THE CHALLENGES OF BUILDING TRULY ROBUST ROBOTIC AUTONOMY - DEFINING THE LEVELS OF AERIAL AUTONOMY

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Exyn Technologies presents a framework for Levels of Aerial Autonomy based upon the SAE Levels of Driving Automation in order to better define technical capabilities, maturity, and risks. Presented are definitions and a taxonomy for Aerial Autonomy which is used to map operator and aerial system capabilities to a discrete levels.

INTRODUCTION

Autonomy is the ability to think for yourself and be self reliant - the capacity of self-governance or self-determination. There are different arenas of autonomy, but the one we're most concerned with is personal autonomy -- the capacity to decide for oneself and pursue a course of action in one's life. That's ultimately what we're trying to achieve through our work in autonomous robotics: to create an artificial intelligence platform that can operate a robot in dangerous environments, complete multiple operations successfully, and take care of itself with minimal or no human interaction.

With Driverless Automation pushing into Level 4 and aiming toward Level 5, we were getting questions about our robot's level of autonomy and found we were lacking a clear set of guidelines on what classifies as Aerial Autonomy and defining the levels therein. Work has already been done around classifying autonomy for Unmanned Aerial Vehicles. But in its current state, aerial autonomy is placing the pilot further out of the loop, but still an essential element to operation, and we find the available level classifications inadequate. Additionally, it is becoming increasingly important for UAVs to fly beyond the operator's visual line of sight (BVLOS) for industrial applications, search & rescue missions, and Intelligence, Surveillance and Reconnaissance (ISR) for government operations. Level 4 & 5 autonomy is crucial for these applications to be successful.

PROBLEMS

Current Disjointed Level Definitions

Aspects of aerial autonomy have been siloed in individual organizations since their inception, creating their autonomy in a vacuum. As you'll see in the resources listed at the end of the submission, the problem of defining aerial autonomy has been discussed since ~2002, with each new iteration adding more straw to the pile. And while we acknowledge this is yet another level definition

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added to that pile, we aim to bring these together cohesively and have the larger UAV community collaborate and agree to them as an industry.

Defining Environmental Complexity

One of the biggest challenges we face when trying to classify levels of autonomy for aerial robots is nailing down what environment they will be able to fly in. Much like a self driving car, a robot can appear to be operating at quite a high level of autonomy if the environment is built to specific robot sensors or capabilities. This isn't so much an issue in the early stages of autonomy, but making steps through Level 4 and Level 5 autonomy will require clearer definitions to prevent false claims using a dubious setup.

Infrastructure

Driverless autonomy is built around road infrastructure that is ubiquitous around the world. Due to assumptions that come along with having such infrastructure (in this case, a largely known and mappable road network) the problem becomes much more tractable. The complexity of environments for aerial robots are generally less well defined, making it much more difficult to prepare an Autonomous Aerial Robot for every eventuality. Current aerial infrastructure includes air traffic control, airspace classifications, air corridors, altitude restrictions, FAA regulations, etc. However those mainly apply to high-altitude aircraft, whereas drones and UAVs might fly underground, throughout an urban environment, or only as high as a general electric tower for inspection (for example).

Rotor vs Fixed Wing

Autonomy, in the form of an auto-pilot, has been an aspect of fixed wing flight for quite some time. While the work we're doing deals mainly with multi-rotor flight -- a type of vertical take-off and landing aircraft -- we have to include fixed-wing in these levels for completeness.

AUTONOMY VS. AUTOMATION

Both terms are thrown around interchangeably, but in reality they are two completely different things. Automation has been around for quite some time, and corresponds to a machine performing a programmed action. For example, autopilot on a commercial airliner. It instructs the aircraft to stay on a chosen course and altitude but a pilot must be present to monitor a variety of other conditions to achieve a successful flight and landing.

Autonomy means that the system has choices to make free of outside influence. Current autopilot systems cannot detect approaching objects or storms and determine the safest and most efficient course to the destination. Future UAVs must be able to think and act on their own without human intervention to be cost effective at scale.

If we look at SAE's Levels of Driving Automation[1], we can see increasing levels of autonomy. At each level, the driver can remove themselves more and more from immediate actions and instead rely on the robot's best judgment.

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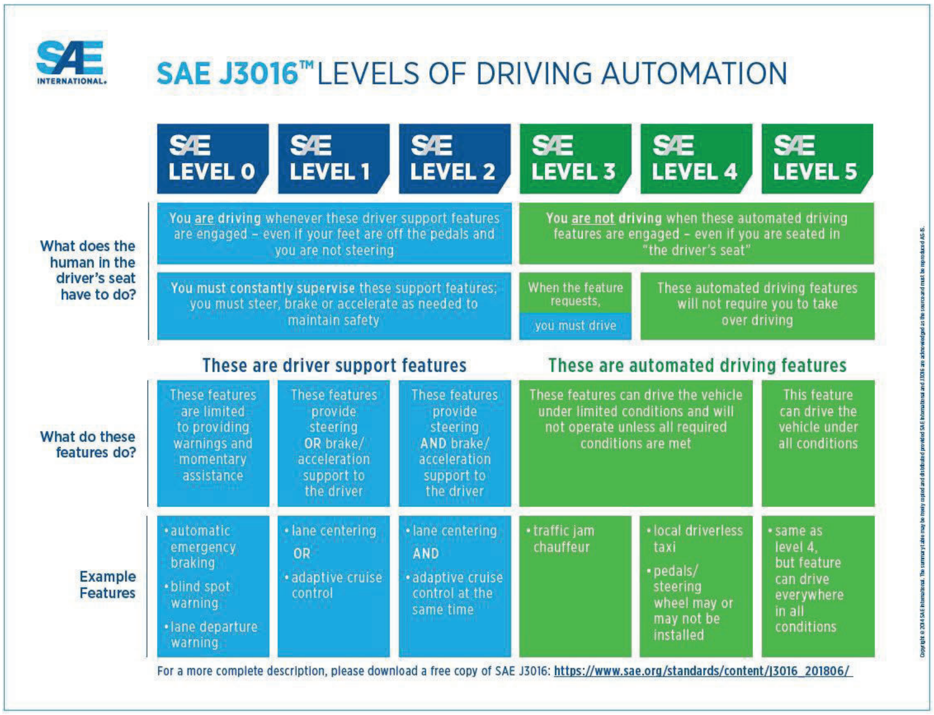

Figure 1. SAE J3016 Levels of Driving Automation

WHAT DOES TRUE AERIAL AUTONOMY LOOK LIKE?

- The robot must be aware of its own sensors and state (operational integrity)
- Decides to launch / complete a mission dependant on the health of the robot
- The robot must sense and react to its environment without human assistance
- The robot must perform its mission successfully without human assistance
- The robot must be able to replicate a successful mission without human assistance
- The robot must be able to keep itself out of harmful situations unless designed otherwise
- More advanced levels of autonomy would feature the robot foraging for its own food (energy) and spare parts, maintaining its operational integrity
- Above everything else, the robot must keep people safe, and sacrifice itself for their safety

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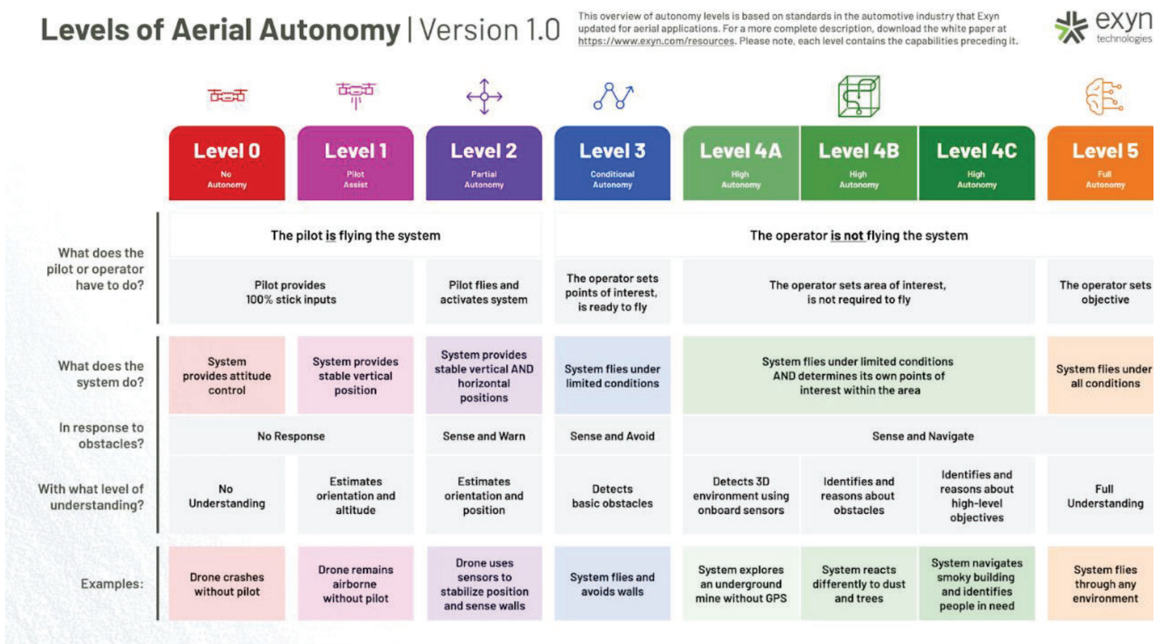

Figure 2. Proposed Levels of Aerial Autonomy

CREATING LEVEL DEFINITIONS AND TAXONOMY FOR AERIAL AUTONOMY

These level definitions, along with additional supporting terms and definitions provided herein, can be used to describe the full range of aerial automation features equipped on airborne vehicles in a functionally consistent and coherent manner.

Table 1. Terms and Definitions

Term	Definition
What is an Operator?	• A general term for referencing the human role in aerial automation
What is an Aerial Vehicle?	• Any vehicle designed to be flown by a pilot or dispatched through an autonomous system • A machine designed to provide conveyance through the air
What is an Aerial Autonomy System (AAS)?	• The hardware and software that are collectively capable of performing part or all of the Dynamic Flight Task (DFT) on a sustained basis; this term is used generically to describe any system capable of level 1-5 aerial autonomy.

What is DFT (Dynamic Flight Task)?	• All of the real-time operational and tactical functions required to operate an aerial vehicle, excluding the strategic functions such as trip scheduling and selection of destination and waypoints, and including without limitation: o Autoflight & hover motion control via rotors (operational); o Yaw, pitch and roll motion control via IMU & rotors (operational); o Monitoring the environment via object and event detection, recognition, classification, and response preparation (operational and tactical); o Object and event response execution (operational and tactical); o Maneuver planning (operational)
What is ODD (Operational Design Domain)? Autonomous Understanding & Reasoning (AUR A, B, C)	• Operational conditions under which a given aerial autonomy system or feature is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain landscape characteristics o Examples ▪ A UAV designed to inspect electrical infrastructure will be bounded to only fly along the electrical grid ▪ A UAV in the mining industry will only map tunnels and shafts when not in use, recharging during operating hours • Autonomy Levels 4 & 5 will require further definitions of the complexities of their environment and at what level the autonomous system can sense and navigate accordingly. Rather than ranking the environmental factors a UAV will need to overcome (light, dust, wind, etc.), complexity will be ranked by how the autonomous system interprets and overcomes obstacles these various environments present. o Examples ▪ A UAV can sense and avoid dynamic obstacles (AUR A) ▪ A UAV can determine an obstacle is dust and fly through it (AUR B) ▪ A UAV can interpret obstacles and use that information to plan aspects of its mission (AUR C)
What is DFT fallback?	• A response by the operator to either perform the DFT or achieve a minimal risk condition after occurrence of a DFT performance-related system failure(s) or upon ODD exit, or the response by an AAS to achieve minimal risk condition, given the same circumstances. o Even at high levels of autonomy (level 3), while the AAS is capable of performing all DFTs within its ODD, it may be unable to perform the DFT fallback in all situations.

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What is a minimal risk condition?	• A condition to which an operator or an AAS may bring a vehicle after performing the DFT fallback in order to reduce the risk of a crash when a given trip cannot or should not be completed. o EXAMPLE: When the AAS detects a potentially dangerous wind gust or orientation shift, the AAS or operator (if necessary) would steer the robot to a safe auto hover location to complete the mission (if safe) or return to a safe landing zone.
What is a request to intervene?	• Notification by an AAS to a fallback-ready user indicating that they should promptly perform the DFT fallback, which may entail resuming manual operation of the aerial vehicle, or achieving a minimal risk condition if the vehicle is not operational.
What is a mission?	• A mission is a set of directives that are sent to the robot to complete. This could be as defined as a series of waypoints for the robot to maneuver to, or less specific such as "explore this building" or "find the fire extinguishers in this mine."

IMPACTS OF ENVIRONMENTAL COMPLEXITY ON EVALUATING AUTONOMOUS REASONING

While the steps between Level 0 through Level 3 aerial autonomy are fairly linear, differentiating between High and Complete autonomy (Levels 4 & 5) is remarkably more complex. Robots can achieve large leaps in autonomous intelligence while still remaining inside the Level 4 classification. In order to make these classifications less opaque we must incorporate a subsection of levels outlining the environmental complexities an aerial robot must navigate safely.

Table 2. Autonomous Understanding & Reasoning

	Autonomous Understanding & Reasoning	Autonomy Level
AUR-A	The UAV is capable of sensing & navigating around obstacles in its environment with onboard sensors	4 A
AUR-B	The UAV is capable of sensing & navigating around obstacles in its environment, but also can make determinations about perceived obstacles and how to approach them • Examples o The UAV can delineate between “phantom” obstacles induced by dust while still avoiding actual obstacles.	4 B

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AUR-C	The UAV is capable of sensing & navigating around obstacles in its environment, and uses that information to make determinations about how to adjust its mission objectives • Example o In a search and rescue operation a robot may have a primary objective of exploring a man-made or natural disaster site for any people or survivors. When the UAV identifies a survivor it can determine whether the person's physical condition warrants immediate attention. If so, the robot can determine whether to pause exploration and instead bring medical support. o The UAV can identify people, doorways, windows through dust & smoke and use that information to execute its mission.	4 C

LEVELS OF AERIAL AUTONOMY

Operator Performs Part or All of the DFT

Level 0 - No Aerial Autonomy

- Operator (at all times):
  - Performs the entire DFT
- Aerial Autonomy System (if any):
  - Does not perform any part of the DFT on a sustained basis (although other vehicle systems may provide warnings or support, such as visible or auditory cues to the pilot, e.g. low-battery indicator)
  - Flight controller can help support the operator's angular rates
    - EXAMPLE: a FPV racing drone

Level 1 - Pilot Assistance

- Operator (at all times):
  - Performs the remainder of the DFT not performed by the aerial autonomy system
  - Supervises the aerial autonomy system and intervenes as necessary to maintain safe operation of the vehicle
  - Determines whether/when engagement or disengagement of the aerial autonomy system is appropriate
  - Immediately performs the entire DFT whenever required or desired
- Aerial Autonomy System (while engaged):
  - Automatically maintains the specified yaw/pitch/roll rates from the operator
  - Disengages immediately upon operator request
    - EXAMPLE: Commercial drones for photography or recreation

Level 2 - Partial Aerial Autonomy

- Operator (at all times):
  - Performs the remainder of the DFT not performed by the aerial autonomy system

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    - Supervises the aerial autonomy system and intervenes as necessary to maintain safe operation of the robot
    - Determines whether/when engagement or disengagement of the aerial autonomy system is appropriate
    - Immediately performs the entire DFT whenever required or desired
- Aerial Autonomy System (while engaged):
    - Automatically maintains the specified yaw/pitch/roll rates from the operator
    - GPS-enabled allowing the robot to return to it's take-off location (in event of a low battery, for example)
    - Disengages immediately upon operator request
        - EXAMPLE: Upper-tier commercial drones for videography

AAS Performs the Entire DFT While Engaged

Level 3 - Conditional Aerial Autonomy

- Operator (while the AAS is not engaged):
    - Verifies operational readiness of the AAS-equipped vehicle
    - Plans waypoint-based mission for the AAS to execute
    - Determines when engagement of AAS is appropriate
    - Becomes the DFT fallback-ready user when the AAS is engaged
- DFT fallback-ready user (while the AAS is engaged):
    - Is receptive to request to intervene and responds by performing DFT fallback in a timely manner
    - Is receptive to DFT performance-relevant system failures in vehicle systems and, upon occurrence, performs DFT fallback in a timely manner
    - Determines whether and how to achieve a minimal risk condition
    - Becomes the operator upon requesting disengagement of the AAS
- AAS (while not engaged):
    - Permits engagement only within its ODD
- AAS (while engaged):
    - Performs the entire DFT
    - Object avoidance enabled
    - Determines whether ODD limits are about to be exceeded and, if so, issues a timely request to intervene to the DFT fallback-ready user
    - Determines whether there is a DFT performance-relevant system failure of the AAS and, of so, uses a timely request to intervene to the DFT fallback-ready user
    - Disengages an appropriate time after issuing a request to intervene
    - Disengages immediately upon operator request
        - EXAMPLE: A UAV equipped with waypoint based autonomy executing a mission with onboard intelligence

Expanding the ODD to Account for Increased Environmental Complexity & Understanding and Reasoning

Level 4 A - High Aerial Autonomy With Moderate Environmental Complexity

- Operator/Dispatcher (while the AAS is not engaged):
    - Verifies operational readiness of the AAS-equipped vehicle
    - Designates area of interest for AAS to explore
    - Determines whether to engage the AAS

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    - Becomes a safety pilot when the AAS is engaged only if physically present by the vehicle
- Operator/Dispatcher (while the AAS is engaged):
    - Need not perform the DFT or DFT fallback
    - Need not determine whether and how to achieve a minimal risk condition
    - May perform the DFT fallback following a request to intervene
    - May request that the AAS disengage and may achieve a minimal risk condition after it is disengaged
    - May become the operator after a requested disengagement
- AAS (while not engaged):
    - Permits engagement only within its ODD + AUR A
- AAS (while engaged):
    - Performs the entire DFT
    - May issue a timely request to intervene
    - Performs DFT fallback and transitions automatically to a minimal risk condition when:
        - A DFT performance-relevant system failure occurs or
        - An operator does not respond to a request to intervene or
        - An operator requests that it achieve a minimal risk condition
    - Disengages, if appropriate, only after:
        - It achieves a minimal risk condition or
        - An operator is performing the DFT
    - May delay operator-requested disengagement

Level 4 B - High Aerial Autonomy With Increased Environmental Complexity

- Operator/Dispatcher (while the AAS is not engaged):
    - Same as Level 4 A
    - Becomes a passive safety pilot when the AAS is engaged
- Operator/Dispatcher (while the AAS is engaged):
    - Need not perform the DFT or DFT fallback
    - Need not determine whether and how to achieve a minimal risk condition
    - May perform the DFT fallback following a request to intervene
    - May request that the AAS disengage and may achieve a minimal risk condition after it is disengaged
    - May become the operator after a requested disengagement
- AAS (while not engaged):
    - Permits engagement only within ODD + AUR B
- AAS (while engaged):
    - Same as Level 4 A

Level 4 C - High Aerial Autonomy With Severe Environmental Complexity

- Operator/Dispatcher (while the AAS is not engaged):
    - Same as Level 4 A
    - Less severe need for a safety pilot fall-back when AAS is engaged
- Operator/Dispatcher (while the AAS is engaged):
    - Need not perform the DFT or DFT fallback
    - Need not determine whether and how to achieve a minimal risk condition
    - May perform the DFT fallback after disengaging AAS

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- May request that the AAS disengage and may achieve a minimal risk condition after it is disengaged
- May become the operator after a requested disengagement

- AAS (while not engaged):
    - Permits engagement only within ODD + AUR C
- AAS (while engaged):
    - Same as Level 4 A

AAS Performs the Entire DFT Under Any ODD

Level 5 - Full Aerial Autonomy

- Operator/Dispatcher (while the AAS is not engaged):
    - Verifies operational readiness of the AAS-equipped vehicle
    - Sets a high-level mission objective with the AAS
    - Determines whether to engage the AAS
    - Becomes a non-actor when the AAS is engaged
- Operator/Dispatcher (while the AAS is engaged):
    - Need not perform the DFT or DFT fallback
    - Need not determine whether and how to achieve a minimal risk condition
    - May perform the DFT fallback following a request to intervene
    - May request that the AAS disengage and may achieve a minimal risk condition after it is disengaged
    - May become the operator after a requested disengagement
- AAS (while not engaged):
    - Permits engagement of the AAS under all ODD conditions
    - Complete autonomous understanding and reasoning
- AAS (while engaged):
    - Performs the entire DFT
    - Performs DFT fallback and transitions automatically to a minimal risk condition when:
        - A DFT performance-relevant system failure occurs or
        - An operator does not respond to a request to intervene or
        - An operator requests that it achieve a minimal risk condition
    - Disengages, if appropriate, only after:
        - It achieves a minimal risk condition or
        - An operator is performing the DFT
    - May delay operator-requested disengagement

DIFFERENCES BETWEEN LEVEL 4 AND LEVEL 5 AUTONOMY

In the early levels of aerial autonomy, the main differentiators between them are the capabilities of the system to take over control of the robot. You can see this in how the human operator is receding farther away from overall control, and they're only needed in an emergency situation. But Levels 4 and 5 are remarkably similar. The main differentiator is in the operating environment the robots are capable of flying in.

To achieve Level 5 Autonomy, a UAV must repeatedly demonstrate successful flight in any environment without requiring interaction or assistance from a pilot or operator. Achieving this

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Level of autonomy will likely require advances in nearly all elements of a Level 4 stack from motion planning to advanced perception. The goal is to enable a system to exhibit safe behavior through degenerate, degraded visual environments and under high levels of environmental and system uncertainty. It is a formidable challenge.

WHAT COMES NEXT?

While our team put extensive thought and care into the creation of this paper, we acknowledge that they are still incomplete without input from the larger UAV community. If you would like to collaborate with us to improve these levels for the entire autonomous industry, please email us, hello@exyntechnologies.com.

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REFERNECES

[1] SAE International. (2018, 12 11). *SAE International Releases Updated Visual Chart for Its "Levels of Driving Automation" Standard for Self-Driving Vehicles*. Retrieved from SAE International: https://www.sae.org/news/press-room/2018/12/sae-international-releases-updated-visual-chart-for-its-%E2%80%9Clevels-of-driving-automation%E2%80%9D-standard-for-self-driving-vehicles

[2] NIST. *Autonomy Levels for Unmanned Systems (ALFUS) Framework.* Retrieved from: https://www.nist.gov/system/files/documents/el/isd/ks/NISTSP_1011_ver_1-1.pdf

[3] *DRONEII: Tech Talk – Unraveling 5 Levels of Drone Autonomy:* Retrieved from: https://dronelife.com/2019/03/11/droneii-tech-talk-unraveling-5-levels-of-drone-autonomy/

[4] Clough, B.T. (2002). Metrics, Schmetrics! How The Heck Do You Determine A UAV's Autonomy Anyway.

[5] Valavanis, K.P., Vachtsevanos, G.J. (2015). UAV Autonomy: Introduction. In: Valavanis, K., Vachtsevanos, G. (eds) Handbook of Unmanned Aerial Vehicles. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-9707-1_144

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