Autonomous Systems Taxonomy

NASA Autonomous Systems Capability Leadership Team (AS-CLT)

The purpose of this taxonomy is to provide common definitions and a functional decomposition of the technology that is required for NASA's autonomous systems. The taxonomy serves as a framework for: (1) assessing the state of NASA's autonomous systems capability (workforce, technology, etc.) and (2) assessing the state of the art in autonomy technology. The taxonomy will be reviewed and updated as needed by the AS-CLT.

Definitions

- **Autonomy** is the ability of a *system* to achieve goals while operating independently of external control [NASA Technology Roadmaps, TA 4: Robotics and Autonomous Systems, 2015]. Autonomy is not the same as artificial intelligence (AI), but may make use of AI methods. Autonomy is not the same as automation, but often relies on automation as a building block.
- A **system** is the combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. [NASA Systems Engineering Handbook, NASA SP-2016-6105 Rev 2]. An *autonomous system* may involve any combination of elements (e.g., humans and machines) and is not limited to "unmanned capability."
- **Autonomy technology** consists of the elements and methods required to build, test, certify, and operate an autonomous system. The purpose of autonomy technology is not primarily about making a system adaptive, intelligent, or "smart," but rather to enable a system to achieve goals while operating independently of external control.

Notes

- The order of Level 1 and 2 categories does not imply priority or importance.
- The use of common terms (e.g., "static analysis") does not imply that the taxonomy fully encompasses a particular domain, field, or technology. If not explicitly stated, common terms should be understood to apply only in the context of autonomous systems (e.g., "static analysis for autonomous systems").
- The taxonomy is understood to apply to both single and multiple assets.
- Many autonomous capabilities require multiple Level 2 categories. For example, autonomous surface navigation may include use of sensing and perception (1.1), state estimation and monitoring (1.2), knowledge and model building (1.3), hazard assessment (1.4), motion planning (2.3), and execution and control (2.4). System health management may similarly make use of sensing and perception (1.1), state estimation and monitoring (1.2), knowledge and model building (1.3), event and trend identification (1.5), anomaly detection (1.6), fault diagnosis and prognosis (2.5), and fault response (2.6).

1.0 Situation and Self Awareness	2.0 Reasoning and Acting	3.0 Collaboration and Interaction	4.0 Engineering and Integrity
1.1 Sensing and Perception	2.1 Mission Planning and Scheduling	3.1 Joint Knowledge and Understanding	4.1 Verification and Validation
1.2 State Estimation and Monitoring	2.2 Activity and Resource Planning and Scheduling	3.2 Behavior and Intent Prediction	4.2 Test and Evaluation
1.3 Knowledge and Model Building	2.3 Motion Planning	3.3 Goal and Task Negotiation	4.3 Operational Assurance
1.4 Hazard Assessment	2.4 Execution and Control	3.4 Operational Trust Building	4.4 Modeling and Simulation
1.5 Event and Trend Identification	2.5 Fault Diagnosis and Prognosis		4.5 Architecture and Design
1.6 Anomaly Detection	2.6 Fault Response		
	2.7 Learning and Adapting		

1.0 Situation and Self Awareness	Interrogation, identification, and evaluation of both the state of the environment and the state of the system.	**Challenges:** • Data fusion from heterogeneous sensors with varying uncertainties • Multi-rate asynchronous sensor-data sources • Interpretation and abstraction of knowledge from raw, noisy and potentially faulty data • Computational resources and storage for managing large data streams • Information from multiple and potentially some non-cooperative assets
1.1 Sensing and Perception	Collection and processing of information internal and external to the system from sensors and instruments.	**Examples:** • Three-dimensional sensing and perception from stereo vision or LIDARs • Force and tactile sensing • Science-instrument sensing (e.g. spectrometers) that is eventually used in decision-making • Tools that assess data validity and manage uncertainty • System-health and housekeeping sensors • Space-suit sensors that track astronauts' motions

1.2 State Estimation and Monitoring	Estimation of internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.	**Examples:** • Pose estimation for a rover • Pose estimation for an in-space robotic-assembly arm • Velocity estimation for an aerial vehicle • Oxygen-level estimation and monitoring • Battery health-state estimation • Wind-speed estimation for a balloon explorer *(see also 2.5)*
1.3 Knowledge and Model Building	Creation of information sources about the environment or the system from sensing, perception and human interaction that can be queried.	**Examples:** • Fusion of multi-sensor data over time to generate physical or dynamical models of the system or environment. • Topographic mapping of a planetary surface from multiple surface and/or near-surface assets • Atmospheric-modeling for aerial mobility • Ontologies for natural-language processing • Ontologies for object manipulation
1.4 Hazard Assessment	Evaluation of whether the state of the environment, the state of the system, and/or their interaction pose a threat to the safety of actions (or inactions) that are contemplated, which could compromise the system or mission.	**Examples:** • Terrain hazard assessment for spacecraft planetary-landing • Traversability analysis for surface mobility • Collision-risk assessment of aerial mobility • Safety-assessment for a life-support system *(see also 2.5)*

1.5 Event and Trend Identification	Analyses of data (about environment or system) to identify events and trends that may affect future state, operations, or decision-making.	**Examples:** • Characterization of system performance • Prediction of weather events • Prediction of air-traffic • Science data analytics for decision making *(see also 1.6, 2.5)*
1.6 Anomaly Detection	Determination that the environment or system does not exhibit expected characteristics.	**Examples:** • Detection of abnormal behavior in a component or subsystem • Identification of a weather anomaly • Identification of excessive rover sinkage in loose sandy terrain *(see also 1.5, 2.5)*

2.0 Reasoning and Acting	Analysis and evaluation of situations (present, future or past) for decision making and for directing actions to achieve a goal or a mission.	**Challenges:** • Appropriately and robustly responding in the presence of uncertainties and faults. • Reasoning across strategic (mission) and tactical (activity) timescales. • Providing theoretical guarantees and trade-offs between completeness / optimality and response time. • Synchronization among reasoning components that have different latency or response times. • Integration of planning, execution, control and system health management. • Integration of continuous-time (e.g. motion planning) and discrete-time domain (activity planning) technologies. • Development of approaches that are compatible with the processing characteristics (CPU, memory, architecture, etc) of flight processors. • Presenting alternatives and recommendations to humans. • Taking input from humans (new constraints, request for alternatives, what-ifs).

2.1 Mission Planning and Scheduling	Selection of goals, objectives and activities to achieve a mission, subject to the situation, and constraints.	**Examples:** • Selection of science observations (e.g. for satellites and UAVs) • Replanning / rescheduling after unexpected event (e.g. opportunistic science, responding to changing weather conditions) • Replanning / rescheduling after system fault (e.g. choosing new observation after instrument fails, choosing new objectives after mechanical system fault limits motion, etc.) • Mixed initiative planning/scheduling of human spacecraft activities *(see also 2.2, 2.3, 3.3)*
2.2 Activity and Resource Planning and Scheduling	Selection and ordering of activities to be performed while managing system resources to achieve mission goals.	**Examples:** • Power / energy consumption and production planning / scheduling • Planning / scheduling given constraints, such as fuel, life support system consumables (air, water), spacecraft memory, communication link (availability, bandwidth, latency), etc. • Planning / scheduling given consumables for science ops (e.g. # of sample containers) • Mixed initiative planning/scheduling of human spacecraft activities • Piloted aircraft decision support *(see also 2.1, 3.3)*

2.3 Motion Planning	Generation or modification of a path or trajectory to reach a desired target physical location or configuration subject to system and environment constraints.	**Examples:** • Robotic arm/manipulator kinematics/dynamic planning • Robot surface motion planning • Spacecraft attitude / trajectory planning • Aircraft path planning *(see also 2.1)*
2.4 Execution and Control	Change of system state to meet mission goals and objectives, according to a plan or schedule, subject to control authority and permission, and based on mission phase, environment or system state.	**Examples:** • Reactive control (e.g. aircraft see-and-avoid, rover hazard avoidance, fault response). • Discrete control / scripting / mode control. • Contingent control (e.g. integration of fault management and planning/scheduling) • Subsystem procedure and automation control and situational awareness for human operator. *(see also 1.2, 1.4, 2.2, 2.3, 2.5, 4.5)*
2.5 Fault Diagnosis and Prognosis	Identification of faults, prediction of future faults, and assessment of system capability as a consequence of those faults.	**Examples:** • UAV / Spacecraft battery prognostics • Structural health monitoring • Spacecraft control moment gyro monitoring • Cryogenic storage leak detection (internal/external). • Aircraft engine health monitoring *(see also 1.2, 1.5, 1.6)*

2.6 Fault Response	Restoration of nominal or best possible system configuration and operations after a fault.	**Examples:** • Spacecraft fault impacts reasoning • Power system reconfiguration • Life-support system reconfiguration • Robot arm reconfiguration • Aircraft emergency landing planner *(see also 2.1)*
2.7 Learning and Adapting	Adapting to changing environments and conditions without explicit re-programming using knowledge collected from the past, or from other systems' experiences.	**Examples:** • Learning planning/scheduling models • Learning fault models • Learning anomalies *(see also 1.2, 1.5, 1.6, 4.1, 4.3)*

3.0 Collaboration and Interaction	Two or more elements or systems working together to achieve a defined outcome.	**Challenges:** • Acquisition of adequate data needed for understanding collaboration • Integration of information across activities and elements • Understanding of collaboration and interaction requirements for mixed initiative systems • Coding of collaboration information requirements • Prognostics data acquisition and analysis • Human-machine interfaces, particularly for complex, non-deterministic systems • Understanding of communication across different modalities (e.g. gestures) • Limited bandwidth for collaboration that requires sharing of large data • Response prediction and limitations for alerting and interaction • Predicting activities and estimating confidence across activities and elements • Prediction of precursors for rare events
3.1 Joint Knowledge and Understanding	Collection, assembly, sharing, and interpretation of information and intent among elements to solve problems and plan actions/responses.	**Examples:** • Management of aircraft and spacecraft fault diagnostic and prognostics • Speech recognition interfaces (including non-verbal attributes such as prosody) for aircraft flight management • Integration of information across activities and systems

3.2 Behavior and Intent Prediction	Forecasting the actions of other elements or systems to support collaboration and interaction.	**Examples:** • Workload estimation across mixed initiative systems • Integration of information for prognostic system prediction • Response prediction and limitations for alerting and interaction (e.g. aircraft "Detect And Avoid" alerting) • Confidence estimation for predictions across activities and elements (e.g. weather events) • Prediction for precursors for rare events
3.3 Goal and Task Negotiation	Agreement on current and future activities, their priorities, and their disposition among elements or systems.	**Examples:** • Space mission planning systems • Airline Operations Center (also known as Airline Operations Control Center) *(see also 2.1)*
3.4 Operational Trust Building	Assurance that the system is operating in a manner consistent with expectations of all elements.	**Examples:** • Aircraft Flight Mode Annunciators (FMA) • Aircraft navigation performance monitoring

4.0 Engineering and Integrity	Design considerations, processes, and properties necessary to implement autonomy.	**Challenges:** • Characterizing system behavior when the operating environment is largely unknown and/or the system can adapt to its surroundings during operations. • Distinguishing between incipient faults and slow degradation in system performance. • Architecting and assessing complex interactions between humans and machines. • Adjusting engineering methodologies to support increases in numbers, capabilities, and complexity.
4.1 Verification and Validation	Determination that an autonomous system meets the requirements (verification) and fulfills its intended purpose (validation).	**Examples:** • Scalable formal methods for adaptive and uncertain systems (i.e., model checking, theorem proving, static analysis) • Model validation frameworks • Work analysis and operations concepts for autonomous behaviors • Uncertainty propagation analysis
4.2 Test and Evaluation	Characterization of autonomous system functionality and capabilities.	**Examples:** • Automated systems testing • Model-based testing and accreditation • Statistical edge-case testing approaches • Non-destructive testing • Testbeds for assessment of autonomous systems in laboratory and operational settings.

4.3 Operational Assurance	Confirmation, before or during operations, that an autonomous system is operating safely, efficiently, and in a manner that does not adversely affect the operation of other systems.	**Examples:** • Runtime monitoring • Certifications for adaptive systems • Model invalidation • Operational approval method for complex integrated systems • Risk management approaches
4.4 Modeling and Simulation	Representation of an autonomous system and/or its operation for use in system design, evaluation, or operational assessment.	**Examples:** • Monte Carlo techniques • Immersive environments • Standardized simulation infrastructure and frameworks • Model-Based Systems Engineering
4.5 Architecture and Design	Methods and tools for system composition and development that promote the existence and support the assessment of attributes of the system, such as performance, resilience, robustness, scalability, safety, and reliability.	**Examples:** • Correct-by-design controller synthesis • Scalable frameworks • Contract-based design • Fault-tolerant design • Distributed communications infrastructure

Change Log

Change Number	Date	Description
1	2018-04-26	Initial release