Hazard Analysis and Safety Requirements for Small Drone Operations: To What Extent Do Popular Drones Embed Safety?

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Currently, published risk analyses for drones refer mainly to commercial systems, use data from civil aviation, and are based on probabilistic approaches without suggesting an inclusive list of hazards and respective requirements. Within this context, this article presents: (1) a set of safety requirements generated from the application of the systems theoretic process analysis (STPA) technique on a generic small drone system; (2) a gap analysis between the set of safety requirements and the ones met by 19 popular drone models; (3) the extent of the differences between those models, their manufacturers, and the countries of origin; and (4) the association of drone prices with the extent they meet the requirements derived by STPA. The application of STPA resulted in 70 safety requirements distributed across the authority, manufacturer, end user, or drone automation levels. A gap analysis showed high dissimilarities regarding the extent to which the 19 drones meet the same safety requirements. Statistical results suggested a positive correlation between drone prices and the extent that the 19 drones studied herein met the safety requirements generated by STPA, and significant differences were identified among the manufacturers. This work complements the existing risk assessment frameworks for small drones, and contributes to the establishment of a commonly endorsed international risk analysis framework. Such a framework will support the development of a holistic and methodologically justified standardization scheme for small drone flights.

1. INTRODUCTION

The drone market contributes billions of dollars to economic growth. By 2021, it is expected that the market of unmanned aerial systems (UASs) will have a value of $4.8 billion worldwide.[1] Although

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a broad range of industries use drones (e.g., agriculture, energy, mining, construction, real estate, news media, film production), the highest growth in the drone industry regards commercial and civilian applications. In the United States alone, the market for commercial and civilian drones is expected to grow at a compound annual growth rate of 19% between 2015 and 2020;[2] however, it seems that the increase of drone sales has brought new safety challenges. Aviation authorities and police departments have been receiving reports of drones flying near airplanes and helicopters, or close to airports without permission.[3] In the last two years, there has also been a sharp increase in reporting such events.[4–6] In these cases, mid-air collisions are a major risk, and

security breaches are a major source of concern. In addition, injuries and property damage resulting from drone flights over populated areas are not unusual. Small drones are affordable and capable of carrying cameras, lightweight cargo, or other equipment over areas where people on the ground are unaware of drones flying overhead.

Having recognized the risks posed by drone operations, a wide spectrum of stakeholders such as military, police, civil aviation authorities, companies, and manufactures have developed or used anti-drone procedures, measures, and technology. For example, Dutch police departments have trained falcons to attack small drones;[7] tracking systems[8] have been developed to follow small, unmanned vehicles and jam their sensors and signals,[9] leading the drone to crash; nets operated by humans on the ground[10] or airborne robots[11] can be employed against drones. Recently, the Federal Aviation Administration (FAA) has tested a defense system that has been selected for evaluation at U.S. airports as part of its Pathfinder Program.[12] This program is designed to evaluate technologies that can be used to detect and identify unauthorized unmanned aerial vehicles (UAVs) or drone flights near airports.

Although accident and incident reports unveil the potential for drones to threaten public safety if not managed properly, it seems that a reactive approach has been adopted. Yet, a common regulatory framework based on a systemic risk assessment is missing. The majority of the directives and regulations applied in different countries focus on the drone user, without having completely addressed the design and certification of small drones or the responsibilities of the authorities.[13] Furthermore, as presented in the literature review and discussed in the following sections, published hazard analyses are not obviously based on systemic approaches that address, in a holistic manner, the responsibilities of all actors contributing to drone flights, such as manufacturers, authorities, and drone operators.

Taking into account the safety challenges in small drone operations and the absence of a corresponding comprehensive risk analysis framework, this article presents the complete results of a preliminary study;[14] its scope is fourfold. First, it presents a set of safety requirements generated from the application of the systems theoretic process analysis (STPA) method and assigned to the authority, manufacturer, operator, and drone automation levels. Second, we present a gap analysis between the set of safety requirements and the ones met by 19 popular

drone models to show how much safety those models "embed." Third, we present a statistical comparison of the same drone models pairwise on the basis of the safety requirements they meet, as a means to present the extent of the respective differences, and we search for any variations across manufacturers and countries of origin. Fourth, we explore the association of drone prices with the extent they meet those requirements.

The results from the analysis of the drone models suggest low to moderate fulfillment of the safety requirements derived by STPA and remarkable differences among the drone models studied, especially regarding the ones produced by different manufacturers. In addition, the results from statistical calculations indicate that the drones with a higher market price meet more safety requirements from those suggested in our study. The set of the safety requirements derived by the STPA might serve as a reference for a harmonized approach to small drone design, certification, and standardization.

2. LITERATURE REVIEW

2.1. Published Hazard Analysis for Drone Operations

Dalamagkidis *et al.*[15] considered a UAS regulatory system as vital for assuring appropriate levels of safety. More specifically, they adopted a comparative perspective, according to which a model for assessing the UAS-related risks would be derived from the evaluation of safety performance of manned aviation. They suggested that statistical analysis of historical data on the fatality rates of manned aviation could be the basis for defining an equivalent level of safety for UASs; hence, they reviewed various regulations, standards, and documentation for manned aircraft. Furthermore, Dalamagkidis *et al.*[15] questioned the reliability of UASs in terms of automation, based on the argument that UASs introduce new failure modes. They also mentioned that, should the components of the system be sufficiently reliable, the whole system would be compliant with a target level of safety. In practice, targets were seen as a risk reference system where events were categorized by severity and likelihood. Relying on statistics, the "best available estimate" was also suggested. It should be noted that, although Dalamagkidis *et al.*[15] embraced a reliability assessment, carrying out a failure modes and effects analysis and a fault tree

analysis (FTA) for particular UAS models, they acknowledged the existence of a gap in data availability when newer systems might not yet have exhibited failures, which in turn may lead to accidents. Conclusively, the aforementioned authors linked directly the reliability of UASs with their safety. It is also worth mentioning that Dalamagkidis et al.[15] took into account cost tradeoffs, and pointed out that strict UAS operation requirements can seriously impede the commercialization of UASs.

Similarly, Hosseini et al.[16] defended the notion that when there are insufficient data to develop a good estimate of probabilities, then probability mathematics will be ineffective in developing a safety management system about drones. Instead, they proposed a multidisciplinary design optimization algorithm for the technical parts of heavy UASs. The aim of their work was to provide system engineers with a tool that facilitates the understanding of compromises in the design process to identify the optimal solution. According to Hosseini et al.,[16] compromises are usually necessary to minimize resource and technology costs. Using Monte Carlo simulation, system engineers can design the most reliable UAS that meets most of the operational requirements and matches resource constraints. Clothier and Walker[17] presented a risk management framework for UASs with reference to international standards,[18–20] and they discussed the primary and secondary hazards. The latter type of hazards might result from the former, might be linked to contributing failures and conditions, and the whole set of hazards and causal factors can be derived with methods such as functional hazard analysis, hazard and operability analysis, and failure modes and effects analysis; however, an exhaustive list of hazards and contributing factors especially for UASs was not provided. The aforementioned authors suggested a probabilistic approach (i.e., severity and likelihood estimations), and adopted the as-low-as-reasonably-practical principle for the mitigation of risks. Aligned with Dalamagkidis et al.,[15] Clothier and Walker[17] provided examples of accepted level of safety criteria stated in various guidance material and state documents, and they proposed a list of equivalent levels of safety based on statistical analysis of data from manned aircraft.

In 2005, Kuchar[18] published a work about new methods for ensuring collision avoidance between UASs. The author used FTA in combination with dynamic simulation. The former was used to model the outer-loop system failures or events, which, in turn,

defined the environment for a Monte Carlo inner-loop simulation of a close encounter. For example, the probability that an encounter would occur in visual conditions can be estimated in the fault tree, and the probability of mid-air collision for that type of encounter can be computed in a detailed fast-time simulation. In the aforementioned work, it was argued that results can be combined afterwards in a fault tree with corresponding performance data and probabilities for other conditions, including intruder aircraft equipage, and system failures, thus leading to a global estimate of system safety. Lee et al.[19] were also concerned with the probabilistic safety assessment of UAS operations. They developed a distributed UAS traffic model using actual data provided by the U.S. Air Force and collected over a one-year period. Afterwards, they computed the collision rates, which were defined by the number of collisions per unit time of UAS operation. The results were for specific scenarios, and they suggested that collision rates during high-traffic activity remain high.

Johnson[20] used the events and causal factors accident analysis technique to identify various ways in which human factors contributed to the loss of a heavy UAS flown for military purposes. He noted that the increasing reliance on autonomous and unmanned operations signifies the importance of other aspects of human-system interaction as a causal factor of major incidents. Wild et al.[21] performed a postaccident analysis for 152 accidents to identify the safety deficiencies specific to UASs. Accident data were collected from 2006 to 2015 for all UASs regardless of their weight. With the use of statistical analyses, they found that most of the occurrences resulted from system component failure and inadequate human performance, which jointly led to a loss of in-flight control in most cases. To improve safety in the UAV industry, Wild et al.[21] suggested that legislation should enforce reporting of accidents and incidents of all UAV categories, and they emphasized the type of information to be reported to allow the recognition of patterns in future studies. Loh et al.[22] addressed topics concerning the development of future UASs so that they can operate safely, complying at the same time with the FAA requirements. This was mainly a discussion paper that pointed out the need for UAS developers to understand safety certification for operations in U.S. airspace. They claimed that safety certification starts with safety requirements, safety design, safe development processes, safety verification, and

safe operating procedures in the planned operational environment.

2.2. The Systems-Theoretic Accident Model and Processes Model and Systems-Theoretic Process Analysis Technique

Leveson's[23] Systems-Theoretic Accident Model and Processes (STAMP) is a relatively new type of accident model based on systems theory; it extends traditional analytic reduction and reliability theory. The model mainly advocates that accidents occur in the context of complex, dynamic processes; thus, they are not merely the results of chains of component failures. Rather, safety is an emergent property that arises when components or subsystems interact with each other within a larger system, without neglecting the importance of reliability of individual components or systems with simple architectures.

STAMP views systems as interrelated components kept in a state of dynamic equilibrium through feedback control loops, but it also examines systems that are not in equilibrium and migrate toward states of higher risk. As illustrated in the control loop of Fig. 1, a system controller (human or automated) that uses a defined algorithm controls a process (or more processes depending on the system) through actuators, and receives data or information from sensors to update the process model. In the glossary of STAMP, the process model includes the desired system state and receives information about the actual system state so that the controller can decide whether the processes under responsibility require adjustment to meet predefined objectives. Possible hazardous scenarios determine which data from the controlled process are important to collect in terms of monitoring and adjusting the system in a timely manner, and to delimit the responsibilities of the controllers. In Fig. 1, the three principal elements are depicted: the controller who enforces constraints in order to ensure the safety of the system under control. The controller issues commands through actuators that execute the commands in order to control the process, and the sensors take readings from the controlled process and feed the controller with data or information.

Systems-theoretic process analysis (STPA)[24] is a hazard analysis technique that encapsulates the principles of the STAMP accident causality model. STPA is a top-down system engineering approach to system safety that can be used early in the system development to generate high-level safety requirements and constraints. In fact, it does not generate a probability number related to a hazard because the only way to generate such a probability of an accident for complex system is to omit important causal factors that are not stochastic or for which probabilistic information does not exist. Contrariwise, STPA identifies unsafe control actions and aims to examine scenarios or paths to accidents. STPA also includes those causal factors not included or poorly handled by traditional hazard analysis methods, such as software requirement errors, uncontrolled component interactions, human decision-making flaws, inadequate coordination among multiple controllers, and flawed management and regulatory decision making.[25] Safety is thus treated as a dynamic control problem, rather than solely as a component reliability problem.

STPA is preceded by the definition of accidents, high-level hazards, safety requirements for the system under study, and the drawing of the safety control structure. Those steps stem from the STAMP model. Thereafter, the hazard analysis is performed in three main steps:

1. Identification of hazardous states that might result from inadequate control or enforcement of the safety constraints, namely, an unsafe control action (UCA), because:
   a. A control action (CA) is not provided.
   b. A CA is provided but generates a hazard.
   c. A CA is provided too early, too late, or in a wrong sequence.
   d. A required CA is stopped too soon or applied too long.[4]
2. Determination of how each UCA identified in the previous step could occur by examining the possible contribution of the control loop components (Fig. 1).
3. Determination of how a control action that is performed in a "safe" context might not be followed or executed properly (Fig. 1).

The identification of system hazards, causal factors, and causal scenarios leads to the statement of safety requirements, which must be collectively in place to ensure the safety of the system and can be used as a means to test the rigorousness of the system and to unveil any unidentified flaws.[5]

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[4](a) and (b) apply to discrete, binary control actions; (c) and (d) apply mainly to continuous control actions.
[5]See http://psas.scripts.mit.edu/ for an extensive collection of studies and applications of STAMP/STPA.
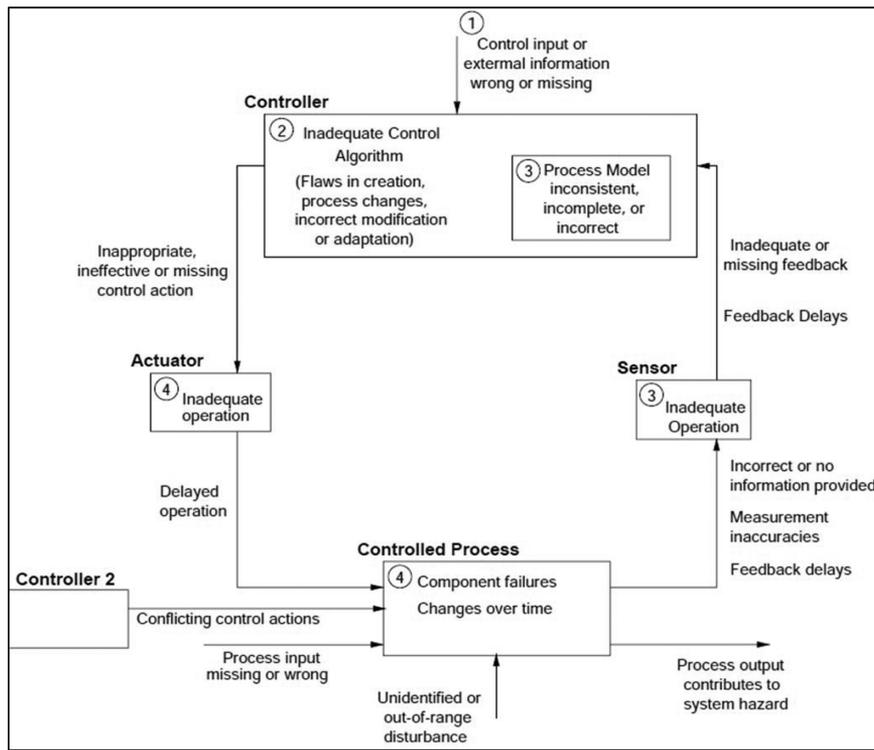
Fig. 1. A standard control loop and associated causal factors.[23]

3. METHODOLOGY

To identify the hazards and the associated causal factors in the operation of a small drone system and to derive respective safety requirements, the authors applied STPA. The specific technique was chosen because of its analytic power, as explained in Section 2.2. The following assumptions were made as a means to define the system under study and the research scope:

- The drone system is not subject to civil aviation requirements (i.e., drone weights less than 25 kg for the United States and 20 kg for the European Union according to current regulations or legislation).
- The drone system consists of a remote controller, the drone, and a display. The display is used for monitoring telemetry data and is sometimes part of the remote controller (e.g., software application in a smartphone).
- The drone is a rotary aircraft and is therefore not subject to aerodynamic limitations.
- Mission losses due to factors other than degraded safety were not addressed.

- Collisions with flying fauna were not considered.
- The drone system was analyzed down to the level of end user and drone interaction. Further decomposition (e.g., architecture and links of software and hardware subsystems) was beyond the scope of this study.

To perform the analysis, we conducted the preliminary steps of STPA (Table I), and drew the safety control structure (Fig. 2).

Next, the authors identified the UCAs (i.e., STPA Step 1), the causal factors (i.e., STPA step 2), the safety requirements for a small drone system structure (Fig. 2), and the system controllers of higher order (Fig. 3). Those requirements were suggested as a means to eliminate or mitigate the causal factors or unsafe situations, identified through STPA. As shown in Fig. 3, the aviation authority and the manufacturer are considered as parts of the wider safety control structure. Although this study concentrates on the generation of safety requirements that are related to the UASs, we derived requirements that were assigned to the aviation authority and the manufacturer, in line with the systems

Table I. Preliminary Steps of STPA

Accident definition: Injuries or property damage resulting from the operation of a drone

High-Level Hazards	High-Level Safety Requirements
[H1]: Unsafe separation from terrain or objects on ground during controlled flight	[SR1]: Drone shall maintain a safe separation from terrain or objects on ground.
[H2]: Uncontrolled flight over congested area	[SR2]: Drone shall be controlled during flight.
[H3]: Unsafe separation from other powered flying objects during controlled flight	[SR3]: Drone shall maintain a safe separation from other powered flying objects.
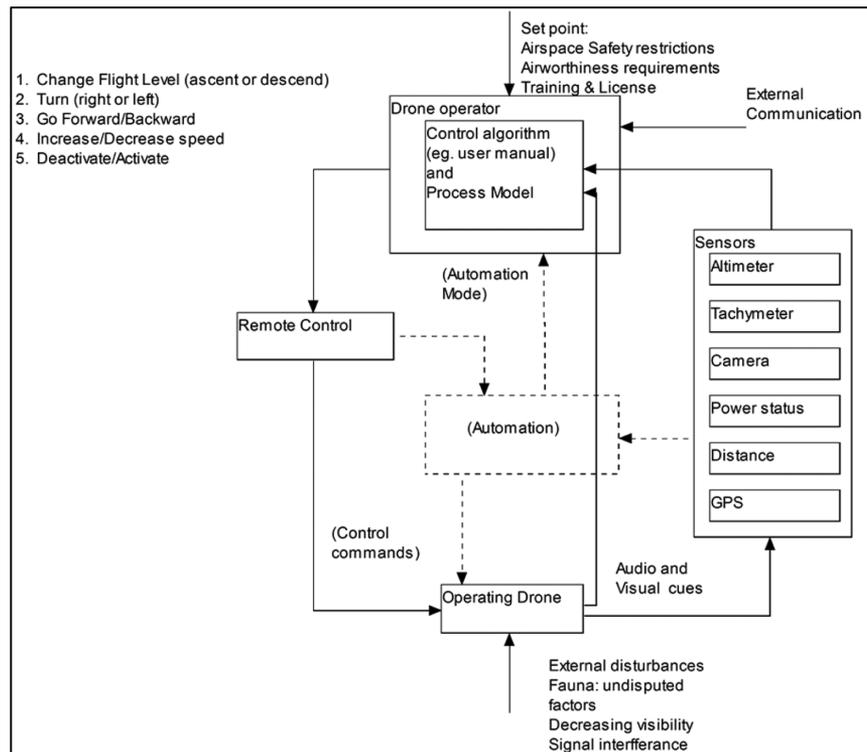
Fig. 2. Control structure for a generic small-drone system.

approach of STAMP. In this manner, the researchers demonstrated the top-down enforcement of safety constraints supported by STPA. Nonetheless, a full STPA analysis of the authority and manufacturer levels was beyond the scope of this study; therefore, an analysis of the control actions, their unsafe states, and the corresponding causal factors and scenarios are not included.

The STPA steps were performed iteratively and they were peer reviewed by the researchers to ensure the quality and robustness of the results, by effectively combining technical knowledge in aviation and experience in the application of the method. The

analysis presented in this article is traceable through respective coding to be understood easily and possibly revised in future studies. It is noted that although Step 2 of STPA is typically followed by the development of scenarios that include combinations of multiple conditions under which control actions might be proved hazardous or ineffective, it was beyond the scope of this study to present a list of all possible scenarios; however, a few examples are provided in Section 5. The generation of causal scenarios is a critical element of the analysis, and it actually completes the STPA results in the sense that such scenarios represent the complex dynamic relationships among many
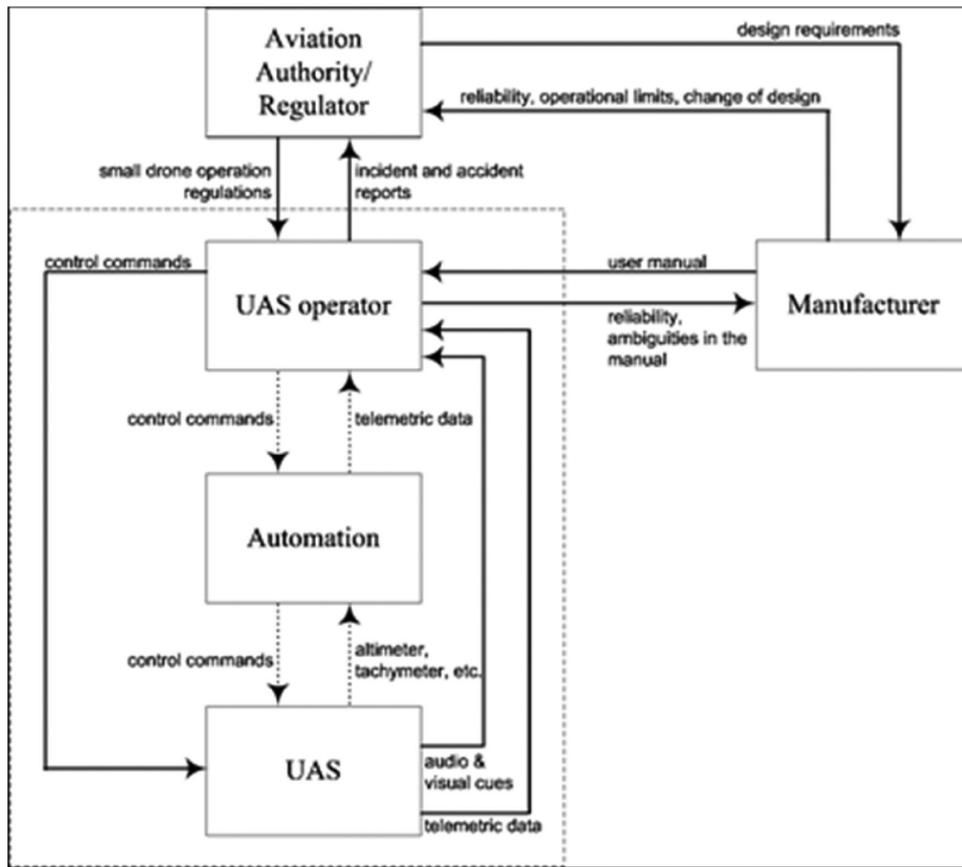
Fig. 3. High-level hierarchical structure.

factors. The system must be tested against those scenarios to validate its safety, even when all individual safety requirements derived from STPA are met.

Because of the different levels of authority over the safety requirements across the system controllers, those requirements were grouped into four categories, each one corresponding to each of the "controllers" of the system under study: authority, manufacturer, end user, and drone automation. Thereafter, a gap analysis between the list of requirements generated by the application of STPA and the specifications of 19 small drones was performed for the manufacturer, end user, and automation. Concerning the authority level, a comparison across regions was performed by Plioutsias *et al.*[13] The selection of drone models was based on the availability of manuals on the Internet and their sale volumes, and they correspond to 10 different manufacturers. The gap analysis resulted in the frequencies of requirements that the 19 small drones met as a first indication of the extent to which those drones embedded

safety "by design." Those frequencies were also used to perform a Kruskal–Wallis test as a means to examine whether the requirements met are significantly different across the countries of origin of the examined drones and across various manufacturers (i.e., for the ones whose two or more drone models were included in this study).

Furthermore, similarity measurements were conducted among the 19 drones and pairwise (e.g., drone 1 with drone 2, drone 1 with drone 3), aiming to reveal the extent to which those drones fulfilled the same safety requirements. The comparison was performed with SPSS version 22[26] with the use of the intraclass correlation coefficient (ICC) under the settings: two-way mixed, absolute agreement, test value $= 0$, confidence level 95%. The values of the coefficient range from 0 (i.e., absolute disagreement) to 1 (i.e., absolute agreement). Moreover, we applied Spearman's correlations to explore whether there was an association between the ratio of the requirements' fulfillment per type of controller and

the market prices of the 19 drones. The results of the test would offer an indication of the relation between purchase cost and the safety embedded in the drones studied. The market prices were retrieved twice (April 2016 and May 2017) from the official website of each vendor. A significance level of 0.05 was used for all statistical calculations.

4. RESULTS

The application of Step 1 of STPA resulted in 20 UCAs for the nine CAs (Appendix A), and 31 causal factors (CF) leading to UCAs or rendering CAs ineffective were identified through Step 2 (Appendix B). The connections of CA and UCAs with the CFs are provided in the aforementioned appendices. Examples include:

- UCA-1 "Operator does not provide ascend command when drone approaches lowest limit of range area" can lead to the high-level hazard H1 (see Table I) and be caused by inadequate functioning of the display and drone data transmission (CFs: 1b, 1c, 2b, 2c, 3b, 3c, 4d, 4c), inadequate communication in the channel between drone and display (CFs: 5b, 6b), ineffective communication between the operator and the display (CFs: 7, 8, 9), or inadequate UAS operator performance (CFs: 10a, 10b, 10c, 11a, 11b, 12, 13, 16, 17, 18).
- CA2 "Descend" can be provided under safe conditions, but could be ineffective because of inadequate functioning of the remote controller and the data reception and flying systems of the drone (CFs: 1a, 1c, 2a, 2c, 3a, 3c, 4a, 4c), inadequate communication in the channel between the remote controller and the drone (CFs: 5a, 5b), or insufficient battery level (CFs: 19, 20).

It is noted that the causal factors can be detailed further according to the analysis needs and the particular drone model under study. Considering the list of UCAs and causal factors, 70 individual safety requirements were derived, as shown in Appendix C, where the CFs, UCAs, and ineffective CAs to be addressed by each requirement are also presented. Furthermore, each requirement was assigned to one of the controllers—namely, the authority, manufacturer, end user, and drone automation—and in each case the corresponding responsibility was stated (see respective table columns in Appendix C). The types of responsibilities are explained in Table II.

Table II. Types of Responsibilities per Controller

Responsibility	Controller	Task/Responsibility
Regulate	Authority	Includes the requirement in respective standards, regulation, and legislation
Document	Manufacturer	Documents the requirement and the respective specifications in the drone manuals
Define	Authority	Defines the value needed for the realization of the requirement and includes the value in the respective standards and regulatory framework
	Manufacturer	Defines the value needed for the realization of the requirement and includes it in the drone documentation
Act	Authority Manufacturer End user Automation	Operationalizes the requirement
Informed	End user	Knowledgeable of the requirement or respective specification
Support	Automation	Operationalizes the requirement on behalf of the operator when in automation mode

The analysis of the manuals accompanying the 19 drones under study resulted in the ratios of requirements met per model and controller, as presented in Table III. At the manufacturer level, model number 14 scored highest by meeting approximately 78% of the requirements, and model number 11 met the fewest requirements—approximately 30% of the ones derived by STPA. Regarding end users, model number 14 fulfilled approximately 75% of the requirements and drone number 11 fulfilled only about 29% of them. Regarding drone automation, model number 14 supported the safe operation of drones by meeting approximately 79% of the requirements, whereas model number 11 fulfilled approximately 21% of the requirements. The Kruskal–Wallis test did not show differences resulting from the country of origin of each drone in regard to the ratio of safety requirements that the 19 drones met per type of controller. However, significant differences were found among the four manufacturers producing more than one model studied in this research (manufacturer level: $N = 4$, $p = 0.039$; end-user level: $N = 4$; $p = 0.036$; and automation level: $N = 4$, $p = 0.028$).

Table III. Ratios of Requirements Met per Controller

Drone Model	Manufacturer Code	Requirements Met per Controller		
		Manufacturer	End User	Drone Automation
1	M-1	0.565	0.462	0.421
2	M-2	0.739	0.662	0.763
3	M-2	0.739	0.677	0.763
4	M-3	0.667	0.631	0.605
5	M-3	0.464	0.431	0.421
6	M-3	0.638	0.600	0.632
7	M-4	0.478	0.446	0.421
8	M-1	0.638	0.585	0.526
9	M-5	0.507	0.492	0.342
10	M-6	0.319	0.323	0.500
11	M-7	0.304	0.292	0.211
12	M-8	0.623	0.615	0.316
13	M-9	0.363	0.354	0.342
14	M-2	0.783	0.754	0.789
15	M-10	0.638	0.585	0.553
16	M-10	0.594	0.538	0.395
17	M-10	0.623	0.578	0.500
18	M-8	0.667	0.646	0.579
19	M-8	0.667	0.646	0.579

The ICC statistics revealed that the 19 small drones were moderately similar in the extent to which they met the same requirements at the manufacturer, end-user, and automation levels. The corresponding coefficient was 0.430 for the manufacturer, 0.445 for the end user, and 0.433 for the automation, all results being statistically significant ($p < 0.05$). Further pairwise calculations showed a high range of ICC values (see Appendix D). Drones 18 and 19 and drones 15, 16, and 17, which are produced by the same manufacturers (i.e., M-8 and M-10, respectively), were completely or highly similar at the manufacturer and end-user levels (i.e., ICC values ranging 0.908–1.000), whereas drones 7 and 11 were the most distant ones (i.e., ICC values 0.057 and 0.034, respectively). Regarding automation, drones 2 and 3 and drones 18 and 19, both pairs of drones belonging to the same manufacturers (i.e., M-2 and M-10, respectively), met exactly the same requirements (ICC: 1.000), and drones 4 and 11 had the most differences (ICC: 0.111).

The Spearman correlations revealed significant associations between the market prices of the 19 drones and the requirements fulfilled by the drones for both sets of prices in April 2016 and May 2017 at the manufacturer, end-user, and automation levels (Table IV). In addition, correlations were also significant between the ratios of requirements met by pairs of system controllers: manufacturer–end user

Table IV. Correlations Between System Controllers and Drone Prices ($N = 19$)

System Controller	Spearman Correlations (Fulfilment of Requirements vs Drone Price)	
	April 2016	May 2017
Manufacturer	$r_s = 0.645, p = 0.003$	$r_s = 0.489, p = 0.033$
End user	$r_s = 0.603, p = 0.006$	$r_s = 0.491, p = 0.033$
Automation	$r_s = 0.818, p = 0.000$	$r_s = 0.594, p = 0.007$

($N = 19$, $r_s = 0.981$, $p = 0.000$), end user–automation ($N = 19$, $r_s = 0.856$, $p = 0.000$), and manufacturer–automation ($N = 19$, $r_s = 0.788$, $p = 0.000$).

5. DISCUSSION

The regulatory framework for small drones focuses almost exclusively on the limitations that the user needs to consider, without the authorities having currently developed mechanisms to enforce and proactively monitor such limitations directly. The requirements and expectations imposed solely on the end user might turn the main scope of flying a drone—leisure and passion for flight—into a complex sociotechnical problem, which at the same time threatens public safety. In addition, a strict regulatory environment focusing mainly on the responsibilities of the end user might also

discourage consumers from purchasing small drones and, inevitably, affect the sustainability of the specific market. Nonetheless, current protections against losses resulting from drone-related events seem to rely mostly on the competency of end users to fly drones safely and their vigilance to maintain the rules released by the respective authorities, or on reactive technological countermeasures.

Apart from the regulatory bodies, the challenges regarding the safety of UASs have captured the attention of various academics, researchers, and practitioners. Research is still ongoing and is expected to intensify as UASs become more prevalent. However, to date, all published risk assessments for UASs are based mainly on data collected from manned aircraft and not on a hazard analysis for small drones operated in uncontrolled airspace. Thus, the hazards lying in the interaction between the end user and a small drone under various levels of automation have not been fully studied and adequately considered. In addition, little has been written about how to support the aviation community in the establishment of a regulatory framework grounded in a systematic and transparent analysis.

The STPA hazard analysis performed in this work led systematically to the identification of 20 hazardous states and 31 causal factors associated with three high-level safety hazards in the operation of a small drone system. The analysis also drove the generation of 70 safety requirements. Those requirements were grouped into four categories—authority, manufacturer, end user, and drone automation—and the ones in the last three categories were used as a benchmark to assess the safety "embedded" in 19 small drones currently on the market. The requirements proposed in this study cover a range of hazards and causal factors that are not yet explicitly and holistically addressed in published risk analyses and regulations (e.g., language of display and manual, end user familiarization and abilities, interferences, overwhelming of the operator with multiple alerts and messages, environmental conditions). Indicatively, in the work of Dalamagkidis *et al.*,[15, p. 121–122] 10 requirements are stated in addition to the technical reliability of the drone system, but the operationalization of those requirements is not explicitly assigned to any system actor. In addition, it is not clear how those functional and operational requirements were derived and whether they comprised an exhaustive list or some indicative examples.

Most importantly, in this work, different responsibilities of the actors in the system were assigned per safety requirement as a means to suggest the level of control over the system under study, from authority to drone automation. In this manner, the end user has not been the only focal point for safe small drone flights, as is implied in current regulations and directives. Rather, the assignment of responsibilities across the system actors and their maintenance is paramount for ensuring public safety and minimizing the need for devising countermeasures against drones.

We would like to stress that according to the STPA technique, the causal factors and requirements derived from the analysis shall be accompanied by the generation of causal scenarios, with a scope to test whether a specific drone system will meet its safety objectives under various combinations of factors. Although the statement of causal scenarios was beyond the scope of this research, generic scenarios can be based on the results of this analysis and later tailored to any specific drone model to be assessed. Examples of generic scenarios include:

- Operator does not provide the *ascend* command when the drone approaches the lowest limit of the range area reaching the low limit (UCA 1) because the operator is not aware of the respective limits set by the authority (CF 10a) or the manufacturer (CF 10b), or the operator receives inadequate feedback about the location of the drone because of inadequate functioning of the drone data transmission system (CFs 1c, 2c, 3c, 4c) or the display (CFs 1b, 2b, 3b, 4b) or because of signal disruption between the drone and the display (CFs 5b, 6b) … (rest of the causal factors)…etc.
- Operator's command to turn was provided when required or appropriate, but it was not effective because of inadequate functioning of the remote controller (CFs 1a, 2a, 3a, 4a), signal disruption between the remote controller and the drone (CFs 5a, 6a), inadequate battery power level in the remote controller (CF 19), inadequate power level in the drone (CF 20).

Furthermore, the analysis of the 19 small drones did not only show that they cover the safety requirements derived by the STPA at low to moderate levels, it also indicated major dissimilarities regarding the extent to which the drones met the same safety requirements at the manufacturer, end-user, and automation levels. It also appeared that the more expensive drones met more safety requirements than

the cheaper ones. Indeed, the more the requirements met by one system controller (i.e., manufacturer, end user, automation), the more the requirements met by the rest of those controllers for the same drone model. These findings seem to reflect the efforts of manufacturers to define restrictions and to provide instructions about the safe operation of the system along with the support of the end user with detailed operating manuals and automated functions. The more expensive models carry advanced technological characteristics that are expected to transfer task load and responsibility from the end user to drone automation, thus enhancing the operator's awareness of the environment where drones are operated, and achieving the recreational purposes of small drone flights while guarding safety. As the test results also suggested, the level of requirements' fulfillment was not a matter of country of origin, but of individual manufacturer.

6. CONCLUSIONS

Although there is some research on UAS safety, it is based mainly on statistical analysis and specific accident scenarios or UAS models. In addition, it is not clear whether there is a structured hazard analysis underlying those studies. This indicates that the increasing interest in UAS has not been accompanied by an analogous effort towards proposing rigorous methods to address the emerging safety problems and to produce concrete proposals towards advancing an internationally harmonized regulatory framework.

In this study, we confirmed that STPA provides the analyst with the ability to reach concrete results in a structured and systematic manner (i.e., STPA Step 1), uses expert judgment and current knowledge of the analysts (i.e. STPA Step 2), and extends traditional hazard analysis methods. Certainly, the hazards, causal factors, safety requirements, and responsibilities across system controllers presented in this study might be subject to further review from authorities and manufacturers to complete any missing parts that the authors have not identified; this should be followed by the generation of causal scenarios to provide the manufacturers and authorities with cases against which they will test drones. In this way, the application of STPA to new and existing drone systems and analyses at technical levels deeper than the ones considered in this study are expected to support the fulfillment of the safety requirements proposed in

this work and to allow the development and testing of scenarios in the framework of drone certification. It is also noted that in this article we did not derive specific control actions and feedback mechanisms at the level of authority and manufacturer; these must be designed to control and monitor the whole system and to minimize deviations that might threaten safety.

Despite the limitations of the first approach presented in this study, we envisage that the work presented in this article is the starting point to move toward a commonly endorsed international risk analysis framework that will enable the development of a holistic and methodologically justified standardization scheme for small drone flights. Perhaps the currently available technology and possible limitations on the embedding of automation in small drones (e.g., increased weight) might not enable the fulfillment of the whole set of safety requirements related to automated functions. Under these conditions, the initial analysis presented in this article can be a factor in the application of international risk management standards, to classify and mitigate risks based on data from drone operations, which become increasingly available. Our analysis might also function as a reference point for improving system safety over time when technological advancements and other factors allow.

The comparisons of the 19 small drones and the statistical correlations suggest that drone prices are related to the level of their embedded safety. It must be noted that it is not the authors' intention to discourage consumers from purchasing cheap drones; however, we aim to increase public awareness of the various capabilities of drones, and we suggest that the purchase of models shall be based on the condition of the operator (e.g., age, flight experience) and the environment in which the drone will be flown (e.g., congested airspace, populated area).

Manufacturers are encouraged to continue introducing automated functions that, apart from the support to the end user, will facilitate regulatory compliance. This might be feasible by allowing an adjustment of embedded safety limitations (e.g., through updates from online platforms and software) according to the region in which the drone will fly. The authorities might also develop a tailored certification framework based on a classification of drones, depending on how risk control is distributed between the operator and the automated functions of drones.

APPENDIX A: UNSAFE CONTROL ACTIONS IN SMALL DRONE OPERATION (STPA STEP 1)

Control Action (CA)	Hazardous or Unsafe Control Actions (UCA)	
	Not Providing Causes Hazard	Providing Causes Hazard
[CA1] Ascend	[UCA1] Operator does not provide *ascend* command when drone approaches lower limit of range area.[a] [H-1]	[UCA2] Operator provides *ascend* command when drone closer than TBD[b] distance and beneath flying object. [H-3] [UCA3] Operator provides *ascend* command when drone approaches upper limit of range area. [H-2, H-3]
[CA2] Descend	[UCA4] Operator does not provide *descend* command when drone approaches upper limit of range area. [H-2, H-3]	[UCA5] Operator provides *descend* command when drone closer than TBD distance and above flying object. [H-3] [UCA6] Operator provides *descend* command when drone approaches lowest limit of range area. [H-1]
[CA3] Turn	[UCA7] Operator does not provide *turn* command to the opposite direction when closer than TBD distance from flying object approaching from the side. [H-3]	[UCA8] Operator provides *turn* command when there is a flying object on the side of the turn direction and closer than TBD distance. [H-3]
[CA4] Go forward	[UCA9] Operator does not provide *go forward* command when closer than TDB distance with flying object approaching in trail or beam. [H-3]	[UCA10] Operator provides *go forward* command when drone on collision trajectory and closer than TBD distance with flying object. [H-3] [UCA11] Operator provides *go forward* command when drone approaches boundaries of range area. [H-2, H-3]
[CA5] Go backward	[UCA12] Operator does not provide *go backward* command when drone on collision trajectory and closer than TBD distance with flying object. [H-3] [UCA13] Operator does not provide *go backward* command when drone approaches boundaries of range area. [H-2, H-3]	[UCA14] Operator provides *go backward* command when there is a flying object in trail and closer than TBD distance. [H-3]
[CA6] Increase speed		[UCA15] Operator provides *increase speed* command when drone on collision trajectory and closer than TBD distance with flying object. [H-3] [UCA16] Operator provides *increase speed* command when drone approaches boundaries of range area. [H-2, H-3]
[CA7] decrease speed	[UCA17] Operator does not provide *decrease speed* command when drone on collision trajectory and closer than TBD distance with flying object. [H-3] [UCA18] Operator does not *provide decrease* speed command when drone approaches boundaries of range area. [H-2, H-3]	
[CA8] Deactivate		[UCA19] Operator provides *deactivate* command when drone is airborne. [H-2]
[CA9] Reactivate	[UCA20] Operator does not provide *reactivate* command when drone is deactivated and airborne [H-2]	

[a]The range area is defined by the lowest set of the space limits defined by the manufacturer (operational limits) and the authority (airspace boundaries) apart from altitude. Altitude of range area is the highest value regarding the minimum allowed altitude and the lowest value regarding the maximum allowed altitude.
[b]TBD: Values to be defined by the manufacturer or authority.

APPENDIX B: CAUSAL FACTORS FOR (UNSAFE) CONTROL ACTIONS IN SMALL DRONE OPERATION (STPA STEP 2)

Generic Causal Factors	Detailed Causal Factors	Causing	
		Ineffective Control Action	Unsafe Control Action
Inadequate functioning of remote control, display, drone[a]	1. Inherent technical flaws (i.e., design or production)		
	a. Remote control	1–7, 9	
	b. Display		1, 3, 4, 6, 11, 13, 16, 18
	c. Drone	1[b]–7, 9	1[c], 3, 4, 6, 11, 13, 16, 18
	2. Excessive environmental conditions (e.g. humidity, high / low temperature) *[applicable for hardware]*		
	a. Remote control	1–7, 9	
	b. Display		1, 3, 4, 6, 11, 13, 16, 18
	c. Drone	1–7, 9	1, 3, 4, 6, 11, 13, 16, 18
	3. Unintentional drop prior to the flight		
	a. Remote control	1–7, 9	
	b. Display		1, 3, 4, 6, 11, 13, 16, 18
	c. Drone	1–7, 9	1, 3, 4, 6, 11, 13, 16, 18
	4. Inadequate maintenance		
	a. Remote control	1–7, 9	
	b. Display		1, 3, 4, 6, 11, 13, 16, 18
	c. Drone	1–7, 9	1, 3, 4, 6, 11, 13, 16, 18
Inadequate communication[d]	5. Signal disruption because of frequency interference		
	a. In the communication channel between remote controller and drone	1–7, 9	
	b. In the communication channel between remote drone and display		1, 6, 11, 13, 16, 18
	6. Signal disruption caused by physical impenetrable obstacle		
	a. In the communication channel between remote controller and drone	1–7, 9	
	b. In the communication channel between remote drone and display		1, 6, 11, 13, 16, 18
Ineffective communication between UAS operator and display[e]	7. Limited visibility of display (e.g., glare, angle of view, reflections of environment)		1, 3, 4, 6, 11, 13, 16, 18
	8. Indistinct information on the display (e.g., size of fonts and symbols, colors)		1, 3, 4, 6, 11, 13, 16, 18
	9. Unfamiliarity of operator with terms or language used		1, 3, 4, 6, 11, 13, 16, 18
Inadequate UAS operator performance	10. Inadequate knowledge or skills (where applicable) in		
	a. Regulations and requirements of the authority		1–18
	b. Operation[f] of the drone		1–20
	c. The terrain		1, 6, 11, 13, 16, 18
	d. Initial weather forecast[g]		3, 4
	11. Inadequate (e.g., incomplete, unclear, written in language unfamiliar to operator)		
	a. Authority requirements and regulations		1–18
	b. Operating instructions		1–20
	12. Exceedance of cognitive capacity		1–20
	13. Effects of emotional state		1–20
	14. Inadequate weather forecast update		3, 4
	15. Inadequate information about density of operating drones in flying area		2, 5, 7, 8, 9, 10, 12, 14, 15, 17
	16. Chronic, known physiology problems		1–20
	17. Unanticipated physiology limitations		1–20
Insufficient energy level[h]	18. Display battery depleted		1, 3, 4, 6, 11, 13, 16, 18
	19. Remote control battery depleted	1–7, 9	
	20. Drone battery depleted	1–7, 9	

[a] Including the battery, which in these drones is lithium and subject to failure or leakage.
[b] Across the specific column, the reference to the drone corresponds to problems in its data receiving and flying functions.
[c] Across the specific column, the reference to the drone corresponds to problems in transmitting functions.
[d] In addition to UAS failures.
[e] In addition to display failures.
[f] Operation of drone includes flight instructions, system limits, and maintenance requirements.
[g] Regarding the operating limitations (i.e., cloud ceiling and state, wind conditions, visibility).
[h] During operation; not related to technical flaws.

APPENDIX C: SAFETY REQUIREMENTS FOR SMALL DRONE OPERATION

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions
1	Operator shall maintain continuous visual contact with drone during flight.	Regulate	Document	Act		1b, 2b, 3b, 4b, 5b, 6b, 7, 8, 9, 10c, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20
2	Define health-related precautions (e.g., leakages, radiation, body contact with moving surfaces).	Define	Document	Act		17	
3	Specific set of safety constraints shall be supported by automation during drone operation.	Define	Act	Informed		1a, 1c, 2a, 2c, 3a, 3c, 4a, 4c, 5a, 5b, 6a, 6b, 7, 8, 9, 10a, 10b, 10c, 12, 13, 14, 17, 18, 19, 20	1, 3, 4, 6, 11, 13, 16, 18, 19, 20
4	Operator shall meet technical competencies.	Define	Document	Act		4a, 4b, 4c, 5a, 5b, 6a, 6b, 9, 10a, 10b, 12, 14, 18, 19, 20	
5	Operator shall accomplish familiarization stages for drone operation.	Regulate	Define	Act		6a, 6b, 7, 8, 9, 10a, 10b, 10c, 11a, 11b, 12	
6	Operator shall be physically fit to operate the drone.	Define	Document	Act		16	
7	Operator shall command English at TBD level when in country where operator's native language is not the official one.	Define	Document	Act		10a, 10d, 14, 15	
8	State agencies supporting drone flights shall offer operator's communication in English.	Act	Document	Informed		10a, 10d, 11a, 14, 15	
9	Operator shall meet cognitive requirements for drone control.	Define	Document	Act		12	

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions
10	Drone shall be operated in designated flight areas, where a minimum altitude at least equal to the highest physical obstacle shall be defined.	Define	Document	Act	Support	6a, 6b, 10c	
11	Drone shall be operated in flight areas designated according to other scheduled flying activity (maximum altitude and radius).	Define	Document	Act	Support	5a, 5b, 6a, 6b, 15	
12	Drone shall be operated in flight areas designated by taking into account effects of external electromagnetic fields.	Define	Document	Act	Support	5a, 5b	
13	Designated flight areas shall be periodically reassessed.	Act				5a, 5b, 6a, 6b, 15	
14	Drone shall be turned to the opposite direction when object approaches from the side.	Regulate	Document	Act			7
15	Drone shall maintain vertical and horizontal separation of TBD (length units) from other flying objects.	Define	Document	Act			2, 5, 7, 8, 9, 10, 12, 14, 15, 17
16	Drone shall be operated when designated flight area has not reached maximum drone (or other flying objects) population TBD.	Define	Document	Act			2, 5, 7, 8, 9, 10, 12, 14, 15, 17
17	Drone shall be operated at TBD frequency range of designated flight area.	Define	Document	Act	Support	5a, 5b	

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions	
18	Drone shall be operated only when TBD weather minima are met.	Define	Document	Act	Support	6a, 6b, 10d		
19	Operator shall consult weather forecasting every TBD (time units).	Define	Document	Act	Support	14		
20	Information about drone technical condition when activated shall be provided to the operator.	Regulate	Document	Informed	Support	1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
21	Drone shall meet reliability requirements.	Define	Act	Informed		1a, 1b, 1c, 4a, 4b, 4c, 5a, 5b, 12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20	1, 2, 3, 4, 5, 6, 7, 8, 9
22	Drone subsystems allowing full control in manual mode shall be operative before takeoff.	Regulate	Define	Act	Support	1a, 1c, 2a, 2c, 3a, 3c, 4a, 4c, 5a	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
23	Communication among drone subsystems required for at least manual flight shall be established before takeoff.	Regulate	Document	Act	Support	1a, 1c, 2a, 2c, 3a, 3c, 4a, 4c		
24	Drone shall be landed when any subsystem or component needed for drone's full control in manual mode is not operative more than TBD (time unit) or failed temporarily more than TBD times during flight.	Define	Document	Act	Support	1a, 1c, 2A, 2c, 3a, 3c, 4a 4c	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
25	Drone shall be landed when communication between any subsystem or component is lost more than TBD (time unit).	Define	Document	Act	Support	1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 6a, 6b	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions	
26	Drone shall be landed when any automation failure cannot be compensated by manual control.	Regulate	Define	Act	Support	1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 6a, 6b	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9
27	Drone shall be landed when any communication problem occurred more than TBD times during flight.	Define	Document	Act	Support	1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 6a, 6b	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9
28	Display shall provide information for display power level.	Regulate	Document	Informed	Support	18		
29	Information must be provided for remote control power level.	Regulate	Document	Informed	Support	19		
30	Drone shall be landed when remote control power level drops under TBD (power unit).	Regulate	Define	Act	Support		1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
31	Drone shall be landed when environmental conditions into which drone maintains designed reliability are not met.	Regulate	Define	Act	Support	2a, 2b, 2c		
32	Environmental conditions into which drone maintains designed reliability shall be met before takeoff.	Regulate	Define	Act	Support	2a, 2b,2c		
33	Display shall provide information for drone operating mode (e.g., automatic, semi-automatic, or manual).	Regulate	Document	Informed	Support	12		
34	Display shall provide information regarding drone's position.	Regulate	Document	Informed	Support	6a, 6b, 10c, 12		

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions	
35	Display shall provide information for auto-functions' (de)activation.	Regulate	Document	Informed	Support	12		
36	Display shall provide information for drone power level.	Regulate	Document	Informed	Support	20		
37	Display shall provide information for malfunctions.	Regulate	Document	Informed	Support	1a, 1b, 1c, 2a, 2b, 2c, 3a, 3b, 3c, 4a, 4b, 4c, 12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9
38	Display shall provide information for proximity to range area.	Regulate	Document	Informed	Support	12	1, 3, 4, 6, 11, 13, 16, 18, 20	
39	Drone shall be landed when any drone's movement in space not a result of command input.	Regulate	Document	Act	Support	1c, 2c, 3c, 4c, 5a	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
40	Drone shall self-land when no input received after TBD (time units) of hovering.	Define	Document	Informed	Act	1a, 2a, 3a, 4a, 5a, 6a, 12, 13, 16, 17, 19	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
41	Drone shall be landed when drone power level drops to less than TBD (power unit).	Regulate	Define	Act	Support	1c, 2c, 3C, 4c, 20	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18	1, 2, 3, 4, 5, 6, 7
42	Maintenance of drone shall be performed after fall from height at least equal to TBD (length unit).	Regulate	Define	Act		3a, 3b, 3c	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9
43	Drone shall provide information for drone flight altitude.	Regulate	Document	Informed	Support	6a, 6b, 10c, 12	1, 3, 4, 6, 11, 13, 16, 18	
44	Drone shall be subject to periodic maintenance.	Regulate	Define	Act		1a, 1b, 1c, 2a, 2b, 2c, 4a, 4b, 4c		
45	Drone shall be subject to on-condition maintenance.	Regulate	Define	Act		2a, 2b, 2c, 3a, 3b, 3c		
46	Generate aural warning when failure is detected.	Regulate	Document	Informed	Act	10b, 11b, 12		

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions	
47	Generate aural warning when drone reaches range limits.	Regulate	Document	Informed	Act	10a, 10b, 11b, 12	1, 3, 4, 6, 11, 13, 16, 18	
48	Drone documentation shall include manual and automated functions of operation.	Regulate	Act			3a, 3b, 3c, 4a, 4b, 4c, 10b	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20	1, 2, 3, 4, 5, 6, 7, 9
49	Drone documentation shall include technical specifications.	Regulate	Act			3a, 3b, 3c, 4a, 4b, 4c, 10b		
50	Drone documentation shall include maintenance instructions.	Regulate	Act			3a, 3b, 3c, 4a, 4b, 4c, 10b		
51	Operator shall observe limitations of display view.	Regulate	Document	Act		7	1, 3, 4, 6, 11, 13, 16, 18	
52	Operator shall use system documentation written in native language.	Regulate	Document	Act		4a, 4b, 4c, 10b, 11b		
53	Manufacturer shall provide system documentation in official language(s) of targeted market.	Regulate	Act			4a, 4b, 4c, 10b, 11b		
54	The display characteristics related to discernment shall be adjustable.	Regulate	Document	Act		8, 12		
55	Display shall not be set in standby or sleeping mode when it is required by current flight mode.	Regulate	Define	Act	Support	14	1, 3, 4, 6, 11, 13, 16, 18	
56	Messages on the display shall be displayed in native language.	Regulate	Act	Informed		4a, 4b, 4c, 9, 10a, 10b, 10c, 10d, 14		
57	Prioritization of actions, alerts, and messages shall be provided on the display to facilitate the operator's reaction under emergency.	Regulate	Document	Informed	Support	10b, 11b, 12		
58	Operator should not be in a high emotional state.	Regulate	Document	Act		13		

Requirement	Assigned to the Level of Authority	Addressing Manufacturer	Operator	Automation	Causal Factors	Unsafe Control Actions	Ineffective Control Actions
59	Drone shall auto-hover when no command is received.	Regulate	Document	Informed	Act	1a, 2a, 3a, 4a, 5a, 6a, 10b, 12, 13, 16, 17	
60	Drone shall not ascend command before passing beneath overflying object.		Document	Act			2
61	Drone shall ascend before crossing lower limit of range area.		Document	Act	Support		1, 6
62	Drone shall not descend before passing over object flying beneath.		Document	Act			5
63	Drone shall descend before crossing upper limit of range area.		Document	Act	Support		3, 4
64	Drone shall not turn before passing next to objects flying on the side of the turn direction.		Document	Act			8
65	Drone shall go forward when flying object approaches in trail or beam.		Document	Act			9, 14
66	Drone shall not go forward when other traffic at same altitude and heading.		Document	Act			10
67	Drone shall decrease speed and go backward when on collision trajectory with flying object.		Document	Act			12, 15, 17
68	Drone shall decrease speed or go backward, or both, when approaching boundaries of range area.		Document	Act	Support		11, 13, 16, 18
69	Drone shall be reactivated when drone is deactivated and airborne.		Document	Act	Support		20
70	Drone shall not be deactivated when airborne.		Document	Act	Support		19

APPENDIX D: INTRACLASS CORRELATIONS RESULTS

Table ADI. Agreement Between Small Drone Models Regarding Fulfilment of Manufacturer Requirements

MODEL	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.509	0.509	0.306	0.401	0.372	0.253	0.673	0.481	0.255	0.286	0.163	0.219	0.409	0.432	0.469	0.465	0.367	0.367
2		0.926	0.624	0.471	0.570	0.379	0.703	0.537	0.287	0.270	0.148	0.337	0.804	0.570	0.558	0.544	0.555	0.555
3			0.624	0.471	0.570	0.379	0.703	0.537	0.287	0.221	0.214	0.337	0.882	0.570	0.558	0.544	0.555	0.555
4				0.551	0.684	0.518	0.429	0.333	0.227	0.104	0.213	0.233	0.575	0.365	0.292	0.340	0.417	0.417
5					0.549	0.567	0.435	0.453	0.348	0.197	0.176	0.382	0.391	0.321	0.403	0.291	0.381	0.381
6						0.574	0.502	0.509	0.371	0.191	0.288	0.384	0.523	0.502	0.423	0.475	0.557	0.557
7							0.402	0.366	0.267	0.057	0.141	0.299	0.296	0.345	0.371	0.315	0.289	0.289
8								0.625	0.265	0.297	0.162	0.330	0.592	0.565	0.667	0.537	0.557	0.557
9									0.340	0.485	0.538	0.484	0.448	0.509	0.539	0.480	0.509	0.509
10										0.429	0.284	0.713	0.233	0.424	0.434	0.391	0.227	0.227
11											0.316	0.549	0.171	0.349	0.410	0.316	0.259	0.259
12												0.352	0.228	0.350	0.273	0.324	0.340	0.340
13													0.276	0.438	0.508	0.406	0.340	0.340
14														0.523	0.452	0.499	0.575	0.575
15															0.909	0.969	0.684	0.684
16																0.880	0.663	0.663
17																	0.719	0.719
18																		1.000

Table ADII. Agreement Between Small Drone Models Regarding Fulfilment of End User Requirements

MODEL	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.553	0.465	0.370	0.444	0.428	0.290	0.760	0.634	0.276	0.400	0.338	0.216	0.382	0.335	0.423	0.354	0.462	0.462
2		0.829	0.667	0.562	0.609	0.469	0.710	0.606	0.341	0.352	0.238	0.329	0.709	0.451	0.436	0.445	0.630	0.630
3			0.698	0.535	0.639	0.441	0.676	0.575	0.265	0.225	0.266	0.306	0.815	0.415	0.403	0.409	0.592	0.592
4				0.558	0.679	0.525	0.521	0.422	0.214	0.113	0.250	0.202	0.578	0.327	0.313	0.320	0.504	0.504
5					0.555	0.535	0.463	0.511	0.324	0.186	0.227	0.330	0.400	0.282	0.364	0.237	0.412	0.412
6						0.582	0.590	0.605	0.371	0.207	0.326	0.364	0.524	0.462	0.379	0.421	0.644	0.644
7							0.430	0.418	0.364	0.034	0.192	0.240	0.303	0.369	0.332	0.326	0.317	0.317
8								0.696	0.336	0.342	0.299	0.329	0.566	0.497	0.536	0.457	0.615	0615
9									0.478	0.477	0.575	0.478	0.485	0.513	0.481	0.473	0.575	0.575
10										0.427	0.292	0.729	0.220	0.452	0.405	0.411	0.306	0.306
11											0.301	0.514	0.189	0.342	0.348	0.298	0.262	0.262
12												0.341	0.271	0.363	0.283	0.320	0.410	0.410
13													0.253	0.447	0.462	0.405	0.352	0.352
14														0.432	0.363	0.428	0.606	0.606
15															0.908	0.968	0.680	0.680
16																0.875	0.595	0.595
17																	0.708	0.708
18																		1.000

Table ADIII. Agreement Between Small Drone Models Regarding Fulfilment of Automation Requirements

MODEL	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.276	0.276	0.241	0.358	0.298	0.140	0.693	0.397	0.428	0.427	0.335	0.508	0.233	0.541	0.625	0.638	0.287	0.287
2		1.000	0.533	0.375	0.700	0.276	0.411	0.283	0.375	0.156	0.166	0.283	0.926	0.449	0.343	0.375	0.605	0.605
3			0.533	0.375	0.700	0.276	0.411	0.283	0.375	0.156	0.166	0.283	0.926	0.449	0.343	0.375	0.605	0605
4				0.650	0.837	0.446	0.206	0.215	0.480	0.111	0.173	0.315	0.587	0.468	0.198	0.375	0.517	0.517
5					0.602	0.467	0.169	0.285	0.638	0.193	0.222	0.508	0.331	0.437	0.408	0.428	0.493	0.493
6						0.501	0.366	0.375	0.638	0.275	0.334	0.472	0.634	0.519	0.358	0.428	0.676	0.676
7							0.169	0.397	0.533	0.193	0.335	0.397	0.233	0.437	0.408	0.428	0.390	0.390
8								0.333	0.322	0.393	0.283	0.333	0.355	0.530	0.538	0.533	0.369	0.369
9									0.480	0.684	0.708	0.539	0.249	0.497	0.556	0.480	0.455	0.455
10										0.428	0.638	0.690	0.322	0.585	0.585	0.690	0.533	0.533
11											0.738	0.684	0.136	0.361	0.587	0.428	0.331	0.331
12												0.471	0.136	0.449	0.607	0.533	0.410	0.410
13													0.249	0.395	0.556	0.480	0.354	0.354
14														0.502	0.302	0.428	0.543	0.543
15															0.697	0.897	0.418	0.418
16																0.794	0.446	0.446
17																	0.428	0.428
18																		1.000

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