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Mass threshold for 'harmless' drones

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Abstract

Today it is possible to buy small and cheap drones in toy stores, super markets, and on numerous online shops. Often, these drones are very light-weight and even though they are flown in back yards, sport fields, parking lots, and such places, they typically pose no lethal threat to people in the vicinity of the drone. Nonetheless, in many countries such drones are regulated by aviation rules that does not distinguish between these drones and the larger hobby or professional drones. Consequently such small drones are flow illegally. This has prompted the Danish Transportation Authority to suggest a category labeled 'Harmless', which should be based on a mass threshold. To aid such a classification this work proposes a mass threshold of 250 grams, below which, we argue, it is reasonable to classify drones as 'harmless' in the sense that the expected fatality rate is equivalent to that of manned aviation.

This threshold is found by combining probabilities for crashing a drone, for impacting a person, and for the impacted person to sustain a fatal injury. Drone technology is still in its infancy and statistical basis for these probabilities is therefore scarce. As a consequence the probabilistic approach in this work is based a numerous assumptions, such as the reliability of drones, the average mass to speed ratio, and the severity of drone inflicted injuries.

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Keywords:
Drone, unmanned aircraft, threshold, UAS category, harmless

1. Introduction

Introducing new legislation for unmanned aircraft is a worldwide challenge that national aviation authorities in most countries find difficult and time-consuming. This comparatively new area within aviation is in many aspects different from manned aviation, and therefore requires new regulation. One such difference is the size and weight of the aircraft; once unmanned an aircraft can become arbitrarily small. As a consequences it makes sense to divide the unmanned aircraft into size categories and impose less stringent requirements on comparatively smaller categories. One interesting category is the 'no harm' size, which is loosely defined as aircraft that cannot do harm to people through physical interaction (except intentionally through chemicals, explosives, and other such means). For aircraft of this size it would not be necessary to consider the safety measures that otherwise apply to drones, making them much easier to manufacture and operate as well as making the regulation easier to enforce.

1.1. Background

This work was prompted by a request from the Danish Transportation Authority to the UAS community in Denmark to suggest a mass threshold below which it would be reasonable to significantly relax regulatory restrictions without compromising public safety. The threshold would be a 'no harm' threshold in the sense that drones below this mass in all probability would not cause severe or fatal injuries under any circumstances. It seems justified that with some reasonable assumptions (detailed later, but for instance that we do not include a casualty of a car accident caused by a driver having his attention caught by seeing a drone) such a limit do exist; large drones obviously can be lethal on impact, while tiny drones (say, less than 1 gram) does not pose any threat to human safety. The challenge is to find a threshold where we pass from the latter situation to the former.

The fast development in miniaturization and low-cost manufacturing of simple consumer electronics means that drones are now available to everybody through toy vendors, super markets, etc. as well as from 'add to basket' web sites. The national 'drone regulations' are not updated at the same fast pace and were typically written for recreational use of model aircraft. That means small aircraft flown by (semi-)experienced pilots operating the control surfaces directly, thus having full and immediate control of the aircraft. It also means that such flights usually take place in secluded areas where the people present are few and generally aware of the risks involved. Consequently, when inexperienced users operate very small toy drones in their back yards they might inadvertently violate regulations even though the drone probably could be categorized as 'harmless'. Being unable to – and generally not interested in – limiting this widespread use of toy drones civil aviation authorities might introduce the proposed 'harmless' category to legalize at least the smaller of these aircraft.

Recognizing that although a limit on the mass of a drone is very easy to enforce (in the sense that determining the mass of a drone is easy) determining a meaningful threshold is perhaps not so easy. From a safety point-of-view the threshold should be sufficiently low to reduce the probability of fatalities to almost zero. But the large variety of drone designs will then inevitably lead to a fairly or even very conservative limit for a significant part of the drone types. This is because the limit has to be based on a long series of assumptions that will lower the threshold, even though most assumptions will not apply to most drones. However, since combining only worst case scenarios will lower the limit to the point where it is no longer useful this work will instead propose a mass threshold based on probabilities.

1.2. Previous work

Categorization or classification of unmanned aircraft has been the subject of previous publications. Indeed most national regulations already categorize aircraft according to mass, for instance using 1.5 kg, 7 kg, 20 lbs, 20 kg, 55 lbs, 25 kg as thresholds. Such thresholds are probably based on empirical observations and serve well to provide a useful classification of aircraft. However, there is a merit to proposing an analytically derived classification as opposed to waiting for the injury data to emerge from the use of unmanned aircraft when introducing new classes. This work takes outset in the thorough investigation conducted in [1], which focuses on drones in the mass span from 1 to 1000+ kg. The smallest class proposed there is called 'Harmless' and suggested to limit the mass to 80 gram (under some assumptions equivalent to a kinetic energy of 33.9 J). While the method to achieve this mass limit is very useful (and to some extend use in the present work) it does hinge on extrapolation of drone properties well beyond the data set available. As such the 80 gram threshold is somewhat arbitrary since the extrapolation disregards some of the distinct properties of very small drones.

There are numerous other publications that present and discuss classes of drones, and often they make use of the term 'Micro' for the smallest drone class which typically include drones below a mass of 1 to 2 kg. In [2] there is a list of national classifications for a number of countries. A British classification is presented in [3] and a German in [4]. Also, a number of Civil Aviation Authorities have publicly proposed, and in some cases implemented, drone classes that go beyond the classical recreational-based classifications, where there is no need to subdivide the 'below 10 kg' type of class.

2. Methods

This section is divided into four parts. The first part in Sections 2.1 and 2.2 presents the assumptions necessary to determine the threshold. The second part in Section 2.3 presents the probabilistic methods used. The third part in Sections 2.4, 2.5, and 2.6 explains the relation between kinetic energy and human injury, and how to find a kinetic energy threshold. Finally, the fourth part on establishing the mass threshold is presented in Sections 2.7 and 2.8.

2.1. Basic assumptions

The development of a mass threshold will be based on a number of assumptions, divided into two categories. The basic assumptions which in some sense are circumstantial to the investigation, and the simplifying assumptions described in the next sections. The basic assumptions are listed here and are unchanged throughout this work. They serve to frame the problem and described the circumstances under which the threshold is meant to have effect.

Upper limit: It is assumed that the mass threshold is at most 1 kg, and as such the list of drones forming the basis of the statistical analysis will exclude any drones above 1 kg maximum take-off mass (MTOM).

Indirect injury: The probability of a fatality P_{fatality} is solely based on impact between a drone and a human being. Injuries resulting from incidents caused by a person's lack of attention for their own well-being when observing a drone are not included. Injuries resulting from subsequent actions following a drone incident (for instance a drone breaking a window and glass falling down) are also not included.

Air-to-air collisions: As a consequence of the above assumption mid-air collisions are not considered.

Awareness: It is assumed that people are not aware of the presence of a drone. That is, we do not assume that people will attempting to avoid a drone coming at them, or attempt to take cover.

Multiple person injury: It is assume that a drone is not large enough to injure multiple people simultaneously, or to impact an obstacle and a person simultaneously. That is, it is assumed that any energy dissipated at impact goes into one human.

Shelter: It is assumed that people are not sheltered in any form, neither by walls, fences, or even clothes.

Body regions: It is assumed that a person is impacted either in the head, thorax, or abdomen. These are typically the exposed body parts in most posture, and injury to arms and legs are typically not fatal.

Fatal injuries: We only considerer fatalities. That is, non-fatal injuries, including bleeding, pain, disabling injuries and similar are not considered.

2.2. Simplifying assumptions

To be able to quantify the probability of fatal injuries we will make a number of simplifying assumptions. In future work these might be detailed, replaced, or altogether removed to achieve a more accurate quantification.

Kinetic energy: We will assume that kinetic energy of a drone is reasonable measure for person injury upon impact. This is a key assumption which will help introduce the mass threshold. However, it is not difficult to realize that this is a severely simplifying assumption, and future work might very well focus on removing/replacing this (see Section 4 for further discussion).

Deformation: The drone is assumed to be complete rigid and not deform upon impact. All deformation occurs in the tissue, and as such the dissipation of energy is in the person only.

Propellers and rotor: While most drones are equipped with exposed rotating propeller(s) or rotor(s) we will assume that they do not constitute a lethal threat.

Speed: A drone can either impact through flight speed or through ballistic speed. The latter typically occurs for rotary winged drones when propulsion is lost and it moves solely through the influence of gravity and wind. While a falling drone might attain high speed, in this work we assume that impact occurs at the top flight speed of the drone.

Worst case: Most parameters in this work originates in bad to worst case scenarios (such as the assumption above on top speed).

2.3. Probability of lethal incidents

The ultimate goal is to determine a mass such that it is improbable for a drone below this mass to inflict fatal injuries to any person under any circumstance. Obviously it is not possible (on the long term) to completely avoid fatalities, and it would therefore be reasonable to accept a fatality rate in the same order of magnitude as manned aviation. This is a widely accepted concept termed equivalent level of safety, see [5, 6, 7].

Different sources report different fatality rates for manned aviation, but they general range from 10^{-7} to 10^{-8} fatalities per flight hour, see for instance [8, 9]. Some figures are based on statistics from actual incidents, others on recommendations for manned as well as unmanned aviation. There is no significant difference between the ground fatality rates and the mid-air collision fatality rates. In this work we will assume that 10^{-8} fatalities per flight hour is acceptable.

The probability can quantified as a product of a series of probabilities

$$P_{\text{fatality}} = P_{\text{crashing}} \times P_{\text{impact}} \times P_{\text{fatal injury}}, \tag{1}$$

where P_{crashing} is the probability of the drone crashing at (near) top speed, P_{impact} is the probability of hitting a person in the crash, and $P_{\text{fatal injury}}$ is the probability that the injuries sustained are fatal. Per tradition in aviation P_{crashing}, and thus also P_{fatality} has the unit 'per flight hour'. As argued above by adjusting the drone mass the combined probability can be reduced, and the challenge is therefore to find the mass such that P_{fatality} is comparable to manned aviation. However, all three probabilities are difficult to determine and obviously highly situation-specific.

In an attempt to quantify these probabilities it is useful to further divided them

$$P_{\text{crashing}} = P_{\text{error}} \times P_{\text{loss of control}} \times P_{\text{high speed}} \tag{2}$$

$$P_{\text{impact}} = \rho_{\text{people}} \times A_{\text{person}} \tag{3}$$

$$P_{\text{fatal injury}} = P_{\text{injury}} \times P_{\text{injury fatal}} \tag{4}$$

where the individual factors expresses various parameters of the flight. Each of the factors are described in a little more detail in Table 1.

This work will focus primarily on the two factors in (4), starting with $P_{\text{injury fatal}}$ in the following sections.

2.4. Injury mechanics

The following is a paraphrased and "drone-adapted" description from [11, p. 59] of mechanics of person injury for a non-penetrating impact: A rapid inward displacement is the primary mechanical response of the body wall to the loading of an impacting drone and this is the principal factor responsible for the transfer of energy into the body and the production of internal injury. The maximum displacement produced and the velocity attained in the early stages of the motion are the primary parameters for the extend of the injury. Subsequent to impact and the following rapid deformation of the body wall the drone will have negligible rebound velocity and the body wall returns only very slowly to its original shape. The drone simply distorts the body wall and falls down. That is, the thoracic or abdominal wall is not acting like a spring being compressed and then releasing the kinetic energy back to the drone. The lack of significant rebound velocity shows that the body is highly damped or 'viscous'. This is a significant observation in that for a system having an elastic and viscous behavior (viscoelastic), the displacement upon impact loading is velocity dependant. The faster that a viscoelastic material is deformed, the more resistance it offers (it becomes stiffer). This behavior is broadly similar to that of a car suspension; a slow push will depress the suspension but the shock absorber stiffens the suspension to severe blows during driving. Thus, the type and severity of internal injury is dependant not only upon the magnitude of the distortion of the body wall, but also upon the velocity at which distortion occurs.

2.4.1. Importance of drone design

The human torso can withstand rather severe compressions without sustaining significant injury. In fact, as much as 50% reduction in body dimensions can be sustained in the direction of the applied force, provided that the peak velocity of the distortion occurs at least 50 milliseconds after impact. Conversely, high velocity distortions occurring at least ten times faster can produce severe internal injury even with body wall distortions of only 3-4 cm ([12]). This means that temporal extensions of the impact is very important, and that prolonging the period of energy dissipation can greatly reduce the severity of the injury. Therefore, if a drone is designed in such way that it takes a long time (i.e.

Table 1. Short description of the factors in the probability equations, and the ranges used in this work.

Factor	Description	Range
P_{error}	The probability of an error, either piloting error or technical malfunction. We will assume this to be fairly high for the smaller drones, and decrease with increasing size.	0.1 – 2
$P_{\text{loss of control}}$	The probability that the error leads to permanent loss of control of the drone. Piloting error often cause temporary loss of control, while technical error, such as empty battery or loss of communication typically lead to permanent loss of control. In this work we will assume a fixed value.	0.5
$P_{\text{high speed}}$	The probability that loss of control leads to the drone traveling at near top speed. This include free fall from higher altitudes as a consequence of loss of power, while loss of comm typically does not result in high speed crash. For this work we will assume a significant (for smaller drones) to high (for larger drones) probability.	0.2 – 0.5
ρ_{people}	Whether a crashing drone will impact a person depends hugely on the person density in the vicinity of the drone. This is the probability that can be regulated by requiring drones to only fly away from roads, buildings, crowds, etc. The density can range from vanishing to about 4 persons/m^2 (large crowds at public events, see [10]). For this work we will assume smaller density for smaller drones and reasonably high density for larger drones (which are typically flown over wider areas).	0.4 – 1
A_{person}	The average size of a person seen from above. For predominantly horizonal impact trajectories the value might increase, but only slightly, since we assume impact in either head, thorax, or abdomen.	0.25
P_{injury}	The probability that a given drone at top speed inflicts injury upon impact. This value is the primary adjustable parameter (adjustable by mass) and will be investigated further in this work. While this factor can be reduced by mitigating factor (such as the ability of the drone to absorb energy during impact) in this work it will solely be based on the total kinetic energy of a drone.	10^{-3} – 10^{-5}
$P_{\text{injury fatal}}$	The probability that a sustained injury is fatal. This depends on the person being impacted (adult or child, heavy or lightly clothed etc), posture of the person (stand, sitting, crouching, etc), impact point on the body (i.e. chest is much worse than shoulders). This probability is derived from previous works in the field of medicine, and is an average over a variety of non-sheltered persons in various postures.	10^{-3}

more than 50 ms) for the impact to peak, typically by having a compressible front area, it can be acceptable from a safety perspective to allow much higher kinetic energy than for a completely rigid construction that resembles a bullet when impacting.

2.4.2. Non-penetrating drones

The injuries sustained by the human body are rather different for skin penetrating and for crushing (non-penetrating) impacts. Skin penetration typically occurs with high kinetic energy density (high energy on a small impacting area), and in this work we will assume that the drones (subjected to the mass threshold) are designed such that kinetic energy density is sufficient low so that penetration will not occur. However, this is not always the case, for instance if a carbon fiber frame from a multicopter impacts a person in the head where the skin is thin and there is no deformation of underlying tissue. It should noted that the resulting bleeding in itself rarely is lethal.

2.5. Kinetic energy threshold

The injury mechanics described above suggests that deformation velocity of the tissue is the primary factor in the severity of an impact injury. But the fact that this velocity depends on properties of the impacting object (kinetic energy density, deformability) makes it difficult suggest a single-parameter threshold. However, by making a number of assumptions on the impacted person as well as the impacting object (a mix of averages and worst case scenarios) it is indeed possible to come up with a reasonable kinetic energy threshold that in turn can provide a quantification of $P_{\text{injury fatal}}$. There are numerous articles and reports that have investigated the fatality rate for various types of impacts where kinetic energy is the primary factor. In this work we will draw upon some of these investigations to recommend an appropriate kinetic energy threshold.

In [13] it is concluded that a 25 ft-lb (33.9 J) threshold is applicable for avoiding fatal injuries (AIS level 4, Abbreviated Injury Scale, see [14]) from debris impacts. This is in turned derived from lethality curves by body parts presented in [15]. To avoid serious injuries (AIS level 3) altogether a 11 ft-lb (14.9 J) threshold is recommended. This lower threshold for determining injuries from falling and explosion debris is also found in the FAA Flight Safety Analysis Handbook ([16]). These threshold are to be interpreted as 1 percent threshold meaning that the probability of sustaining a AIS level 3/level 4 injury is 1%. The AIS level 3 and 4 injuries have in themselves a 10% and (up to) 50% probability of being fatal, respectively ([17]).

The sources reporting the above stated thresholds focus on debris and fragments from various incidents, such as explosions and other violent occurrences. These fragments tend to be small and with high velocity (and thus having a high kinetic energy density), and the method used for deriving the thresholds would therefore tend to give a higher threshold value when applied to drones. For this work we will therefore use an intermediate kinetic energy threshold of 25 J as the 1% threshold for AIS level 3 injuries.

2.6. Example of extremes

In order to put the above discussions on injuries and kinetic energy into context, we will provide a short example of two extremes. While this example does not lend itself directly to drone design it might still establish some perspective on the importance of the relation between human injury and the kinetic energy of moving objects. This example compares two objects; a styrofoam ball and a large kitchen knife.

One could ask, how large a styrofoam ball would it take to produce a kinetic energy of 25 J in free fall, and how large a kitchen knife? The kinetic energy E_{sphere} of a sphere at terminal velocity in free fall (under influence of gravity) is given by

$$\begin{aligned} E_{\text{sphere}} &= \frac{1}{2}mv^2 = \frac{1}{2}m\frac{2mg}{\rho_{\text{air}}AC_{\text{D}}} \\ &= \frac{m^2 g}{\rho_{\text{air}}\pi r^2 C_{\text{D}}} = \frac{16\pi r^4 \rho_{\text{sphere}}^2 g}{9\rho_{\text{air}}C_{\text{D}}} \ . \end{aligned}$$

Here v is replaced with the expression for terminal velocity of a sphere in air, A with the area of a disc, and m with the volume of a sphere times the sphere mass density. Gravity is $g = 9.82$ m/s^2 and air mass density $\rho_{\text{air}} = 1.3$ kg/m^3. For a sphere the drag coefficient is $C_{\text{D}} = 0.47$. For a sphere made of expanded polystyrene (EPS) with a (typical) mass density of 100 kg/m^3 the sphere radius will be 7.2 cm for a kinetic energy equal to 25 J. The sphere will have mass of 160 gram and the terminal velocity will be 17.6 m/s.

For a kitchen knife the terminal velocity will be very high due to the low drag. Instead we will assume that the knife has a mass of 250 gram (similar to the recommended mass threshold, and equivalent to a fairly large kitchen knife). The height h from which this knife has to free fall to have a certain kinetic energy is given by

$$E_{\text{knife}} = \frac{1}{2}mv^2 = mgh \qquad \Leftrightarrow \qquad h = \frac{E_{\text{knife}}}{mg}$$

and for a mass of 250 gram and energy of 25 J the height becomes 10.2 meters, roughly equal to dropping the knife from a fourth floor window.

2.7. Data set

In this work the data set is a series of toy drone randomly selected from a number of vendor web sites. Only drones below 1 kg has been included, and even very small drones below 10 grams are part of the set. Unlike the larger drones of 1+ kg it is sometimes difficult to find mass (except if you actually acquire and weigh the drone), and it is often difficult to find the top speed. The list here contains 24 drones all of which has the mass listed among the specs. Only in a few cases is the top speed listed, and it is therefore estimated based on a variety of factors, primarily commercial

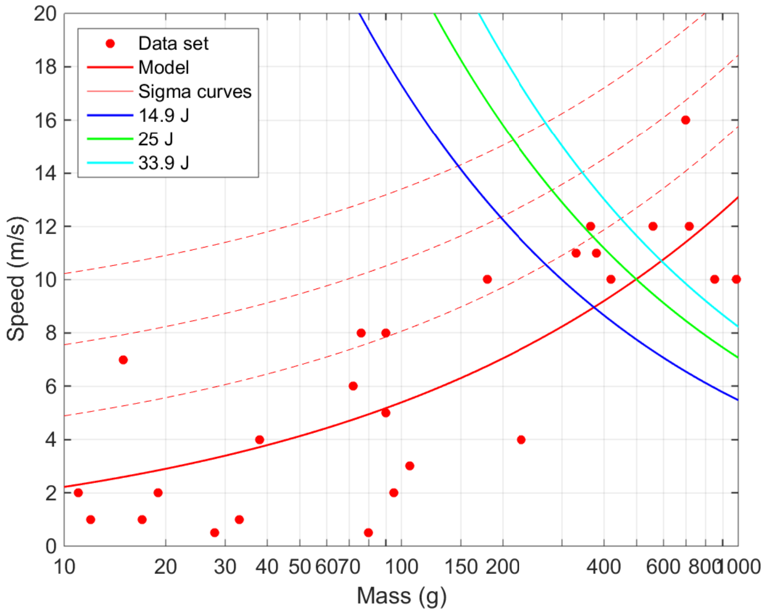

Figure 1. Mass versus top speed for the drone in the data set. The solid red curve is the power model, and the three dashed red curves are the 1σ, 2σ, and 3σ curves. The three joule curves at 14.9 J, 25 J, and 33.9 J are also shown.

video of the drone in flight and the author's first hand experience with similar drones. It is noteworthy that small drones built for high speed flight do exist, and they can reach fairly high top speeds. Such specialized drones have been excluded from this analysis since they do not represent the majority of toy drones.

2.8. From kinetic energy to mass

The relation between mass and kinetic energy depends on the velocity (squared), and therefore in order to establish a mass threshold we will look at the mass and velocity properties of a series of typical drones. We expect that the velocity of a drone in general will increase with it's mass, i.e. larger drones tend to have higher top speeds that smaller drones. We also expect that it makes sense to talk about 'typical' drones, i.e. 10 gram drones tends to have a top speed below, say, 1 m/s, and 100 gram drone tends to have top speed in the range 3 to 8 m/s, say. Under these two assumption we can establish the probability that the top speed will be within certain limits for a given mass by deriving the stochastic properties of a sample set of typical drones. While this will be done through computation we can also visualize the process.

We do this in the following way. The drones from the data have been plotted in Figure 1 using a log scale on the mass axis (first axis) and a linear scale for speed. Each dot represent one drone. We will assume that the relation between mass (m) and top speed ($v_{\max}$) follows a power model on the form

$$v_{\max} = a \cdot m^b , \tag{5}$$

where a and b are parameters to be determined through fitting to the data set. The same model was used in [1] on their data set, and in that work it seems to capture well the relation between mass and speed. In Figure 1 the solid red curve shows the model as fitted to the data set using a least square metric. The fitting parameters are $a = 13.10$ and $b = 0.3853$.

To capture the spread of the drones around the model curve we will assume that for a given mass the top speed is normally distributed. The standard deviation for the data set is then $\sigma = 2.67$ and in the figure the three dashed red curves show 1, 2, and 3 times the standard deviation (1σ, 2σ, and 3σ). The 14.9 J, 25 J, and 33.9 J curves are also shown.

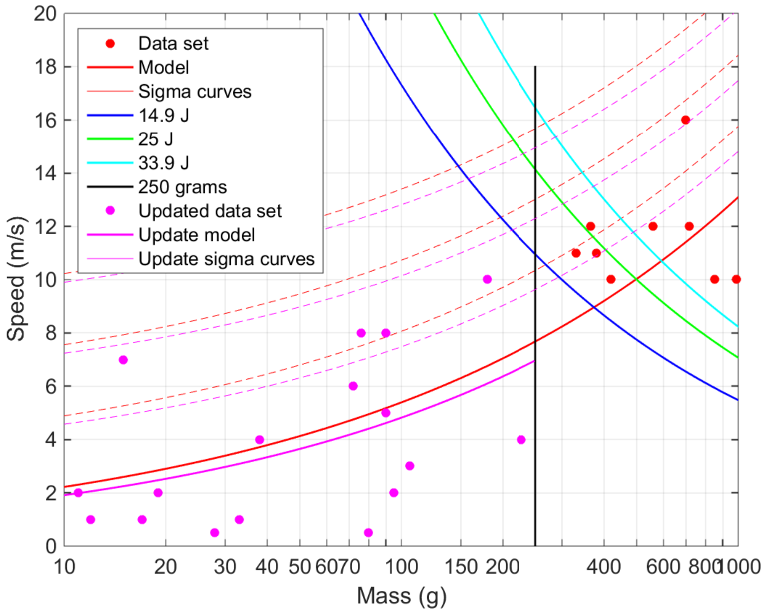

Figure 2. Mass versus top speed for the modified parameters. The purple lines show the same as the red lines, except for the modified parameters. The black vertical line is at 250 grams.

We can now relate the drone mass to the kinetic energy threshold in a quantified manner. Since the 3rd standard deviation curve represents an upper limit for 99.7% of drones we see that on average only 3 of 1000 drones with a mass at 215 gram (the approximate mass value at the point of intersection between the 25 J curve and the 3σ curve) will have a kinetic energy exceeding 25 J. Since we assume that 25 J is the threshold for sustaining an injury, this means that $P_{\text{injury}} = 3 \times 10^{-3}$ (see (4)). If we consider 0.3% an acceptable 'risk' (including considerations on all the other factors in (2), (3), and (4)) then indeed the mass threshold should be 215 grams. It is certainly worth noting that the 3 to 1000 probability is for 215 grams drones only. For drones below 215 gram the probability quickly drops. For instance for 100 gram drones the 25 J curve is at 6σ, which mathematically is vanishing (1 to a billion). Of course, in real life this is not the case, and this discrepancy comes from the assumption that the drone top speed is normally distributed.

While the attained value for P_{injury} indeed has an acceptable magnitude (see Sections 2.3 as well as Section 3 below) a 'non-round' number might not be desirable since the purpose of a mass threshold is to provide the general public with an easy-to-relate-to threshold. Thus, it seems appropriate to round this number to either 200 or 250 gram. From a purely safety perspective the obvious choice would be the former, reducing the probability of being above the threshold to 1 to 1000 (3.2σ). Choosing 250 gram makes this number 20 to 1000 (2.4σ) for the 25 J curve, but in fact 1 to 1000 (3.2σ) if we were to use the 33.9 J curve instead.

2.8.1. Updated model

With a recommended mass threshold of 200 to 250 gram we can further increase the accuracy of the model by determining the parameters in (5) to include only the drones below 250 gram. For this subset the parameters (using the same approach as above) become $a = 12.16$ and $b = 0.4018$. This model is shown in Figure 2.

For the update model the probability of exceeding the 25 J curve for 250 gram drones is now 8 to 1000 (2.7σ). The updated parameters change the outcome in favor of a higher threshold, however not significantly.

Table 2. Examples of estimated probabilities for three drone scenarios.

Probability		Unit	Small (<25 g)		Medium (< 150 g)		Large (<250 g)	
P_{crashing}	P_{error}	Per flight hour	1	10	0.05	0.2	0.025	0.1
	$P_{\text{loss of control}}$			0.5		0.5		0.5
	$P_{\text{high speed}}$			0.2		0.5		0.5
P_{impact}	ρ_{people}	persons/m^2	0.1	0.4	0.25	1	0.25	1
	A_{person}	m^2		0.25		0.25		0.25
$P_{\text{fatal injury}}$	P_{injury}		10^{-8}	10^{-5}	10^{-7}	10^{-4}	8×10^{-6}	8×10^{-3}
	$P_{\text{injury fatal}}$			10^{-3}		10^{-3}		10^{-3}
P_{fatality}		Per flight hour	1×10^{-9}		1.25×10^{-9}		5×10^{-8}	

3. Results

The purpose of this work is to determine an appropriate mass threshold for 'harmless' drones. In the methods section above we first look at how to find an appropriate measure for human injury. Unfortunately, there is no simple measure for this that can be applied directly to drones. Consequently, we adopt the approach of other works (focusing on injury from debris) and use kinetic energy. Various sources report varying thresholds for injury; we decided to use some of the more well-documented sources. As a result a kinetic energy threshold at 25 J was selected, and the assumptions it that this threshold provides a $P_{\text{injury fatal}} = 10^{-3}$ probability of lethal injury.

Then we combine the kinetic threshold with a probability analysis based on a sample set of drones to convert the kinetic energy threshold to a mass threshold. This analysis reveals that for a 25 J threshold the equivalent mass threshold is in the range 200 to 250 gram. We saw that in the initial analysis the probability of a 25+ J impact at 250 gram is approximately $P_{\text{injury}} = 2 \times 10^{-2}$, while this drops to $P_{\text{injury}} = 8 \times 10^{-3}$ for the analysis with the updated model.

3.1. Obtaining manned aviation safety limits

To determine the joint probability P_{fatality} some examples are given in Table 2, where all the probabilities described in Section 2.3 are quantified. Some values are results from this work, some are estimates, which are described below. The purpose is to provide an overview of possible distributions of probabilities among the factors in the 'fatality equations' (1) through (4).

We have now established that for a mass threshold of 250 gram we will have $P_{\text{fatal injury}}$ from (4) to be at a magnitude of 10^{-6}. In order to achieve an equivalent level of safety with manned aviation, that is achieving $P_{\text{fatality}} \leq 10^{-8}$, we need another two orders of magnitude from the two other factors in (1). While it is indeed a separate study worthy to determine either P_{crashing} or P_{impact} we will here make some guesses at these values in order to demonstrate how to reach the equivalent level of safety. While P_{crashing} depends largely on the drone itself, P_{impact} depends largely on the environment the drone is flying in.

If we image the smaller drones are use primarily as toys in back yards, parks, beaches, and in other recreational contexts P_{impact} would typically be fairly low. The larger drones (above say 150 grams) will also be used recreationally, but probably also as hobby or semi-professionally, for instance equipped with a camera. In this case it is not unlikely that the people density near the drone will be somewhat higher. While P_{impact} reaches it's maximum at 1, equivalent to about 4 persons/m^2, we will assume a slightly lower value of 0.25, which is roughly equivalent to 1 persons per square meter.

The reliability of the drone obviously plays a significant part in the probability of crashing. We will assume that the reliability, including the abilities of the pilot, is rather low for smaller drones, and that it increases with the drone mass. That is, for a 150 or 250 gram drone, we will assume the mechanics and electronics are more reliable, and the pilot is on average more able. In the examples in the table we have set $P_{\text{error}} = 10$ errors per flight hour for the smallest drones, and significantly lower values for the 150+ gram drones. These heavier drones are less likely to escape undamaged from a crash and they are also more expensive, leading to more caution and better preparation on the part of the pilot. The probability that an error results in the pilot permanently loosing control is set to a fixed $P_{\text{loss of control}} = 0.5$, and probability of a high speed crash is less for smaller drones, but still set fairly high in all three cases.

As can be seen in the table all three scenarios lead to probability of a fatality at the same or lower order of magnitude as the equivalent level of safety in manned aviation.

4. Discussion and Future Work

This work recommends a mass threshold for 'harmless' drone to be 250 gram. This recommendation is based on a long series of estimates and assumptions, many of which may be altered to achieve a higher or lower threshold. Some estimates are somewhat uncertain and could benefit greatly from more in-depth investigations, and some assumptions could be argued to be either very conservative or overly optimistic as they are based on indications from other literature and the impressions by the author. As such, further work might reveal a different recommendation for a mass threshold.

4.1. Uncertainties

This is to the best of the authors knowledge the first attempt at quantifying the fatality rate of very small drones. Therefore, in order to do so a number of assumptions were made and probabilities were derived based on literature rather than statistics from actual flight. This introduces some degree of uncertainty in the final result, but hopefully the probabilities throughout this work have on average been sufficiently conservative to warrant a useful result. To aid future work the following is a short discussion on some of the key questions that one could ask.

4.1.1. What is the reliability really of a drone?

The best way to learn the reliability of a particular drone is to fly it. To achieve a reasonably good statistical basis the drone should be used in a typical context and flown for sufficiently many hours to have a statistically significant result. Even for smaller drones with a high error rate (P_{error} is expected to be high) it takes a significant number of flight hours to establish a 5% or even 1% significance level. For larger more reliable drones the flight hours needed could easily be in thousands. This is certainly not unachievable eventually (some drones have clocked 10^4 to 10^6 flight hours) and testing through flight hours is indeed part of an ongoing discussion about certification of drones. However, for most drones such flight records are still far in the future.

In this work we rely on estimates based on immediately observable reliability of existing drones. In Table 2 the smallest drones are estimated to experience an error every 6 minutes of flight. The reasoning is that such small toy drones experience both pilot errors and mechanical malfunctions all the time (and 6 minutes is equal to the round figure 10 errors per flight hour). For the largest drone (up to 250 gram) we expected that on average there will be an error every 10 flight hours. It stands to reason that the pilot only makes few mistakes (disregarding an initial learning period) with more expensive drones and that drones of that size are significantly more mechanically and electronically reliable.

4.1.2. How likely is it actually that a person is hit by a drone?

In this work the density of people on the ground is the only factor in the probability equation to account for the probability of impacting a person when a drone is crashing. And the probability is fixed at 0.25, a very conservative estimate for most scenarios. This value indicates a 'loose' crowd, a scenario that most drone flights would be quite far from. Further, one could argue that most intelligent pilots would fly their larger drones at unpopulated areas until they are relatively comfortable with its operations and reliability (after a software upgrades, for instance). However, P_{impact} is also the only factor of the three in (1) which is not in any way related to the drone itself. This makes it somewhat more difficult to control, and thus the conservatism.

On top of this the basic assumption is that people are unaware of the drone crashing, and therefore do not attempt to avert the drone using arms or legs, cover their face or chest with their arms, take a crouching or prone posture, or indeed avoid the drone altogether. For situations where only people that are directly or indirectly involved in the flight (pilot and spectators) this is rather conservative, but for situations where a broader collection of people are present, such as a city streets and event crowds, one might expect the majority of people to be completely ignorant of the presence of the drone. In this case the person density is probably a good measure of the impact probability.

4.1.3. Is the data set representative?

For this work only a small sample set of drones is used, and as such the uncertainty in the joule to mass relation is relatively high. A bigger data set containing a wider variety of drones might reveal different results, and push the mass threshold either way. However, this is only true if drones with different top speed than those used are added to the data set. That is, more drones with higher top speed (relatively independent of mass) would decrease the recommended mass threshold. But in the used methodology the distribution of drones on the mass axis does not affect the outcome. That is, if smaller drones are predominant in the market, and a representative data set therefore would contain more smaller than larger drones, this would not in itself change the recommended mass threshold even though the average drone would be fairly small.

The top speed of smaller drones can be difficult to determine without actually measuring it during flight (using for instance a radar or a camera system). Some drones do have a top speed value specified, but since top speed is a relatively uninteresting property for most smaller drones, this specific value is often either missing or (probably) estimated by the manufacturer or the vendor. This work would certainly benefit from a more thorough investigation into the actual mass and top speed relation, but it is hard to do without actually acquiring a significant number of drones and conduct the necessary test flights.

4.1.4. What about mid-air collisions?

Aviation regulation today does not permit unmanned aircraft (at least not the kind that are of interest here) to operate in non-segregated airspace. This is done by requiring drones to stay below a certain altitude limit, typically 100 m or 400 ft. While this indeed separates drones from the vast majority of manned aviation, there are still very low altitude activities such as military aircraft and search and rescue helicopters. Evidently there is a risk of mid-air collision between a drone and a manned aircraft, and there is arguably a significant probability of a fatal outcome from such a collision. However, the mass of the drone is of little significance in such accident scenarios since even the smallest drones could cause significant damage to a high speed aircraft or if ingested into a turbine engine [1, 13]. Therefore, to avoid such accidents operational restrictions is much more effective than a mass threshold.

4.2. Alternative threshold

It is quite obvious that the shape of an impacting object is crucial, and that there is great potential for designing drones for which a threshold much higher than 25 J would be appropriate. However, rather than having a dynamic kinetic energy threshold it would probably be better to have a restriction on the 'lethality' of a drone by imposing a threshold on the deformation velocity of a human body that a given drone can inflict. While this is indeed somewhat more difficult to determine than the mass of a drone (and certainly beyond the skills of any person acquiring a drone from a toy store for recreational purposes) it is nonetheless possibly for professional drone manufacturer to demonstrate that their particular drone design is likely to not cause tissue deformation velocities beyond a given threshold. A recommendation for such a threshold and how to stay below it is beyond the scope of this work.

4.3. Regulatory use

The 250 gram threshold is a comprise between numerous conflicting interests, and as described above not really a good measure for the lethality of a drone. But from a regulatory point-of-view such a simple and easily measurable threshold is straightforward to both implement and enforce. This means that it can be used for regulating the use of drones for the general population, without having to resort to more difficult measures such as top speed, kinetic energy, design etc. The 'harmless' category fits well into a larger framework of classifications of unmanned aircraft, where the 'harmless' category naturally will have the least restrictions, possibly even very few restrictions, such as to allow people to legally fly recreationally without any knowledge of aviation regulation.

In order for the recommended threshold to apply it is important to observe the assumptions listed previously. Many of these will fit quite well with the intentions of regulatory bodies, for instance the assumption that people are not prepared for a drone impact. Other assumptions might required limitations in the permitted use of 'harmless' drones. For instance the assumption on people density in the three scenarios might lead to the requirement that a drone cannot be operated directly over crowds of people. And the assumption that the toy drones are representative for the average use, thus disregarding some small subsets of all acquirable drones (such high speed specialized drones), might lead to an additional requirement that high speed drones are exempted from the 'harmless' category.

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