Small Remotely Piloted Aircraft Systems (drones)

Mid-Air Collision Study

Contents

Executive summary

The Department for Transport, the Military Aviation Authority and British Airline Pilots' Association commissioned a study into the effects of a mid-air collision between small remotely piloted aircraft systems (RPAS, commonly known as a drones) and manned aircraft.

The study was conducted by QinetiQ and Natural Impacts using laboratory collision testing and computer modelling.

This report was authored jointly by the commissioning stakeholders in order to summarise the findings of this work performed by QinetiQ, and give consideration to how the results will be used.

This study aimed to find the lowest speed at collision where critical damage could occur to aircraft components. Critical damage was defined in this study to mean major structural damage of the aircraft component or penetration of drone through the windscreen into the cockpit. The study has indicated that:

- Non-birdstrike certified helicopter windscreens have very limited resilience to the impact of a drone, well below normal cruise speeds.
- The non-birdstrike certified helicopter windscreen results can also be applied to general aviation aeroplanes which also do not have a birdstrike certification requirement.
- Although the birdstrike certified windscreens tested had greater resistance than non-birdstrike certified, they could still be critically damaged at normal cruise speeds.
- Helicopter tail rotors are also very vulnerable to the impact of a drone, with modelling showing blade failures from impacts with the smaller drone components tested.
- Airliner windscreens are much more resistant, however, the study showed that there is a risk of critical windscreen damage under certain impact conditions:
  - It was found that critical damage did not occur at high, but realistic impact speeds, with the 1.2 kg class drone components.
  - However, critical damage did occur to the airliner windscreens at high, but realistic, impact speeds, with the 4 kg class drone components used in this study.
- The construction of the drone plays a significant role in the impact of a collision. Notably, the 400 g class drone components, which included exposed metal motors, caused critical failure of the helicopter windscreens at lower speeds than the 1.2 kg class drone components, which had plastic covering over their motors. This is believed to have absorbed some of the shock of the collision, reducing the impact.

- The testing and modelling showed that the drone components used can cause significantly more damage than birds of equivalent masses at speeds lower than required to meet birdstrike certification standards.

The study resulted in an increase in knowledge regarding the severity of a mid-air collision between a manned aircraft and a small drone. It should be noted that to understand the risk fully, work should also be done to estimate the likelihood of a collision.

Recommendations were made on further work and possible mitigations and, alongside other work evaluating the likelihood of a collision, will be used to inform future rules and regulations on the use of drones.

1. Introduction

1.1 Drones are gaining in popularity for both leisure use and for commercial activities. The Government's ambition is to ensure that drones are used for the benefit of society by delivering public and commercial services in a way that ensures the safety of other airspace users as well as the public on the ground, while also giving due consideration to security and privacy.

1.2 The safety of the public on the ground and of manned aviation are the most important considerations. The rise in the popularity of drones has come with a rise in the number of Airprox reports. An Airprox is a situation in which, in the opinion of a pilot or air traffic services personnel, the distance between aircraft as well as their relative positions and speed have been such that the safety of the aircraft involved may have been compromised.[1] In the UK these Airprox incidents are investigated by the UK Airprox Board.[2] The number of incidents reviewed by the Airprox board involving objects believed to be drones has risen from six such events in 2014, to 29 in 2015 and 70 in 2016. In 2017, there have been 34 drone-related Airprox incidents up until the end of May; for the corresponding time period in 2016 the number was 28. Conversely, the number of Airprox incidents between manned aircraft has decreased in recent years from 206 in 2014, to 175 in 2015 and 168 in 2016.[3]

1.3 To provide further context on the likelihood of a collision, the number of confirmed birdstrikes reported to the CAA in 2016 was 1835, with an additional 821 unconfirmed bird impacts and 268 near misses.[4]

1.4 Airlines, flight crews, aviation authorities and the general public are understandably concerned about the potential consequences of a possible collision with a drone. Whilst much is already understood about the degree and type of damage likely to be caused to aircraft structures by a birdstrike, little was previously known about the potential risks presented by drones to manned aircraft.

1.5 The Department for Transport (DfT), the Military Aviation Authority (MAA) and the British Airline Pilots' Association (BALPA), hereafter referred to as the stakeholders, all came together to commission this study to gain greater knowledge in this area.

1.6 While this study looks at the severity of an impact with a drone, it is important to also consider the likelihood of such a collision when assessing the risk. Any existing or future work on assessing the likelihood of a collision should be considered alongside the findings of this project in order to fully assess the risk.

1.7 This significant study was organised and scoped in collaboration with the Unmanned Air System Capability Development Centre (UAS CDC) within the Ministry of Defence. The UAS CDC were instrumental in guiding the tender process and QinetiQ and Natural Impacts were chosen by the stakeholders to conduct the study. Both organisations have a wealth of experience in their respective fields, and are highly

[1] https://www.airproxboard.org.uk/Learn-more/Frequently-asked-questions/
[2] https://www.airproxboard.org.uk/home/
[3] Removing drones, balloons, models, parachutists and unknowns from the total number of Airprox reports.
[4] http://www.caa.co.uk/Data-and-analysis/Safety-and-security/Datasets/Birdstrikes/

regarded organisations who conduct studies for defence, international companies and regulators. They also have first-hand experience with birdstrike testing and impact modelling.

2. Previous Work

2.1 To date the perceived threats posed by drones to aviation safety have been the subject of significant speculation but minimal evidence-based substantiation. This study was exceptional in its scope and approach, and is one of only a very small number of studies that directly addresses the topic of drone collisions.

2.2 While there are many references on the subject of birdstrikes against manned aircraft, where the impacting bird is typically described as a fluid, some drone components such as the motors and batteries, are harder and potentially more damaging for comparable masses.

2.3 Particularly relevant previous research has been conducted by Imperial College, sponsored by the Defence Science and Technology Laboratories (Dstl). Their project involved modelling and impact tests that compared the effect of birdstrikes on aircraft with those of nano-UAVs (very small unmanned air vehicles), as represented by generic quad-copters of masses up to 200 grams. The work was undertaken to inform the discussion on whether it was safe to operate nano-UAVs in the vicinity of military aircraft. Important distinctions between the impact characteristics of birds and nano-UAVs were identified and therefore, it was concluded that the assessment of drone impact requires particular consideration, and cannot be inferred directly from birdstrike response. The Imperial study also showed that levels of damage from the drone impacts were dependent upon the particular components and impact conditions.

3. Scenarios

3.1 For this project, the stakeholders investigated several scenarios based on real-world situations that were considered to be most likely to occur and to pose the greatest risk.

Aircraft structures

3.2 The aircraft structures chosen were:

- Helicopter windscreens (one birdstrike certified and one not).
- Helicopter tail rotors
- Large airliner windscreens

3.3 Part of the reasoning for choosing a non-birdstrike certified windscreen was to enable a comparison to general aviation aircraft which do not have a requirement for birdstrike certification.

3.4 Birdstrike certification of aircraft components requires demonstration, by testing, that the components are resistant to bird impacts. This testing covers several parameters relevant to bird impacts and when these are all passed the component is certified for future use.

3.5 Two airliner windscreens were used, one with two layers glass construction which was used to test the projectile launching mechanism, referred to as Airliner-B. The main testing and modelling was conducted using a more complex windscreen with three glass layers, referred to as Airliner-A.

Drones

3.6 The most widely available small drone types were considered and a number were selected covering the range of sizes. Drone components were selected that would represent drones that would be typically found in the following classes:

- A 0.4 kilogram class maximum take-off weight (MTOW) quadcopter; referred to as a ‘400 gram class’ quadcopter or drone through this document: This covers the toy market and small hobbyist drones.
- A 1.2 kilogram MTOW class quadcopter of 1.2 kilogram; referred to as a ‘1.2 kilogram class’ quadcopter or drone throughout this document: This covers the majority of hobbyist and some smaller professional drones.
- A 4 kilogram class MTOW quadcopter; referred to as a ‘4 kilogram class’ quadcopter or drone throughout this document: This covers some professional drones and some larger hobbyist drones.

- A 3.5 kilogram class MTOW fixed-wing drone; referred to as ‘3.5 kilogram class’ fixed wing drone throughout this document: This was considered to be representative of professional longer endurance drones, in addition to some hobbyist drone types. The fixed wing type with the nose-mounted propeller was used as this was considered to represent a greater impact risk than tail-mounted propeller.

Impact speeds

3.7 For a given collision, the range of possible impact velocities and other impact conditions are too numerous to fully consider within a practical programme of testing. It was therefore necessary to determine an appropriate set of impact speeds for each collision scenario to represent a worst-case in normal flight conditions in the live tests.

3.8 Based on their expert knowledge, the stakeholders selected a number of impact speeds for the live tests. They did this by considering the usual cruise speeds of helicopters and the typical speeds of airliners at various stages of low to medium altitude flight. The top end of the test and modelling speeds were based upon a typical range of operating speeds, and speeds that aircraft are typically limited to by Air Traffic Control. For the airliners, they do not represent typical cruise speeds at altitude.

3.9 It was assumed that the drone and manned aircraft are on a direct collision course, and are travelling in opposite directions such that the impact velocity is the sum of their true airspeeds. For the computer modelled collisions a large range of speeds, covering the whole range of realistic speeds, were selected and modelled.

3.10 The helicopter tail rotor blades were modelled as rotating at their normal operating speed.

4. Testing and Modelling

4.1 A combination of techniques were used to carry out the project, these included highly detailed computer modelling, using finite element analysis software, and impact tests against genuine aircraft windscreens. No live testing was performed for the tail rotor blades due to difficulty in acquiring blades and the limited resources available for the study.

4.2 Use of impact-modelling software can provide additional insight and can enable a wider range of impact conditions to be considered, but to do so reliably requires that the models be validated by experimental tests. This calibration and validation activity was at the centre of the study's requirements, to ensure that an accurate model was created which could be used for this and future work.

4.3 It should be noted that both the live testing and the modelling were conducted using conditions which were as close to real life as was practically achievable. However, some factors could not be replicated, for example:

- the aerodynamic pressure on aircraft structures during flight
- the internal pressurisation of the cockpits
- the low temperatures experienced in flight which could change the way that drone and aircraft materials would behave during an impact

4.4 Figure 1 shows the Airliner-A cockpit with one of the windscreens used for testing, and the corresponding computer model on which the simulation was based.

Figure 1: Airliner cockpit for impact testing (left) and computer reference model

Testing environment

4.5 The impact tests were carried out at the Natural Impacts specialist testing facility in Farnborough. The aircraft components were installed in the impact test lab and a large gas gun was used to shoot the drone components against them.

4.6 The gas gun is made up of a very long, over ten metres, gun barrel and a compressed air system. The air pressure is built to a controlled pressure then suddenly released to propel the drone down the barrel into the target windscreen. The use of this gas gun allowed a very fine tuning of the impact speeds leading to scientifically valuable and repeatable results.

Drone components

4.7 The drone configurations considered include quadcopters and fixed-wing drones. Quadcopters typically have four arms and motors in a cruciform arrangement attached to a central body with battery and usually a camera used for aerial photography. Fixed-wing drones typically have a central fuselage including the battery, the propeller and other components, with lightweight wings attached. An important point is that the study focussed on typical RPAS that would be encountered within each of the different classes of drones on the market today. For example, the large quadcopter studied was within the 4 kg class, but is representative of a typical hobbyist drone within this class that would carry a digital SLR camera and would weigh approximately 2 kg.

4.8 A novel solution was found to launch a complete 1.2 kilogram class quadcopter, however, the 4 kilogram class quadcopter and the fixed-wing drone would not have fitted into the gas gun. The decision was made to use the central components of these, removing the lightweight elements, which was considered to be an acceptable approximation. Although the mass of the 4 kilogram class quadcopter test projectile was reduced by approximately 50% compared to the upper limit mass of the 4 kilogram class complete drone, the other two motors, which make up most of the rest of the mass, would impact well away from the main impact point. Furthermore, it was considered that the effect of removing two of the arms was minimal, because the arms are weak so would likely break off in the collision. Therefore, the arms and the motors they are carrying would not contribute greatly at the main point of impact. These justifications were based on expert advice from the project team, but would need further testing to verify.

4.9 The computer model used the same configuration to allow comparison with the live tests. As an example, Figure 2 shows the components used to construct the 4 kg class quadcopter used for testing and Figure 3 shows an image of the computer model for this drone. This drone includes motors, battery and a camera similar to those used on drones used for aerial photography, but only two of the four arms. The original glass-fibre central hub plates were replaced with aluminium which could better withstand the acceleration loads when launched.

4.10 For the fixed-wing drone, only the core components were used, i.e. the battery and propeller spinner, without the lightweight wings and fuselage casing.

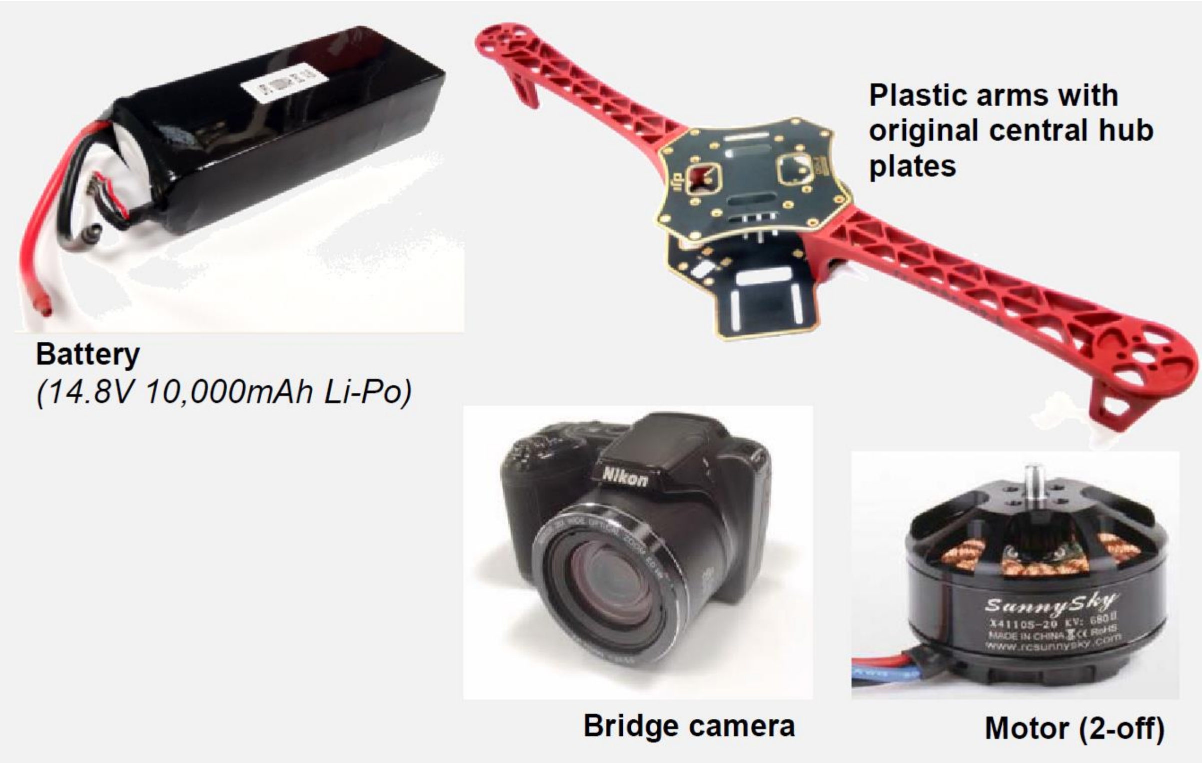

Figure 2: 4 kg class drone components

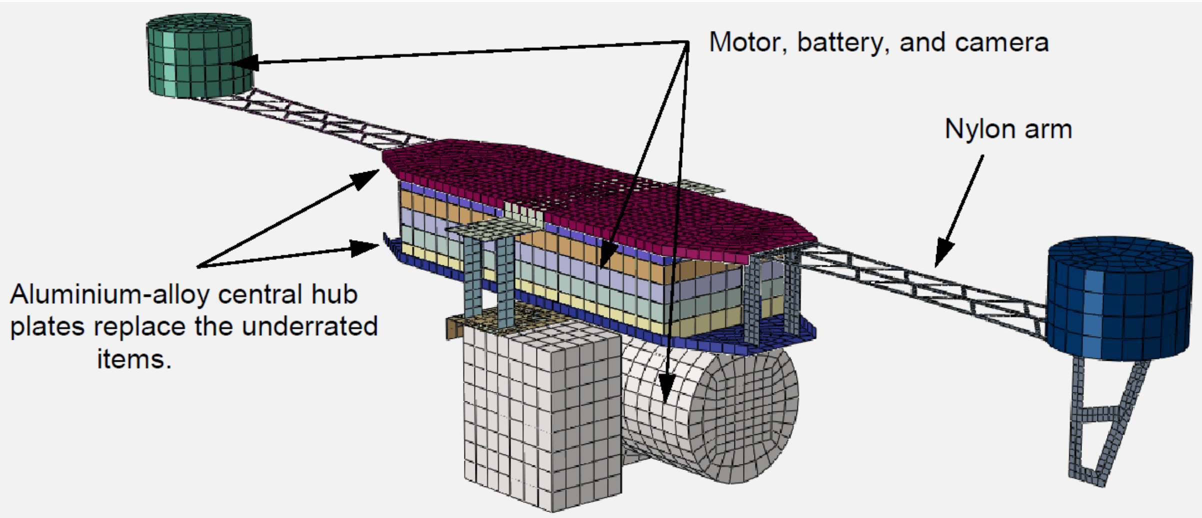

Figure 3: 4 kg class drone components model

Calibration of computer model

4.11 A number of impact tests were conducted and results were filmed with high-speed cameras. The results were compared with the finite element method modelled results and where necessary, the material properties included in the computer model were adjusted to better reflect the reality of the live tests. The model required only minor calibration, with maximum adjustments to the material properties being only 10%.

4.12 Lab tests including crush tests and impact tests were also performed to measure the strength and behaviour of the individual drone components. The results from these tests were also used to calibrate the properties included in the model.

4.13 The final calibrated model showed a strong correlation with the live tests, giving confidence that the model was accurate. The exception was the airliner windscreen, where the real-life tests showed less damage than predicted by the model at the same speeds. This was thought to be due to the complexity of constructions and some uncertainty as to the exact composition of the glass, details of which were unobtainable at the time. However, the model showed more conservative results than indicated by real-life testing, i.e. showed critical damage at lower speeds than the real-life tests. In any future work, more should be done to refine the structural and material details of these complex windscreens.

4.14 This final calibrated model was then used to simulate the collisions covering the full range of impact speeds agreed by the stakeholders.

5. Results

5.1 Prior to conducting this research, the resistance of aircraft components to a drone collision was open to considerable speculation. This project has resulted in an increase in knowledge regarding the severity of mid-air collisions between drones and the manned aircraft components tested.

Non-birdstrike Certified Helicopter Windscreens

5.2 The non-birdstrike certified helicopter windscreen proved to have a low resistance to all the classes of drones tested, with penetration through the windscreen shown to occur at speeds well below the normal cruising speed of a helicopter of that type. For the fixed-wing drone, which is itself capable of a significant speed in flight, it was found that the drone could penetrate a helicopter windscreen of this type even if the helicopter was stationary.

5.3 As general aviation (GA) aircraft do not have a requirement for birdstrike certification, the result from the non-birdstrike certified helicopter could be read across to GA aircraft with comparative severity in the result of a collision.

Birdstrike Certified Helicopter Windscreens

5.4 The birdstrike certified helicopter windscreen was found to be much more resistant, but it was found that the quadcopter drones could penetrate these windscreens when the closing speed was similar to the helicopter's typical cruising speed. The speed the fixed-wing drone can itself reach meant that it could penetrate the windscreen if the helicopter was moving at a speed significantly below the normal cruising speed. When the helicopter was stationary, however, it was shown that a fixed-wing drone, when flying at its maximum speed, was unlikely to penetrate this windscreen.

Helicopter Tail Rotors

5.5 The modelling of helicopter tail rotors showed that they would be vulnerable to impacts with all types of drones. Due to the very high speed of a rotating tail rotor blade, it could be critically damaged by an impact with any drone.

5.6 Again, it should be noted that although the most accurate properties available were used, the helicopter tail rotor results were based on modelling only, with no live testing to calibrate the model.

Airliner Windscreens

5.7 Airliner windscreens have a more complex and much tougher construction than those of helicopters. It was found that the airliner windscreens, although substantially damaged, could retain integrity during impacts with drones up to speeds typically flown at during the aircraft landing and later stages of the approach.

5.8 At higher altitudes and speeds, modelling and testing showed that severe damage to the Airliner-A windscreen, including complete structural failure of the windscreen, did not occur with the 1.2 kilogram class quadcopter components, but could occur during impacts with the 4 kilogram class quadcopter components. Additionally, during one high speed live test with the Airliner-B windscreen, the 3.5 kilogram class fixed-wing drone components penetrated the windscreen.

5.9 While there is a risk of critical windscreen damage to airliners travelling at higher speeds from the more advanced and heavier drones, especially those with exposed metallic components, the likelihood of encountering these drones is significantly less than toy drones. It is nevertheless important to note what the Airliner test has demonstrated; that fixed wing drones with metallic components can do significant damage to aircraft windscreens. The drone construction plays a critical part in the severity of a collision.

Drone Construction and Orientation

5.10 An important point that this study confirmed was that the components of drones do not behave in the same way as an equivalent mass bird under similar conditions. In fact, the work showed that some of the lower mass projectiles caused more damage than those with a slightly higher mass. This occurred when the harder and denser components, such as motors and batteries, were more exposed on the particular drone model used during the testing.

5.11 A simple plastic surround covering a drone motor had a notable effect in lowering the impact forces during component testing.

5.12 The configuration of the drone, angle of collision, component masses and orientation of the motor shaft, all had a significant effect on the extent of the collision damage. The high speed video showed that when plastic components impacted the windscreens before the harder metallic components, the damage was reduced. For example, with the airliner windscreen tests, even at the maximum speed tested, the windscreen retained integrity when the plastic elements of the drone impacted first, slightly deflecting the main body and components.

5.13 Different live tests were performed with the 4 kg class components, some with the camera on the lower side as in Figure 3 and some inverted so the camera was on the upper side. It was found that the damage was less with the camera on the lower side, where the camera impacted the windscreen before the main body of the drone. This implies that the camera was providing some level of shock absorption and again suggests that the configuration of the drone is important.

6. Conclusions

6.1 Unlike birdstrikes, the aviation industry is only beginning to understand the risks of drone collisions. This study has resulted in an increase in knowledge in this area.

6.2 It is clear from the results that helicopter windscreens could be critically damaged by collisions with a drone in several realistic scenarios. It has also been shown that helicopter tail rotors can also be severely damaged.

6.3 Whilst more resilient than helicopters, the modelling and testing in this study has shown that airliner windscreens could be critically damaged by mid-air collisions with 4 kilogram class quadcopter components, and 3.5 kilogram class fixed-wing drones with exposed metallic components at high, but realistic speeds. These impact speeds would usually be encountered when the aircraft is at higher altitudes, 10,000 feet or above, but aircraft do sometimes operate at these speeds at lower altitudes.

6.4 The testing has also shown that the construction of a drone can make a significant difference in the impact of a collision. Where the toughest and densest drone components were covered with a plastic casing, or did not hit the windscreen first, the impact of the collisions was lessened.

6.5 With regard to the comparison with the severity of a birdstrike, it was realised that drones can cause significantly more damage than a bird of equivalent mass at the same speed. This seems to be due to the hard metallic components present in drones and means that birdstrike certification cannot necessarily be used as a prediction of complete protection from drones.

7. Recommendations

7.1 Whilst this work considers the severity and nature of damage of a drone collision with the windscreen or tail rotor of manned aircraft, it does not consider the likelihood of such a collision. In order to understand the full risk picture and develop risk-appropriate mitigations, it is recommended that a better understanding of the likelihood of a collision is developed and that other manned aircraft components are also considered. Any existing or future work looking at collision likelihood should be considered in order to fully understand the risk picture.

7.2 As with all airspace users, drone operators are responsible for operating their drone safely and should be aware that there are significant penalties for endangering an aircraft. However, the rise in the number of reported encounters between drones and manned aircraft and the evidence from this study and others does suggest that more needs to be done. The UK Government is considering how best to ensure this as part of its work resulting from its recent wide-ranging drone policy consultation.

7.3 More widely, it is recommended that:

1. The results of the study are used to help inform risk assessments for all aircraft operations. In particular when helicopters are operated, the vulnerabilities in the event of a mid-air collision with a drone should be taken into account and appropriate operational mitigation measures should be considered. For airliners, one operational option could be for air traffic control to advise aircraft to operate at a reduced, safe speed if a drone is reported in the area.
2. The study considered a limited number of aircraft components and drone types. It is recommended that consideration should be given to conducting further similar work which would cover a wider range of scenarios, and further improve the modelling capability.
3. As the study has shown that drone configurations and construction designs significantly affect the severity of a collision, it is also recommended that drone manufacturers consider implementing design adaptations that mitigate the impact of a collision, such as plastic casing for motors. Consideration should also be given to further research on drone frangibility and energy absorption with a potential ultimate outcome being the implementation of a design requirement for civil and military drones.