocean Worlds (ARROW)

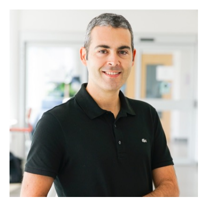
RASPBERRY SI

Resource Adaptive Software Purpose-Built for Extraordinary Robotic Research Yields - Science Instruments

https://nasa-raspberry-si.github.io/raspberry-si







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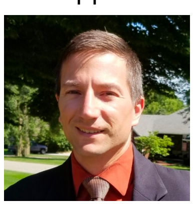

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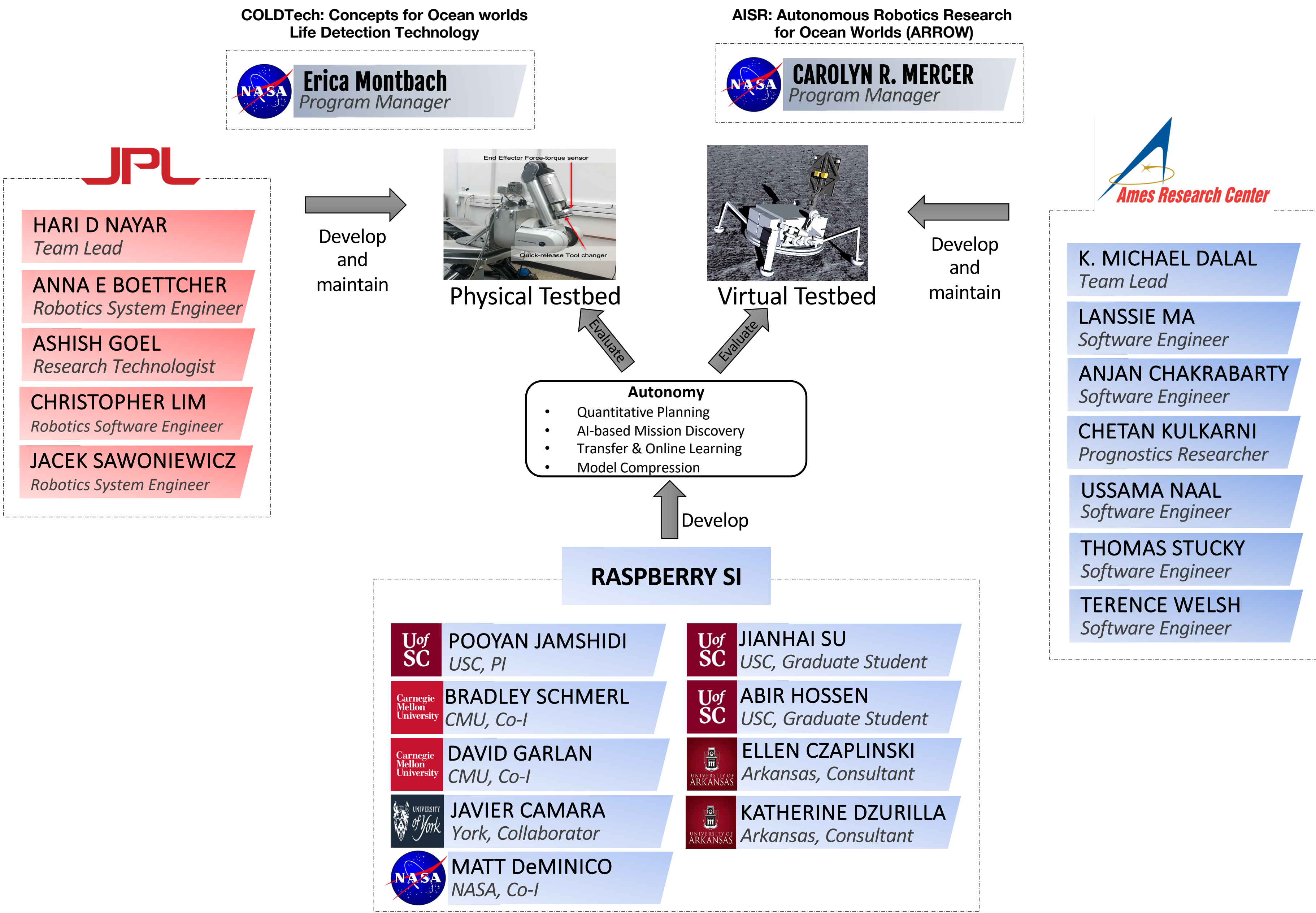
COLDTech: Concepts for Ocean worlds Life Detection Technology
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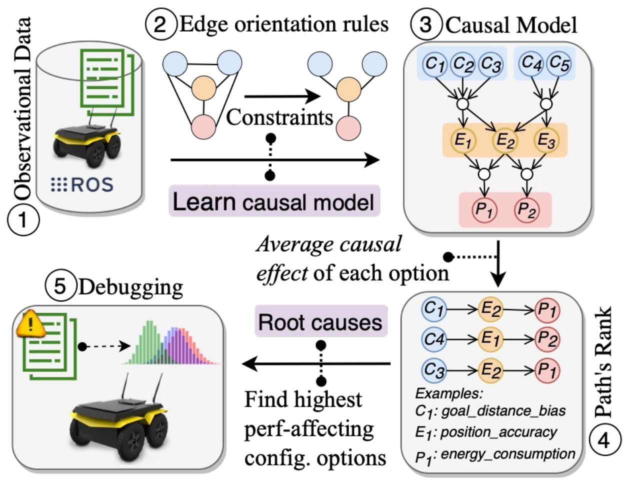
CARE: Finding Root Causes of Configuration Issues in Highly Configurable Robots

https://github.com/softsys4ai/care

Challenges:

- Non-trivial human efforts due to the large configuration space.
- Performance influence models are non-transferable across different robotic platforms and environments
- Incorrect explanations of root causes in debugging
- Data collection is expensive from physical hardware

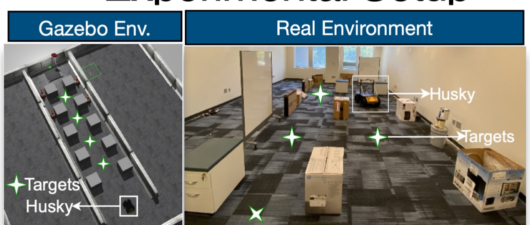


CARE Overview

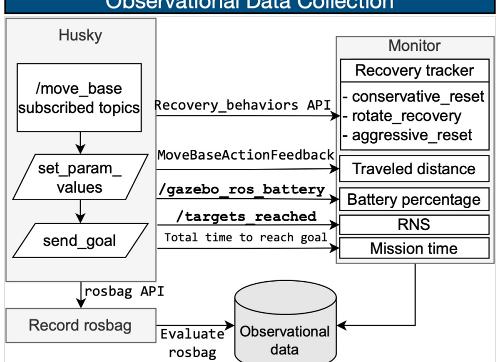
Contributions:

- Proposed a novel framework for finding the root causes of the configuration bugs in robotic systems.
- Demonstrated the transferability of the causal models by learning the causal model in the Husky simulator and reusing it in the Turtlebot 3 physical platform.

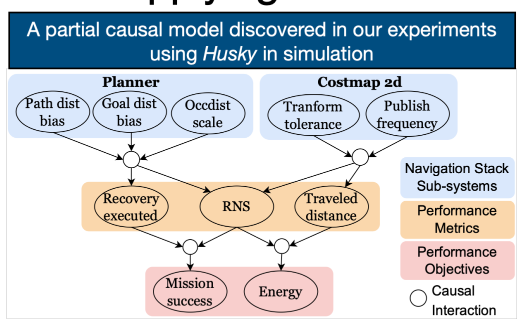
Experimental Setup

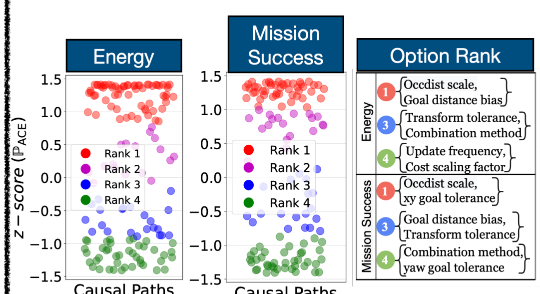


Observational Data Collection

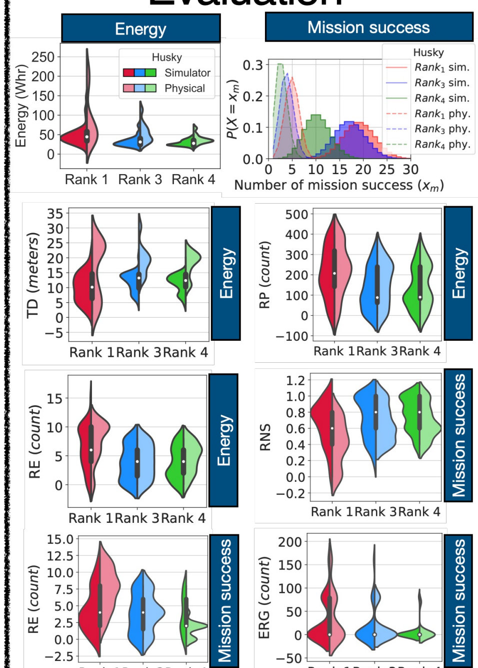


Applying CaRE





Evaluation



CURE: Simulation-Augmented Auto-Tuning in Robotics

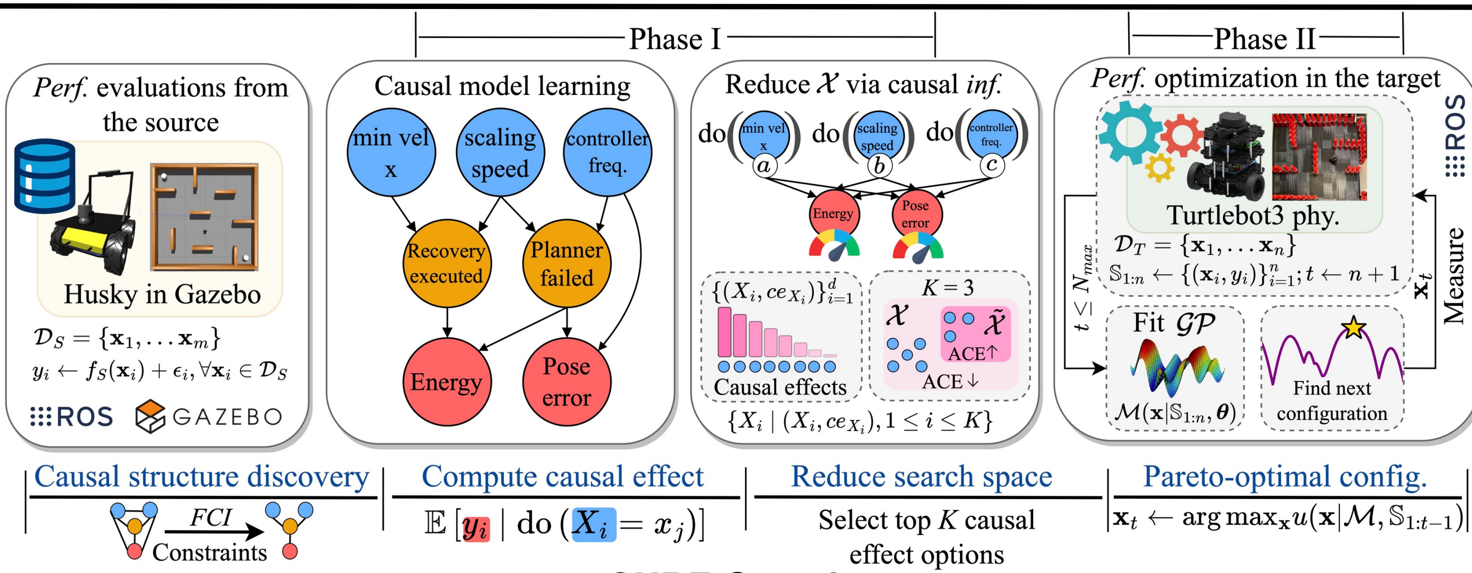
https://github.com/softsys4ai/cure

Challenges:

- Large configuration space
- Conflicting multiple performance objectives
- Costly acquisition of training data
- Safety-critical structure of robotic systems

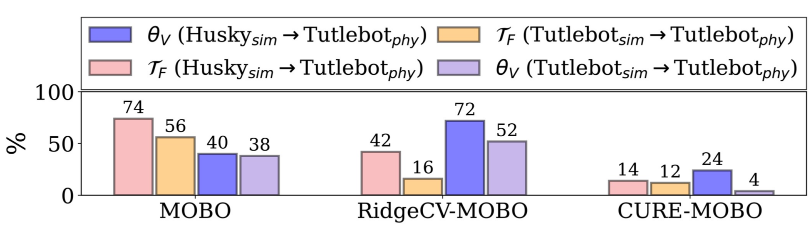
Contributions:

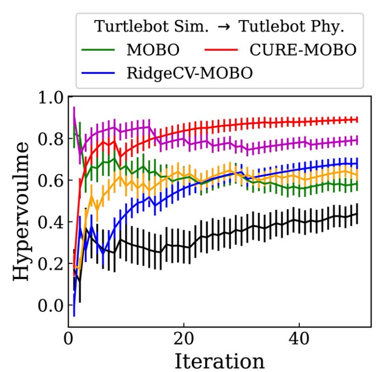
- Proposed a multi-objective optimization method that operates in the reduced search space involving causally relevant configuration options and allows faster convergence.
- Demonstrated transferability on *Husky* and *Turtlebot 3 platforms,* both in simulation and real robots, with different severity of deployment changes

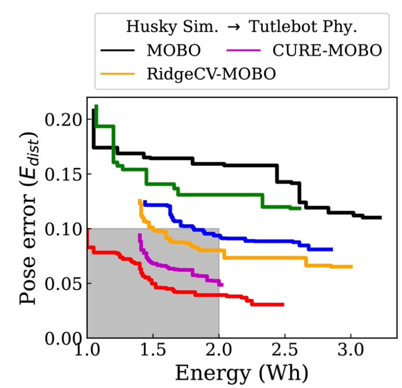


CURE Overview

Evaluation and Results:







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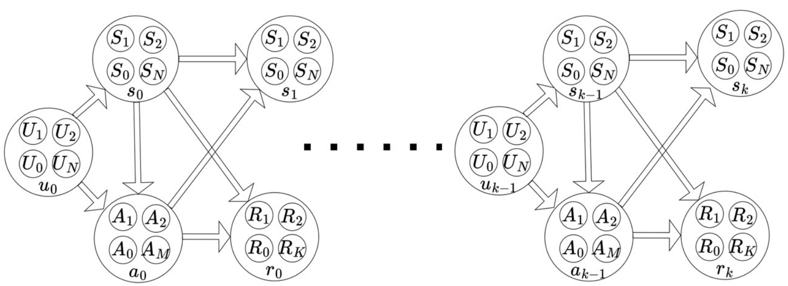
From Roots to Probabilities:
A Causal Exploration in the Probabilistic Model Checking

Challenges:

- Model uncertainty
- Complex reward structures
- State space explosion
- Computational complexity

Contributions:

- Causal-MDP as a modeling framework in probabilistic model checking
- Reward and transition probabilities computation considering causal dependencies, enabling the use of system dynamics for robust predictions
- Efficient and scalable verification procedures, ensuring property satisfaction and reducing computational complexities.



Causal evolution for 'k' step CIMDP

Transition Probability:

$$\mathcal{P}(s'|s,a) = \frac{\mathbb{E}_{u\sim\tilde{P}}[P(s'|s,a,u)\cdot\pi(a|s,u)]}{\mathbb{E}_{u\sim\tilde{P}}[\pi(a|s,u)]}$$

$$P(s'|s,a,u) = \prod_i \tilde{P}_i \forall i \in V \setminus S \cup A \cup R$$

Rewards:

$$R(s'|s,a) = \frac{\mathbb{E}_{u\sim\tilde{P}}[R(s'|s,a,u)\cdot\pi(a|s,u)]}{\mathbb{E}_{u\sim\tilde{P}}[\pi(a|s,u)]}$$

$$R(s'|s,a,u) = \mathbb{E}_{\tilde{P}}[R(s,a,u)]$$

Computational Complexity:	Model size	Verification
	$\mathcal{O}(\lvert\mathcal{S}\rvert \sum_{i=0}^{\lvert S\rvert-1} \lvert\mathcal{A}(s_i)\rvert)$.	Linear with model size

Evaluations and Results:

Table: Statistical Analysis for numerical and verification queries for autonomous vehicle

Property	Result	Parameter	MDP	CIMDP	MDP	CIMDP	MDP	CIMDP
NQ_1: $Pr_s^{max}(reach(\texttt{goal}))\ \forall s \in \mathcal{S}$	0.909	State Space Size	2160	524	1584	396	1008	252
		Reachability iterations	16	16	12	12	9	8
NQ_2: $Pr_s^{min}(reach(\texttt{goal}))\ \forall s \in \mathcal{S}$	0.019	Model construction time	28.589	1.859	14.053	0.895	5.043	0.388
		States	115	75	83	55	51	35
VQ_3:$Pr_{\geq 0.8}[F^{\leq 10}\texttt{goal}]$	False	Transitions	390	316	278	228	166	150
		Choices	197	117	144	85	85	53
VQ_4: $R'^{ec'}_{\leq 500}[C^{\leq 8}]$	True	Nonzero Transition Rewards	386	314	274	228	162	138
NQ_5: $R'^{ec'}_{min=?}[F\ (\texttt{goal})]$	413.1285	No. of Nonzero value states	110	72	78	52	46	32
NQ_6:$R'^{ec'}_{max=?}[C \leq 5]$	364.0112	Verification time (seconds)	0.01	0.007	0.009	0.005	0.007	0.003
NQ_7:$multi(R'^{ec'}_{min=?}[C], R'^{col'}_{max=?}[C])$	[(283.467, 0.0)]	Reward computation time	0.138	0.05	0.096	0.04	0.04	0.028

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Fault Tolerant Autonomy Design for Ocean World Lander System

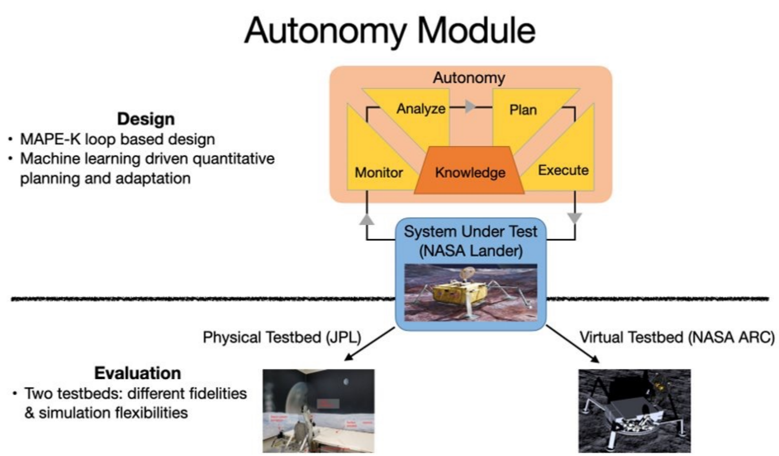
https://nasa-raspberry-si.github.io/raspberry-si

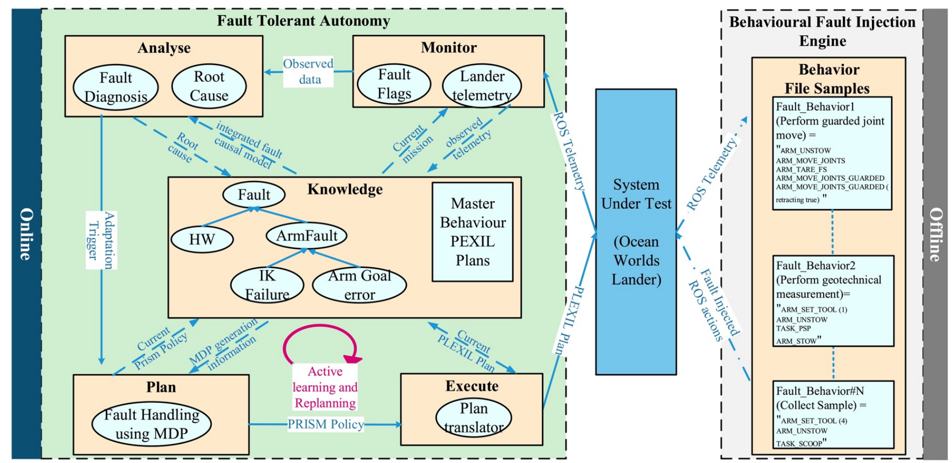
Challenges:

- Limited arm workspace
- Unexpected surface behavior
- Communication delays
- Battery constraints

Contributions:

- Autonomy design using the MDP framework
- Causal MAPE-K for fault-tolerant autonomy
- Search space reduction for planner
- Capability demonstration on physical and virtual testbeds





Evaluations and Results:

Evaluation Criteria:

Stage	Description
Stage A (Baseline): PLEXIL plan, No-Fault, No Autonomy	Test connection between autonomy and testbed
Stage B (Baseline): PLEXIL plan, Fault, No Autonomy	Show need for autonomy
Stage C.A (Challenge Stage - Design time)	Autonomy in Naive mode with design time fixes
Stage C.B (Challenge Stage - Runtime)	Autonomy with synthesized adaptation plan

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