Autonomous Networks Summit Copenhagen 1:30pm - 3:30pm 19 June 2024

Towards Autonomous Network Level 4 – Marrying AI and Communication Networks

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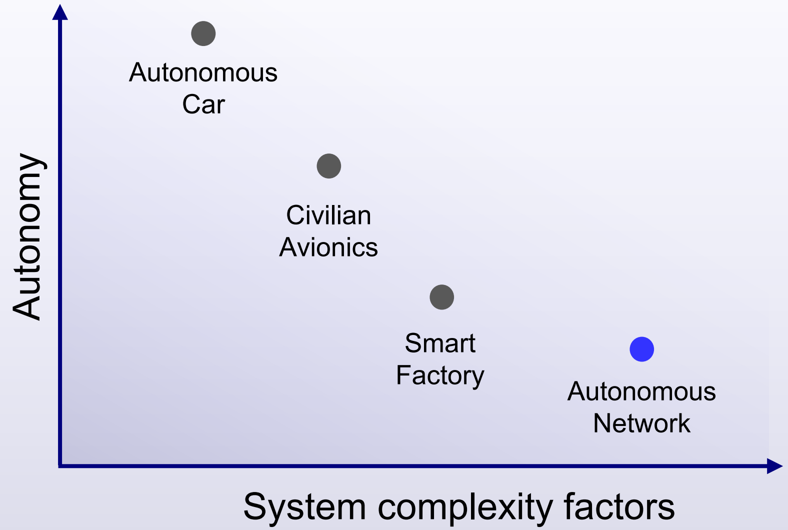
Autonomous Systems – Industrial Trends

Autonomous Systems

1. Are the ultimate stage in the evolution of AI.
2. Consist of agents each pursuing specific goals and coordinate to achieve global system goals.
3. Demonstrate situational awareness and adaptability in managing potentially conflicting goals



Technical Progress

Smart Sensor

Camera, mm-wave Radar, LiDAR, Airspeed sensor, Accelerometers, Gyroscope sensor, Barometric sensor

Prediction/Analysis Engines

Risk assessment, Customer churn prediction, Recommendation systems

Intelligent O&M support

Customer support chatbots, SLA report generation

Adoption by Industry

Autonomous Car:
ADAS(Automatic parking, Lane keep assistance)
→ ADS (Robotaxis)

Avionics:
Automatic flight control, Predictive maintenance
→ UAV, Autonomous flight, eVTOL.

Smart Factory :
Welding robot, transfer robot(AGV)
→ Collaborative robot(Cobot), Intelligent grasp robot

Autonomous Network:
Rule-based trouble RCA, Predictive calling abnormal detection
→ Autonomous network maintenance

1. Technical progress, such as smart sensors, prediction/analysis engines, and Intelligent O&M support, have rapidly improved the level of industrial autonomy.
2. The autonomous car sector is leading the way with AI-based end-to-end solutions, while progress in other sectors such as avionics, smart factories, and networks, is more gradual.
3. Current industrial trends are reinforced by the advent of generative AI, but obtaining trustworthiness guarantees remains an unavoidable and challenging objective.

Key Challenges and Technical Proposals for AN Level 4+

Key Challenges of Autonomous Networks

ANs are probably the most difficult systems to build, operate and maintain.

1. **Super complicated systems**:
   - Distributed multi-agent real-time systems
   - Highly dynamic, reconfigurable systems, never stop and evolve online;
   - Adapt to the constantly changing environments and user requirements – design-time vs. runtime correctness.

2. **Layered systems:**
   - Business, Service, Resource
   - Highly heterogeneous components: sensors, HW, servers to application SW and the Cloud.

Autonomous network levels

Level	L0	L1	L2	L3	L4	L5
Execution	P	P/S	S	S	S	S
Awareness	P	P	P/S	S	S	S
Analysis	P	P	P	P/S	S	S
Decision-making	P	P	P	P/S	S	S
Intent/Experience	P	P	P	P	P/S	S
Application scope	N/A	Specific scenarios				All

Key Technical Proposals for AN Level 4+

1. **AN agent reference architecture integrating (next slides)**

2. **Agent intelligence through knowledge development (next slides)**

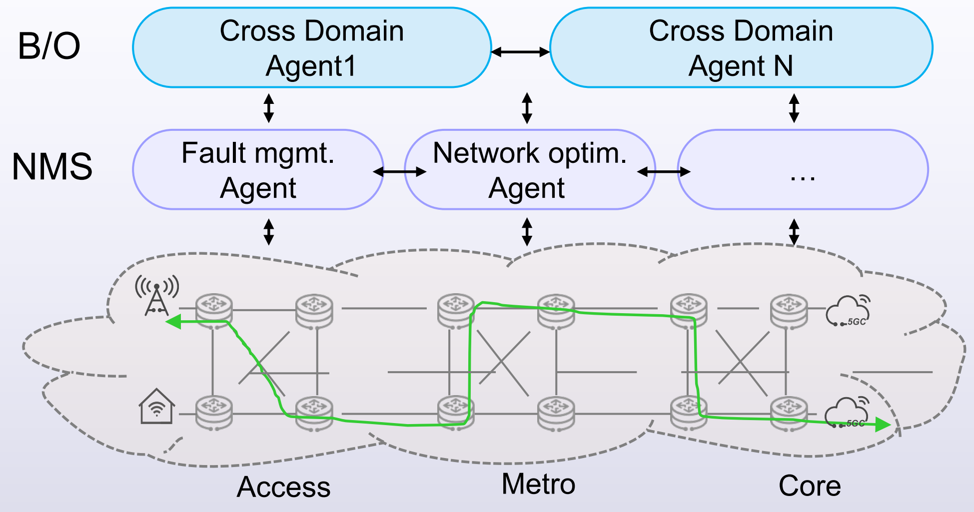
3. **Trustworthiness by striking the right balance: design-time/run-time correctness**
   - **Design-time:** ensure control for a given configuration and a set of goals concerning traffic management and self-healing in the event of foreseeable failures;
   - **Runt-time:** deal with intent and new goals for reconfiguration and adaptation to change.

4. **Collective intelligence though symbiotic interaction and collaboration**
   - **Agent interaction:** synthesize knowledge for global situation awareness;
   - **Consensus algorithms:** achieve optimal behavior with respect to given KPI's.

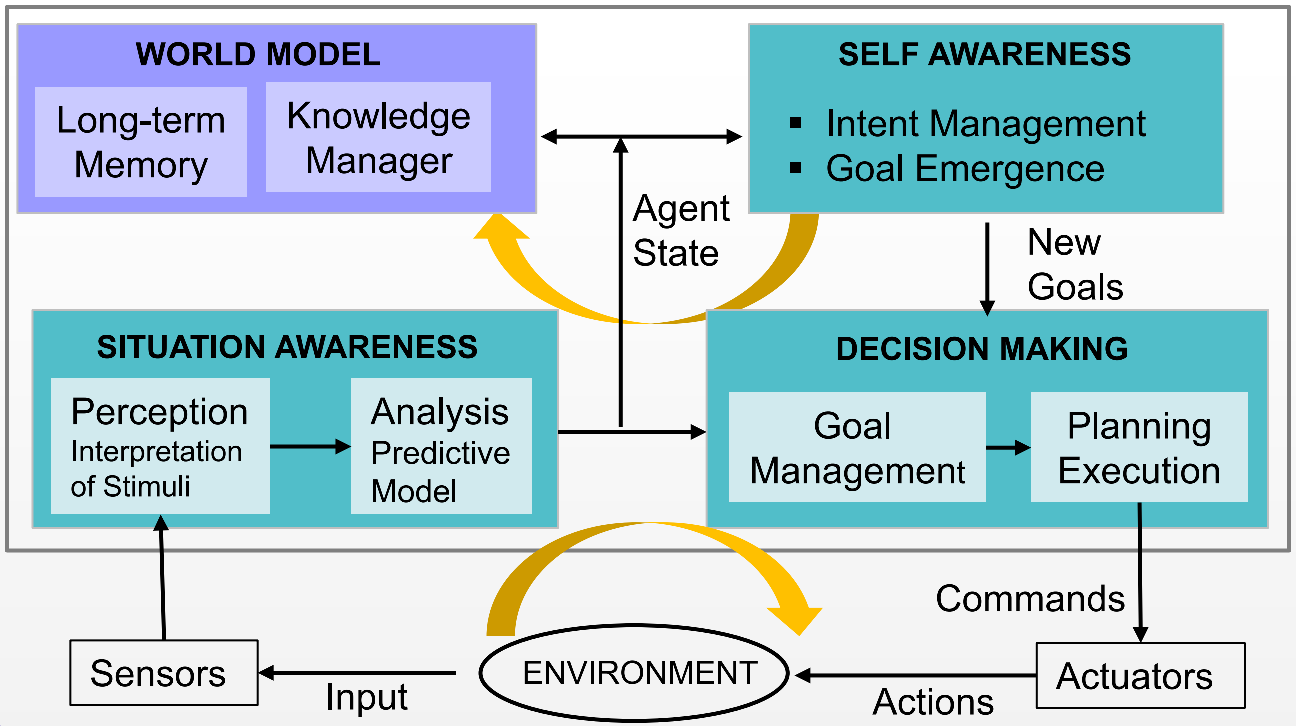
Proposal 1: AN Agent Reference Architecture

Multi-agent autonomous system

1. Multiple agents exist in the autonomous network
2. A single agent should enable autonomous closed-loop (see right)
3. A multi-agent system should enable agents to interact east-west and south-north



Agent reference architecture

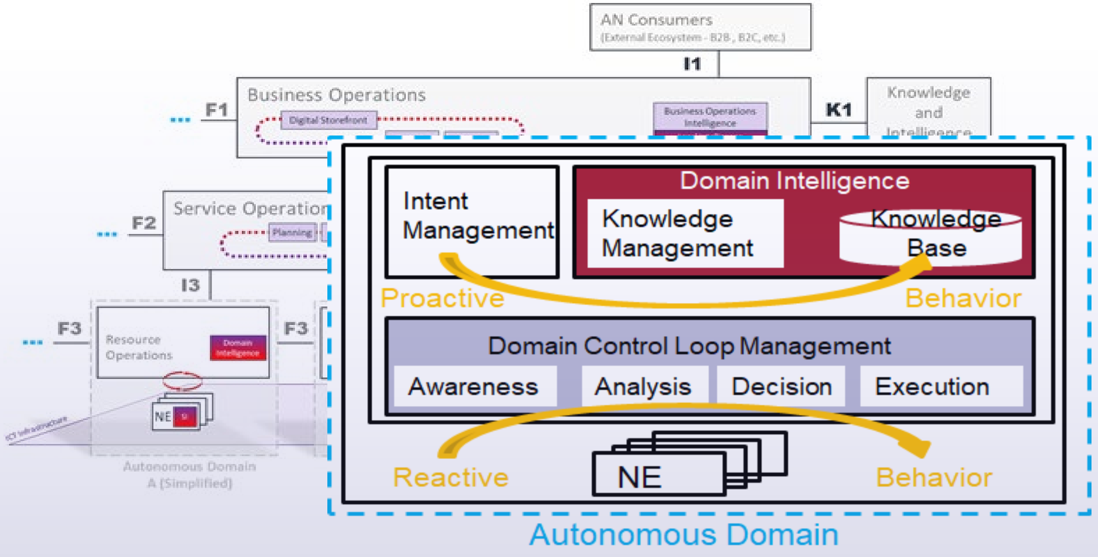


Key technical issues:

1. **Hybrid Architecture**: seamless integration of traditional ICT components and AI components
2. **Complexities**
   - **Complexity of perception**: difficulty to interpret stimuli (ambiguity, vagueness) to timely generate a corresponding percept.
   - **Complexity of uncertainty:** lack of predictability about the environment with dynamic changes caused by physical or human processes
   - **Complexity of decision:** impacted by factors such as the diversity of goals and the size of the space of solutions for planning.
3. **Knowledge-based self-awareness and adaptation:** using stored and generated knowledge to manage Intent and adapt pursuing new goals.

Proposal 1: AN Agent Reference Architecture

TM Forum IG1251 AN Reference Architecture



❶ **Reactive + Proactive:** Human-like Fast-Slow thinking mode

a. **Reactive behavior**: FAST, Automated
- ensuring control of the network for given configuration and set of goals
- traffic management and self-healing for predictable failures

b. **Proactive behavior**: SLOW, Reasoned
- involving the emergence of new goals with possible human intervention assisted by knowledge managers and validation tools
- reconfiguration and adaptation to any kind of hazard.

❷ **Goal-driven behavior:** combining reachability and safety properties.

IP BGP Goal and Properties:

a. *Goal definition - property: No network address transmitted from R2 to ISP2 should originate at ISP1 and R1,R2 should receive the network address from ISP1.*

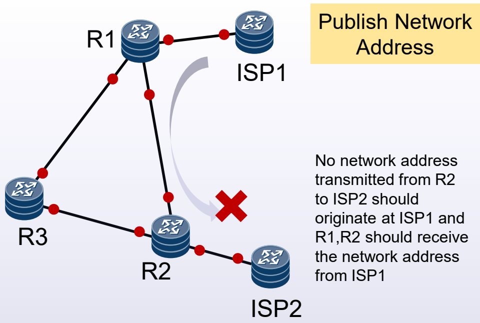
b. *➔ Goal formulation: exit(R1)&¬from(ISP1)*

c. *➔ Goal decomposition:*
   - I. *from(ISP1) to (R3) with comm(100:1)*
   - II. *from(R1) to (ISP2) with comm(100:1) & (reject(R1.out) || reject(ISP2.in))*
   - III. *…*

d. *➔ Goal conflict detection: …*

e. *➔ Goal-based close loop: …*

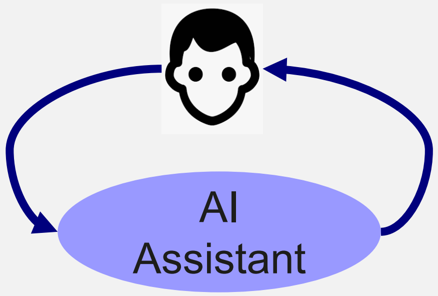
f. *……*

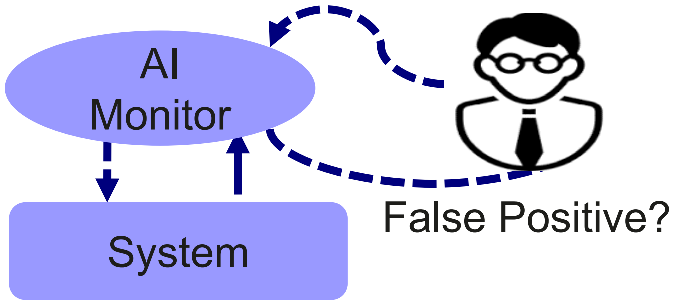


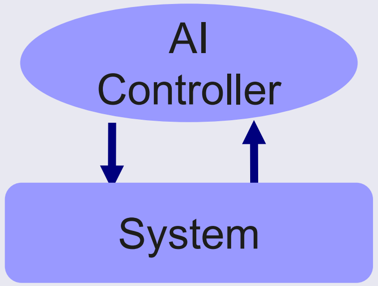
Example: IP Network Goal and associated properties

Architectural trends for AN L4+			
AN Architecture	**Current**	**AN L4+**	**Purpose**
Autonomy level	Reactive	❶ **Reactive + Proactive**	1. Closed-loop automation 2. Intent-driven emergence of goals relying on endogenous intelligence
Granularity of Decision Making	Function	❷ **Goal**	Adaptation to dynamic environments and tasks

Proposal 2: Agent Intelligence – Four Different Uses for AN







	1. Conversation	2. Analysis	3. Prediction	4. Autonomy
Purpose	Human machine Interaction	continuously monitor a system and analyze its behavior	continuously monitor a system and predict situations of interest in its behavior	interact with environment showing awareness and acting in order to achieve goals
Technologies	Generative AI (LLMs)	Traditional ML or rule-based systems (Symbolic)	Traditional ML or rule-based systems.	mixture of different types of AI.
Scenarios	Human intent input, SLA report generation	RCA (root cause analyses), causal clustering and detection of relevant situations (classification, recommendation)	prediction of potential safety or security issues and of performance variations	decision making and action control to replace humans operators

The four uses will coexist for long time: providing complementary services, such as identifying and predicting key status and committing network configuration/transfer behavior.

Proposal 2: Agent Intelligence – Trends in Agent AI

a. Move from monolithic E2E models to architectures with World Models

- to estimate missing information about the state of the world not provided by perception;
- to predict plausible future states of the world.

b. Linking ML and symbolic computation is essential to achieve autonomous AI

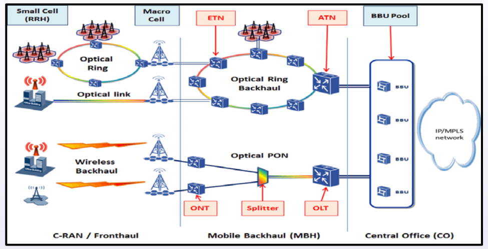
- **Approach 1**: symbolic computation can emerge from learning with increasingly powerful machines (“scale is all you need!”).
- **Approach 2**: symbolic reasoning must be hard-coded from the outset, e.g. neurosymbolic techniques.

c. LLMs are not enough: linking to domain specific knowledge for accuracy and predictive power

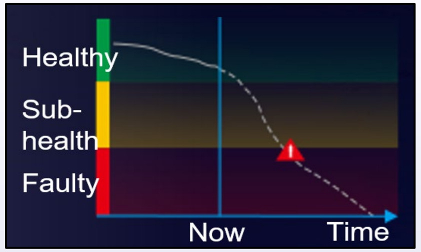
- LLMs grounded to symbolic engines such as AlphaGeometry, WolframAlpha, simulators, probabilistic programming tools…
- LLMs use World Models stored in long-term memory, e.g. Retrieval-Augmented Generation (RAG).

AN World Models

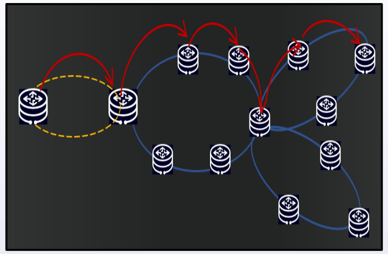
General Knowledge: Scientific&Technical, Concepts and Ontologies, Methods.
Specific Knowledge: Agent’s Internal State, Resources, Actions, ODD, Rules, Value System, Value Scales .



Conceptual model: Network topology with links between NEs and roles

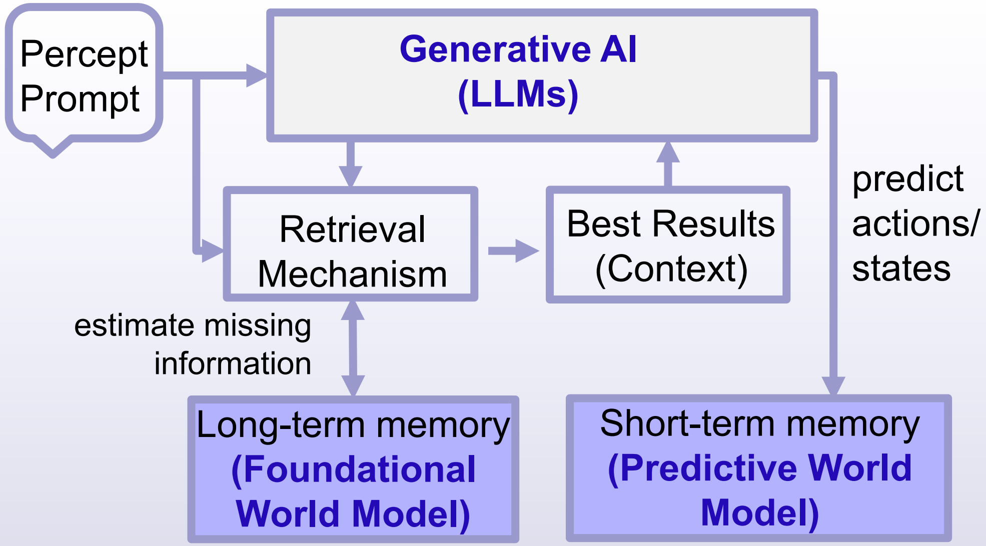


Spatial-temporal model: fiber subhealth prediction model



Domain-specific Rules: IP BGP configuration rules

RAG Architecture integrating an LLM & World Models

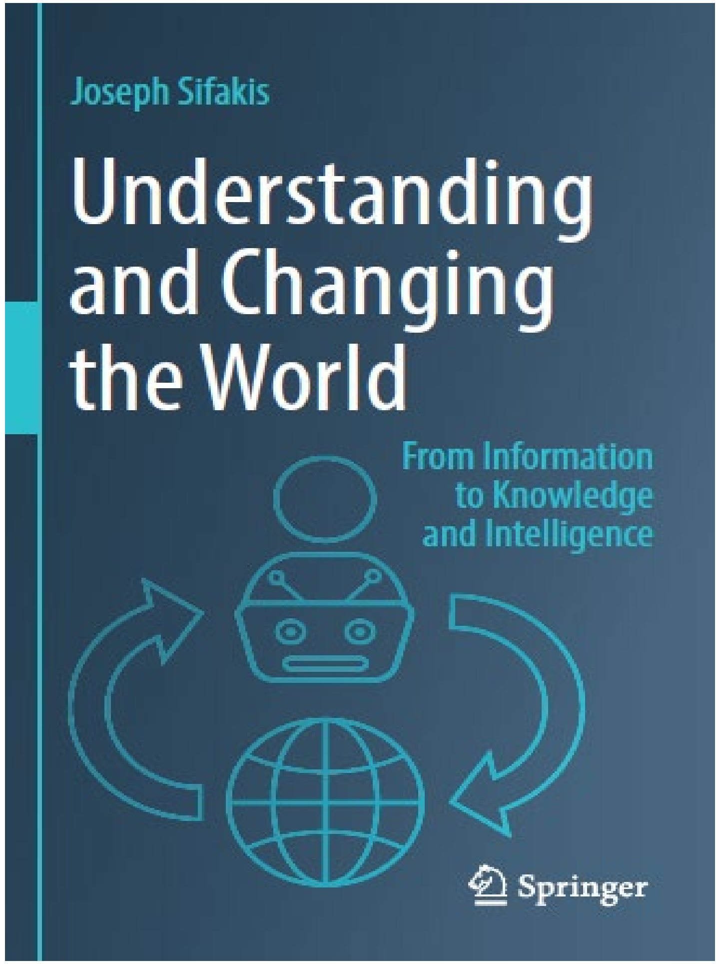


Toward AN L4 – Takeaways

AN Evolution Steps	AN Assistant (Now)	AN Agent (for Autonomous Domain)	AN Multi-Agent (for Network E2E)	AN self-learning&optimization (AN L5)

- **The AI industry revolution has only just begun! Reaching the AN vision depends largely on our ability**
  - To bridge the gap between traditional model-based engineering flows and data-based system development.
  - To cover the whole spectrum of needs, from conversational to predictive, analytical and autonomous AI components.
  - To assess, predict and guarantee trustworthiness of solutions.
- **Develop domain-specific AI infrastructure, components and tools, which are sorely lacking**
  - Specific common data infrastructure and technology: for identifying the necessary data, ensuring that it is clean, well labelled and enriched with relevant meta-data.
  - Methods for building accurate AI models that are statistically compliant with their training data sets.
  - RAG solutions integrating LLMs or SLMs to enhance their robustness and precision.
  - World Models encompassing knowledge complementary to that provided by LLMs.
- **Hybrid trustworthy reference architectures**
  - Seeking trade-offs between traditional and AI components
  - Striking the right balance between correctness at design time and runtime assurance techniques
  - Seamlessly integrating reactive closed loop behavior and proactive intent-driven behavior
  - Cognitive self-adaptation through knowledge-based decision making and optimization
- **Trustworthy and cost-effective AN operation through interoperability, connectivity and distributed intelligence**
  - Domain-specific framework for Human-Network NLP interoperation
  - Global situation awareness by synthesising knowledge through agent interaction
  - Consensus decision-making algorithms targeting key performance indicators.

Publications on Autonomous Systems



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2. Joseph Sifakis. System Design in the Era of IoT— Meeting the Autonomy Challenge, Methods and Tools for Rigorous System Design (MeTRiD 2018), EPTCS 272, 2018, pp. 1–22, doi:10.4204/EPTCS.272.1.
3. Joseph Sifakis. Can We Trust Autonomous Systems? Boundaries and Risks, ATVA, 2029, LNCS 11781, pp. 1–14, 2019. https://doi.org/10.1007/978-3-030-31784-3_4.
4. David Harel, Assaf Marron, Joseph Sifakis. Autonomics: In Search of a Foundation for Next Generation Autonomous Systems. PNAS, July 21, 2020, 117 (30) 17491-17498, https://doi.org/10.1073/pnas.2003162117
5. Joseph Sifakis David Harel. Trustworthy Autonomous System Development. ACM Transactions on Embedded Computing Systems, Volume 22,Issue 3, Article No.: 40, pp 1-24, April 2023, https://doi.org/10.1145/3545178
6. Joseph Sifakis. Testing System Intelligence. https://arxiv.org/abs/2305.11472, August 2023.

Thank You!