Uncertainty Taxonomy for Self-Adaptive Robotics:
Supplementary Material

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1 Introduction

This document introduces an uncertainty taxonomy for self-adaptive robotics, derived from research published in *IEEE Software* [1]. The taxonomy provides a common vocabulary and structured classification to describe where uncertainty arises, how it behaves, and how it impacts robotic systems and their stakeholders.

Section 2 presents an overview of the taxonomy dimensions that serve as the interpretive basis for the taxonomy. Following that, Section 3 presents the uncertainty taxonomy in tabular form. For each dimension, the tables enumerate covering aspects: identification methods, uncertainty sources, impacts, mitigation techniques, and uncertainty cases.

References

[1] Hassan Sartaj, Jalil Boudjadar, Mirgita Frasheri, Shaukat Ali, and Peter Gorm Larsen. "Identifying Uncertainty in Self-Adaptive Robotics with Large Language Models." *IEEE Software*, vol. 43, no. 1, pp. 89-97, Jan.-Feb. 2026, doi: 10.1109/MS.2025.3620578.

2 Taxonomy Dimensions Overview

Table 1 provides a concise description of each dimension of the uncertainty taxonomy.

Table 1: *Brief description of uncertainty taxonomy dimensions*

Dimension	Explanation	Example
Nature	How uncertainty behaves: Deterministic/Stochastic, Static/Dynamic.	Stochastic: Random sensor noise; Dynamic: Moving target.
Type	Nature of uncertainty: Aleatory (randomness) versus Epistemic (lack of knowledge).	Aleatory: Sensor noise; Epistemic: Incomplete map of the environment.
Stage	When uncertainty occurs: Design, Development, Testing, or Operation stages.	Design: Incomplete requirements; Operation: Real-time obstacle detection.
Temporal	Time characteristics: Short-Term/Transient and Long-Term/Persistent.	Short-Term: GPS signal loss; Long-Term: Sensor drift.
Context of Occurrence	Where uncertainty arises: Environmental, Task, Interaction, or Mission.	Environmental: Weather; Task: Unclear goals; Interaction: User input.
Source of Adaptation	Origin of adaptation: External (from environment) versus Internal (within the robot).	External: Changing environmental conditions; Internal: Hardware wear.
Scope	Where uncertainty impacts: Local/Global, Component/System Level.	Local: Single sensor; Global: Uncertainty affecting the entire robot.
Risk/Severity	How risky the uncertainty is: Low/High Risk.	High Risk: Uncertainty in braking during autonomous driving.
Affect	What is impacted: Performance, Safety, Adaptability, or Reliability.	Safety: Avoiding collisions; Performance: Task completion.
Propagation	How uncertainty spreads: Isolated versus Cascading.	Cascading: Localization error leading to path-planning errors.
Resolution	Approach to handling uncertainty: Reactive/Proactive, Manual/Automated.	Reactive: Robot reacts to obstacles; Proactive: Prediction models.
Data Characteristics	Nature of data: Incomplete, Ambiguous, or Noisy.	Noisy: Sensor data errors; Ambiguous: Misinterpreted readings.
Ethical Implications	Considerations for trust, transparency, bias, and fairness.	Bias: Incorrectly prioritizing users due to biased training data.

3 Uncertainty Taxonomy

Table 2 details uncertainty identification methods that are typically used for self-adaptive robots in both research and industry. Table 3 categorizes the common sources of uncertainties for self-adaptive robots, such as hardware failure and external factors like environment and human interaction. Table 4 outlines potential impacts of uncertainty on robotic systems, such as safety risks, reduced performance, and increased development complexity. Table 5 presents typical mitigation techniques used by industry practitioners and researchers in the field, such as adaptive planners and formal verification. Table 6 presents specific uncertainty cases/scenarios encountered by industry practitioners from four robotic use cases.

Table 2: *Uncertainty Identification Methods in Robotics*

Identification	Nature	Type	Stage	Temporal	Occurrence	Adaptation	Scope	Risk	Affect	Propagation	Data	Ethical
Hardware specifications	Static, Deterministic	Epistemic	Design	Long-term	Hardware	Internal	Local, Component	Low	Safety, Reliability	Isolated	Precise	Transparency
Assembling hardware parts	Static, Deterministic	Epistemic	Developmen	Short-term	Hardware, Environmental	Internal	Local, Component	Moderate	Performance Safety	Cascading	Ambiguous	Bias
Operations/ field testing	Dynamic, Stochastic	Aleatoric	Operational	Short-term	Environmenta Software	External	Global, System	High	Safety, Reliability	Cascading	Noisy	Fairness
Analyzing deviations from expected behavior	Dynamic, Stochastic	Epistemic	Testing	Long-term	Software	Internal	Global, System	High	Adaptability Performance	Cascading	Incomplete	Trust
Formal modeling with nondeterminism	Static, Deterministic	Epistemic	Design	Long-term	Software, Environmental	Internal	Global, System	High	Performance Adaptability	Isolated	Precise	Transparency
Intuition	Dynamic, Stochastic	Other	Design	Short-term	Environmenta	Internal	Local, Component	Moderate	Safety, Reliability	Isolated	Ambiguous	Bias
Proof of concept demonstration	Static, Deterministic	Aleatoric	Testing	Short-term	Hardware, Environmental	External	Local, Component	Low	Performance Safety	Isolated	Precise	Fairness
Component variations	Static, Deterministic	Aleatoric	Operational	Short-term	Hardware	External	Local, Component	Moderate	Reliability, Safety	Cascading	Noisy	Transparency
Sensor data analysis	Dynamic, Stochastic	Epistemic	Developmen	Short-term	Environmenta Hardware	Internal	Local, Component	High	Reliability, Safety	Cascading	Noisy	Trust

Table 3: *Common Sources of Uncertainty in Robotics*

Source	Nature	Type	Stage	Temporal	Occurrence	Adaptation	Scope	Risk	Affect	Propagation	Data	Ethical
Human Interaction Errors	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	High	Safety, Reliability	Cascading	Noisy	Transparency
Sensor Noise	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	Moderate	Reliability, Safety	Isolated	Noisy	Fairness
Actuator Noise	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	Moderate	Performance Safety	Isolated	Noisy	Fairness
Environment	Dynamic, Stochastic	Aleatoric	Operational	Long-Term	Global, System	External	Global, System	High	Adaptability Safety	Cascading	Ambiguous	Trust
Network Issues	Dynamic, Stochastic	Epistemic	Operational	Short-Term	Global, System	External	Global, System	High	Performance Safety	Cascading	Incomplete	Transparency
Hardware/ Mechanical Failure	Static, Deterministic	Aleatoric	Operational	Long-Term	Local, Component	Internal	Local, Component	High	Reliability, Safety	Cascading	Incomplete	Transparency
Frequent Software Updates	Dynamic, Stochastic	Epistemic	Developmen	Long-Term	Global, System	Internal	Global, System	Moderate	Adaptability Performance	Cascading	Ambiguous	Trust
Machine Learning Components	Dynamic, Stochastic	Epistemic	Design	Long-Term	Global, System	Internal	Global, System	High	Adaptability Reliability	Cascading	Ambiguous	Bias
System Integration	Static, Deterministic	Epistemic	Testing	Long-Term	Global, System	Internal	Global, System	High	Adaptability Safety	Cascading	Incomplete	Transparency
Mathematical Models and Parameter Inaccuracies	Static, Deterministic	Epistemic	Design	Long-Term	Local, Component	Internal	Local, Component	Moderate	Adaptability Performance	Isolated	Precise	Trust
Localization Issues	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	Moderate	Performance Safety	Cascading	Noisy	Fairness

Table 4: *Uncertainty Impacts in Robotics*

Impact	Nature	Type	Stage	Temporal	Occurrence	Adaptation	Scope	Risk	Affect	Propagation	Data	Ethical
Safety Risk	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Global, System	External	Global, System	High	Safety	Cascading	Noisy	Trust
Prediction Accuracy Suffers	Dynamic, Stochastic	Epistemic	Testing	Long-Term	Global, System	Internal	Global, System	High	Performance Reliability	Cascading	Ambiguous	Transparency
Adds Complexity	Dynamic, Stochastic	Epistemic	Design	Long-Term	Local, Component	Internal	Local, Component	Moderate	Performance	Isolated	Incomplete	Fairness
Unpredictable Behavior and Wrong Actions	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Global, System	External	Global, System	High	Safety, Reliability	Cascading	Noisy	Trust
Limit the Scope of Verification Activities	Static, Deterministic	Epistemic	Testing	Long-Term	Global, System	Internal	Global, System	Moderate	Reliability	Isolated	Precise	Transparency
Increase Cost and Development Time	Static, Deterministic	Epistemic	Developmen	Long-Term	Global, System	Internal	Global, System	Moderate	Performance	Isolated	Ambiguous	Fairness
Reduced Performance	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	Moderate	Performance	Cascading	Noisy	Trust
Need for Human Intervention and Reduced Autonomy	Dynamic, Stochastic	Epistemic	Operational	Long-Term	Global, System	Internal	Global, System	High	Reliability, Adaptability	Cascading	Incomplete	Transparency
Necessity for Frequent Machine Learning Model Training	Dynamic, Stochastic	Epistemic	Developmen	Long-Term	Global, System	Internal	Global, System	High	Reliability, Adaptability	Cascading	Ambiguous	Bias
Compromise Reliability	Dynamic, Stochastic	Epistemic	Operational	Short-Term	Global, System	Internal	Global, System	High	Reliability, Safety	Cascading	Noisy	Fairness
Affects Usability	Static, Deterministic	Epistemic	Design	Long-Term	Local, Component	Internal	Local, Component	Moderate	Usability	Isolated	Precise	Transparency

Table 5: *Typical Uncertainty Mitigation Techniques for Robotics*

Mitigation Technique	Nature	Type	Stage	Temporal	Occurrence	Adaptation	Scope	Risk	Affect	Propagation	Data	Ethical
Risk Assessment	Static, Deterministic	Epistemic	Design	Long-Term	Global, System	Internal	Global, System	High	Safety, Reliability	Cascading	Precise	Transparency
Failure Identification and Localization	Dynamic, Stochastic	Epistemic	Operational	Short-Term	Local, Component	Internal	Local, Component	High	Safety, Performance	Cascading	Noisy	Trust
Use Additional Data Sources	Dynamic, Stochastic	Epistemic	Developmen	Short-Term	Local, Component	External	Local, Component	Moderate	Reliability, Performance	Isolated	Ambiguous	Fairness
Probabilistic Modeling of Errors and Failures	Dynamic, Stochastic	Aleatoric	Design	Long-Term	Global, System	Internal	Global, System	High	Safety, Reliability	Cascading	Noisy	Transparency
Testing and Validation	Static, Deterministic	Epistemic	Testing	Long-Term	Global, System	Internal	Global, System	Moderate	Reliability, Performance	Cascading	Precise	Trust
Simulation and Digital Twins	Dynamic, Stochastic	Epistemic	Design	Long-Term	Global, System	Internal	Global, System	Moderate	Performance Adaptability	Cascading	Incomplete	Bias
Observers for Control and Continuous Monitoring	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	External	Local, Component	High	Safety, Adaptability	Cascading	Noisy	Transparency
Behavior Comparison	Static, Deterministic	Epistemic	Testing	Short-Term	Local, Component	Internal	Local, Component	Moderate	Reliability	Isolated	Precise	Fairness
Theorem Proving and Formal Verification	Static, Deterministic	Epistemic	Design	Long-Term	Global, System	Internal	Global, System	High	Safety, Reliability	Cascading	Precise	Transparency
Hardware Upgrade	Static, Deterministic	Aleatoric	Developmen	Long-Term	Local, Component	External	Local, Component	High	Performance Reliability	Cascading	Noisy	Fairness
Machine Learning and Data-Driven Methods	Dynamic, Stochastic	Epistemic	Developmen	Long-Term	Global, System	Internal	Global, System	High	Adaptability Performance	Cascading	Ambiguous	Trust
Task Isolation for Incremental Testing and Development	Static, Deterministic	Epistemic	Developmen	Short-term	Local, Component	Internal	Local, Component	Moderate	Performance	Isolated	Precise	Transparency
Plausibility Checks and Acceptance Testing	Static, Deterministic	Epistemic	Testing	Short-Term	Local, Component	Verified	Local, Component	Moderate	Reliability, Safety	Isolated	Specific	Responsibility
Sensor Fusion	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	Integrated	Local, Component	Moderate	Reliability, Safety	Medium	Real-time	Fairness
Adaptive Planners and Safety Systems	Dynamic, Stochastic	Epistemic	Operational	Long-Term	Global, System	Adaptive	Global, System	High	Safety, Adaptability	High	Dynamic	Accountability
Uncertainty Quantification	Static, Deterministic	Epistemic	Design	Long-Term	Global, System	Quantitative	Global, System	High	Reliability, Performance	Medium	Statistical	Transparency
Human Aware Navigation	Dynamic, Stochastic	Aleatoric	Operational	Short-Term	Local, Component	Responsive	Local, Component	High	Safety, Reliability	High	Context-aware	Ethics-Driven
Trustworthiness Verification	Static, Deterministic	Epistemic	Testing	Long-Term	Global, System	Verified	Global, System	High	Safety, Reliability	Low	Comprehens	Trust
Compliance with Safety Standards	Static, Deterministic	Epistemic	Design	Long-Term	Global, System	Standardized	Global, System	Moderate	Safety, Reliability	Low	Specific	Regulation
Software and Algorithms Upgrade	Static, Deterministic	Epistemic	Developmen	Long-Term	Local, Component	Upgradable	Local, Component	High	Performance Reliability	Medium	Modular	Adaptability

Table 6: *Robotic Uncertainty Cases*

Uncertainty Case	Nature	Type	Stage	Temporal	Occurrence	Adaptation	Scope	Risk	Affect	Propagation	Data	Ethical
Sensor Occlusion, Camera and LIDAR errors due to ambient or harsh light	Aleatoric	Operational	Dynamic, Stochastic	Short-Term	Local, Component	Limited	High	Reliability, Safety	Medium	Real-time	Verified	Privacy
Less Experienced Human Interaction	Aleatoric	Operational	Dynamic, Stochastic	Short-Term	Local, Component	Adaptive	Moderate	Safety, Reliability	Low	Context-aware	Reviewed	User-Centric
Object Miss Detection or Localization	Aleatoric	Testing	Dynamic, Stochastic	Short-Term	Local, Component	Specific	Moderate	Reliability, Performance	Medium	Statistical	Verified	Responsibility
Unexpected Navigation Behavior	Epistemic	Operational	Dynamic, Stochastic	Short-Term	Global, System	Adaptive	High	Safety, Adaptability	High	Dynamic	Compliant	Accountability
Extreme Environmental Conditions (slippery path, sea states, wind)	Aleatoric	Operational	Dynamic, Stochastic	Long-Term	Global, System	Predictive	High	Adaptabili Safety	High	Context-aware	Verified	Safety
Inaccuracies in Interactions with Objects	Aleatoric	Testing	Static, Deterministic	Short-Term	Local, Component	Limited	Moderate	Reliability, Performance	Low	Specific	Reviewed	Responsibility
Deviation from the Goal (E.g., move to undesired place)	Epistemic	Operational	Dynamic, Stochastic	Short-Term	Global, System	Adaptive	High	Performan Safety	High	Dynamic	Compliant	Safety
Interface Complexity	Epistemic	Design	Static, Deterministic	Long-Term	Local, Component	Standardized	Moderate	Usability	Low	Modular	Reviewed	User-Centric
Incorrect Parameters Usage and Misconfigurations	Epistemic	Developmen	Static, Deterministic	Long-Term	Local, Component	Verified	High	Reliability, Performance	Low	Modular	Compliant	Responsibility
Low Data Quality, Accuracy, and Precision	Epistemic	Developmen	Static, Deterministic	Long-Term	Local, Component	Verified	High	Reliability, Safety	Medium	Statistical	Reviewed	Data Integrity
Localization Drift and Errors	Aleatoric	Operational	Dynamic, Stochastic	Short-Term	Local, Component	Limited	Moderate	Performan Safety	Medium	Real-time	Verified	Safety
Unexpected Human Behavior	Aleatoric	Operational	Dynamic, Stochastic	Short-Term	Local, Component	Adaptive	High	Safety, Reliability	High	Context-aware	Reviewed	User-Centric
Self-collision	Aleatoric	Testing	Dynamic, Stochastic	Short-Term	Local, Component	Limited	Moderate	Safety	Low	Specific	Verified	Safety
Unexpected Sensor Malfunctions	Aleatoric	Operational	Dynamic, Stochastic	Short-Term	Local, Component	Predictive	High	Reliability, Safety	Medium	Real-time	Verified	Reliability
Transfer Learning Challenges	Epistemic	Developmen	Static, Deterministic	Long-Term	Global, System	Adaptive	High	Adaptabili Performance	High	Statistical	Reviewed	Fairness
Component Misalignment and Variability	Aleatoric	Developmen	Static, Deterministic	Short-Term	Local, Component	Limited	Moderate	Reliability, Performance	Medium	Modular	Verified	Responsibility