A-UGV Capabilities

Recommended Guide to Autonomy Levels

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***Abstract*— Automatic-through Autonomous Unmanned Ground Vehicle (A—UGV) has been defined by ASTM Committee F45 as an "Automatic, Automated, or Autonomous vehicle that operates while in contact with the ground without a human operator". However, what do the three "A" levels actually mean to manufacturers, users, or especially potential users? This paper defines, and in many cases provides examples of, recommended autonomy levels for all three automatic, automated, and autonomous unmanned ground vehicles.**

Keywords- A-UGV, autonomous, capability, ASTM F45, classifiers

I. Introduction

A-UGV (A-unmanned ground vehicle) has been defined by ASTM Committee F45 [1] as an "Automatic, Automated, or Autonomous vehicle that operates while in contact with the ground without a human operator". However, what do the autonomy or capability levels actually mean to manufacturers, users, or especially potential users? Aside from cost, their focus is most likely on A-UGV capabilities, configuration, facility integration, industrial application, and/or many other vehicle functions that will help the user. Potential A-UGV users who search for A-UGVs mainly hear of two current types of systems: automatic guided vehicles (AGVs) - which are preprogrammed vehicles - and mobile robots. "Mobile robot" is an informal term for a vehicle that includes all intelligent functionality beyond automatic guided vehicles. Meanwhile, the term AGV has been expanded over the years to include laser, self, and other guided vehicles. [2] F45 defined the A-UGV term to minimize confusion, first within the committee and second to express a less ambiguous set of terms for the industry. The A-UGV term therefore includes both AGVs and mobile robots, although further definition is required to again limit confusion and misinterpretation since it spans a broad range of capabilities. During the development of the A-UGV term, the following were defined by the F45 terminology task group, although were not formalized as standard:

- automatic-UGV, n—vehicle capable of following a pre-programmed path and that does not deviate from the path without human intervention,
- automated-UGV, n—automatic vehicle with limited ability to deviate from the pre-programmed path,
- autonomous-UGV, n—self-guided vehicle that is able to travel without a pre-programmed path and operates independently to navigate around fixed and moving obstructions.

With these definitions, AGV capabilities, e.g., offboard, pre-planned navigation path segments between waypoints, fit mainly within the 'Automatic' term, whereas mobile robot capabilities can typically fit within all three terms. 'Automated' UGVs can deviate from the originally-planned path, whereas, onboard, continuously-re-planned paths are typical of 'Autonomous' UGVs. Additionally, there are many other functions that can define the Autonomous-UGV's autonomy, such as navigation, docking and software/hardware reconfiguration control based on sensory interaction, knowledge representation, and judgement, and behavior expectations. The combination of the latter functions can also be described as intelligence. As will be described in following sections, the concepts 'autonomy' versus 'intelligence' have been discussed among many groups and for many applications. Briefly, some definitions for autonomy and intelligence are as follows:

Autonomy	Intelligence
Ability to perform intended tasks based on current state and sensing, without human intervention [3]	Ability to acquire and apply knowledge and skills [5]
Self-directing freedom and especially moral independence [4]	1. Ability to learn or understand or to deal with new or trying situations, also the skilled use of reason 2. Ability to apply knowledge to manipulate one's environment or to think abstractly as measured by objective criteria (such as tests) [4]
Freedom from external control or influence; independence [5]	One's capacity for logic, understanding, self-awareness, learning, emotional knowledge, planning, creativity, and problem solving [6]

Other definitions have been developed and provide similar concepts of independence and accomplishing goals based on knowledge and perception of the world. For example, according to [7], to be autonomous, a system must have the capability to independently compose and select among different courses of action to accomplish goals based on its knowledge and understanding of the world, itself, and the situation. However, understanding and perceiving the world and situations can broadly vary.

Unfortunately, the current F45 terminology covers only three levels of autonomy, again suggesting all functions beyond automated fall within autonomous. It is clear that there are further autonomy-level divisions that are needed. As more autonomous industrial vehicles are manufactured and marketed, standard test methods and practices are needed to help inform the user of the expected performance for these advanced capabilities. Consensus-based standards also provide an unambiguous and precise language with which users can specify their required levels of autonomy prior to procuring systems. Laying the groundwork for test methods, a Standard Guide to A-UGV Autonomy-Level would aid the A-UGV user to first understand the variety of vehicle types and capabilities available and to match the advanced vehicle to the advanced task. As opposed to automatic and automated systems, the increased complexity in capability and function also provides increased difficulty in understanding which A-UGV to apply to tasks. To define A-UGV autonomy levels for clear understanding and use by the industrial vehicle industry begins with generically establishing the variety of levels and then fitting their control, capabilities, and functionalities into clear categories.

This paper includes initial sections briefly describing prior efforts towards defining autonomy levels with extended description of Autonomy Levels for Unmanned Systems [8] and then describing the relationship between autonomy and intelligence. This background is essential to allow a focused classification of autonomy for industrial vehicles. This is followed by a section with recommended autonomy levels which includes a table of example industrial vehicle implementation scenarios of each autonomy characteristic for each autonomy level.

II. Prior Efforts Towards Defining Autonomy Levels

There have been numerous prior efforts in defining autonomy levels. One of the most well-known is the ALFUS (Autonomy Levels for Unmanned Systems) effort that has been absorbed within the SAE AS4-D [9]. ALFUS was originally developed by a government informal working group addressing the lack of autonomy measures to support new major Department of Defense programs. The ALFUS development team mined and built upon several other relevant frameworks [10], including: National Aeronautics and Space Administration (NASA) Spacecraft Mission Assessment and Re -planning Tool (SMART) [10], Observe, Orient, Decide, Act (OODA) [11], NIST 4D/Real-time Control System Reference Architecture [27],"Sheridan" Model [12], Defense Science Board Summer Study on Autonomy [13], and others. Some of these, such as the Sheridan model, focused on categorizing the levels of dependence/independence of the automated system from the human.

The resulting ALFUS framework [14] is based on a hierarchical, multi-dimensional model of the main factors that affect autonomy. The three main dimensions (or axes) are: human independence, mission complexity, and environmental complexity. Therefore, the degree of autonomy of a system is characterized not only by how much it relies (or doesn't) on human direction and interaction, but also on the types of tasks it is capable of performing and the types of environments within which it performs them. Each of these axes themselves represent a number of characterization aspects. Detailed discussions and guidance are found in [14], but some examples are:

Mission Complexity potential metrics
- Mission time constraint
- Precision constraints in navigation, manipulation, etc.
- Rules of engagement
- Knowledge requirements in order to plan mission and adjust/adapt to respond to changing conditions

Environmental Complexity potential metrics
- Traversability of terrain (flat clear support surface/floor versus highly uneven, non-uniform)

Visibility
- Dynamicism of environment (moving objects versus static known surroundings)

Human Independence potential metrics
- Scope and range of mission that the system can plan and execute independently
- Ability to generate high-level complex plans versus just derive lower-level plans or signals to system actuators from higher-level plans that were given to it.
- Ability to communicate the relevant information to the appropriate human (including distinguishing between human roles, such as operators, bystanders, adversaries, etc.)

As can be deduced from the examples, the autonomy level for a system is always dependent on the context within which the system performs. Therefore, ALFUS evolved to define a "Contextual Autonomous Capability (CAC) Model for Unmanned Systems." [15][16]

Several other standards that discuss safety and performance of autonomous systems are or have been developed within several standards development organizations. For example, ISO TC 299 Robotics defines autonomy and employs autonomy in several robot standards within several working groups. The International Electrotechnical Commission (IEC) TR 60601-4-1 [18] provides guidance and interpretation of medical electrical equipment and medical electrical systems employing a degree of autonomy. The Institute for Electronic and Electrical Equipment [19] has an active project to develop standard IEEE 7009 for fail-safe design of autonomous and semi-autonomous systems. Given the growing interest in self-driving vehicles, the U. S. Department of Transportation has begun efforts at classifying what they term as automation levels. [17] The aforementioned report references on-road autonomous vehicle taxonomy and definitions in SAE International standard J3016_201609 [20], including three main driving factors: the human driver, the driving automation system, and other vehicle systems. Industrial Truck Standards Development Foundation [21] B56.5 covers safety of automatic guided industrial vehicles and American National Standards Institute (ANSI)/Robotic Industries Association

(RIA) [22] 15.08 is developing a mobile robot and mobile manipulator (i.e., robot arm(s) onboard a mobile robot base) safety standard. None of these standards efforts currently provide guidance on the expected operation of industrial autonomous vehicles as is considered in this document and is expected to fall within ASTM F45.

III. The Relationship Between Autonomy and Intelligence

To put autonomy and intelligence into a fairly general example, consider this scenario: babies are relatively intelligent, as compared to adults, born with basic abilities such as reflexes, general motor skills, eating, face matching, and discerning details in the world through their senses. As babies grow, they become more independent or autonomous from care-givers while learning about their environment through experience and education, improving on motor skills, and becoming able to generalize from experiences in order to respond to new situations.

Sometimes, the terms "autonomy" and "intelligence" are used interchangeably. We examine both terms and their relationship as applied to machines, building on the ALFUS high-level summary above. Within the ALFUS framework, the definition of fully autonomous is "a mode of unmanned system (UMS) operation wherein the UMS accomplishes its assigned mission, within a defined scope, without human intervention while adapting to operational and environmental conditions" [23]. Within the scope of ALFUS, intelligence in an unmanned system is defined as its possession of and the ability to exercise contextual autonomous capability [ibid.]. Sanz et al. defined autonomy as the ability of a system to fulfill a task within a given context without external help [24].

A similar perspective is present in the Albus [25] definition of intelligence, initially posed as "the ability of a system to act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral subgoals that support the system's ultimate goal" [26]. In later works which were more application-focused (e.g., [27][28]), the definition was expanded:

- An intelligent system is a system with the ability to act appropriately in an uncertain environment.
- An appropriate action is that which maximizes the probability of successfully achieving the mission goals.
- A mission goal is a desired result that a mission is designed to achieve or maintain.
- A result is represented as a state or some integral measure of a state-time history.
- A mission is the highest-level task assigned to the system.

The Albus definitions of intelligence do not explicitly mention the role of the human in a system's operation. The attribute of being able to independently achieve success is the explicit expression of the autonomy concept. Combining the Albus definition with the Sanz concept "without external help" merges the intelligence and autonomy attributes: "the ability of a system to independently act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral subgoals that support the system's ultimate goal."

IV. Recommended Autonomy Levels for A-UGVs

For industrial vehicles, A-UGVs have large amounts of human-machine interaction in lower autonomy levels, building to more autonomous functionality having small amounts or no human-machine interaction with increasing A-UGV autonomy. Matching the A-UGV autonomy level to the task may be challenging to the user and therefore, some guidance is warranted. The following sections first define classifiers and recommended autonomy levels for autonomous-UGVs, and then show an example A-UGV classification. Context should also be added to the recommended levels and is then briefly described.

A. *Classifiers*

Classifiers are a set of terms and their definitions, as shown in Table I, that the A-UGV is capable of performing (e.g., Navigation, Docking, etc.) and that affect the A-UGV performance (e.g., Environmental difficulty, Situation awareness, etc.). Bolded classifiers are defined terms within ASTM F3200-17 [1]. Table 1 defines twelve classifiers specifically focused on A-UGV implementation where the definitions, including those shown in F3200-17, may be different from ones researched in dictionaries. For example, situation awareness is defined in the table by [5]. However, decision-making was modified from existing definitions to be more focused on A-UGV implementation.

TABLE I. AUTONOMY CLASSIFIERS

Classification Category/Metric	**Definition**
Navigation	deciding on and controlling the direction of travel derived from localization and the environment map; see simultaneous localization and mapping (SLAM), localization. DISCUSSION—Navigation can include path planning for location-to-location travel and complete area coverage
Docking	arrival and act of stopping at a position relative to another object
Subtasks	a portion or portions of **tasks** (sequence of movements and measurements that comprise one repetition within a test)
Organization structure	**control**, communications, interaction requirements between the A-UGV and an offboard controller (e.g., central) and/or with other A-UGVs to accomplish desired goal(s)
Decision-making	the action or process of making decisions including the associated system to make the decision (e.g., central control, another A-UGV)
Situation awareness	the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their status after some variable has changed, such as time, or some other variable, such as a predetermined event. [5]
Knowledge requirements	the amount of information and experience necessary to achieve a goal(s)

Environmental Difficulty	the A-UGV situation to overcome, deal with, or understand due to natural (e.g., weather, climate, terrain, vegetation), modified (e.g., specific induced environments) and/or observed conditions by the A-UGV during operation
Terrain variation	surface conditions (e.g., ramps, roughness, softness/hardness, etc.) that the A-UGV can traverse
Communication dependencies	reliance upon communication with external A-UGV sources for the A-UGV to achieve goal(s)
Tactical behavior	required A-UGV actions towards a goal(s) beyond the current situation
Human-machine interaction (HMI)	information and action exchanges between human and A-UGV to perform a task by means of a user interface

B. Autonomy Level Guide

A recommended guide, shown in Table II, has been developed that adopts aspects of the referenced autonomy level structures from the "Prior Efforts Towards Defining Autonomy Levels" section and applies a more focused industrial A-UGV perspective that exemplifies expected vehicle performance at each level. Autonomy levels are defined using the classifiers shown along the vertical axis of Table II where the highest level may be, perhaps, a top-level goal for Autonomous – UGVs.

Each level includes a generic definition of that level or groups of levels followed by example capabilities that may fit within that A-UGV level. The first two levels (1 and 2) are defined prior to Table II to allow the A-UGV, at all levels, to be fully or partially controlled by the human operator. The third level (3) is more closely related to the typical automatic guided vehicle (AGV) systems while the fourth level (4) expands the AGV abilities to allow for obstacle detection and avoidance while controlled from the central controller. The term guidepath (and all other bolded terms) is defined in ASTM F3200-17 as the "intended path for an A-UGV used with automatic or automated guidance". The fifth through eighth levels (5 through 8) define autonomous-UGVs. Levels three through eight functionalities are best described in Table II where the table expands autonomous-UGVs across four additional levels to include the minimal (e.g., level five) through maximum (level eight) functionalities. All levels build on previous levels and some level 4 Automatic classifiers simply carry the same functionality from one level to the next with no additional functionality. This is because the Automated-UGV expands only the navigation and docking from the Automatic-UGV.

1. A-UGV (no autonomy)
- Definition: An A-UGV that is controlled only by an A-UGV operator and lacks any autonomy
- Example Capabilities:
  Manual mode, manual control, manual operation of an A-UGV
  - Using an operator control unit to move the A-UGV when not being used in production

2. A-UGV (shared control)
- Definition: Shared control between the A-UGV operator and the A-UGV
- Example Capabilities:
  - A-UGV operator uses human-machine interaction to control minimal A-UGV functionality (e.g., speed) while the A-UGV moves using automated functionality.
  - A-UGV operator is aware of and the A-UGV is not aware of the environment.

3. Automatic-UGV
- Definition: A computer-controlled, unmanned A-UGV that can navigate guidepaths with directed movement by a combination of software and sensor-based guidance systems [30].
- Example Capabilities: (see Table II)
  - Automatic Guided Vehicle (AGV)
  - Guidance for navigation is typically achieved using: laser; embedded wire or magnets in floors; chemical, tape, or other floor markings

4. Automated-UGV
- Definition: A level 3 A-UGV that can also re-plan and navigate away from and return to a guidepath.
- Example Capabilities: (see Table II)

5. through 8. Autonomous-UGV
- Definition: A level 4 A-UGV that can re-plan and navigate without the need for a guidepath and using natural features in the environment.
- Example Capabilities: (see Table II).

V. CONTEXT

Context means the "circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood and assessed". [4] In this case, the definition could be modified as "form the setting for an A-UGV event(s)" and "fully understood and acted upon". [4] In addition to A-UGV autonomy levels, context is also important and includes, for example, the location (e.g., indoor or outdoor) where the vehicle is being used, the task complexity and computation speed required to accomplish the task, the environmental conditions (i.e., bright sun/dark, high heat/extreme cold), and many other possible criteria that place the vehicle in an infinite number of potential situations. Additionally, as the A-UGV moves through its environment, whether factory, hospital, outdoors, or other, the dynamically changing unknowns create an even more complex setting for the A-UGV to complete its task.

TABLE II. Examples of A-UGV performance for recommended A-UGV Autonomy Levels 3 through 8

	A-UGV CAPABILITY LEVELS					
METRIC	**3 - Automatic**	**4 - Automated**	**5 - Autonomous**	**6 - Autonomous**	**7 - Autonomous**	**8 - Autonomous**
Navigation	levels 1, 2 + follows preprogrammed path	level 3 + leaves path and returns to path, e.g., to avoid an obstacle/A-UGV and returns to path	level 4 + mapping using natural features; finds and self-routes to mainly follow guidepaths, e.g., can deviate from path, not follow initial path	level 5 + no guidepath required, self-routes to waypoints toward goal in intended path areas	level 6 + self-routes to goal along intended or alternative and allowable paths	level 7 + no waypoints required, self-routes to goal along paths using decision-making and value judgement
Docking	levels 1, 2 + stops at preprogrammed waypoints with preprogrammed tolerance	Level 3 + able to dock while off preprogrammed path	level 4 + servo to docking pose in heading, translation, and azimuth	level 5 + servo to docking pose in 6 DoF	level 6 + automatic tolerance variation based on situation, e.g, ± 5 mm dock station alignment, then ± 0.5 mm fine tolerancing with no fixturing	level 7 + dynamic docking with moving objects, e.g., moving agile assembly line (independent vehicle) with 6 DoF low tolerance docking
Subtasks	levels 1, 2 + preprogrammed stop points; e.g., pickup/drop-off loads; pull trailor	same as level 3	level 4 + minimal preplanned stop sequence, e.g., follow lines, edges, paths, and/or no lines or natural features to support navigation through minimally complex areas	level 5 + no preplanned stop sequence, e.g., replan paths and navigation through a complex facility having an unstructured environment with periodically blocked and open paths	level 6 + e.g., follow complex contours of spatially-independent object surfaces using sensory intelligence, adapt speed and position to dynamically acquire suspended loads from overhead cranes and AUVs	level 7 + full decision-making e.g., detect, understand humans vs. objects, and vary speed and functionality based on human vs. object recognition; adjust the payload pose according to delicate handling, vehicle speed, ramps, emergency-stop conditions
Organization structure	levels 1, 2 + central controlled; no collaboration	same as level 3	level 4 + central fleet control + self-controlled; fleet replanning when A-UGV(s) is busy	level 5 + A-UGV-to-AUGV map info. (e.g., obstacle, busy, routes knowledge); on-the-fly route(s)-changes from host take effect during operation	level 6 + self-controlled; send A-UGV commands/route-changes to/from other A-UGVs, e.g., idle A-UGV sent for pickup;	level 7 + integration with other vehicle types (UAV's) and facility equipment (cranes, machine tools)
Decision-making	levels 1, 2 + centrally, offboard -controlled decisions (e.g., A-UGV intersection and zone minding); no self-decisions	same as level 3	level 4 + minimal self-decisions (e.g., pass another A-UGV)	level 5 + moderately complex self-decisions from learned events	level 6 + complex self-decisions from learned events	level 7 + full, self, efficient, real-time planning and execution, highest precision and success rate, maximizes/minimizes on values/cost, benefit/risk.
Situation awareness	levels 1, 2 + none, zone or segment known by central controller	level 3 + detect off-path; continuous plan back to path	level 4 + preplanned route and natural-feature mapping/learning	level 5 + self-planned route; high/low-level learning, e.g., single vs. clustered obstacles, humans vs. obstacles	level 6 + multi-level obstacle grid populated with orders of magnitude obstacles; humans vs. obstacle	level 7 + no obstacle grid required; learn complex situations
Knowledge requirements	levels 1, 2 + digital/analog input/output	same as level 3	level 4 + minimal knowledge/information, e.g., detected obstacles placed in map, infrastructure vs. transients	level 5 + medium knowledge/information, e.g., obstacle prediction from motion	level 6 + obstacle recognition, e.g., humans	level 7 + maximum knowledge/information, e.g., detailed learning (textures, transparency/opaque, soft/hard)
Environmental Difficulty	levels 1, 2 + lights on/off; cold/hot; transitions; e.g., slow/stop when 2D safety sensed obstacles	same as level 3	level 4 + dense obstacle field, e.g., obstacle avoidance	level 5 + navigation, environment sensing unaffected by e.g., sunlight-to-dark, hot-to-cold transition, moderatetly-high humidity, moderate air particle density	level 6 + vary avoidance dependent upon recognized obstacle	level 7 + adaptable to extreme terrain and climate variations and obstacle density and frequency. e.g., high humidity; high air particle density
Terrain variation	levels 1, 2 + moderate friction; flat, hard surface; fine particulates	same as level 3	level 4 + moderately flat surface	level 5 + shallow inclines at any angle	level 6 + to 15% grade, moderate friction ground surface; course particulates	level 7 + outdoor ground surfaces (e.g., soft, rough (> 10 mm dia. stone rubble)); low friction
Communication dependencies	levels 1, 2 + receives commands/monitors progress wireless through central computer; finishes segment upon comm. failure with central source and stops	same as level 3	level 4 + initial comm. reliance with commanded route(s) from central host; no A-UGV control effects with comm. failure although monitor interupts	level 5 + comm. via verbal human commands; e.g., "start route 100", "stop", "pause"	level 6 + complex verbal or gestured human commands; e.g., "take-over A-UGV 4 routes", hand wave, point, etc. to command A-UGV routes; monitor from any wireless comm.	level 7 + fully independent from comm. link; e.g., A-UGV gets initial goals, routes through previous level means with no need for human or host comm. for successful goal
Tactical behavior	none	none	low complexity	level 5 + middle complexity, multi-functional tasks;	level 6 + collaborative, high complexity, multi-functional tasks;	level 7 + highest complexity for all tasks, total independence
Human-machine interaction	levels 1, 2 + maximum HMI	same as level 3	level 4 + HMI for periodic path/task correction	level 5 + infrequent HMI, e.g., stuck with poor plan solution (difficult route)	level 6 + rare HMI, e.g., stuck in extremely complex situation; alert with no self-plan solution	level 7 + no HMI required

As in [26], “context impacts the appropriateness of virtually all aspects of an agent’s behavior” and “context-sensitivity is fundamental to intelligent behavior”. An A-UGV with Level 7 Navigation and Level 6 Subtasks can self-route while replanning paths within a complex facility and an unstructured environment. Context can further provide autonomy level implementation challenges where appropriate tests must be considered to measure the A-UGVs performance. For example, an A-UGV with relatively challenging environmental conditions of, for example, frozen factory walls and floors, bright lights reflecting off the walls and floors, and potentially slick spots on the floor would be completely different than a warm, office-lit, non-slippery floor condition when testing the same autonomy levels. Therefore, the recommendation is that once the autonomy level for a subset or all of the 12 classifiers is determined, the context must also be established and recorded to allow comparison of A-UGV performance to the task. ASTM F3218-17 [1] provides a practice for recording the environmental conditions that can help with recording this aspect of context where the A-UGV is to operate. However, in addition, all other context criteria should also be recorded to capture any environmental effects that might affect the A-UGV performance. Using the previous example, bright lights would be recorded in F3218-17, although bright lights reflecting off shiny, frozen walls and floors may not be recorded on the current form and yet may affect performance of the A-UGV.

VI. ASTM Committee F45 Early Recommendations

A workshop was held as part of the July 2018 ASTM Committee F45 meeting, called: A-UGV Capability Levels. During the workshop, the contents of this paper were presented and discussed. The committee accepted the concept of developing a standard guide to A-UGV capabilities, as opposed to autonomy levels, and is considering an alternative to the examples shown in Table II, beginning with navigation and docking classifiers. The alternatives, shown in Table III, will be discussed in future ASTM F45 meetings.

TABLE III. ASTM COMMITTEE F45 EARLY RECOMMENDATIONS FOR A-UGV CAPABILITY LEVELS FOR NAVIGATION AND DOCKING CLASSIFIERS

	A-UGV CAPABILITY			
CLASSIFIER	3	4	5	6
Navigation	Follows preprogrammed path	Leaves preprogrammed path and returns to preprogrammed path	Can find an alternate preprogrammed path	Self-routes to the goal
- infrastructure dependence	relies on infrastructure	relies on infrastructure	relies on infrastructure	relies on infrastructure
	does not rely on infrastructure; corrects for errors	does not rely on infrastructure; corrects for errors	does not rely on infrastructure; corrects for errors	does not rely on infrastructure; corrects for errors
Docking	Docks at preprogrammed waypoints	Able to adjust based on local docking position	Dynamic docking with moving objects	
- infrastructure dependence	relies on infrastructure	relies on infrastructure	relies on infrastructure	
	does not rely on infrastructure; corrects for errors	does not rely on infrastructure; corrects for errors	does not rely on infrastructure; corrects for errors	
- docking degrees of freedom	x (heading)	x (heading)	x (heading)	
	y (side-to-side)	y (side-to-side)	y (side-to-side)	
	z (vertical)	z (vertical)	z (vertical)	
	roll (rot. about x)	roll (rot. about x)	roll (rot. about x)	
	pitch (rot. about y)	pitch (rot. about y)	pitch (rot. about y)	
	yaw (rot. about z)	yaw (rot. about z)	yaw (rot. about z)	

VII. Conclusions

This document is intended to provide a broad overview of the nature of defining and categorizing autonomy for industrial vehicles. It builds upon existing work that explored the many dimensions of autonomy for unmanned systems. This effort focuses on the A-UGV domain specifically, seeking to clarify the nomenclature of Automatic, Automated, or Autonomous vehicle. Users can use this framework to use a more functionality-based method with autonomy metrics to describe the advanced capabilities of autonomous-UGVs beyond a single autonomous-UGV category. Manufacturers of A-UGVs can more fully describe their vehicle’s capabilities by identifying the autonomy levels for various capabilities, as well as for the overall A-UGV. This framework can provide standards committees, such as ASTM F45, and possibly ITSDF B56.5, and RIA 15.08, a means to expand their standards development roadmap, incorporating relevant aspects of the autonomy categories.

References

[1] ASTM Committee F45 Driverless Automatic Guided Industrial Vehicles, www.astm.org/F45, accessed January 26, 2018.

[2] Josh Bond, “AGVs: Predictably Flexible”, http://www.mmh.com/article/agvs_predictably_flexible, January 19, 2018, Accessed January 26, 2018.

[3] International Organization of Standards (ISO) 8373:2012 Robots and robotic devices – Vocabulary, 2012.

[4] Merriam-Webster, https://www.merriam-webster.com/dictionary/, accessed 1/24/2018.

[5] Google, www.google.com, accessed 1/24/2018.

[6] Wikipedia, www.wiki.com, accessed 1/24/2018.

[7] L.G. Shattuck, “Transitioning to Autonomy: A human systems integration perspective”, Presentation at Transitioning to Autonomy: Changes in the role of humans in air transportation, March 11, 2015. Available at human-actors.arc.nasa.gov/workshop/autonomy/download/presentations/Shaddock%20.pdf (Accessed November 3, 2017.)

[8] Hui-Min Huang, Kerry Pavek, James Albus, Elena Messina, “Autonomy Levels for Unmanned Systems (ALFUS) Framework: An Update”, 2005 SPIE Defense and Security Symposium, Orlando, Florida, 2005.

[9] SAE AS4-D Unmanned Systems Steering Committee, https://www.sae.org/servlets/works/committeeHome.do?comtID=TEAAS4, accessed November 2, 2017.

[10] Ryan W. Proud, Jeremy J. Hart, and Richard B. Mrozinski, “Methods for Determining the Level of Autonomy to Design into a Human Spaceflight Vehicle: A Function Specific Approach, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100017272.pdf, accessed November 2, 2017.

[11] Lieutenant Colonel Jeffrey N. Rule, “A Symbiotic Relationship: The OODA Loop, Intuition, and Strategic Thought”, Strategy Research Project, US Army War College, http://www.dtic.mil/dtic/tr/fulltext/u2/a590672.pdf, accessed January 26, 2018.

[12] Sheridan, T.B., and Verplank, W. L., Human and Computer Control for Undersea Teleoperators. 1978, MIT Man-Machine Systems Laboratory.

[13] Defense Science Board Summer Study, https://www.hsdl.org/?view&did=794641, June 2016, accessed November 2, 2017.

[14] Hui-Min Huang and Elena Messina, “Autonomy Levels for Unmanned Systems (ALFUS) Framework Volume II: Framework Models Initial Version,” National Institute of Standards and Technology Special Publication 1011-II-1.0, December 2007.

[15] Hui-Min Huang, Kerry Pavek, Mark Ragon, Jeffry Jones, Elena Messina, James Albus, “Characterizing Unmanned System Autonomy:

Contextual Autonomous Capability and Level of Autonomy Analysis,” Proceedings of the 2007 SPIE Defense and Security Symposium Unmanned Systems Technology IX, Orlando, FL, April 2007.

[16] Hui-Min Huang, H., Elena Messina, Adam Jacoff, Robert Wade, Michael McNail, “Performance Measures Framework for Unmanned Systems (PerMFUS): Models for Contextual Metrics,” Proceedings of the 2010 Performance Metrics for Intelligent Systems Workshop (PerMIS’10), NIST Special Publication 1113, September 2010.

[17] “Automated Driving Systems 2.0: A Vision for Safety”, DOT HS 812 442, Version 9a, 13069a, September 6, 2017.

[18] IEC TR 60601-4-1:2017 Medical electrical equipment -- Part 4-1: Guidance and interpretation -- Medical electrical equipment and medical electrical systems employing a degree of autonomy, 2017.

[19] Fail-Safe Design of Autonomous and Semi-Autonomous Systems, https://standards.ieee.org/develop/project/7009.html, accessed 3 February 2018.

[20] Standard J3016_201609 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, https://www.sae.org/standards/content/j3016_201609/, accessed 3 February 2018.

[21] Industrial Truck Standards Development Foundation B56.5 Driverless Automatic Guided Industrial Vehicles, www.itsdf.org, accessed 3 February 2018.

[22] American National Standards Institute/Robotic Industry Association 15.08, Mobile Robot Safety, www.robotics.org, accessed 3 February 2018.

[23] Hui-Min Huang, Ed., “Autonomy Levels for Unmanned Systems, Volume I: Terminology, Version 1.1,” NIST Special Publication 1011, September 2004.

[24] R. Sanz, F. Matia and S. Galan, "Fridges, elephants, and the meaning of autonomy and intelligence," Proceedings of the 2000 IEEE International Symposium on Intelligent Control. Held jointly with the 8th IEEE Mediterranean Conference on Control and Automation (Cat. No.00CH37147), Rio Patras, 2000, pp. 217-222. doi: 10.1109/ISIC.2000.882926

[25] James S. Albus, "Outline for a theory of intelligence," in IEEE Transactions on Systems, Man, and Cybernetics, vol. 21, no. 3, pp. 473-509, May/Jun 1991. doi: 10.1109/21.97471.

[26] Hui-Min Huang, “Autonomy Levels for Unmanned Systems (ALFUS)”, Presentation to the ALFUS Working Group, SAE AS4D Committee, 2005.

[27] Albus, J., Huang, H., Messina, E., Murphy, K., et al., “4D/RCS Version 2.0: A Reference Model Architecture for Unmanned Vehicle Systems,” NIST Interagency/Internal Report (NISTIR) 6910, August, 2002.

[28] Meystel, A.M. and E.R. Messina. Measuring the Performance and Intelligence of Systems. Proceedings of Performance Measurement of Intelligent Systems (PerMIS), Gaithersburg, MD, 2000.

[29] Turner, RM. Context-sensitive reasoning for autonomous agents and cooperative distributed problem solving. In Proceedings of the IJCAI Workshop on Using Knowledge in its Context 1993 (pp. 141-151).

[30] Material Handling Industry of America, http://www.mhi.org/fundamentals/automatic-guided-vehicles, accessed November 2, 2017.