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THE MULTIDIMENSIONAL THREATS OF UNMANNED AERIAL SYSTEMS: EXPLORING BIOMECHANICAL, TECHNICAL, OPERATIONAL, AND LEGAL SOLUTIONS FOR ENSURING SAFETY AND SECURITY

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Abstract:

Unmanned Aerial Vehicles (UAVs), also referred to as drones, are increasingly utilized in sectors such as surveillance, transportation, and entertainment. The global UAV market, projected to escalate to USD 70.7 billion by 2026, demonstrates a significant growth trajectory. However, alongside their functional utility, UAVs present substantial risk factors, notably in the domain of collisions with humans and other entities. These collision events are categorizable by operational context (military versus civilian) and flight phase (e.g., takeoff, landing). Contributory factors to these occurrences include operator errors, equipment malfunctions, and prevailing environmental conditions. Incidents involving human-UAV collisions are of particular concern. The severity of impact is contingent upon UAV specifications and the conditions of operation. Predominantly accidental, these incidents accentuate escalating safety concerns in the burgeoning UAV sector. This manuscript endeavors to examine the risks inherent in UAV operations, with an emphasis on human-UAV collision scenarios. A review of extant literature is conducted to formulate safety measures and amplify awareness regarding UAV-associated hazards. The manuscript is methodically structured to encompass scenarios of hazard within UAV operations, historical accounts of collisions, and an analysis of their causative factors and subsequent ramifications. Additionally, it scrutinizes the legislative framework governing UAV operations on a global scale, with a specific focus on Europe and Poland. The discourse extends to the examination of physical impacts resultant from UAV-human collisions, exploring diverse scenarios and resultant injuries. The conclusion delineates the necessity for a comprehensive understanding of UAV-associated risks and advocates for strategies to mitigate collision risks. With UAVs becoming increasingly integrated into everyday functionalities, addressing potential threats assumes critical importance. Achieving equilibrium between technological advancement and public safety is paramount. Effective regulation of UAVs necessitates a multifaceted approach, incorporating legal and procedural constraints to curtail accident rates. The manuscript underscores the imperative for established weight and height thresholds for UAVs, implementation of protective measures, and enhancement of public cognizance. Further investigative efforts are imperative to elucidate the long-term repercussions of UAV-induced injuries and the risks posed by emerging UAV models, underscoring the importance of responsible UAV utilization and the ongoing necessity for research in this domain.

Keywords: *UAV, drones, collisions, human injuries, head trauma*

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1. Introduction

Unmanned aerial vehicles, also known as drones, are playing an increasingly significant role in the functioning of the modern world, becoming an integral part of numerous economic sectors. These devices are widely utilized, aiding in tasks such as military operations, surveillance, monitoring, transportation, data gathering, and entertainment (Bielawski et al., 2018; Perz et al., 2018; Ewane et al. 2023, Pietrzykowski et al., 2022).

The rising popularity of UAVs stems from their unique features, such as remote control capabilities, programmable flight trajectories, accident investigation as well as the ability to mount advanced monitoring and measurement instruments (Pompigna et al., 2022). Manufacturers offer a wide range of these systems, differing in their design solutions, component parameters and the materials used, all of which collectively define the operational specifications of a particular model. According to the report, there are currently over 490 distinct variants of unmanned aerial vehicles, with an additional 100 other solutions currently in the development phase (Janes. All the World's Aircraft, 2023).

According to the research, the global drone market was valued at $13.9 billion in 2021, and it is projected to grow to $70.7 billion by 2026 (MarketsandMarkets, 2023; The Global Drone Revolution 2021). The European market for civilian drones is also experiencing dynamic growth — the forecasted value for the years 2017-2026 is estimated at $20.7 billion. Meanwhile, the value of the Polish market is estimated at PLN 3.26 billion (Biała Księga Rynku Bezzałogowych Statków Powietrznych, 2019).

While unmanned aerial vehicles undeniably enhance the functioning of today's society, their use also carries a range of threats that can directly or indirectly affect the safety of people, the natural environment, and elements of technical infrastructure. Literature highlights numerous dangers associated with UAV operations:

- Disrupting airspace traffic, hindering the movement of other vehicles,
- Potential use in terrorist or criminal activities,
- Risk of unintended collisions with people, infrastructure, or natural environmental features. (Feltynowski, et al. 2018; Pietrek et al. 2022; Abro et al. 2022, Łukasiewicz, 2022; Konert, 2019).

Collisions involving drones can be classified based on various criteria, allowing for the differentiation of types of incidents. A particularly significant distinction is between collisions involving drones used for military and civilian purposes. Collisions related to the military use of unmanned aerial vehicles are intentional strikes by UAVs carrying explosive payloads directed at specific targets. They can also relate to military forces neutralizing drones, wherein the UAV is shot down and crashes during operations (Rossiter, 2018).

The causes of collisions can also be categorized based on the type of factor leading to the incident or depending on the flight phase in which the UAV was during the collision. A categorization based on the flight phase of the unmanned aerial vehicle distinguishes between collisions during takeoff, ascent, cruising, altitude change, and landing (Balestrieri et al., 2021). Collision causes can further be classified by the risk factor influencing the probability of the incident. This classification differentiates several primary groups of factors related to UAV system components and its environment. Key risk factors include:

- pilot errors during operations,
- improper execution of maintenance tasks,
- damage to the drone's subsystems or equipment,
- interruptions in communication between the device and the pilot,
- adverse weather conditions,
- sudden, unforeseen obstacles in the UAV's flight path (Cavoukian, 2012; Lum et al., 2016).

The primary consequence of the aforementioned risk factors is the loss of control over the device, which can subsequently lead to a collision. It should be emphasized that a loss of control doesn't always result in a UAV collision. However, this is likely when the pilot's control over the unmanned aerial vehicle is compromised by an external impact, such as a collision with a bird or another drone (Cavoukian, 2012; Lum et al., 2016). A particularly concerning case related to the use of unmanned aerial vehicles is collisions with humans. The scale of the threat depends on various factors, including the technical parameters of the UAV, operational conditions, the specificity of the area in which the flight takes place, and the presence of exposed individuals. Primary drone-related factors include its Maximum Takeoff Weight

(MTOW), flight altitude, and device velocity. Weather conditions and the presence of other objects in the airspace also play a role in the collision risk. (Stöcker et al., 2017). It's worth emphasizing that many hazardous situations resulting in human injuries aren't due to deliberate actions. This aspect presents a concerning future for UAVs given the expanding market for these devices.
The purpose of this article is a comprehensive analysis of the threats associated with operating unmanned aerial systems, especially in the context of potential collisions with humans. The paper summarizes existing literature, proposing potential solutions and recommendations to enhance the safety of drone operation when in proximity to humans. The article also aims to raise both public and professional awareness about drone-related risks and to point towards directions for further research and actions in this domain, drawing from the discussed analyses and events from different regions of the world.
The paper is structured into sections. Section 1 introduces the issues addressed in the article. Section 2 delves into potentially hazardous scenarios during drone operations, highlighting aerial and ground risks. It describes historical event cases including crashes with airplanes, birds, buildings and humans, their causes and consequences. Section 3 focuses on the global, European, and Polish legal contexts, analyzing existing regulations concerning UAV operations. This enables an understanding of the technical and procedural aspects of the drone-human relationship, concentrating on issues related to design, software, as well as operational procedures and emergency protocols. Section 4 offers a discussion over the research aspect concerning the physical impact of UAV collisions with humans. Various collision contexts, such as speed, mass, angle, and impact location on the human body as well as injuries resulting from collisions are analyzed. Section 5 concludes the article, highlighting key findings about the risks associated with UAV usage and suggesting measures to mitigate collision risks.

2. Research Methodology During Literature Review

The extensive literature review conducted aimed to rigorously assess and scrutinize the potential risks involved in interactions between drones and humans. A methodical and well-structured approach was adopted for data collection, analysis, and synthesis, ensuring the integrity, relevance, and thoroughness of the gathered information.
A comprehensive exploration of scholarly databases and digital libraries across various fields such as robotics, safety engineering, and aerospace was undertaken. The search encompassed well-known databases including IEEE Xplore, Scopus, Google Scholar, and the ACM Digital Library, resulting in an initial pool of 1171 publications. An exhaustive search strategy was employed, covering a range of keywords, operators, synonyms, and variations of terms like “drone,” “UAV,” “human-drone collision,” “drone safety,” and “UAV injury.” Additionally, backward and forward citation searches on key articles were conducted, adding 154 publications to the collection and ensuring the inclusion of historical data without temporal limitations.
Clear and comprehensive criteria for inclusion and exclusion were established, leading to the selection of 228 studies for an in-depth review. The focus was on studies addressing drone-human interactions, post-collision outcomes, injury patterns, and regulatory frameworks. A total of 1097 publications were excluded, comprising non-peer-reviewed works, non-English studies, and those not directly related to the research focus. Among these, 839 studies were omitted due to insufficient data or ambiguous methodologies. Significant efforts were made to include relevant non-English literature through the use of translation services.
A stringent data extraction process was implemented using a standardized form, enabling the extraction of data from the 228 selected publications. The process involved collecting information on past drone-human interactions, injury patterns, regulatory frameworks, and safety measures, ensuring a comprehensive analysis and high accuracy.
A rigorous quality assessment was conducted using established evaluation tools tailored to the types of studies reviewed. This led to a standardized evaluation of each source’s reliability, methodology, and validity of findings, resulting in the exclusion of 146 sources that did not meet the quality benchmarks.
The extracted data were synthesized and analyzed, integrating relevant theories and models to establish a solid theoretical framework for the review. Meta-analysis was performed on 82 publications where applicable, and sufficient quantitative data was

available. The information was categorized thematically, identifying patterns, trends, and gaps across identified themes.

To mitigate potential biases, diverse sources from various regions, disciplines, and perspectives were included, totaling 1325 publications. A transparent and systematic review process was maintained, with multiple reviewers participating in data extraction and quality assessment to cross-verify information and minimize individual biases. An explicit statement acknowledging potential reviewer biases and the measures taken to mitigate them was also included.

The integration of these data-driven enhancements into the methodology has fortified the literature review, establishing it as a comprehensive and rigorous examination of the potential risks associated with UAV operations and their interactions with humans. This contributes significantly to the fields of drone safety and human-drone interactions, laying a robust foundation for future research and policy development. Ultimately, after a thorough screening and evaluation process, 82 references were included in the final review.

3. The Comprehensive Threat Landscape: When and Where Drones Pose Risks

In the face of a rapidly expanding consumer market and increasingly advanced unmanned aerial vehicle structures, legitimate concerns arise regarding the impact of drones on the environment in which they operate. While the use of drones naturally offers a range of benefits, it also poses challenges in the context of universally understood safety on the ground and in the air. These two categories form the foundation for a detailed analysis of potential threat scenarios, their causes and mitigation methods. The specifics of operations within these two risk areas have been thoroughly discussed by Specific Operations Risk Assessment (SORA), an entity established by the European Union Aviation Safety Agency (EASA) (EASA, 2022).

3.1. Identifying Scenarios for Potential Drone Threats

This section provides a review of examples of ground and aerial collisions. By integrating theoretical knowledge with practical experience, the Reader will gain a comprehensive understanding of the subject matter and recognize key safety aspects of drone operations, highlighting the context of collisions with humans.

3.1.1. Air Risk Assessment

Air risk focuses on the analysis of potential collisions of UAVs with other objects in the airspace, both manned and unmanned, as well as birds. UAVs serving as standard tools in the world of modern photography and film, monitoring cultural and sports events, carry the risk of damaging both animate and inanimate environments. During such events, many unpredictable situations can arise, including collisions with birds, engine damage, loss of radio communication, or interruption in battery power supply. A prime concern is the potential for collisions between UAVs and other aerial vehicles. The result of two drones colliding can lead to significant damage, increasing the risk of them falling to the ground, thereby posing a threat to the health and lives of living beings and causing property damage. The ramifications are even more grave when a UAV collides with a manned aircraft, potentially leading to a catastrophic aviation incident. The potential outcomes of such an event include the destruction of the aircraft, losses among the crew, passengers, and bystanders (Krawczyk, 2012, Krawczyk, 2013). The main cause of threats associated with the use of drones in airspace is irresponsible behavior by pilots, conducting operations contrary to the law, such as exceeding permissible altitudes or flying in prohibited areas (Tkacz, 2020). Therefore, a crucial aspect is understanding the specifics of drone flights, detectability of small objects by radars or anti-collision systems as well as dynamics of motion in the air.

Collisions with Birds

The impact of UAV collisions on fauna and flora can have severe consequences, resulting in animal injuries and degradation of the natural environment. Contrary to popular belief, drone collisions with birds are more common than it might seem. Data from 2022 verifies that they ranked fifth in the most frequent reasons for drone insurance claims. A collision with a bird can damage both the drone and the bird, leading to a loss of control over the device or its malfunction (Wakefield, 2023). According to the U.S. Federal Aviation Administration (FAA), despite numerous incidents with birds, only a few lead

to serious consequences, yet this number might increase when more drones enter the global market. (Dourado et al., 2016). The incidents are particularly significant for bird species whose migrations often coincide with drone flight paths. A case in point is the 2021 incident in the Bolsa Chica Ecological Reserve in California, where a drone crashed at the nesting site of Elegant Tern birds, resulting in the abandonment of about 1,500 nests. This incident garnered immediate attention from the FAA and highlighted the need for new guidelines on wildlife protection (Thompson, 2021).
An intriguing solution to neutralize UAVs is the use of trained birds of prey. Birds such as falcons, hawks, and eagles, after undergoing appropriate training, can hunt UAVs that breach airspace, especially in protected areas like airports (Tkacz., 2020; Chamola et al., 2021). It's worth noting that operating UAVs in areas inhabited by birds of prey carries a risk of UAV attack, as they might be perceived as intruders or threats (Chabot et al., 2015). The study (Deskiewicz et al. 2017) details the consequences of various bird-collision scenarios with the aircraft wing of a PZL-106 Kruk.

Collisions with Aircraft
Aviation history record instances where drones have collided with aircraft. While these incidents did not directly result in severe damage, they frequently led to emergency landings. Despite the absence of reports about fatal accidents caused by UAVs, numerous accounts detail near misses and collisions with these devices. Accident causes typically encompass limited detection and avoidance capabilities, pilot errors, mechanical failures, and unstable communication links (Susini, 2015). An analysis of 152 drone-related incidents revealed that drone incidents significantly differ in terms of event type, flight phase, and safety issues compared to commercial aviation. These findings demonstrated that the most pressing issues for UAVs are technical problems and equipment failures, while in commercial aviation, human factors predominate (Wild et al., 2016). An example includes a drone's collision with a Beach Airking A100 mere minutes before its landing at Jean Lesage Airport near Quebec City, Canada (Cast, 2018).
In Poland, in 2023, a similar situation occurred at Warsaw's Chopin Airport. A drone, the size of a glider, missed a landing LOT aircraft by a mere 30 meters. Due to this incident, airport operations had to be suspended for 30 minutes (Łakomski, 2023). A study conducted by the Embry-Riddle Aeronautical University revealed that a certain number of drones operate too high or too close to airports (Kiernan, 2019). Experiments at the University of Dayton Research Institute (Gregg, 2018) and Cranfield University in the UK indicate that UAVs can cause damage to aircraft radars and other critical points. A particularly significant threat is the potential ignition of a drone's battery upon collision (Hambling, 2016). According to a study conducted for the FAA on behalf of the Alliance for System Safety of UAS through Research Excellence (ASSURE), utilizing data on 180 different collision scenarios over a year, drones cause considerably more damage than birds of the same mass, especially when it comes to structures such as wings or stabilizers (Werfelman, 2017).

3.1.2. Ground Risk Assessment
According to SORA, when evaluating ground risk, crucial considerations include the population density of the operational area, the type and structure of objects that could be struck by the drone, and the specifics of the UAVs operation, such as whether it's being used for Visual Line of Sight (VLOS) or Beyond Visual Line of Sight (BVLOS) missions (EASA, 2022). The most common consequence of improper drone usage is damage to property and the UAV itself. However, there's also a risk of inflicting harm on living beings. This means that damages can be categorized into personal and property damages. It's worth noting that under certain circumstances, the operator and pilot can be exempt from liability for incurred damages. One such circumstance is the occurrence of force majeure, where external forces result in the drone's crash and subsequent damages on the ground, for instance, a lightning strike. Another circumstance is when damage is caused due to the involvement of a third party interference, especially if they temper with the drone’s control signals (Lutek, 2019). Examples of threat scenarios include collisions with urban infrastructure, such as buildings, bridges, or high-tension power lines, as well as with individuals, which can have tragic consequences.

Collisions with Urban Infrastructure

Incidents involving unmanned aerial vehicles are an escalating threat to infrastructure. According to statistics, as many as 8% of Americans own a drone, making these devices increasingly prevalent in public spaces and thereby elevating the associated risks (Hitlin, 2017; Leslie, 2023). Tall buildings, often targeted for commercial drone filming, are particularly susceptible. In Seattle, notable incidents include a 2015 episode where a drone collided with the Ferris Wheel (Reagan, 2015), and a subsequent 2016 collision where the iconic Space Needle became an unintended target (McNabb, 2018). In the 2015 event, a drone crashed onto the White House's South Lawn in the early morning, raising questions about the Secret Service's capability to protect the nation's leader from potential terrorist threats (BBC News, 2015). While these accidents did not cause direct damage, they prompted discussions about tightening regulations for all operators. In 2020, a drone crashed in a field in Pennsylvania, causing no harm but embedding itself mere meters from a power plant. This incident raised alarms, marking the first time a UAV was directed at civilian energy infrastructure. Despite heightened precautions, drones still appear near critical civilian structures: they have been spotted in Holland near the Orano nuclear fuel production facility, Sweden's Forsmark and Oskarshamn nuclear power plants; in The Hague, and near the Ocean Stonehouse railway bridge and Dawlish sea wall in the UK. Unauthorized drone usage incidents indicate the potential of the UAV market being tapped by entities with dubious intentions (Barrett, 2021). When evaluating drone interactions with non-living structures, it's essential to acknowledge the military applications of this technology. The actions of the Russian military in Ukraine stand out as a significant example. In June 2023, during an aerial combat over Odessa, remnants of a Russian drone struck a skyscraper, igniting a fire, which points to the potential geopolitical ramifications of such incidents (PAP, 2023).

Collisions with Humans

A primary consequence of unmanned aerial vehicle collisions with humans is the resultant damage to both the drone and the injuries sustained by the individual. The severity of such damages hinges on a myriad of factors, encompassing the drone's parameters (weight, construction materials, dimensions), collision circumstances (velocity, angle, and point of impact) and individual biological conditions of the victim (Dulaney, 2019).

Given the escalating advancements in technology and the soaring popularity of drones, understanding and highlighting human-involved incidents becomes paramount. These examples can heighten public awareness of potential risks and outcomes linked to the inappropriate or careless use of UAVs. Citing specific incidents also plays a crucial educational role, spurring the development of more stringent regulations and safety practices. Moreover, they underscore an urgent need to understand the intricate interplay between technology and human life, emphasizing societal responsibility in this realm. Accidents can vary in nature, have a global reach, and are associated with a broad spectrum of human consequences. One such incident occurred at Virginia Motorsport Park in 2013, where a drone capturing video footage unexpectedly crashed into the stands, injuring several spectators. While no one required hospitalization, the event highlighted the hazards of drone usage in densely populated areas. (Weil, 2013) During a 2015 skiing competition in Italy, Marcel Hirscher had a close encounter with a UAV, narrowly avoiding a collision. This incident led the International Skiing Federation to impose a ban on the use of drones in similar events. (Lippi et al., 2016) In Seattle, during the 2017 Pride Parade, a woman was struck by a small drone, leading to her loss of consciousness. The drone was operated by a man who mishandled the device in a public setting. (Miletich, 2017). These events underscore the need for increased caution, particularly when drones are used recreationally at public events. Tragically, not all encounters with drones result in only minor injuries or potentially hazardous situations. In a heartrending incident in 2003 at Dartford Heath, a remotely piloted aircraft model fatally struck 13-year-old Tara Lipscombe in the head. Investigations later showed that the model had been improperly assembled, deviating from the provided guidelines (Shelley, 2016).

These cases accentuate the urgent need to implement more rigorous regulations and safety procedures concerning drone usage and other flying models in public spaces. As this technology continues to evolve and finds broader applications, safety must remain a top priority for all involved parties.

3.2. Flying Responsibly: Challenges and Prospects of Safety Regulation

An intriguing aspect of aerial disruption caused by unmanned aerial vehicles is the necessity for rescue helicopters to fly at higher altitudes due to the presence of amateur drones filming fires (Feltynowski et al., 2018). What is more, the FAA also cautions drone operators against unauthorized operations near fires, threatening substantial fines and potential criminal proceedings. The FAA emphasizes that drones pose a collision risk to firefighting aircraft and can distract their pilots, possibly even leading to a suspension of firefighting activities. There have been numerous instances where drones have hindered firefighting operations, as confirmed by fire agency reports (Flight Safety Foundation, 2018). This example proves that despite the widespread use of drones in various economic sectors, their deployment in key areas like cargo transport, police operations or the aforementioned firefighting remains limited. These sectors are viewed as the most significant potential markets for UAV systems, highlighting the need for further analysis and regulation for their safe and effective implementation. Such operations would involve flying over people, an aspect still contentious due to a lack of comprehensive safety data for humans and the resulting lack of global legal standards. Despite strict regulations, the pick-up and delivery is nowadays an emerging trend in logistics and is solved by combining UAVs and trucks. In such scenarios, a drone, initially attached to a truck, may depart to serve specific clients before returning to the same or a different truck (Bekrar et al., 2021). Nevertheless, safety standards are prevalent in most industries to regulate the potential for catastrophic injuries and fatalities and are worth in-depth analysis for future benefits. For instance, in the automotive sector, standards like Federal Motor Vehicle Safety Standards (FMVSS) 208 and 214 together with the New Car Assessment Program (NCAP) program, have reduced the mortality rate from car accidents by 80% over the past 50 years. Similarly, in sports, the National Operating Committee on Standards for Athletic Equipment (NOCSAE), which sets performance minimum standards for protective helmets, reduced fatal head injuries in football by 74% when first introduced for American football (Eamon, et al. 2017). The emphasis on safety standards remains paramount, especially as technologies and their applications evolve.

4. Legal, Technical, and Operational Aspects of Human-Drones Operations

Nowadays, for just a few hundred euros, anyone can purchase a drone capable of flying within a range of several kilometers, equipped with the ability to photograph and record from the air. This emerging niche necessitated legal regulations for public safety. The legal aspect should be considered on several fronts: international law, European Union law, and more detailed provisions in national law. This section will also delve into the interactions between drones and humans in terms of technological and procedural factors. Understanding these factors is crucial not only for ensuring safety and efficiency but also for promoting the harmonious coexistence of drones and people in shared spaces. The section explores the nuances of these encounters, examining technological advancements and procedural protocols that shape the dynamics of interactions between drones and humans.

4.1. Laws Regulating UAV Operations

In the context of international law, the primary document governing the use of unmanned aerial vehicles (UAVs) is the Chicago Convention of 1944, which forms the basis for regulating civil aviation at an international level. The International Civil Aviation Organization (ICAO) has developed guidelines for UAV use, including flight safety and reporting procedures. In 2011, the ICAO released Circular 328, which served as a foundation for subsequent efforts to integrate unmanned aircraft systems into unified airspace. As per Section 2.2 of this publication, all types of unmanned aircraft, whether remotely piloted, operating autonomously, or a combination thereof, are subject to the regulations laid out in Article 8. However, only remotely piloted aircraft systems (RPAS) will qualify for inclusion in the global airspace (ICAO, op.cit., p. 3). This implies that while the provisions of the Chicago Convention apply to all unmanned aircraft systems, the integration of these aircraft is specifically considered in the context of RPAS. The author (Gregorski, 2017) highlights an intriguing point: while the regulations stipulated in the Convention apply to civilian drones, this definition does not encompass aircraft models, especially those intended "solely for recreational purposes." Aircraft models are not subject to the Chicago Convention and are governed by national statutory and executive regulations. The exclusion of aircraft models and toys results in potential overlaps and contradictions in the regulations. For example, an operator piloting a large unmanned aircraft crossing the border between two countries would be subject to the interpretation of the Chicago Convention and its supplementary annexes. However, if the sole purpose of the flight is recreation, it isn't covered by its provisions due to its definition (Završnik, 2015). This example illustrates that even in high-level documents, there are significant gaps in definitional precision. And, since the issue is relatively new, there's a need to standardize provisions to avoid inconsistencies.

From the perspective of European Union law, of which Poland is a member, the aspect of controlling UAVs is governed by regulations 2019/45 and 2019/947. These regulations came into effect in the EU from December 31, 2020, in all member states, including Norway and Liechtenstein (it's anticipated they will soon be effective in Switzerland and Iceland as well). National drone operation laws have therefore been adapted in accordance with the principle of the supremacy of EU law over national law. The approach outlined therein is risk-based, making no distinction between recreational or business activities involving civilian drones. What is considered is the weight and technical details of the civilian drone, as well as the nature of the intended operation. It's worth noting that this interpretation primarily seeks to prevent harm to citizens, aligning with the main objective of the legislation – a goal that is unquestionably valid. The regulation defines three classifications of civilian drone operations based on prior risk assessment conducted by an expert: the "open" category, the "specific" category, and the "certified" category.

The "open" category pertains to civilian drone operations with a lower risk level, where safety is ensured as long as the drone operator adheres to appropriate conditions for the planned activity. This classification is further divided into three subcategories: A1, A2, and A3, addressing flying near people and crowds. Basic A1-A3 rights apply to aircraft weighing 0.025kg – 25kg. There's also a requirement to maintain a 150m distance for drones exceeding 2kg. The A2 certificate further permits flights over buildings. In this category, the potential risk associated with the operations is deemed minimal, eliminating the need for obtaining operational permission before initiating a flight. Additionally, mandatory flight registration is required if the drone's weight exceeds 250 g, or if its kinetic energy surpasses 80 joules upon impact, or if the drone is equipped with a sensor capable of collecting personal data (e.g., a camera), unless the aircraft is classified per Directive 2009/48/EC as a toy, meant for children below 14 years of age. After completing the free registration on the website https://drony.ulc.gov.pl/, an operator receives a Registration Confirmation with a unique identification number. This number must be placed on every drone that requires registration. Complete provisions regarding each subcategory are presented in Table 1.

The "specific" category encompasses more hazardous civil drone activities, for which the operator requires operational approval from the relevant national authority before commencing operations - in the case of Poland, this is the Civil Aviation Authority. To obtain such permission, a risk assessment (by the operator) must be conducted, which will determine the preliminary conditions necessary for the safe operation of the aircraft. EASA lists the following examples in its documentation (EASA, 2023):

– BVLOS flights
– When using a drone weighing more than 25kg
– During flights at altitudes greater than 120m above ground level
– During flights 120m above ground level
– When using a drone in an urban environment with MTOM> 4 kg or without an identification label

In the "certified" category, the level of safety risk is significantly elevated. As a result, ensuring safety requires certification of both the operator and their aircraft, along with licensing of the remote pilot(s). The certified category encompasses flights conducted over gatherings of people or is associated with the transport of people or hazardous materials. Hazardous materials, as defined by regulations, are materials with explosive, oxidizing, toxic, corrosive, radioactive, infectious, and flammable properties. This category of hazardous materials includes solid substances, gases, and liquids. Unmanned aircraft undergo certification that meets at least one of the listed conditions (Commission, 2019):

– The drone is intended for transporting people,
– The typical dimension exceeds 3m, and the drone is intended for operations over gatherings of people,

– The drone is intended for transporting hazardous materials.

Based on the listed conditions, it can be determined that the certification obligation for UAVs applies to devices intended to perform tasks categorized at the highest risk level. The certified category covers VLOS and BVLOS flights. Operations generating a high level of risk due to other types of factors indicated in the risk assessment can also be included in the certified category. Figure 1 illustrates the relationship between the category of operation and the requirements set for the pilot and other personnel.

The classification standard for certificates for unmanned aircraft operators in Poland and Europe [35,50] distinguishes:

- Unmanned airplanes, designated as category A,
- Unmanned helicopters, designated as category H,
- Unmanned airships (dirigibles), designated as category AS,
- Multirotor aircraft, designated as category MR,
- Other unmanned aircraft, designated as category O.

Table 1. Categories and Flight Regulations for Civil Drone Operations

Designation	Flight Conduct Rules
A1	UAVs in class C0 and C1. Flights cannot traverse over gatherings of people or uninvolved persons.
A2	UAVs in class C2. Flights cannot traverse over gatherings of people. Minimum distance from uninvolved persons horizontally is 30 m, and 5 m in low-speed mode
A3	UAVs in class C2 – C4. Flights cannot traverse over gatherings of people. Minimum distance from residential, utility, industrial, and recreational areas horizontally is 150 m."

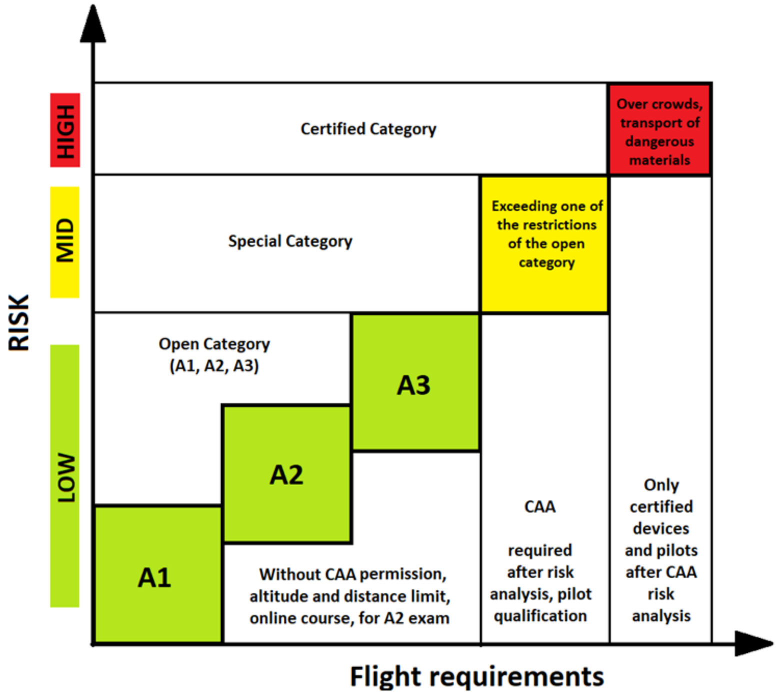

Fig. 1 Relationship between Risk Levels and Flight Requirements across Flight Categories

Another point worth noting is the potential accidents aspect in the context of the law. Collisions between drones and humans can result in severe injuries. A collision with a large drone weighing over 25kg could be fatal. Even a collision with a lightweight drone can be deadly, especially if the drone falls from a significant height. Liability for drone accidents depends on the circumstances. If the damage results from a drone's defect (as a product), product liability regulations apply. This strict liability for damages is harmonized throughout the EU under Council Directive No. 85/374/EEC on liability for defective products. In most cases, the drone pilot is responsible for any damage caused in an accident. EASA regulations require insurance if your drone weighs more than 20 kg. If the drone weighs less than 20 kg, there's no specific insurance requirement. However, most EASA member states also mandate third-party liability insurance, even for lighter drones. Yet, few drone pilots are insured. If a commercial drone causes injuries, potential defendants could include the pilot, the company that hired the pilot, the drone's owner, and the owner's insurance policy. The drone's designer and/or manufacturer may also be held accountable for accidents caused by defective parts or designs.

In addition to the new regulations in the unmanned aircraft regulation and the amended air navigation regulation, the impact of general regulations on drone flying listed in the article (Booth, 2021) should also be considered:

– If you intentionally or recklessly hit someone with your drone, you could be held liable for battery, which carries both criminal and civil sanctions.
– If you intentionally or recklessly damage someone's property using a drone, you may face criminal liability.
– If you fly a drone without observing a reasonable standard of care and injure someone or damage their property, you may be found negligent and liable for compensation to the victim for bodily injuries or property damage.
– If you fly a drone low over someone's property without their consent, you could be held liable for trespass, even if you did not physically enter their property (though this is typically a civil matter, not criminal).
– Furthermore, local regulations restricting drone use, such as during take-off or landing, should be checked.

Another gray area concerning unmanned aircraft is their potential invasion of privacy or overt espionage activities. Regarding data protection law, if a drone is equipped with a camera, the implications of the General Data Protection Regulation (GDPR) on the collection of footage should be considered. Guidelines from the Information Commissioner's Office suggest that compliance with data protection would entail making it clear that you are responsible for the drone and that the drone is capable of filming. These guidelines also emphasize ensuring that you only record with your drone in appropriate locations - for instance, using a drone to film a neighbor's garden could obviously breach their privacy; doing this repeatedly might constitute harassment.

4.2. Technological and Procedural Factors in Drone-Human Encounters

In the era of swift advancements and widespread popularity of unmanned aerial vehicles, it becomes imperative to discuss the complexities surrounding collisions. This issue is multifaceted, ranging from the threats emanating from individual drone components, to damage prevention through ergonomic design, and further, the establishment of procedures for behavior during potentially hazardous scenarios.

Before delving into the consequences of control loss or pilot errors, it is crucial to consider the underlying causes that may lead to such situations and what factors influence drone behavior. Broadly, these causes can be segmented into:

– Internal: issues originating from within the machine, such as signal disruptions, technical malfunctions, and power failures,
– External: factors independent of the operator and the vehicle, for instance, sudden atmospheric changes or third-party interference, including sabotage,
– Human-induced: this entails factors like inadequate control, non-compliance with standards, or insufficient qualifications. In most scenarios where these factors are present, operators often lose the ability to control the drone.

In the study (Yang Liu et al., 2021), the authors aptly note that during a UAV's descent due to malfunction, two primary forces —gravity and drag, act upon it. Adding to these are forces associated with transient wind conditions, introducing a randomness element to the entire event. To estimate potential collision points, one must first calculate the horizontal distance traversed from the malfunction onset point to the impact point on the ground. Given the unpredictable effects of drag and unique UAV characteristics, combined with wind impacts, the ground area where the descending UAV might collide becomes a geographical area rather than a straight-line segment. Based on this, it becomes feasible to approximate the vehicle's impact speed, which is pivotal in such analyses.

Upon the occurrence of a drone collision, the potential damages can be sourced from three primary areas:

– Kinetic Energy of the Vehicle: The kinetic energy (KE) during a drone's collision sequence is a function of its mass and velocity. Among the feasible solutions are potential weight reduction and material modification. Using brittle materials that crack, deform, or bend upon impact can ensure minimal threat to any person or object it might collide with. Examples include brittle plastics, paper, wood, and foam. A clear representation of this concept is a fixed-wing UAV with wings designed to detach during a collision sequence. This wing detachment results in a reduced KE transfer during the collision, presenting a tangible means of reducing the severity of a ground collision for that platform. Broadly speaking, materials that absorb energy would be the ideal choice. However, engines, batteries, and payloads are dense components that are resistant to deformation or breakage upon impact, meaning they don't dissipate KE easily. Depending on the UAV's design, the payload and batteries may also detach upon impact, posing an additional collision threat.
– Ignition Sources from Power Systems: The vast majority of UAS weighing under 25kg use batteries for power. Furthermore, nearly 100% of the permissions granted for commercial UAS operations concern aircrafts using lithium-polymer (LiPo) batteries. LiPo batteries can catch fire when punctured, exposed to air or water, crushed, overcharged, or improperly maintained (Mikolajczak, 2012). While the risk is relatively minimal, there currently aren't additional protective measures in place beyond standard procedures.
– Rotating Parts of the Vehicle: The rotating propellers and rotors of drones pose a significant risk of injury to those in close proximity to an operational UAV. Lacerations represent the most common injury type associated with small UAVs. In particular, operators are most susceptible to such injuries during take-off/landing procedures and ground handling of the drone. Laceration severity ranges from minor to fatal. Perhaps the most practical way to limit rotating part injury risk is to use protective guards around them, significantly reducing the chance of accidental contact.

To prevent such incidents, significant emphasis must be placed on the assessment of Reliability, Availability, Maintainability, and Safety (RAMS). This study is pivotal in the development of UAVs. This type of analysis is mandatory if the ultimate reliability of the drone is to be heightened while keeping repair and maintenance costs minimal. A key aspect in handling emergency situations is to be prepared for them well in advance. Some pilot manuals/guidelines offer advice on handling specific emergency scenarios. It's crucial for the operator to familiarize themselves with these before flying. The article (Waite, 2021) enumerates several such situations along with the actions pilots should take, as detailed in Table 2.

Table 2. Emergency situations along with pilot's counteraction

Emergency Situation	**Pilot's Counteraction**
Engine Failure	Initiate an immediate landing, depending on controllability, away from people; alert everyone in the vicinity.
Power Failure	Alert individuals nearby.
Loss of Control Connection with the Aircraft	Toggle the controller off and on; activate the automatic 'Return To Home' function.
Loss of GPS Signal	Attempt to regain control and initiate a manual return flight to the launch area.

Frequently understated in publications but of equal importance is the software reliability of drones. This topic needs a dual perspective – assessing both internal reliability and vulnerability to third-party interference.
When discussing internal reliability, we're talking about specific software parameters that, in case of failure, help to minimize the risk of serious damage to both the drone and its surroundings. One such system is the Independent Flight Termination System (FTS). It allows the drone to terminate its flight in a controlled manner, maximizing the chances of avoiding injuries or damage to individuals on the ground. It's recommended that drones operating within the BVLOS have this functionality. Another safety-enhancing feature is the GeoFencing system. Geofencing technology creates location-based virtual barriers that prevent drone flights and take-offs in sensitive areas, typically around airports or at one-time events with large crowds, such as festivals or sports events. This provides an added layer of protection against human operator errors.
The aforementioned external threats pertain to attempts to take control of the aircraft. Several fundamental principles enhance drone cybersecurity. The first is encryption, which involves converting data into a coded language, decipherable only with the correct key or password. Drone operators, for instance, can use encryption to protect communication channels between drones and other devices like ground stations or remote controllers. Encryption can also be employed to safeguard the storage and transmission of data, such as flight data, sensor readings, or other confidential information. Another pivotal software component should be the firewall, a protective device that monitors and filters inbound and outbound network traffic based on predefined security rules. Monitoring traffic allows the identification of suspicious activity and the termination of the underlying process. The integration of UAVs into civilian airspace presents both opportunities and challenges, particularly when it comes to maintaining the safety and efficiency of airport operations. In paper (Gołda et al., 2021) has demonstrated through simulation tools the potential for improved efficiency and reliability of airport processes, which could be further leveraged to manage air activities. With the rise of air traffic, the risk of hazardous events on the apron increases, necessitating sophisticated simulation tools such as those developed by (Izdebski et al., 2023) to minimize dangerous occurrences. In paper (Izdebski et al., 2022) has also explored the use of an ant algorithm to safely manage traffic organization, specifically addressing the safe routing of ground handling vehicles in aircraft active environments. This approach could be adapted to the unique operational patterns of aircraft to ensure harmonious integration. Meanwhile, paper (Fiuk, et al. 2022) discuss energy efficiency in air SAR systems which, although focused on the Baltic Sea, highlight the importance of base location and resource allocation that could influence aircraft staging and operations. Lastly, the database architecture outlined by (Jacyna-Gołda et al., 2019) for assigning air transport tasks may provide a framework for scheduling and managing operator tasks, ensuring compatibility with manned aircraft operations and enhancing overall air traffic safety.
In conclusion, it's worth reiterating the standard safety protocols that should be undertaken before each drone flight. A technical review of the drone is recommended to minimize the risk of unexpected failures. This involves a general mechanical check: a visual inspection for possible hull or propeller damage, a thorough check of mounts for tightened screws, and verification of the antenna's proper functioning. The next step is to ensure the battery's state of charge and inspect for any leaks or damages that could lead to power loss. The final element is a software check – ensuring it's updated and that the connection is stable. It's imperative to highlight that infrequent software updates could lead to security loopholes, hence increasing vulnerability to cyberattacks.

5. The Impact of Drone-Human Collisions

5.1. Tools for assessing the aftermath of impacts

Researchers examine the worst possible collision scenarios including the drone's maximum kinetic energy and the most detrimental angle of impact on the human body. An integral part of the research evaluates how the human body responds to such impacts, using various methods relating to tests with anthropomorphic test devices (ATD), post-mortem human models, and computer modeling. The unpredictability of impact outcomes, given the current models, is underscored due to the differences in drone design and their rapid evolution (Rattanagraikanakorn et al., 2020).

Assessing the severity of human injuries occurring during an impact is possible using a variety of tools to estimate the patient's health effects. The various methods focus attention on specific parameters of the impact, such as speed, dimensions or the resulting impact energy. Based on these, it is possible to determine the victim's probability of mortality.
Head Injury Criterion (HIC) is the primary parameter used to determine the level of head injury during a crash, determined by the maximum acceleration value at the time of impact. The maximum acceleration is determined for a specific time period, covering 15 ms. Based on the HIC value, it is possible to determine the level of head injury by assigning it to the Abbreviated Injury Scale (AIS). The higher the HIC value, the more severe the level of head injury sustained by the patient (Prasad and Mertz, 1985; Chybowski and Przetakiewicz, 2020).
The AIS scale is one of the basic tools used when estimating the health effects of motor vehicle impacts, taking into account the risk of mortality. The AIS distinguishes six levels of injury, where AIS1 indicates a minor injury (e.g., a cut on the skin), AIS2 refers to AIS3 indicates a 10% risk of death, AIS4 and AIS5 indicate a probability of death for the injured person of between 5% and 50%, while AIS6 indicates certain death for the victim. To determine AIS, measurements of energy, force or acceleration acting on a person during impact are used (Hsu et al., 2019).
Kinetic energy is one of the key factors shaping human injuries occurring during impact, resulting from the UAV's speed and mass. In the context of impact injuries, it is possible to use the Blunt Criterion (BC) parameter, which characterizes blunt impacts, the calculation formula of which additionally takes into account the diameter of the striking object, the mass of the struck object and the thickness of its soft tissue. Based on the determined BC value, it is possible to determine the probability of damage to the skull by assigning a scale (Raymond et al., 2009).
Neck Injury Criteria is another criterion for assessing the severity of human injury occurring during impact. It quantifies the relationship between upper neck forces and moments and the associated risk of injury. The calculation of Nij is shown below in the equation as a combination of axial force and moment in the sagittal plane, normalized by the critical intersection point of axial force and the intersection point of moment in the sagittal plane (Johnson et al., 2020).

5.2. Injuries occurring during the blunt impact of a UAV on the head

The issue of human injuries occurring during an impact with a UAV has been fairly widely discussed in the literature. Publications on UAV collisions with humans mainly focus on the aspect of collisions with the head, determining the effects of impact based on the results of simulations or experiments.
One of the earliest studies on risk assessment in human-drone collisions conducted at the Virginia Polytechnic Institute and State University identified variances in impact severity based on the orientation of the UAV and found that the devices can deform upon collision, reducing injury risk (Eamon, et al. 2017). In the publication titled "Final Report for the FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, Revision 2", the FAA draws attention to safety aspects related to potential injuries from drone collisions with humans (FAA, 2017; Eamon et al. 2017; Rattanagraikanakorn et al. 2020). Tables 3 and 4 (FAA, 2017) showcase various accident scenarios based on operation types and potential injuries that could lead to permanent disability or even death. An in-depth analysis of most crucial scenarios is provided in Sections 4.3 and 4.4.

Table 3. UAS-Related Injury Concerns and Their Respective Applications (FAA, 2017)

Largest Injury Concern	Applications
Head and Shoulders	Real Estate, Surveying, Construction Photography, Wildlife Observation, Flood Planning, Crop Inspection, Emergency Response, Recreational Use
Face and Torso	Drone Racing, FW aircraft takeoff and landing, Remote Sensing, Search and Rescue
Lacerations	Television Filming, News Filming, Weddings, Flight Training
Payload to Head and Shoulders	Crop Management, UAS Delivery
Chemical / Fire	Wildfire Fighting, Chemical Transport

Table 4. Correlation of UAS Airframes with Mission Types and Flight Profiles (FAA, 2017)

Largest Injury Concern	Example Flight Scenario	Type of UAS Used	Typical Altitude and Forward Speed
Head and Shoulders	Real Estate, Photography	Quadcopters	High altitude, Low speed
Face and Torso	Drone Racing	Quadcopters or Fixed Wing	Low altitude, High speed
Lacerations	Wedding Filming	Quadcopters	Low Altitude, Low Speed
Payload to Head and Shoulders	UAS Delivery	Quadcopters	High Altitude, Medium Speed
Fire	Wildfire Fighting	Quadcopters	Medium Altitude, Medium Speed
Chemical	Cop Spraying	Quadcopters/ Helicopters	Medium Altitude, Medium Speed

The mechanics of human injuries during collisions is a subject thoroughly characterized in numerous research papers. A study by (Jastrzębski et al., 2020) delves into the behavior of ribs during side and oblique impacts. Significantly, the position of a drone during impact influences the nature of injuries caused by a UAV-human collision. A collision can result in contact with the static parts of the drone or with moving parts such as rotors. Interaction with a spinning rotor can lead to lacerations. The most frequent injury from unintentional human contact with UAVs is cuts from blades or other sharp edges of the device. Another frequently reported injury involves head trauma (Gorucu et al., 2021).

The research by Koh et al. (2018) investigated head injuries caused by vertically falling drones using finite element method (FEM) simulations and experimental tests. Health implications were assessed using HIC values and compared to the AIS. Simulations considered various drone weights (0.305 kg to 5 kg) and fall heights (3.05 m to 60.96 m). Key findings showed that a drone of 0.305 kg falling from 60.96 m produced injuries comparable to a 0.405 kg drone from 45.72 m or a 1.6 kg drone from 9.14 m, all approximating AIS=5.7-5.8. Particularly severe injuries (AIS > 6) were observed for drones like a 2 kg unit from 6.1 m or a 3 kg drone from 3.05 m. The highest HICs were recorded for drones like the 3 kg from 6.1 m (HIC=5506.6) and the 0.7 kg from 60.96 m (HIC=9665.8). To validate simulations, experiments were performed with drones (0.305 kg to 5.1 kg) from heights up to 30.48 m, using an electromagnet-held drone and steel cables for accurate targeting. Results highlighted that a 0.820 kg drone from 15.24 m could cause severe injuries (HIC=1023.5, AIS=4). Extreme risks (AIS>6) were seen with drones like the 5.1 kg from 6.1 m. To mitigate injury risks to AIS=3, the study recommends drone weight thresholds of 1.298 kg to 0.256 kg for heights between 7.62 m and 60.96 m.

A study of head and neck injuries occurring during a collision with a UAV is presented in (Campolettano et al., 2017). The experiments were conducted using the head and neck of a Hybrid III dummy equipped with sensors to measure impact forces and accelerations. The study employed drones DJI Phantom 3 (1.2 kg), DJI Inspire 1 (3.1 kg), and DJI S1000+ (11 kg) impacting the head at 16-22 m/s. Frontal and falling head impacts were studied, generating HIC and Neck Injury Criteria values, later mapped to the AIS scale. For frontal impacts with the DJI Phantom 3, direct face hits resulted in peak accelerations of 72 g (HIC15=59, Nij=0.61), whereas a rotational impact from the drone's leg produced a mere 7.2 g (HIC15=1, Nij=0.03). Tests with DJI Inspire 1 were inconclusive, but the DJI S1000+ recorded an acceleration of 43 g (HIC15=12, Nij=0.43). It was observed that while HIC values for frontal impacts were low, injuries were exacerbated by factors like propellers causing eye injuries or detached parts embedding in the face. Falling impacts recorded higher injury levels compared to frontal impacts.

The purpose of the study (Rattanagraikanakorn, et al., 2022) compared injuries from a DJI Phantom III drone (1.28 kg) collision using the Hybrid III crash test dummy and human body simulations via MADYMO software. Nine impact variations were tested, spanning different velocities (0-18 m/s), elevations (horizontal, 45˚ raised, vertical fall), and directions (front, side, rear). The results highlighted increasing drone speed intensifies its kinetic energy, leading to greater head accelerations. Horizontal impacts had the highest HIC value, which decreased for raised impacts and was lowest for vertical falls. Minor variations in HIC values were observed based on impact

direction. When comparing the Hybrid III to the human body, the dummy underestimated head injuries, especially at 45-degree impacts and vertical falls. This difference is attributed to neck complexities, influencing post-impact head accelerations.
The paper (Svatý, et al., 2022) presents results for eight impact tests of UAVs weighing less than 2 kg. Five drones, three multi-rotor quadcopters (weights of 250 g, 680 g, and 1242 g) and two fixed-wing aircraft (weights of 600 g and 1300 g), were used to hit the Hybrid III dummy. The multirotors were vertically lowered overhead from a height of 40 m, while the planes hit the dummy at an angle of 58˚. The results show that the highest level of injury (HIC=413) occurred for a 650-g drone impact at 19.07 m/s. The other variants considered showed a low level of injury (HIC < 50), which was due to lower impact speeds, drone mass and energy distribution during contact.
The study described in (Stark, et al., 2020) addresses the issue of UAV impact injuries for different angles and impact locations and different speeds, using five different Post Mortem Human Surrogates (PMHS). Measurements were carried out with five drones (DJI Phantom 3, DJI Mavic Pro, DJI Inspire 2, Sensefly eBee+, Vendor 1), which were struck at 0˚, 58˚ and 90˚ angles, for speeds ranging from 6 m/s to 21.5 m/s. The results for the 35 individual tests indicate that the most severe injury (HIC=5473) was recorded for a frontal impact with a DJI Phantom 3 drone at a 58-degree angle at 21.5 m/s, which was coded at AIS Severity Level 2, corresponding to a 97.4% risk of skull fracture.

5.3. Other types of injuries caused by UAVs

The paper (Bansal et al., 2021) presents the case of a UAV pilot (Trinity F9 VTOL) who sustained injuries to his hand from propellers while landing a drone. Examination of the patient revealed deep cuts on the dorsal side of the terminal phalanges of the second and third fingers of the left hand, which were accompanied by a fracture of the underlying bone. Examination of the right hand revealed superficial injuries on the inside of the terminal phalanges of the right ring finger and little finger. The paper's authors point out the danger generated by UAV propellers, which, rotating at high speeds, can lead to abrasions, cuts, fractures or even amputations.
The publication (Khan and Brown, et al., 2021) presents an overview of drone-related injuries in children. It outlines the types of injuries that occur when trying to retrieve an immobilized UAV and those associated with attempts to grasp a flying drone, resulting in cuts, sprains, fractures and other injuries. The primary injuries caused by contact with drones included hand cuts, eye injuries, concussions and fractures.
A separate human health risk generated by UAVs is the rotating propellers, which can lead to sequelae such as skin cuts or much more serious injuries, such as finger amputation or eye damage. Drone propellers rotating at high speeds can cause injuries to the eyeball, which can lead to blindness. The paper (Spitzer and Singh, 2018) describes two cases of eye injuries occurring as a result of contact with a propeller. The first case involves a 9-year-old boy who suffered an eye injury from a landing drone. The impact of the propeller resulted in injuries to his right eyelid, right cornea, left ear, nasal bridge and neck, the most serious of which was an injury to the eyeball (the patient's visual acuity after treatment remained at the level of counting fingers at a distance of 5 feet). The second case involves a 21-month-old girl who suffered an injury from being hit on the right side of her face by a toy drone. The impact resulted in a partial incision of the conjunctiva and two linear corneal abrasions, which were successfully operated on.
The purpose of the study (Moskowitz, et al., 2018) was to present the case of a 9-year-old child who was struck in the face by the propeller of a drone over which the operator lost control. The aftermath of the collision resulted in lacerations in the area of the right eyeball, left ear, bridge of the nose and left lateral part of the neck. The treatment administered allowed the patient to recover, except for a complete upper nasal visual field deficit and a partial upper temporal visual field deficit.
Addressing such extremely hazardous situations, the research carried out by the ASSURE through the Advanced Virtual Engineering and Test (AVET) Lab at Wichita State University's National Institute for Aviation Research (NIAR) investigated potential injuries from drone collisions with humans (Gomez, 2021). On the basis of 512 tests and simulations conducted with the use of 16 different UAVs ranging in weight from 0.71 to 13.2 pounds, the findings suggested that drones are flexible and absorb a significant amount of energy during impact. Hence, the most common injuries observed were cuts and bruises. Although drones can cause harm, especially

during high-speed and high-mass collisions, fatalities are rare. The research also pointed out that fuselage impacts are more hazardous than sharp rotor consequences (Tegler, 2019).

Parallelly, a study on sUAS regulations highlighted the need for better injury prediction standards and the potential of automotive vulnerability models (Svaty et al. 2022). A key takeaway is the need for rotor guards and regulations about payloads that drones can carry. Thus, further design advancements in devices are essential for the future.

6. Conclusions

As UAVs become more integrated into our daily lives, the challenges they pose will inevitably increase. However, by studying past incidents, learning from other industries, and proactively addressing potential threats, the Reader can pave the way for a future where drones can be used safely and responsibly. The balance between technological advancement and public safety is delicate, but attainable with careful consideration.

The challenges facing drone regulation are multifaceted. In order to effectively prevent accidents, a series of legal and procedural restrictions have been introduced and still necessary to expand, allowing the risk of harm to the operator and third parties to be minimized. It should be emphasized that the universalization of regulations in this area (e.g., within the EU) significantly increases safety when changing the area of flight operations, although lower-level regulations still vary in member states. Hence, the widespread use of safety procedures related to maintenance and system security contributes to minimizing injuries even when an accident occurs. The problems in this area arise from a combination of technological innovation outpacing regulatory development and a lack of international guidance. With drone technologies continually evolving, regulators often find themselves playing catch-up, trying to fit new drone functionalities into existing regulatory structures that were developed for a different era.

UAV-human collisions can lead to a wide range of injuries, from superficial cuts to severe trauma. The severity largely depends on the drone's kinetic energy, which in turn is influenced by its weight, speed, and height of fall. The head is particularly vulnerable during UAV collisions, as shown by several studies. Not only do drones possess the potential to cause blunt trauma, but other components, such as propellers, can exacerbate the injuries. Children are more susceptible to drone-related injuries, often due to their curiosity and lack of awareness about the potential dangers. Their smaller size and delicate physiology mean that they might sustain more severe injuries even from smaller drones.

The HIC remains a principal measure to determine the severity of head injuries. High HIC values correlate with severe injuries, indicating a greater risk of mortality.

Apart from the impact of the drone body, the rotation of propellers presents a significant risk. High-speed rotating propellers can lead to deep cuts, bone fractures, and even amputations. In several reported cases, drones have led to eye injuries. Some of these injuries have long-lasting effects, including compromised visual fields. Simple models for dummies might not capture the full extent of potential injuries during a collision, especially given the complexities of the human neck and head.

The studies underline the importance of establishing weight and height thresholds for UAVs to mitigate the risk of severe injuries. Additionally, they emphasize the need for protective measures, such as geofencing and collision detection systems, and increased public awareness about potential dangers. Many of the injuries reported arose from loss of drone control, emphasizing the need for rigorous training for drone operators and the implementation of more user-friendly controls and safety measures in drone designs. While numerous studies have provided valuable insights into the effects of UAV collisions on humans, more research is required, especially in understanding the long-term effects of such injuries, the risks associated with newer and more advanced drone models, and the development of safety features to prevent such accidents.

In summary, as UAVs become more common in public and private spaces, understanding the risks associated with human-drone collisions and developing safety measures becomes paramount. The literature underscores the need for comprehensive strategies and regulations to protect individuals from potential injuries, emphasizing responsible drone usage and continued research.

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