Framework of Level-of-Autonomy-based Concept of Operations: UAS Capabilities

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***Abstract*—The utility of unmanned aircraft system (UAS) is growing fast in recent years with applications like parcel delivery and security patrol. However, most of the current applications require the involvement of human operator, posing challenges for large-scale UAS deployment due to the operator's and air traffic control officer's (ATCO) limited cognitive capability to control and monitor the traffic. Autonomous UAS operation that reduces the operator and ATCO workload could be a promising solution to meet that challenge. The main aim of this paper, therefore, is to propose a conceptual framework for Level of Autonomy (LoA) based concept of operations (ConOps). The discussion includes the definition and evaluation of LoA and the investigation opportunities of enabling UAS operation at various LoA via case studies. This could be further extended for mixed operation with vehicles of multiple LoA. The framework is presented around core factors defining levels of autonomy for UAS and character for each level in terms of operational actions. Two use cases involving scheduled parcel delivery and non-scheduled emergency operation are presented to demonstrate the evaluation of LoA for a given operation. The proposed framework could serve to identify opportunities for research and engineering development of UAS operations in urban environments.**

Keywords*¬*unmanned aircraft system; level of autonomy; concept of operations; case studies

I. INTRODUCTION

Small unmanned aerial vehicle has long been used for various missions and tasks, ranging from search and rescue, target tracking, to parcel delivery, inspection, precision agriculture, etc. The rapid booming of small UAS (sUAS) operations in and around urban airspace pose challenges for regulatory bodies, airspace manger, etc., but also bring opportunities to unlock potential of the sky. To accommodate the accelerating demand for UAS operations [1], [2], we must answer questions such as how to integrate the UAS into current airspace framework [3], [4] and how to manage the growing operations in urban environments safely and efficiently by leveraging the emerging technologies and effective airspace and traffic management [5]–[7].

Manual operation controlled by UAS operator is limited in control capacities [8], and even skilled human operator will have difficulties in dealing with multiple operations in complex environments [9], [10]. Given those limitations, autonomous operation is regarded as one of the most effective solutions to handle the large-scale UAS operations in complex urban environments [11]. By enabling high level of autonomy, UAS operations can be achieved by the unmanned system with minimal or no input from human operators [12]. However, to achieve such a sufficient level of automation, there is still a long way to go, and much effort would be needed from research and development (R&D), as well as engineering communities to achieve the higher level of autonomy.

A. Existing ConOps regarding to UAS operations

Numerous ConOps (Concept of Operations)shou aiming to enable UAS operations by various organizations have been proposed in recent years, such as the UAS Traffic Management (UTM) concept of operations (ConOps) v1.0 [13] and UTM ConOps v2.0 [14] jointly developed by NASA and FAA. These ConOps provided and described the essential and conceptual elements of UAS operations serving to offer development solutions across many actors and parties involving the implementation of UTM. On the other hand, the concept of U-space was proposed by SESAR to unlock the potential of the sky for UTM [16]. The concept was further refined [17], with the latest U-space ConOps [18] released in 2019. The U-space ConOps emphasized on the integration and acceptance of UAS operation into current airspace system. Additionally, the European Union Aviation Safety Agency (EUASA) proposed a high-level regulatory framework [19] to describe rules for all types of unmanned operations in the proposed U-space airspace. The International Civil Aviation Organization (ICAO) has also issued the UTM ConOps [20], aiming to introduce a common framework with core principles for global harmonization and interoperability.

The concept of Urban Air Mobility (UAM) branched off in recent years due to the expectation for big growth in passenger air-taxi and air-cargo transportations in urban airspace. On the consumer facing side, Uber released the blueprint of UAM to a future of on-demand urban air transportation [21]. By using large-scale passenger data of taking their ground car-hailing service, Uber analyzed the passenger demand for different types of travel in cities areas and projected the potential users of air-taxi services. Airbus [22] also issued the ConOps which depicts the future urban air traffic and travel model of people. Ehang [23] launched their initiative program to enable air-taxi-hailing services for passenger. Research and regulatory bodies have also put efforts in the UAM ConOps development. Various concept of operations for UAM have been proposed, ranging from technology development [24], airspace integration [3], [7], UAM vehicle material and design [25], to legal and regulatory assessment of UAM operation [26]. The NASA UAM ConOps v1.0 [15] has issued as a comprehensive guidance for UAM development, considering different interests for various stakeholders from regulatory, academia to industry communities.

Throughout the proposed ConOps framework, the autonomous operational capability is consistently listed as one of the key factors to enable large-scale, beyond-visual-line-of-sight (BVLOS), low altitude UAS operations in complex environments. This paper, therefore, will concentrate on the LoA-based ConOps for sUAS in the urban environments.

B. Level of autonomy (LoA)

Defining and evaluating the level of autonomy (LoA) is the prerequisite to understand the current UAS capability and develop the corresponding operation procedures. It is also essential for operators and regulators to assess the safety and efficiency performance of the operation [27]. To do so, the definition of autonomy needs to be clarified to see what requirements and elements each level of autonomy consists of. The definition of autonomy given by the Oxford English Dictionary [28] is as the "*right or condition of self-government*". Furthermore, the North Atlantic Treaty Organization (NATO) defines the autonomy as "*the condition or quality of being self-governing*" [29]. The definition of autonomy given by some other reviews emphasize on "*independence and complexity*" [12]. The independence is pertaining to human operator or controller [30], while the complexity is categorized as mission complexity and environment complexity. Furthermore, ICAO documentation describes autonomy as operation without human intervention [31]. To apply the detailed definition to the domain of unmanned systems, a team has developed a set of autonomy levels, which is so called the "Autonomy Levels For Unmanned Systems (ALFUS) [12]. According to ALFUS, the autonomy in unmanned systems can be classified as degree of human involvement as well as the capabilities of hardware: sensing, perceiving, communicating, navigating, surveilling, etc., and the capabilities of software: planning and scheduling, risk-aware, decision-making, and detect and avoid, etc.

Quantified framework for classification of LoA is also a topic of interest. Some researchers proposed the framework with ten distinct levels [32], with the lowest being human control and the highest being self-control. While others classified the autonomy into six levels, ranging from level 0 with no automation to level 5 with full automation [33], [34]. There are also some demonstration studies with the different levels of autonomy ConOps. For instance, LoA 3 was used to demonstrate the car handover process model from system control to human driver control [35]. And level 5 autonomy was projected for future intelligent road transport, so that policies, regulations can be shaped, and technologies can have directions to develop to accommodate vehicles with level 5 autonomy [36], [37]. Evidence also shows that fully autonomous UAS operations are still yet to be achieved [32], [38]. Technology limitations, dependency on external data and information, etc. still hinder the way towards full automation of various UAS operations [39], [40].

Existing frameworks provide general and conceptual understandings for LoA-based operation. However, these frameworks did not provide sufficient guidance for LoA when applied to UAS operation at very low altitude level with complex urban environments and varying mission objectives. Besides, current discussions on the requirements and elements of LoA are mostly conceptual and lacking detailed descriptions, making it difficult to conduct certification of autonomy levels to determine the applicable ConOps for that operation. This paper, therefore, aims to enhance the LoA-based ConOps for sUAS operations to assists with: (1) the understanding of how UAS operations for each LoA would look like, and what are the building blocks (categories and elements) of the LoA, (2) what are the capability requirements for each LoA, (3) what are the knowledge gaps and bottlenecks to improve the LoA reaching a higher level, (4) how specifically leverage the LoA ConOps to assist the R&D, engineering, management, etc. The LoA-based ConOps is further demonstrated with two use cases involving parcel delivery and unscheduled emergency operation.

II. CONCEPTUAL FRAMEWORK OF LOA

A. Overview of LoA

Level of autonomy is crucial for the UTM ConOps and it significantly influences the UAS operations [28]. For UAS itself, the higher level of autonomy means that the UAS is capable of performing operations in more complex environments and execute more complex missions without operator intervention.

Inspired by ALFUS framework [12], the overall autonomy of UAS operation will be developed with the LoA of the system itself, as well as the mission and environmental complexity (**Figure 1**). Basically, with the increase of complexity, the required system LoA will be higher. In this paper, our scope is to investigate the LoA of unmanned aircraft system. Here, the higher level of autonomy stands for (1) with less requirements for human involvement for operations in all phases of flight; (2) UAS has better software capabilities to independently perform planning, scheduling, decision-making, etc., making the operations safer, more robust and efficient; (3) UAS has advanced hardware to enable better sensing, perceiving, communication, navigation and surveillance.

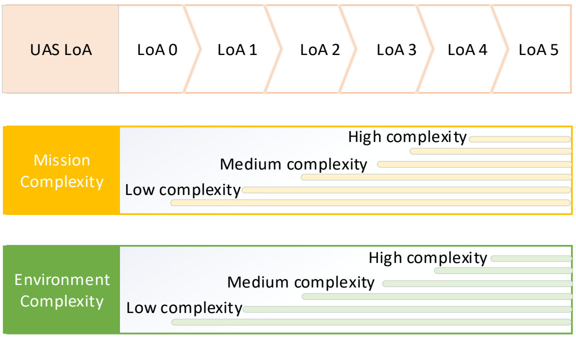

Figure 1. Overall framework of operational capability with LoA, mission complexity and environment complexity

For operators, higher level of autonomy indicates that less human involvement will be required [12], and the UAS can perform missions by itself in most flight situations safely and efficiently. The LoA of the UAS would also affect the workload of the unmanned air traffic control officers (uATCO). Higher level of autonomy makes it possible for UAS to operate cooperatively with trusted planning and decision-making abilities to self-deconflict and to enact contingency plans. Thus, the uATCO would not need to coordinate with operator to ensure safe separation and enforce safety requirements as frequently as needed for managing low LoA operations.

From safety and efficiency points of view, level of autonomy also plays an essential role [27]. With higher LoA, the UAS itself is more capable and reliable so that the first-party risk (operator/pilot) and second-party risk (passenger) can be reduced compared with the lower LoA. What is more, the third-party risk [41] (i.e. ground people, manned aircraft) can also be mitigated because the high LoA is assumed to have abilities to avoid high risk areas by conducting risk-based path planning [42], [43], and by performing conflict resolutions with manned and other unmanned aircraft with advanced DAA capabilities [44]. UAS with higher LoA would also help improve the efficiency of the UTM network. For individual operation, UAS with higher LoA is capable of better allocation of the resources for its mission and able to plan for shorter path [45] and form better air route network with smoother traffic flow [46]. That can shorten travel distance, thus reduce required flight time and energy accordingly. For large-scale operations or swarm operations, higher LoA could help to improve fleet-wide schedule and resource allocation (such as energy and airspace) in order to achieve global optimization, which are hard to be manually managed by operators in real-time due to limited cognitive capability of human. The LoA framework is proposed in the following part which provides description to each level of autonomy.

B. *Framework of LoA*

In the ALFUS framework, the unmanned system (UMS) was defined and proposed as "*A powered physical system, with no human operator aboard the principal categories, acts on physical worked* for *the purpose of achieving assigned tasks*. In this paper, our scope is on the unmanned aerial vehicle, so the Unmanned aircraft Flight Management System (UaFMS) is introduced to autonomously (to varying degrees) perform UAS flight actions. The "operator" control specifically means that flight action control taken by the human UAS operator, whether using RF controller or ground-control station. The unmanned Air Traffic Controller Officers (uATCOs) will not have active control over the UAS and they will only provide traffic services for operator such as traffic monitoring, separation assurance, alert, etc. Finally, the UAS major operational actions (take-off and landing, obstacle avoidance, etc.) will be presented as characteristics to different level of autonomy. Details are depicted in **Figure 2**.

For the description of each level of autonomy, the overall picture of the UAS operations in certain LoA is presented. All of the six LoAs [33], [34] are categorized as two groups based on the primary action control agents (operator or UaFMS). Descriptions for each LoA are presented below.

(1) Level 0: No Automation. The main characteristics of this level are eyes on and hands on, meaning that operator directly control all aspects of the flight and keep Visual Line of Sight (VLoS) of drone operations.
(2) Level 1: Assistive Automation. In this level, operator will be assisted with limited automation capabilities to perform actions like altitude control or obstacle detection warning, but the primary control of the operation is still with the operator.
(3) Level 2: Partial Automation. In the level, operator is allowed to temporarily hands off but eyes on to monitor the operations. The drone itself will have more capabilities to take flight actions like automated takeoff and landing, medium range DAA, etc.
(4) Level 3: Conditional Automation. Come to this

level, the UaFMS will start to take primary control and monitoring, which allows operator temporarily eyes off and hands off. The Beyond Visual Line of Sight (BVLoS) operation can be handled by the UaFMS.

(5) Level 4: High Automation. In this level, automation is the primary control method, with the operator only intervening by exception or only in specific situations (e.g. emergency case), and most of the operational actions will be conducted by UaFMS.

(6) Level 5: Full Automation. This level of autonomy enables fully autonomous UAS operations. Human operator is default to be completely eyes off and hands off. The UaFMS will conduct all actions to ensure the safety and efficiency of the operations.

As to the degree of involvement for UAS flight action control, the two agents, human operator and UaFMS, share the entire authority. As mentioned, the uATCO will not engage in direct flight action control but will only provide operational services to the operator or UaFMS. The control actions will be shared in various degrees by the operator and UaFMS, and they are always inversely proportional. The relationship of them is denoted as $deg_{(\text{operator})} + deg_{(\text{UaFMS})} = 100\%$, where $deg_{(\text{operator})}$ and $deg_{(\text{UaFMS})}$ are the degree of action control by operator and by UaFMS respectively, and their ranges are in [0,1]

The major operational actions which are related to the changes of flight status such as altitude, speed, etc. are presented in **Table I**.

TABLE I. MAJOR UAS OPERATIONAL ACTIONS BASED ON FLIGHT PROFILE

Operational actions	**Descriptions**
Degree of involvement	Operator and UaFMS engage in flight action controls, while uATCO only involves in the provision of traffic services.
Takeoff and landing	Conducting takeoff and landing actions for quadrotor and fixed UASs.
Detect and avoid	Detecting and avoiding obstacles, ranging from static ones (buildings, trees, etc.) to dynamic threats (other UASs, birds, etc.)
Monitor the environments	Having the situational awareness of operational environments as well as the traffic situations.
Fallback when automation fails	Conducting fail-safe actions when automation fails to work.
UaFMS is in control	Flight management system controls the flight and conducts operational actions.

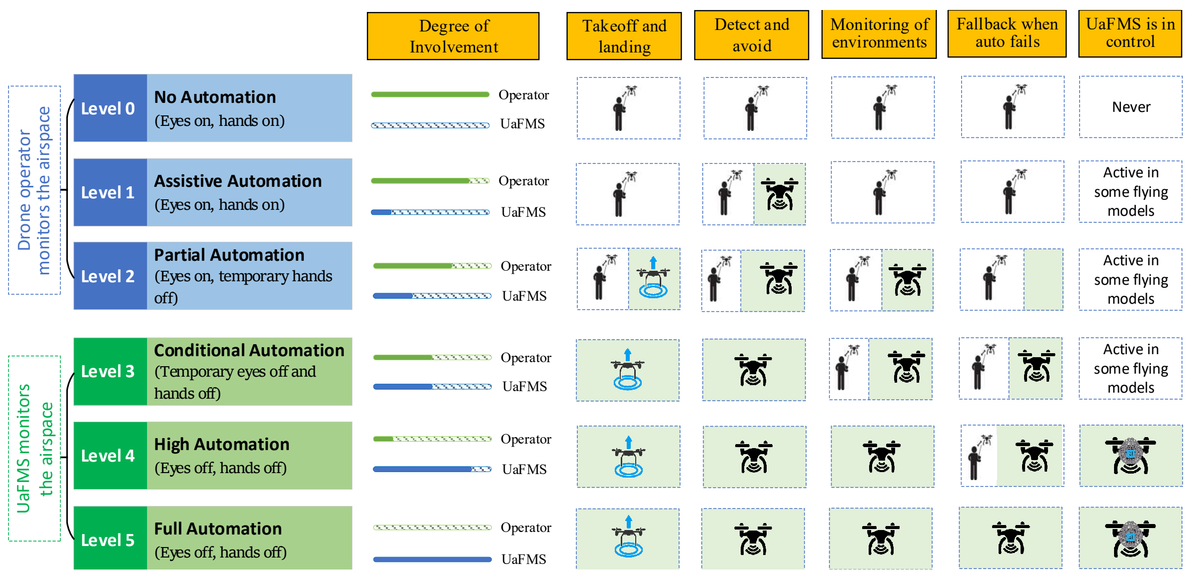

Figure 2. Framework of LoA for sUAS operations (inspired by SAE framework [34])

III. LOA CATEGORIES AND APPLICATIONS

A. Essential categories of LoA

In the previous section, the definition of LoA, degree of control involvement and operational actions are described and discussed. For different level of autonomy, the requirements for human involvement and operational actions are different. Therefore, it is important to investigate the capability requirement for the categories of autonomy. Based on the definition of autonomy [12], the main categories can be categorized into three groups, shown in **Figure 3**.

(1) Human involvement. Operator and uATCO are deemed as the ones who engage in the UAS operation. Requirement for human involvement during flight is one of the key categories to evaluate the capability of the autonomous system. With the increase of LoA, the requirement for human involvement will decrease, and will no longer be required when reaching Level 5, full automation.

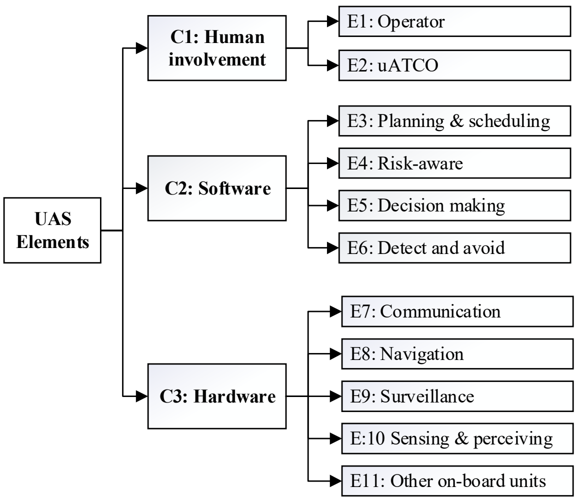

Figure 3. Main categories and elements of unmanned aircraft system

(2) Software. Software performances are those related to control and command, decision-making and acting, which are the essential parts of UAS system. There are extensive research and development (R&D) demands to improve the system capability in terms of planning and scheduling, risk aware system, decision making and acting, as well as the DAA.

(3) Hardware. The hardware performance determines the fundamental capabilities of UAS, and it is the physical building blocks of the UAS. For instance, the sensing and perceiving performance will determine the detect and avoid capability, as well as the planning and scheduling capabilities (these actions need information from sensors). The main hardware categories include communication, navigation, surveillance, sensing and perceiving, as well as other on-board units (i.e. motor, battery).

The performance of these categories and their elements will contribute to the capability of the autonomy system, thus determining the suitable LoA-based operation strategy. The conceptual framework of the capability requirements for each LoA is proposed in **Figure 4**. There are three categories with a total of 11 elements in the LoA evaluation. For each level of autonomy, the capability requirements are different. For instance, level 0 has requirement for full involvement of operator but few requirements for software and hardware capacities. On the contrary, level 5 requires no human involvement, but fully capable of software and hardware performances.

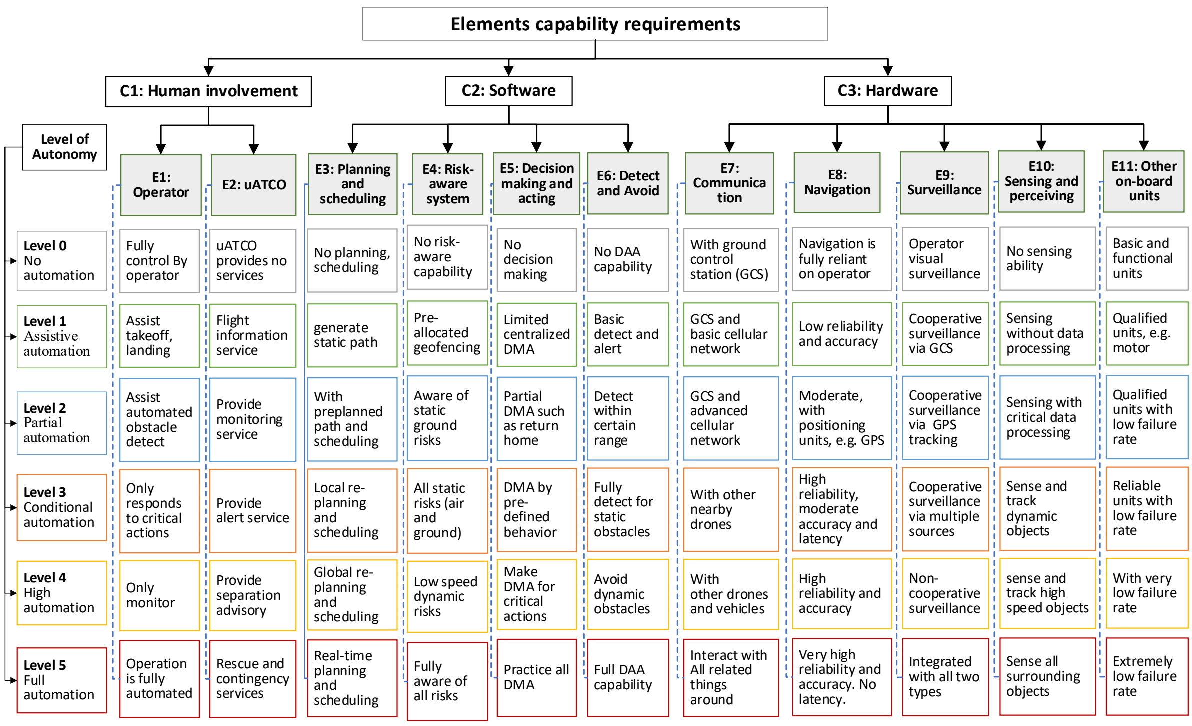

Figure 4. Element capability requirements of respective level of autonomy

B. *Workflow of applying the LoA framework*

This part will discuss the workflow of the LoA framework to facilitate UAS development, illustrated as **Figure 5**. There are seven main steps to apply the LoA framework.

(1) Input information. The information of operation types and missions will be collected as input data. The capability specifications (sensor, CNS performance, etc.) of the UAS should also be obtained and evaluated based on the proposed LoA capability requirement framework (**Figure 4**).

(2) Based on the proposed LoA capability requirement framework, the LoA for each element of these UASs will be assessed and determined the achievable level for each element.

(3) The LoA of system, as introduced, will be determined by the element(s) which has/have the lowest level of autonomy, namely those elements that are incapable of meeting the required LoA for particular operation.

(4) Once the overall system's LoA is obtained, a comparison will be made against performance-based threshold for desired autonomy level for a particular operation to determine if the operation could be carried out at the desired fashion. For instance, the LoA 4 is supported, then the operation can be conducted without operator involvement, while the uATCO will also not be required to monitor the flight separations between UASs. If not, the capability of the undesired elements will need to be improved.

(5) Capability level improvement. There are several domains that could be improved to increase the capability levels of the underperforming elements. For the operation, the more capable and skilled operator can be employed to perform UAS operations in a more demanding and complex environment. Regarding to research and development (R&D) sides, innovative method, algorithms and management can be used to ensure the safer operations. The engineering, of course, can contribute to the improvement of element's LoA by producing higher quality of products such as on-board CNS units.

(6) The improved elements will have higher LoA with higher capabilities, and they will be updated as new input information in the proposed process.

(7) The process will end with that the obtained LoA meets the desired autonomy level and that LoA will be outputted and implemented for the UAS operations.

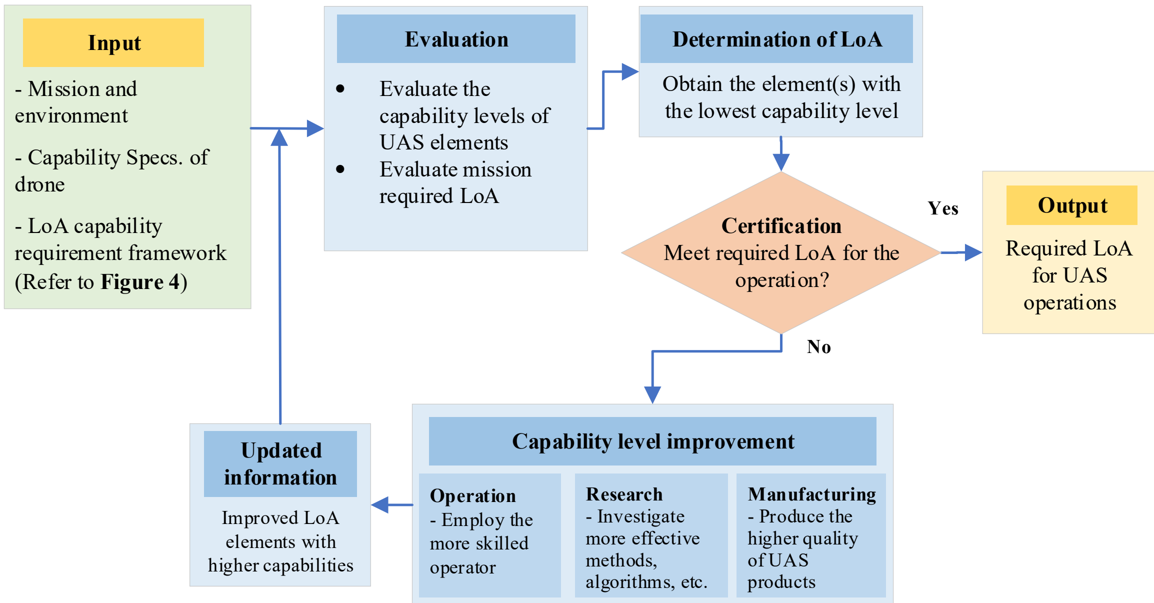

Figure 5. Evaluation of LoA for UAS operations

Above is a generic implementation of the proposed LoA framework. More specific framework can be further developed on a case-by-case basis.

IV. CASE STUDIES

In the previous sections, we proposed the conceptual framework of LoA, the capability requirement for LoA categories, and the foundation of each LoA categories from the application point of view. The proposed LoA concept is an enabler that can be tailored and extended for different UAS applications for different stakeholders. This section will discuss how the proposed ConOps might be applied and used to particular areas to facilitate UAS operation, research, manufacturing, etc. The parcel delivery case and an emergency case will be used to demonstrate the LoA-based ConOps.

A. *Case 1: Parcel delivery*

An example for the considerations involved in the evaluation of the LoA can be seen in **Figure 6**. In this example, a delivery mission is scheduled to take place along a dedicated air-route for cooperative traffic that passes in the vicinity of a park, leading to a low, but not zero, probability of encounter with non-cooperative recreational UAS. One of the commonly used industrial-level drones is selected [47], and the main capability specs of the drone are presented in **Table II.**

Assuming that operating on the air-route does not require the filling of a separate flight plan, the pre-flight preparation would only involve the uploading of waypoint to the UAS by the operator (E1); in the case of Pilot Interface for AirMatrix, the operator would be given a selection of acceptable waypoints for the selected start and end points, thus could be considered as LoA 2 capable.

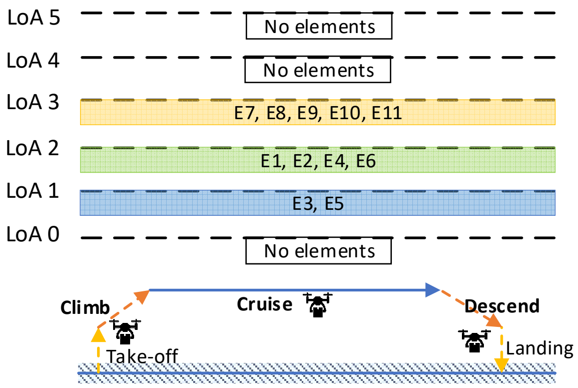

Figure 6. Required LoA for respective elements throughout the whole flight phase. The LoA of the elements are: (1) LoA 1: E3, E5. (2) LoA 2: E1, E2, E4, E6. (3) LoA 3: E7, E8, E9, E10, E11. Note that there are no elements with LoA 0, LoA 4 or LoA 5 in this case.

As the UAS prepares to take-off and join the air-route, the operator would need to communicate with the controller (uATCO) to obtain take-off clearance and merge permission; this could be accomplished under LoA 2 as the clearance issuance (handled by uATCO, E2) and operation commencement (taken care by Operator, E1) are assisted by the AirMatrix backend, thus be considered as LoA 2 capability.

Several LoA evaluations would need to be conducted for the cruise phase of the delivery mission, such as hardware elements (E7, E8, E9, E10, E11). As the parcel delivery mission is considered as BVLOS operation, the required LoA capability for hardware elements are given as LoA 3. While for software elements, there are not too much planning and decision-making during flight as the flight plan has been made and uploaded before the mission. The required LoA for software elements (E3 and E5) are considered as LoA 1. Bur for elements E4 and E6, there are requirements for risk-aware system and basic DAA capabilities to detect and alert. So, the required LoA for E4 and E6 are taken as LoA 2.

The LoA capability of the (UAS) onboard separation assurance system and/or procedure would also need to be assessed for cooperative (E3, E4, E5) and non-cooperative (E4, E5, E6, E10) operations; the former assumes that all traffic tracking data are available through the data link to the automated UTM backend with no uATCO involvement, while the latter depends on the sensors suites available and capability of UaFMS. Finally, the clearance for departing the air-route and joining the landing sequence would involve communication between UAS operator (E1) and uATCO (E2) following similar procedure as the take-off phase. The post-flight "check-out" from the Pilot Interface would involve only the operator (E1). As show in **Table II**, the required LoA of each element for parcel delivery mission does not exceed the drone capability, meaning that the drone is able to perform the parcel delivery mission in this case.

TABLE II. OPERATIONAL REQUIREMENTS OF AUTOMATION LEVEL FOR DIFFERENT APPLICATIONS

LoA elements	**Achievable drone capability**	**Required LoA capability Case 1: Parcel delivery**	**Required LoA capability Case 2: Emergency mission**
E1: Operator	LoA 3	LoA 2	LoA 3
E2: uATCO	LoA 4	LoA 2	LoA 3
E3: Planning and scheduling	LoA 3	LoA 1	**LoA 4**
E4: Risk-aware system	LoA 2	LoA 2	**LoA 4**
E5: Decision making and acting	LoA 3	LoA 1	**LoA 4**
E6: Detect and Avoid (DAA)	LoA 2	LoA 2	**LoA 4**
E7: Communication	LoA 3	LoA 3	LoA 3
E8: Navigation	LoA 4	LoA 3	LoA 3
E9: Surveillance	LoA 3	LoA 3	LoA 3
E10: Sensing and perceiving	LoA 3	LoA 3	LoA 3
E11: Other on-board units	LoA 3	LoA 3	LoA 3

B. *Case 2: Emergency mission*

Another case for the application of LoA evaluation for UTM operation would be a non-scheduled inter-hospital emergency transportation of time-critical medical supplies such as blood bags or donated organs.

As the flight plan is unscheduled and not conforming to established air-routes, the pre-flight process would involve the coordination of the operator and the uATCO to clear the airspace and allocate the waypoints. Alternatively, upon receiving the affirmative instruction by the operator, the UAS could automatically accept and load the waypoints assigned through the dynamic rescheduling functional of the AirMatrix UTM system. In either case, the pre-flight phase could be considered as LoA 3. Since the time span between the flight plan submission ((taken care by Operator, E1)) and clearance issuance (handled by uATCO, E2) would be short with the nature of such mission, considerations for LoA evaluation for the pre-flight and takeoff phase could be done in tandem with similar results.

For emergency transport missions with uATCO (or automated UTM system) assistance and the allocation of dedicated air-lane, the elements that need to be considered during the cruise phase could be reduced, such as the case with cooperative separation assurance. As the dynamic rescheduling and re-planning during the pre-flight phase would already move all cooperative traffic out of the assigned path of the emergency vehicle, the elements involved in cooperative separation assurance would not be considered in the LoA evaluation. On the other hand, assuming that the assigned path for the emergency vehicle is over the central business district airspace with flight restriction for non-cooperative traffic and far enough from recreational airspace to prevent accidental incursion, the evaluation of elements related to non-cooperative separation assurance could be overlooked as well. Thus, the cruising phase would only involve the evaluation of hardware and software capabilities of the UAS for LoA determination.

Assuming that the landing and post-flight phase follow similar procedures to the pre-flight and takeoff phase of the flight, the overall mission of LoA evaluation would involve considering the LoA capability of the operator, the available information from uATCO, and the hardware and software capabilities of the UAS. For this mission, the required LoA of all hardware element (E7-E11) could be considered as LoA 3. While the software is at LoA 4 (E3-E6). The required LoA of each element for emergency mission is given in **Table II**. The achievable drone capability for software elements (E3-E6), in this mission, is unable to meet the required LoA. For instance, the required LoA for DAA in emergency mission is LoA 4, but the drone capability can only support LoA 2 DAA. To this end, the drone used in this case is unable to perform emergency mission.

To be able to conduct the emergency mission, they are several ways to improve. One is to use another more advanced drone, which has better capabilities that can meet all required LoA of this mission. Another is to reduce the required LoA by mitigating the operational risks in the environments of this mission performs, or by reducing the mission complexity through proper planning such as direct and single trip, which has less requirement for decision making of drone.

C. Complexities of mission and environment

For different use cases, as given in this work, their mission complexity and environment complexity are different. That makes the required LoA of specific operation different. As **Figure 1** illustrated, with the increase of the complexities, the required LoA for drone system to perform mission increases. In other word, higher LoA of UAS could enable more complex missions in tougher environments.

The UAS capability, mission complexity and environment complexity are three key contributors to determine the overall autonomy level for operations. To enable more autonomous UAS operations, there are two approaches to explore. One is to improve the UAS capabilities such as hardware and software ones. The other is to reduce the mission and environment complexities through proper planning and management, which reduce the required LoA of operations.

V. CONCLUSIONS

Thanks to the fast-developing technologies, it is now possible to enable UAS operations with certain level of autonomy, and to envision a future with fully autonomous operations by leveraging emerging technologies. However, to achieve the fully autonomous operations, there are still several technical challenges need to be met, ranging from the globally recognized definition of autonomy, terms and terminologies to the evaluation and certification of LoA-based operation. Technology limitations also play a major role of evaluating LoA, involving hardware capabilities like sensor and power units, as well as software capabilities such as planning and decision making. To describe and evaluate each level of autonomy, a specific framework is required to measure the autonomy and to assess the products obtained and research conducted for UAS operations.

This paper described a conceptual framework of LoA with considerations of human involvement, software and hardware capabilities. The operational actions are regarded as benchmarks to define and describe the main characters of different LoA. Under the three major categories of human interaction, hardware, and software, 11 elements are presented and the capability requirements for each element have been discussed and evaluated. Use cases are given to demonstrate the potential application of the proposed LoA framework.

The proposed categories and the associated elements are expanded with detailed description to support LoA evaluation for UTM and UAM operations. The control and monitoring are assigned to human operator and UaFMS, of which the ratio of contribution is inversely proportional, and the amount of control involvement can be determined by the phase of flight and operational actions. As the LoA increases, the primary control agent will shift from operator to UaFMS. Meanwhile, the uATCO is seen as service provider to offer traffic information and other services to the operator or UaFMS. Four main software elements are elaborated with detailed descriptions and capability requirements. Some ConOps of the software elements are discussed such as planning, scheduling and separation assurance. Similarly, the hardware elements are discussed with their functionality and capability.

The goal of this paper is to propose a new concept/framework, although it currently lacking sufficient validation/experimental data to support the proposed ConOps. Some descriptions of the proposed LoA framework can be further defined and improved, while the capability requirement for each element requires quantitative results to better evaluate the LoA. The development of the certification for LoA-based operation would also be needed, possibly using simulation-based method to evaluate the LoA using role-based or performance-based thresholds. In all, much more efforts are needed to increase the autonomy of UAS operations to further expand their utilities in various sectors of life and to enable a safer and more efficient UAS traffic, which could have more operational demands met.

With the timeline for introducing fully autonomous ground vehicle not expected before the 2030s [48], we could see more time needed for the practical deployment of LoA 5 UAS operations due to the tougher challenges on operational environments, regulatory issues and technology limitations. Regardless, it is still essential for us to develop the ConOps capable of managing UAS of various LoA capabilities as the challenges been solved.

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