Mathematical modelling of human injury levels due to unmanned aerial vehicle (UAV) impact

Li, Xin

2018

Li, X. (2018). Mathematical modelling of human injury levels due to unmanned aerial vehicle (UAV) impact. Master's thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/73219>

<https://doi.org/10.32657/10356/73219>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**MATHEMATICAL MODELLING OF
HUMAN INJURY LEVELS DUE TO
UNMANNED AERIAL VEHICLE (UAV) IMPACT**

LI XIN

**SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING
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LI XIN

SCHOOL OF MECHANICAL & AEROSPACE ENGINEERING

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirements for the degree of
Master of Engineering

2018

ABSTRACT

As Unmanned Aerial Vehicle (UAV) accidents were reported frequently, aviation authorities around the world carried out rules on managing the UAV operation. The understanding of the relationship among UAV weight, flying speed and height is of great interest to the authorities for their safety assessments. Therefore, this research is aimed at developing a simulation method to study the relation of UAV weight and drop height with human injury levels.

A mathematical model was proposed in this research to estimate the potential human injury level in UAV-human head impact. The results of the simulation were compared and validated with UAV-dummy head crash results and other traditional computer-aided simulation methods. They are compared in terms of speed and performance in accuracy.

The prediction of the model compares well with the measured results obtained from the UAV-dummy head contact process and the potential head injury level for different UAV crash. The model enables a reduction in the number of measurement of drop tests and thus time-saving, and yet produced prediction with relatively good accuracy.

ACKNOWLEDGEMENT

The author would like to express her gratitude and acknowledgement for the help, advice, and guidance to those who have assisted her throughout the first twenty months of author's candidature period. Without their guidance, supervision help and motivation, the project could not be progressed smoothly.

Firstly, Prof. Low Kin Huat, her supervisor for his invaluable time in guidance, suggestions, continuous encouragement, and valuable advice throughout the course of study. The author had benefited greatly from his kind heart and wealth of experience and knowledge.

Secondly, gratefulness to all the research team members for their support, collaboration, and information sharing. Also, the author would like to thank Dr. Li Lei for his guidance on the research on Dynamic Contact Model, Mr. Tay Lip Ong for his assistance in conducting the experiments, and lastly all the ATMRI team members for all the support and advice.

Thirdly, special thanks to the research committees, Prof. Yeo Song Huat and Prof. Ling Keck Voon, who spend their precious time on supervising the author's research work and their kindness on supporting her research decision. The deepest thanks to Prof. Ooi Kim Tiow for his sincere encourage and support when the author was at her lowest ebb which gave her courage to keep going.

Last but not the least, the author would like to thank her parents who always caring and encouraging, and all the friends for their supports and motivations during her unforgettable time in Singapore.

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1 INTRODUCTION

1.1 Background, Scope and Objective

The popularity of UAV has increased a drastically years especially the micro UAVs. The success and rapid growth of companies such as DJI enable general public accessibility to small UAV and perform flight operations in civil airspace easily. Although the UAV technology has proven its potential, it is crucial for it to be safely introduced and managed.

From the literature review, the possible UAV incidents could be categorized as physical damage to human, public facilities, public order, psychological health and citizens and business privacy[1]. A category of possible consequences of UAV incidents is summarized in Figure 1.1.

In all the possible damages caused by UAV, human safety is the most important, same as the attention on manned aviation safety problems. For human safety, the consequence could be direct injury such as falling UAV crashes on the human head, and in-direct injury such as debris scratch from UAV hitting building beside pedestrian. This research is mainly focused on the direct injury to the human.

Figure 1.1: Possible Consequences of UAV Incidents [1]

Solutions for protecting the people in the UAV crash cases and preserving the public orders have been proposed by aviation regulatory authorities worldwide. Some countries simply separate UAV operation area with the populated areas, such as New Zealand Civil Aviation Authority (CAA) prohibits UAV operation in the airspace above people who has no consent to the operation[2]. Most countries apply regulation to set up a minimum UAV weight threshold, below which the UAV operation can be considered as harmless (causing non-severe injuries or fatality upon impact). For example, the FAA sets that threshold at 250g, UAVs equal or less to the weight is allowed to operate over crowd[3]. Australia required civil UAV operated with weight up to 2kg[4]. In Singapore, the weight limit is set up to 7kg.

There is little information provided on how these weight limits/thresholds were decided. After a detailed literature review, no sufficient data or analysis that could prove the relation between UAV weight and its damage level were found. Thus, a research on the potential damage of UAV especially on a human would be meaningful to the civil aviation industry and aviation authorities.

The Civil Aviation Authority of Singapore (CAAS) initiated the project on “Weight Threshold Study (WeTS) for safety UAV Operation in Singapore” to research on the potential injury on the human body from UAV crash. The task and workflow of WeTS project are shown in Figure 1.2. The project starts from basic theory research, then it attempts to achieve the UAV mass-human injury relation in three methods: mathematical modelling, ANSYS simulation, and real UAV-dummy head crash. These three methods tried to solve the same problem, only when the three methods achieve similar results and verify each other, the final result of WeTS is reliable.

This research is supported by and part of the WeTS project. The research work provides theoretical method and foundation to guide the entire WeTS project. In return, the real UAV-dummy head experiment data and simulation developed on ANSYS were cited as comparison and verification to the mathematical model in this report. A fast, simple, accurate simulation software/model will be chosen as the final estimation tool in analyzing the UAV impact cases.

The objective of this research is to provide a mathematical model in the form of a simulation program, to predict injury level in UAV-human head impact, thus minimalizing the need to conduct actual dropping test, which cost money and time. The simulation program should have good performance in terms of accuracy, speed, and flexibility.

Figure 1.2: Task and Work Flow of WeTS Project

This research concentrates on head injury, not just due to the important functions of the head but that the UAV always operated over humans and the head is the most possible injured part.

1.2 Organization of Thesis

The organization of this thesis is structured as follows:

Chapter 1 provides the background and introduction to the motivation, scope and objective of this research, and the contribution of this report to the WeTS project.

Chapter 2 presents the literature review. Possible UAV caused damages, current government regulation and studies on UAV crash are summarized. To ensure

the robustness of this research, the human head injury mechanism and injury criteria are introduced. The theory about contact mechanisms is also explained.

Chapter 3 includes a theoretical study which analyzes the physical process of UAV failures and impact. Mathematical modelling method was applied to analyze the impact process, which is named as improved dynamic contact model based on volumetric contact theory. The realization of mathematical methods is explained. Experiments are designed to test key coefficient in the model. The model is derived and coded to be able to scale for different conditions.

Chapter 4 compares the simulation results of this research with ANSYS simulation, dynamic contact simulation and WeTS UAV-dummy head experiment data. Its validation and good performance in prediction are in the comparison, some errors are highlighted.

Chapter 5 summarizes the conclusions, creation of the study and potential future work.

2 LITERATURE REVIEW

This chapter presents a review of the related topics of potential UAV damages, the necessary knowledge about human injury under blunt impact and mathematics model in contact mechanism.

The UAV damages are mainly about human injuries as introduced in Chapter 1. Some other damage cases are also included to give the reader a full picture. To better understand the human injury, a brief introduction to the physiological function of the human body is provided. In addition, related injury severity standard and existing injury study methods such as:

1. Abbreviated Injury Scale (AIS);
2. Kinetic Energy Criterion (KEC);
3. Blunt Criterion (BC);
4. Impact Force Criterion (IFC);
5. Head Injury Criterion (HIC).

The mathematical methods in contact mechanism reviewed in this chapter are:

1. Hertz Theory
2. Volumetric Contact Model
3. Finite Element Method

The significance of literature review is that it helps to assess the necessity to conduct the UAV crash experiment and the need of developing a simulation system of UAV crash, which should be applied in supporting further UAV operation regulation in civil aviation and to estimate possible injury in different UAV crash situations.

2.1 Damages Caused by UAV Impact

This section collects examples of UAV collision in recent years, aiming to classify the possible damages. The ground impacts of a UAV were modelled in an event tree as shown in Figure 2.1[5]. The event tree presumes that a failure occurs on the vehicle has possibility resulting in an uncontrolled ground impact,

considering a person is located where the UAV impacts and the debris produced from the crash would penetrate the sheltering in which the person is located.

Figure 2.1: UAV Ground Impact Event Tree [5]

2.1.1 Direct Injury to Human

In any setting involves UAV and people, the aircraft may fail and fall on the people under it. If the people are not wearing any protector such as a helmet or not under shelter, they would get injured.

In April 2014, a female athlete was hit by a dropping UAV during a triathlon competition in Geraldton, Western Australia[6]. The aircraft fell more than 10 meters over the track field and hit the athlete. The accident caused lacerations to the athlete in her head, and debris of the propeller was taken out from her head in the following medical care[7]. Another accident of UAV failure in sporting events was in the US Open Tennis Tournament[8], fortunately, no one was injured in that case.

In some extreme cases, the UAV caused very serious injury. The victims of these accidents were not lucky as in the previous report, some of them got very heavy injured even to death. In April 2003, a UAV lost control and killed a 14-

year-old girl in England[9]. In November 2003, an instructor was killed while he was doing flight instruction to the operators[10]. In July 2013, an operator was killed while flying a UAV in Japan[11]. In September 2013, a UAV fell directly on its owner, a 19-year-old boy, and killed him by inflicting severe head and neck injuries[12]. In Switzerland in 2013, a UAV-striking operator accident happened again, the 41-year-old operator was killed due to severe head injury[13]. From these instances, we can see the possibility of fatality whenever there is a direct impact of UAV to the human head region.

2.1.2 In-direct Injury on Human

In some incidents, the UAV did not hit on human body directly, but the debris from the crash may also hurt surrounding human.

In May 2015, a UAV failed and crashed into a building while flying over a crowd in Marblehead, America. The UAV kept falling after the crash and its debris caused two pedestrians to be injured[14]. One month after the crash, one more UAV hit on building again at the Seattle Pride, the failed UAV fell and knocked on a woman[15]. Fortunately, the woman's friend noticed the falling drone and caught it in time before it causes significant injury. In another case, an 11-month old baby was not as lucky as the woman, he was injured in the face by debris from a crashed UAV in Pasadena in September 2015, CA[16]. Other incidents of small unmanned aircraft hitting buildings and falling to the ground have been reported [17],[18],[19], although there were not any injuries reported in these events.

2.1.3 Damage to Public Order and Privacy

Besides direct or indirect injury to a human on the ground, the UAV crash cases without wounded person could cause mass and perplex in public order and privacy as well.

In late January 2015, a DJI's Phantom UAV operated by a drunk government worker operating crashed into the White House lawn[20]. The US Secret Service launched an investigation immediately. DJI announced they would publish a firmware update in the coming days to prevent repeat accidents.

Within less than one month after this accident, the company stated the following update would stop their drones from crossing national borders due to an accident that its drone was found again on the border between Mexico and US.

In July 2016, a UAV flew at the same altitude as the Boeing 737 and flew left to right across its path, which posed "serious risk of collision" to the commercial jet near Stansted Airport [21]. In August 2016, Prince William's air ambulance in near-miss with a drone in the UK[22]. The incident happened 579 meters in London, it was reported as "high risk" of a crash, "endangering the prince's ambulance and its crew". In October 2015, a UAV flew into power lines and caused electricity blackout in West Hollywood[23]. About 650 people lost access to electricity for about three hours. The incident occurred weeks after Los Angeles City Council introduced tougher laws on the use of personal drones.

2.1.4 Summary of UAV Damage

From above cases, it is found that most serious injuries to human happened in direct impact incidents. Body areas such as head, face, and neck are the easiest hurt. Since the UAV flights are always above people, the top parts of the body are more frequent to be hurt. Also, head and brain are the significant organs of a human, fatal injury happens on the head is reasonable. Thus, this research focus on UAV-human head crash.

The list accidents occurred when UAV activity density was relatively low, thus, a greater number and variety of accidents could be expected in near future. It is also likely that the listed accidents cannot cover all the incidents because only the report recorded online discussion is currently available. UAV crashes could cause an impact on human safety, civil environment and public order with a severity level from a slight injury to extremely serious.

2.2 Current Protection Rules and Regulations

Solutions for the safety of people on the ground and the public orders have been proposed by aviation regulatory authorities from countries. Some country

restricts the distance between UAV operation area and populated area, some ban the UAV to fly over or cross the border, and some of them limit the weight of UAV operated over city directly.

In 2015, the New Zealand Civil Aviation Authority (CAA) amended its Civil Aviation Rules (CAR) to prohibit operation in the airspace above crowd[2]. The Federal Aviation Administration (FAA) established two committees to manage the small UAV traffic issue. One committee is the Micro Unmanned Aircraft Systems Aviation Rulemaking Committee (Micro UAS ARC), the other is Unmanned Aircraft Systems Registration Task Force Aviation Rulemaking Committee. Micro UAS ARC recommended an acceptable threshold as UAV weighing 250g or less are allowed to operate over people[24]. While the other committee recommended that unmanned aircraft weighing 250g or less should not require registration as well in their report.

There is few published analysis or information that supports the various existing and proposed rules. Dalamagkidis calculated the required mean time between ground impacts for the fatality risk from unmanned aircraft[25]. However, this analysis is performed to provide an analysis of the likely “lethal crash area” for military unmanned aircraft; its analysis concerns the harm caused by fire and explosion from the liquid. The Civil Aviation Safety Authority (CASA) of Australia published a report on potential human injuries from UAV-human crash in terms of Blunt Criterion(BC)level[26]. This report supports Australia’s regulation that UAV is not allowed to be operated within 30 meters to ground people.

2.3 Human Head Injury Mechanism

A head injury sustained in accidents is a leading cause of death and disability. This section briefs the head anatomy, definition and classification of head injuries and the relative injury mechanisms. The biomechanical response of the head in various experimental studies is presented as well, followed by widely used injury criteria to quantify the impact response of the head in crash testing are discussed.

2.3.1 Anatomy of Human Head

The human head comprises multi-layered structures. The outermost layer is the scalp, the following is the skull, the meninges and the central nervous system at the innermost[27].

The scalp consists of the hair, skin and a 5 to 7 mm thick muscle and fascial layer. Below the scalp, there is a loose connective tissue and the periosteum that covers the bony skull. From outside to inside under cranial, there are three membranes called the meninges, the dura mater, the arachnoidea mater, and the pia mater. The pia mater is the tissue covering the brain and dipping into the fissures. Cerebrospinal fluid fills in the ventricles and the subarachnoid space in the brain. It provides a buffer to the brain from mechanical shock and helps to support the brain. The power of the brain and the scalp is supplied by blood vessel systems crossing the meninges. Tearing may cause injury to the bridging veins of the power supplying system[27].

2.3.2 Head Injury Mechanism

The most important injuries of the human head are from the skull and brain. Possible head injury category is shown in Figure 2.2.

Figure 2.2: Possible Injuries to Human Head [27]

Skull injuries typically arise from fractures. Table 1 classifies head injuries and relative examples according to the Abbreviated Injury Scale (AIS) scale[28], fracture happen frequently.

Injuries of the brain could be classified into two categories: focal brain injury and diffuse injury. For focal brain injury, the damage is local. Possible focal injuries are hematoma and contusions. The contusion is easily found in head impacts. Diffuse brain injuries could range from concussion to white matter injury, in which the mild concussion is the most common and a serious cerebral concussion could cause immediate loss of consciousness.

There are various mechanisms could cause head injuries. In principle, the main reasons could be categories in static and dynamic loading as shown in Figure 2.3. Typically, the definition of static loading is that a load could last for more than 200ms. The head deforms when it reaches a maximum deformation in the static loading cases. In UAV accidents, the average impact time is from 0.5ms to 3ms, the static loading is rarely found.

Table 1: AIS Classified Head Injury [28]

AIS Code	Description
1	Skin/scalp: abrasion, superficial laceration Face: nose fracture
2	Skin: major avulsion Vault fracture: simple, un-displaced Mandible fracture: open, displaced Maxilla fracture: <u>LeFort 1 and 2</u>
3	Basilar fracture Maxilla fracture: <u>LeFort 3</u> Total scalp loss Single contusion cerebellum
4	Vault fracture: complex, open with torn Exposed or loss of brain Small epidural or subdural hematoma
5	Major penetrating injury (>2cm) Brain stem compression Large epidural or subdural hematoma Diffuse axonal injury (DAI)
6	Massive destruction of both cranium and brain (crush injury)

Dynamic loading is a possible loading scenario. It could be classified as contact and non-contact loading. Due to the bending and location of the impact, direct contact could cause direct fractures or in indirect fractures to the human head. Furthermore, the deformation of the head (even without fractures) causes scalp or brain under the impacted location injured. In addition, the stress waves produced by rapid contact propagate in the skull and brain. This propagation could lead to pressure gradient in the brain, which is proposed as the reason for the generation of intracranial compression and brain tissue focal injuries. Additionally, the pressure gradient could cause shear strain within the deep structures of the brain. Contact loading may result in a relative motion of the brain surface to the inner surface of the skull, which could lead to surface contusions on the brain and tearing of the veins [29].

In the non-contact situations, the head is loaded exclusively due to inertial forces, i.e. acceleration of the head and acceleration results in inertial loading. In consequences, subdural hematoma such as focal skull injuries may arise due to relative motion between brain and skull due to the acceleration. This kind of acceleration responses of the head does also occur in contact loading.

Figure 2.3: Possible Mechanism for Head Injury[28]

Thus, deformation and acceleration of head are two key factors in analysing head injuries.

2.4 Criteria for Injury

To estimate the injury level, standard injury criteria were introduced in this section. Injury criterion is defined as tools relating physical parameters accidental to a probability of a certain injury in a specific fashion[27].

2.4.1 Abbreviated Injury Scale(AIS)

Abbreviated Injury Scale is most widely accepted injury defining the standard. It is regularly revised and updated by the Association for the Advancement of Automotive Medicine (AAAM). AIS uses a systematic approach to define the severity of injuries throughout the human body. In the automotive field, AIS is applied to measure the trauma injury for classifying the type and severity of injuries caused by vehicular crashes, and it provided the survivability of injuries[27].

AIS is a severity rating system which classifies each injury in different body region by assigning a code which ranges from AIS 1 to 6, a higher AIS levels indicate a higher threat-to-life as depicted in Table 2. The AIS scale ranges from AIS 1 to AIS 6, which represent "minor-injured" to "maximum/untreatable injury" respectively[27].

Table 2: Abbreviated Injury Scale [28]

AIS-Code	Injury	Example	Probability of Death
1	Minor	Superficial laceration (Skin cut)	0%
2	Moderate	Minor Skull Fracture	1-2%
3	Serious	Major Skull Fracture	8-10%
4	Sever	Severe Life-Endangering Fracture	5-50%
5	Critical	Ruptured liver with tissue loss	5-50%
6	Un-survivable	Death	100%

In 2016, the Aviation Rulemaking Committee (ARC) published the report and established risk thresholds in UAV-human crash related to AIS level 3 [30]. They suggested that UAV with a maximum risk causing impact injury of a 1% chance of AIS level 3 (or lower) injury should be considered harmless.

Injury criteria are usually calculated from measurements such as energy, forces or accelerations taken on crash objectives. There is no direct formula or mathematical method to convert these physical parameters into certain AIS level. Thus, other injury criteria which can relate to AIS are necessary to relate AIS to impact physical parameters.

2.4.2 Kinetic Energy Criterion(KEC)

The injury mechanics of human suggests that the deformation and its velocity of human tissue is the primary factor in the severity of an impact injury. This deformation velocity depends on properties of the impacting (kinetic energy density and deformability)[31]. Assuming the deformability of a certain human group (such as male adults in 30 to 50 years old) is fixed, the Kinetic Energy Criterion of the UAV which impacts on the human becomes a key factor determining the severity level of injury.

The impact energy E_{imp} is given by:

$$E_{imp} = \frac{1}{2}mv^2 \quad (1)$$

where v is the relative velocity of UAV and human head at the moment just before impact, m is the mass of UAV.

Research on the relation between KE and AIS level were found. The work of Feinstein et al. (1968) [32] indicated that when the impact energy reaches level 25 ft-lb (33.9J), the human would suffer injury level up to AIS 4 and the energy level 11 ft-lb (14.9J) up to AIS 3. These two KE-AIS level relation were concluded and suggested by other independent reports from Rance Commanders Council[33] and FAA[34].

Even though types of research have indicated weight threshold for safety UAV operation in the perspective of KE, the serious deficiency of this method is that the energy threshold is established based on debris/projectiles impact on a human which are different from UAV because a projectile/debris weights up to 200g could obtain maximum velocity of 200m/s. While the velocity (due to free drop) and mass of a UAV are usually 5 to 20m/s and 0.5 to 20kg. Furthermore, another significant factor determines human head injury, the contact time of the crash, is missed in this KE estimation method.

2.4.3 Blunt Criterion(BC)

The Blunt Criterion is introduced while the impact energy alone is not accurate enough for injury estimation. In 2004, Sturdivan et al. pointed that the BC has the stronger capability for predicting the level of injury then KE[35]. The model to calculate the magnitude of BC is[35]:

$$BC = \ln \left(\frac{mv^2}{2M^{\frac{1}{3}}TD} \right) \quad (2)$$

where, m is the mass of projectile, UAV in this case, v is the velocity, D is the diameter of the projectile, M is the mass of the struck body and T is the combined thickness of the soft tissue.

For a head injury, Raymond et al. (2009) [36] developed a function curve to relate BC to skull fracture as follows:

$$P_{Skull\ Fracture} = \frac{1}{1+e^{5.818-3.605BC}} \quad (3)$$

where, $P_{Skull\ Fracture}$ is the probability of obtaining skull fracture.

Providing the impacting UAV's kinetic energy, the impacting UAV's diameter and the diameter of the human head, the BC can be calculated. From the research of CASA of Australia, skull fracture, which is equivalent to AIS=3 was defined as the threshold[31]. The experiment showed that a 50% risk of skull fracture could be related to BC=1.61[36].

2.4.4 Force Criterion(FC)

The impact force is another method accounting for the prediction of injury. The relationship between the impact force and injury severity level was suggested by Payne and Patel (2001)[37] as follows.

$$AIS = \begin{cases} 0 - 1 & (0 < F \leq 2.2kN) \\ 2 & (2.2kN < F \leq 5.5kN) \\ 3 & (5.5kN < F \leq 11kN) \\ 4 & (F > 11kN) \end{cases} \quad (4)$$

A similar conclusion was also concluded by Raymond et al. in 2009[36]. His report carried out seven cadaver head impact tests, the result shows that no fracture occurred at forces of 2.5kN–5.0kN (6 observations) and 6.0kN (one observation) [36].

From a report in New Zealand[38], the impact force of 11kN is suggested as the threshold representing injury level between AIS 3 and 4. The study found that at this threshold a falling object can cause skull fractures.

2.4.5 Head Injury Criterion (HIC)

Head Injury Criterion is a validated predicting standard for skull fractures and brain injuries of certain severities. It is widely used in evaluating the seriousness of a head injury in the automotive industry. HIC was proposed from the Wayne State Tolerance Curve (WSTC), which has a significant influence on developing the relationship between the impact duration and the average acceleration in head impacts.

The relationship between impact head acceleration and HIC index is shown as:

$$HIC = \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right)^{2.5} (t_2 - t_1) \quad (5)$$

where a is the head acceleration in g-force, t_1 and t_2 are the selected starting and ending time, which can generate the largest HIC value. The criteria choose t_1 and t_2 which can give a max HIC value based on Equation (5).

The correlation between HIC and AIS can be represented as follows[26]:

$$AIS = \begin{cases} C_{HIC}^{AIS-1} \cdot HIC & (HIC \leq 25) \\ C_{HIC}^{AIS-1} \cdot HIC + Offset_{HIC}^{AIS-2} & (HIC > 25) \end{cases} \quad (6)$$

where the coefficient is determined by experiments with $C_{HIC}^{AIS-1} = 0.02$, $C_{HIC}^{AIS-1} = 11/3200$ and $Offset_{HIC}^{AIS-2} = 0.414$.

These coefficients which correlate HIC and AIS are obtained from the work of Prasad et al. (1985) based on many cadaver experiments, as shown in Figure 2.4 [39].

Figure 2.4: Correlation between HIC and AIS [39]

There are few types of research founded using HIC to predict the potential UAV damage to humans.

2.4.6 Summary of Injury Criteria

As discussed in this section, AIS is a classic medical standard classifying human injury. However, it is just definition and description of injury levels, not related to physical parameters in accidents. There are several injury criteria developed could relate AIS to impact parameters. These criteria have their own merit and demerit. Chosen of criterion depends on specific cases. From the application of these indexes, almost all the reports choose injury level AIS 3 as a minimum acceptable level for UAV safety operation.

2.5 Theories of Contact Mechanism

Contact model studies the deformation of solids that touch each other at one or more points[40][41]. The physical and mathematical formulation of the subject is built upon the mechanics of materials and continuum. The contact mechanics is considered started with the publication by Heinrich Hertz of his paper “On the Contact of Elastic Solids”[40].

2.5.1 Hertz Theory and Dynamic Contact Simulation (DCS)

Hertz proposed in his research that an Ellipsoidal-Hertzian distribution of contact pressure could produce an elastic displacement in the contact area of two objectives. Hertz Theory concentrates on non-conforming elastic impact. Non-conforming solids touch initially at a point or along a line. With the growth of the stress, the contact objectives deform in the vicinity of their point of the first contact, means they contact over an area is finite small compared with the dimension of the objectives. Under this assumption, the contact stress comprises a ‘stress concentration’ which can be considered independently of the stress volume of the objectives. On the other hand, contact objectives whose size conforms to each other touch each other over an area with significant size compared to the dimension of objectives. Thus, the contact stress is part of the general stress distribution, cannot be separated from the objective body.

It is required to predict the shape of this area of contact and how it grows with increasing impact force and the magnitude and distribution of surface tractions across the surface. And the stress and deformation in both objectives should be calculated in the contact region.

For elastic deformation problems, Hertz Theory proved a classic model to analyse the impact process. Hertz Theory of Elastic Deformation proposed in Contact Mechanics[40] considers the geometrical effects on local elastic deformation properties. This theory relates the circular contact area of a sphere with a plane (or more general between two spheres) to the elastic deformation properties of the materials. In the theory, any surface interactions such as near contact Van der Waals interactions, or contact adhesive interactions are neglected.

Regarding the frictional stresses acting tangentially between the surfaces in this vertical falling case, the main focus in contact mechanics is the pressures according to elastic deformation. In reality, a small contact area is being created through elastic deformation, thereby limiting the stresses considerably. These contact stresses are called Hertz contact stresses[42].

A Dynamic Contact Simulation is modelled based on Hertz Contact Model by Dr. Li Lei[43]. In this simulation, parameters determining simulation result could be controlled. UAV mass m ; UAV material property k ; flight height h ; and speed v could be input for reconstructing impossible crash situations in real UAV-dummy head experiments.

According to Hertz theory, the contact force between UAV and dummy head is given by:

$$F_{imp} = k\delta^n \quad (7)$$

where F_{imp} is the impact force, k is the stiffness of material, δ is the displacement of deformation, the value of n is set as $n = 3/2$ experimentally.

The damping effect is considered for explaining the energy absorption. The damping parameter can be could be expressed as follows[44]:

$$F_{imp} = k\delta^n \left[1 + \frac{3(1-c_r^2)}{4} \frac{\dot{\delta}}{\delta^{(-)}} \right] \quad (8)$$

and for soft material impact[45]:

$$F_{imp} = k\delta^n \left[1 + \frac{8(1-c_r)}{5c_r} \frac{\dot{\delta}}{\delta^{(-)}} \right] \quad (9)$$

where, $\dot{\delta}^{-1}$ is the pre-impact normal velocity, c_r is the coefficient of reinstitution (COR), while $c_r = 1$ for a perfectly elastic contact and $c_r = 0$ for a perfectly plastic contact. The value of c_r is set as 0.5 in this simulation.

Stiffness k dependents on the material property of the impacted objectives. In the cases of sphere-plane impact, k is defined as:

$$k = \frac{4}{3\pi(h_{m,i}+h_{m,j})} (R_h)^{1/2} \quad (10)$$

where R_h is the radius of the dummy head sphere, h_m is material properties. For the dummy head spheres h and UAV plate u , h_m are:

$$h_{m,l} = \frac{1-v_l^2}{\pi E_l} \quad \text{with } l=h,u \quad (11)$$

The variables v_l and E_l are the Poisson's ratio and Young's modulus of UAV body and dummy head material respectively.

Considering the buffer of the human neck, the acceleration of the impact objectives could be calculated as:

$$a_h = \frac{F_{imp} - k_n * d_h}{m_h} \quad (12)$$

$$a_u = \frac{F_{imp} - m_u * g}{m_u} \quad (13)$$

where a_h and a_u is the acceleration of head and UAV respectively; and k_n is the compression stiffness of the neck; d_h is the moving distance. The velocity and the position of the head and UAV can be deduced by Equation (12) and (13).

The input of this Dynamic Contact Model process is; UAV flight height (the moment before failure); UAV mass; human head mass; human neck stiffness; shape parameters of UAV; the mechanical property of UAV material; the mechanical property of human head. The output is: impact force and head acceleration curve. The process flow for the dynamic algorithm is shown in Figure 2.5.

Figure 2.5: Process Flow for Dynamics Algorithm

An example of impact force curve of the human head estimated from Dynamic contact Simulation is shown in Figure 2.6:

Figure 2.6: Impact Force with Different Weight of UAV Dropping from the Height of 10m [43]

In conclusion, Dynamic Contact Simulation method can predict the impact force UAV-dummy head impact. Its accuracy and performance will be explained by comparison in Chapter 6.

2.5.2 Volumetric Contact Theory

In Hertz theory, the shape of the colliding bodies on the resulting contact forces is generally not taken into account, or not modelled in a consistent manner. The Volumetric Contact Theory is a contact model based on volumetric properties which describe the contact mechanism with consideration of colliding body shapes. In this model, the contact forces and moments are expressed in terms of the properties of the interference volume between the two bodies. The interference volume is defined as the volume spanned by the intersection of the two unreformed geometries of the objectives. The theoretical derivation is based on Winkler elastic foundation model, the simplified version of elastic stress theory.

To calculate the pressure at any point of the contact area, the solution of the integral equation for the pressure is required. This difficulty could be avoided by modelling the objective in Winkler elastic foundation. Under Winkler elastic foundation, the contact pressure at any point is decided only on the displacement at that point.

$$p(x, y) = \frac{K}{h} \delta(x, y) \quad (14)$$

where, h is the depth of foundation, and K is the elastic modulus.

In the axis-symmetric case,

$$p = \frac{\pi}{4} \left(\frac{Ka}{h} \right) \frac{a^3}{R} \quad (15)$$

where a is the dimension of the contact area, R is the curvature of impacting objective. From Hertz Theory, we have:

$$a = \left(\frac{3PR}{4E^*} \right)^{1/3} \quad (16)$$

Thus, in the axis-symmetric case, we choose $K/h = 1.70 E^*/a$. For K to be a material constant, it is necessary keep width a in proportion to h . Alternatively, while h is fixed, a is required to be in inverse proportion to K .

2.5.3 Finite Element Method

The Finite Element Method (FEM) is a numerical technique solving boundary value problem for the partial differential equations. It divides a large problem into finite small and simple components, which are so-called finite elements. FEM then use simple equations to describe these small elements and then assemble them into a large system to model the entire problem. FEM utilize other methods such as the calculus of variations to approximate a solution by minimizing an associated error function. As the development of FEM, several solving methods are defined, such as explicit finite element method and central difference method.

In the WeST project, an impact model on FEM with ANSYS was developed. Its simulation result is utilized in this report as reference and comparison.

3 MATHEMATICAL MODELLING OF UAV CRASH

This chapter provides detailed mathematical modelling methodologies to analyse and explain the physical process of UAV after it failed in the air. The methodologies work as the theoretical and guideline support for the following simulation and experiments.

Based on the literature review, AIS is chosen as the standard to assess human injury due to its universality in various fields and its scientific and detailed ranges. This means the results from the mathematical model will be evaluated using the AIS table to determine the human injury level.

3.1 Assumptions and Conditions

From the crash experiments, slow-motion videos were recorded and analysed to study the crash behaviour. Due to the complexity of UAV and the human head, it is very hard to reconstruct all the details of the crash. Therefore, assumptions and limiting conditions were utilized in mathematical modelling. The principle of applying assumption and condition is to ensure the simplified model having severer result than a real case. Because the aim of this research is to support a safety regulation on UAV operation, overprotection is acceptable while less protection is not allowed.

1) Free Fall Impact:

Based on the literature review in chapter 2, the typical direct impact caused by UAV could attack human head from above, sideways, or inclined top. Thus, in the first step of this research, the focus is on UAV falling vertically (no horizontal velocity). The more complex horizontal impact and the inclined top impact would be in the next step research work;

2) Replace Human Head Cadaver with Dummy

The replacement for human cadaver for this research is the Hybrid III 50 Percentile Male Pedestrian as shown in Figure 3.1. The Hybrid III dummy is a humanlike test device, generally used in crashworthiness testing to assess the extent of occupant protection provided by the

vehicle structure and vehicle crash[46]. The weight, size and dynamic impact response of this test dummy represent an “average” of the adult male population;

Figure 3.1: Hybrid III 50 Percentile Male Pedestrian [46]

3) Material Assumption:

From our research on the current market, carbon fibre and plastics are materials generally used on UAV body. The specific type and component of the UAV material are often confidential and some of the property data could not be attained, thus, this research chose several typical UAVs made of plastic and carbon fibre;

4) Flat Impact Area Assumption:

It is assumed that the impact area between UAV and dummy head is flat (no accessories beneath) to guarantee the consistency of test result. It is because the diversity of accessories; such as camera, parcel, grippers would cause significant differences in the impact result;

5) Centre Mounted Payload (weights) Assumption:

To have a uniform weight sale in the test and simulation, weights for normalizing the total UAV weight were mounted at the centre of UAV body. In this way, the impact acceleration is largest (worst case), this conclusion proved in our flight trails; and

6) Centre Point Impact Assumption

To achieve the highest impact acceleration, in the dropping test the impact area is assumed at the centre point of a human dummy. As

depicted in Figure 3.2. If the impact area is not at the centre point of the dummy head, part of the kinetic energy of the UAV would be consumed by the bending, flexion or rotation of the human head. All the kinetic energy of the UAV is considered absorbed by the human dummy when the impact is in the centre of the dummy head. A simulation was conducted in ANSYS and proved this centre impact worst-case assumption[1].

Figure 3.2: Centre Point Impact Assumption

3.2 Modelling of UAV Drop

The dropping process of a failure UAV can be expressed in physical equations in terms of flight height, mass, and other aerodynamic parameters related to the human injury. At the initial moment, when the UAV failure happens and it starts to fall. The flying UAV is assumed having energy E composed of kinetic energy E_k related to its mass and velocity and potential energy E_p related to its mass and flying height. The initial energy is given as:

$$E = E_k + E_p = \frac{1}{2}mv_0^2 + mgh \quad (17)$$

where m is mass of UAV, v_0 is the initial flying velocity, and h is the initial height of UAV. In the following falling process, there are two types of kinetic energies: translational kinetic energy and rotational kinetic energy. In this research, translational kinetic energy is the only concern, and the UAV is assumed to not generate any rotational forces during free fall. Therefore, rigid non-rotating bodies possess rectilinear motion. As such, the translation kinetic

energy is possessed by an object moving in a straight line, which correlates to the falling process of the UAV, as shown in Figure 3.3.

Figure 3.3: UAV Fall from Height h

The drag force from the air makes the falling process complicated. A UAV free falls through the atmosphere experiences gravity and a drag force due to air resistance. The downward gravity force is equal to:

$$G = mg \quad (18)$$

where G is the gravity force, and g is the acceleration due to gravity. The upward drag force F_d is equal to:

$$F_d = \frac{1}{2} c_D A \rho_A v_{rel}^2 \quad (19)$$

where c_D is the drag force coefficient, ρ_A is the density of air (1.225 kg/m^3 at sea level), A is the cross-sectional area of the UAV in the direction of falling, and v_{rel} is the velocity related to air which is assumed to be equal to the actual velocity of the UAV. The drag coefficient, c_D , depends on the shape and surface roughness of the object.

Assuming the UAV is falling from h , the acceleration of the UAV is expressed as:

$$a = \frac{G - F_d}{m} = g - \frac{c_D A \rho_A v_{rel}^2}{2m} \quad (20)$$

If the initial velocity v_0 is zero, the actual velocity could be expressed as:

$$v_{imp} = \int_0^t \left(g - \frac{c_D A \rho_A v_{rel}^2}{2m} \right) dt \quad (21)$$

After integration, we have

$$v_{imp} = \sqrt{\frac{2mg}{c_D A \rho_A} (1 - e^{-h A c_D \rho_A / m})} \quad (22)$$

Therefore, the impact energy E_{imp} with final velocity or impact velocity v_{imp} can be expressed as:

$$E_{imp} = \frac{1}{2} m v_{imp}^2 \quad (23)$$

in which the impact velocity v_{imp} is determined by the drag force coefficient c_D , the density of air ρ_A , the cross-sectional area A , and initial height h . In a stable experiment environment, the drag force coefficient c_D and density of air ρ_A are fixed values, the cross-sectional area A is determined by model or types of UAV (in this research it is measured from UAV product), which is strongly related to the mass. Thus, the variable values are the mass of the UAV m and flight height h .

In the emergency cases, such as engine failure or loss of electrical power, the UAV drops from its operating flight altitude. Therefore, the UAV will possess initial velocity and height, which are significant parameters of the final impact energy.

Therefore, the actual velocity of the UAV can be expressed as:

$$v_{imp} = v_0 + \int_0^t \left(g - \frac{c_D A \rho_A v_{rel}^2}{2m} \right) dt \quad (24)$$

The impact energy is given as:

$$E_{imp} = \frac{1}{2} m v_{imp}^2 = \frac{1}{2} m \left[v_0 + \int_0^t \left(g - \frac{c_D A \rho_A v_{rel}^2}{2m} \right) dt \right]^2 \quad (25)$$

In this equation, the impact velocity u is determined by the drag force coefficient c_D , the density of air ρ_A , the cross-sectional area A , the velocity v and initial height h . The variable values are the mass of UAV m , flight height h , and the initial velocity v_0 .

The results of impact velocity and energy could be estimated based on above equations (free fall cases), as shown in Table 3 and Table 4. Here,

$$c_D = 0.3;$$

$$\rho_A = 1.1225 \text{ kg/m}^3;$$

$$A = 0.0188 \text{ m}^2;$$

initial height h from 10ft to 200ft;

mass of UAV m from 0.5kg to 11kg.

Table 3: Estimated Impact Velocity (m/s) of Falling UAV (Free Fall)

	Height (h)				
Mass (m)	10ft	20ft	30ft	50ft	100ft
0.5kg	7.592	10.633	12.896	16.332	22.036
1kg	7.631	10.742	13.094	16.747	23.141
2kg	7.649	10.793	13.187	16.944	23.684
3kg	7.655	10.810	13.218	17.011	23.869
5kg	7.660	10.823	13.243	17.065	24.020
7kg	7.662	10.829	13.254	17.088	24.085
9kg	7.664	10.832	13.260	17.101	24.121
11kg	7.664	10.834	13.264	17.109	24.144

Table 4: Estimated Impact Energy (J) of Falling UAV (Free Fall)

	Height (h)				
Mass (m)	10ft	20ft	30ft	50ft	100ft
0.5kg	13.83	27.13	39.91	64.01	116.54
1kg	29.12	57.69	85.73	140.23	267.76
2kg	58.52	116.49	173.91	287.12	560.94
3kg	87.92	175.28	262.10	434.09	854.66
5kg	146.72	292.88	438.49	728.06	1442.43
7kg	205.52	410.48	614.89	1022.05	2030.33
9kg	264.32	528.08	791.29	1316.04	2618.27
11kg	323.12	645.68	967.69	1610.04	3206.24

The impact velocity is in m/s and energy in Joules (J). These calculated data are proved to be accurate in the dropping experiments. Thus, they could be used as input directly in the simulations in Chapter 4.

3.3 Modelling of UAV-Dummy Head Impact

As discussed in chapter 2, Volumetric Contact Model yields impact force related to the interference volume. It also specifies that the contact force could be applied at the centroid of the volume.

3.3.1 Parameters and Coordination Frame of UAV-Head Model

Before the impact process can be formulated, a description of the frame of the contacting bodies is necessary. The states of two contact bodies, UAV and dummy head, B_h and B_u are described by defining body-fixed frames attached to B_h and B_u , respectively. The origin of each frame is located by r_h and r_u relative to an overall frame K_w . The frames K_h and K_u translate at velocity v_h and v_u . For the sphere-plane example, the position of the centre of the dummy head (B_h) with respect to K_h is p_h , and the radius is R . The surface of the UAV plane (B_u) is located at a height h_u along the plane normal n from the origin of K_u ; see Figure 3.4. When performing vector operations, all vector quantities are revolved in K_w . Typically, p_h and n are specified in local frame coordinates, but they can be easily transformed into K_w by using R_h and R_u .

The volume V of interference is given by

$$V = \int_S f_s(s) dS \quad (26)$$

where $f_s(s)$ is elastic foundation deformation depth at the point s of the contact surface.

It could be found that $f_s(s) dS = dV$. The centroid p_c of interference volume is found as:

$$p_c = \frac{1}{V} \int_V p dV \quad (27)$$

where p is the position vector of an infinitesimal volume element dV relative to K_w . The contact surface area A_c is given as

$$A_c = \int_S dS \quad (28)$$

and the location of the weighted centroid s_c on S is defined as

$$s_c = \frac{1}{V} \int_S s f_s(s) dS \quad (29)$$

Here, $f_s(s)$ presents the variable density over the surface.

Figure 3.4: Model of UAV-Head Impact.

3.3.2 Contact Force Due to Impact

The contact force could be calculated by integrating the pressure over the contact area. In modified Winkler elastic foundation model[49], the local contact pressure $p(s)$ is presented including the hysteretic damping effect as:

$$p(s) = \frac{df_n}{ds} = k_v f_s(s)(1 + av_n) \quad (30)$$

where, $f_s(s)$ is the normal elastic displacement of the foundation as before. The normal contact force f_n is therefore given as

$$f_n = \int_S df_n = k_v \int_S f_s(s) dS + k_v a \int_S v_n f_s(s) dS \quad (31)$$

The first integral term is and results in $k_v V$. This part corresponds to the normal force due to the material stiffness. The second integral is solved as

$$f_n = k_v V + k_v V a v_{cn} + k_v a n \cdot (\omega_t \times \int_S \rho_t f_s(s) dS) \quad (32)$$

The integral term of this zero. Hence, the value of normal contact force is found to be simply

$$f_n = k_v V (1 + \frac{a}{e_{eff} v^i} v_{cn}) \quad (33)$$

where v^i corresponds to initial normal impact velocity, v_{cn} is the central normal velocity at s_c .

In the compliant contact models, the energy dissipation can be modelled by introducing a hysteretic damping term. From the derivation by Hunt and Crossley and Lankarani and Nikravesh[47], the energy dissipation in the impact process can be modelled using a hysteretic damping term.

The compliant normal-force model for direct central impacts is a model in the form

$$f_n = \lambda |x|^p \dot{x} + k |x|^p \quad (34)$$

where x and $\dot{x} = v_n$ are the penetration depth and velocity (v_n is the velocity in normal direction), λ is the hysteresis damping factor and k is the spring constant.

At low impact velocities and for most linear materials with an elastic range[48], the coefficient of restitution can be approximated by

$$e_{emp} = 1 - \alpha v_n^i \quad (35)$$

where α is an empirically determined constant that is valid for a limited range of impact velocities and v_n^i is the normal relative velocity at the start of the impact phase. For steel, bronze or ivory, α is equal to 0.08 to 0.32 s/m, few α information for dummy skin, carbon fibre and plastics on UAV was found. Assuming that the energy dissipated during the compressive phase and during expansion phase are equal, Hunt and Crossley approximated the hysteresis damping factor as a function of the restitution coefficient and v_n^i as

$$\lambda = \frac{3}{2}(1 - e_{eff})\frac{1}{v_n^i}k \quad (36)$$

where the effective coefficient of restitution for the contact model e_{eff} is defined as:

$$e_{eff} = -\frac{v_n^0}{v_n^i} \quad (37)$$

and v_n^0 is the normal relative velocity at the end of the impact phase. Using the definition of e_{emp} for e_{eff} , Equation (32) simplifies to

$$\lambda = \frac{3}{2}\alpha k \quad (38)$$

If the colliding dummy head and UAV have a mass m_h and m_u , respectively, the equation of relative motion $m\ddot{x} = f_n$ can be written as

$$f_n = k|x|^p(1 + av_n) \quad (39)$$

this equation is separable and can be integrated over the impact phase as follows

$$\int_{v_n^i}^{v_n^0} \frac{v_n}{1 + av_n} dv_n + \frac{k}{m} \int_{x^i}^{x^0} x^p dx = 0 \quad (40)$$

where x^i , x^0 is the penetration depths at the start and end of the impact phase. The second integral term of Equation (40) is the work done by the elastic term over the collision event and is, therefore, equal to zero. Hence, v_n^0 depends

exclusively on v_n^{0i} and a , and is independent of the system's effective mass, stiffness, or the type of spring model used. To get a better understanding of the relationship between v_n^0 , v_n^{0i} and a , the definition for e_{eff} is substituted into Equation (40) and the first integral term is solved. The result is

$$av_n^i - \ln(1 + av_n^i) + e_{eff}av_n^i + \ln(1 - e_{eff}av_n^i) = 0 \quad (41)$$

The solution to Equation (41) could further simplify to

$$\frac{1+d/e_{eff}}{1-d} = e^{d(1+1/e_{eff})} \quad (42)$$

By solving Equation (42) with a numerical bisection algorithm, a good initial guess, $d_{est} = 1 - e_{eff}^2$ is provided. The correlation between d and e_{eff} is shown in Figure 3.5.

Figure 3.5: Dimensionless Damping Factor d as a Function of e_{eff} [49]

Since the relationship between e_{eff} and d is constant, the solution can be found a-priori and does not need to be computed during the simulation. This branch uniquely defines the damping factor d as a function of e_{eff} . Therefore, $av_n^i = d/e_{eff}$ is also a function of e_{eff} only, which is a constant for a given impact. Thus, the damping factor a is always inversely proportional to v_n^i for any e_{eff} and for any impact velocity. The expression for a is

$$a = \frac{d}{e_{eff} v_n^i} \quad (43)$$

The hysteresis damping factor is now given as

$$\lambda = \frac{kd}{e_{eff} v_n^i} \quad (44)$$

3.4 Volumetric Stiffness Measurement Experiment

There are several key coefficients in the contact force model: volumetric stiffness k_v , and damping factor a . There is little information about these parameters of the materials found in the literature review. Although these coefficients could be calculated by equations, to ensure the robustness of this simulation, experiments were conducted to test these value of specific dummy head skin, carbon fibre and plastic in UAV.

3.4.1 Two Models for Volumetric Stiffness Measurement

To test the volumetric stiffness of the material, there are two methods.

Method 1: Measuring Volumetric Stiffness (k_v) from definition

From the assumption of Winker Elastic Foundation shown in Figure 3.6, the normal contact force stiffness is defined as:

$$k_v = \frac{k_f}{h_f} \quad (45)$$

where k_f is the elastic modulus of the foundation, h_f is the depth of the foundation mattress, k_v reflect the static stiffness of the two contact objectives.

Figure 3.6: The Modified Winkler Elastic Foundation Model

Since k_f and h_f are both hard to measure, this definition method cannot be carried out.

Method 2: Measuring Volumetric Stiffness (k_v) from quasi-static force experiment

From the contact force equation in volumetric contact theory (VCT), when the impact velocity v_{cn} is close to zero the effect of damping factor could be ignored.

$$F_N = k_v V (1 + a v_{cn}) \quad (46)$$

$$F_N = k_v V \quad (47)$$

Thus, k_v could be tested from a quasi-static force experiment, with the measurement of normal force f_N and interference volume V .

3.4.2 Design of Experiment for Volumetric Stiffness Measurement

A quasi-static force experiment on compression machine was designed. In the experiment, the tested material of dummy head/UAV body was fixed on an INSTRON Universal Testing System, which is a professional force testing facility. The equipment increases quasi-static payload on the centre of the material. A pair of impact force and penetration displacement are measured in the impacting process.

The experiment was conducted under the concept of design of experiments (DOE). DOE is a systematic method to determine the relationship between factors affecting a process and the output of that process. In this case, three test experiments were designed to test the effect of factors (compression rate, objectives, and protectors) on the experiment results.

Figure 3.7 to 3.9 show the testing equipment, environment and objectives.

Figure 3.7: The Compression Test Machine

Figure 3.8: The Operation Software of Compression Test Machine

Figure 3.9: Carbon Fibre UAV(Left) and Dummy Head(Right) for Compression Test

Experiment 1: The Effect of Compression Rate

The compression machine must be conducted with a compression rate. The compression test machine could change its compression rate in the operating software, as shown in Figure 3.10.

The compression tests were conducted in different rate, 16.6mm/s, 1mm/s, 0.1mm/s and 0.01mm/s. The result of the relation between compression force and displacement are shown in Figure 3.11 to 3.14.

Figure 3.10: Carbon Fibre UAV(Left) and Dummy Head(Right) for Compression Test

Test Mode	Single	Test Type	Compression
Speed	16.6mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name Parameters	Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Stroke Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
1_1	1285.04	1282.99	2.45492	2.45492

Figure 3.11: Force vs Displacement at Compression Rate 16.6mm/s

Test Mode	Single	Test Type	Compression
Speed	1mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name Parameters	Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Stroke Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
1_1	554.880	553.993	1.53769	1.53769

Figure 3.12: Force vs Displacement at Compression Rate 1mm/s

Test Mode	Single	Test Type	Compression
Speed	0.1mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name Parameters Unit	Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Stroke Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
1_1	503.731	502.926	1.69067	1.69067

Figure 3.13: Force vs Displacement at Compression Rate 0.1mm/s

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name Parameters Unit	Max_Force Calc. at Entire Areas N	Max_Stress Calc. at Entire Areas N/mm2	Max_Stroke Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
1_1	500.393	499.593	1.72775	1.72775

Figure 3.14: Force vs Displacement at Compression Rate 0.01mm/s

From the above results of UAV-dummy head test, when the compression test is conducted under rate 0.1mm/s, the result will not be influenced by the

compression rate. In other word, when below this rate, the damping factor does not work on the impact force. Thus, in an effective test, the compression rate should be lower re equal to 0.1mm/s.

Experiment 2: The Effect of Objectives

The compression test was first designed to test dummy head and the UAV separately. Due to internal structure and material differences, dummy and UAV frame have different responses to the compression. Neither of the dummy or UAV frames could represent the feature of UAV-dummy head impact.

Figure 3.15: Display of Compression Experiment on Dummy

Test Mode	Single	Test Type	Compression
Speed	0.1mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name Parameters	Max_Force Calc. at Entire Areas Unit	Max_Stress Calc. at Entire Areas N/mm2	Max_Stroke Calc. at Entire Areas mm	Max_Strain Calc. at Entire Areas %
1_1	49959.0	49879.1	11.8357	11.8357

Figure 3.16: Force vs Displacement of Compression Experiment on Dummy

From the above results, we can find out that the dummy head has a smooth response to the increase of compression force. The dummy skin would be compressed and changing its shape to adjust the compression. When the force reaches some limit, the displacement becomes very hard to be deeper. This is because the dummy skin rubber covers on a metal frame. The deeper the displacement reach, the closer the frame is.

Figure 3.17: Cross-section View of Human Dummy [46]

Figure 3.18: Display of Compression Experiment on UAV Body

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/ Batch:	1

Name	Parameters	Unit
1_1

Figure 3.19: Force vs Displacement of Compression Experiment on Dummy

From the above result, we can see the carbon fibre frame shows elastic feature at the beginning of the test. When the displacement reaches a limit, the carbon fibre starts to break, therefore, the curve becomes horizontal. The carbon fibre keeps break itself to absorb the increased compression force, the curve cannot go up.

A further experiment was conducted, with UAV and dummy head combined together as the compressed objective. As shown in Figure 3.20 and 3.21:

Figure 3.20: Display of Compression Experiment on UAV and Dummy Head

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name	Parameters	Unit
1	1

Figure 3.21: Force vs Displacement of Compression Experiment on UAV and Dummy Head

We can see from this test, the UAV and dummy head work together responding to the compression force. At the beginning, an elastic feature of both dummy skin and frameworks, it curves goes up smoothly. When the force reached about 4000N (similar value as in UAV frame independent test), carbon fibre breaks the first time. In the following process, rubber deformation and UAV break happen alternately, until the displacement reaches a limit (reaching the metal frame), any little further displacement needs huge impact force.

Thus, the different objective has a significantly different response in the compression test. To test the stiffness property of UAV-dummy head impact, the third test method should be selected. Also, from the third result, it could be predicted that the stiffness is not a constant in this case but a function of displacement or interference volume.

Experiment 3 – The Effect of Protector

In the WeTS experiment[1], to fix the weight on UAV frame, the plastic cloth was used. The thickness of protectors are from 0.5mm to 5mm. To reconstruct the real situation of the experiment, and test the effect of protectors, a comparison test of different protectors was designed.

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name
Parameters
Unit
1_1

Figure 3.22: Force vs Displacement without Protector

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name
Parameters
Unit
1_1

Figure 3.23: Force vs Displacement with 1-2mm Protector

Test Mode	Single	Test Type	Compression
Speed	0.01mm/sec	Shape	Plate
No of Batches:	1	Qty/Batch:	1

Name
Parameters
Unit
1_1

Figure 3.24: Force vs Displacement with 4-5mm Protector

From the test reports, the protector has a significant influence on the result, especially at the beginning of the test. The thicker the protector is, the longer the smooth curve is. Also, with thicker protector, the displacement could reach a deeper limit.

3.4.3 Summary of Three Compression Tests

From the three compression test experiments, it could be confirmed that the compression rate, the structure of objective, and the thickness of protector all have an influence on the test of stiffness k_v . To obtain an effective value of k_v , the test should be conducted under compression rate 0.1mm/s, with UAV and dummy head combined as test objective. The thickness of protector should be selected according to the condition of verification experiment.

From the compression report, the relation between force and displacement is obtained. To estimate the stiffness k_v , the relation between displacement and interference volume need to be figured out.

3.4.4 Data Collection of Displacement-interference Volume Relation

A layer scan was conducted on the 3D model, of a dummy head (due to business confidential, the model of Hybrid 3 is not available), to test the corresponded interference volume at each displacement. The result is shown in Figure 3.25:

Figure 3.25: Interference Volume vs Displacement $V=f(d)$

In the 3D model, the top pf head is designed as a perfect sphere, however, in Hybrid 3 dummy, the top of the head is closed to flat. As shown in Figure 3.26, at the very beginning of contact, the contact area is not the point but flat. Thus, error exists at the beginning of the contact. The displacement-interference volume relation could be expressed in Figure 3.27.

Figure 3.26: Flat Contact Area on Dummy Head

Figure 3.27: Interference Volume vs K_v

3.5 Damping Factor Measurement Experiment

3.5.1 Two Models for Damping Factor Measurement

Method 1:

From previous stiffness test, when the impact velocity is zero, the impact/compression force (considered as a static impact force) is expressed as:

$$F_{NS} = k_v V \quad (48)$$

when the impact velocity is not zero, the impact force (considered as dynamic impact force) is expressed as:

$$F_N = k_v V (1 + a v_{cn}) \quad (49)$$

substitute the static impact force into this equation, we have:

$$F_{ND} = F_{NS} (1 + a v_{cn}) \quad (50)$$

where F_{ND} is dynamic normal impact force, F_{NS} is static normal impact force.

Since F_{ND} and F_{NS} are both function of interference volume, we have:

$$F_{ND}(V) = F_{NS}(V)(1 + av_{cn}) \quad (51)$$

Thus, the damping factor could be expressed as:

$$a = \left(\frac{F_{ND}(V)}{F_{NS}(V)} - 1 \right) / v_{cn} \quad (52)$$

In this method, it is needed to measure the impact velocity and interference volume of the entire impact process. Because of the lack of high accuracy impactor that can test these two parameters, this test method was not carried out.

Method 2:

From the definition of α , we have:

$$\alpha = \frac{d}{e_{eff} v_n^i} \quad (53)$$

where

$$e_{eff} = -\frac{v_n^0}{v_n^i} \quad (54)$$

$$d = 1 - e_{eff}^2 \quad (55)$$

The correlation between d and e_{eff} is shown in Figure 3.28.

Figure 3.28: Correlation between Damping Factor and Coefficient of Restitution[49]

Thus, in this method, the key factors to be measured are: initial impact velocity v_n^0 and relative velocity v_n^l when objectives separate. Impact experiment of UAV and dummy head is designed.

3.5.2 Design of Experiment for Damping Factor Measurement

To measure the coefficient, an impact of UAV and the human dummy is designed.

1) Vertical Impacting Test

The ideal impact in this test is supposed to be conducted horizontally, in which the impact velocity measured will not be influenced by the gravity. However, there is no horizontal impacting equipment available in the author's university. Thus, a vertical impacting test was designed instead.

In this vertical test, the gravity influence on the impact velocity in the impact process is calculated. The velocity influenced by gravity could be expressed as:

$$\Delta v = g\Delta t \quad (56)$$

where Δv is velocity difference influenced by gravity, g is acceleration of gravity, Δt is duration time of UAV-Human dummy impact, which is within 5ms[1].

Thus, the difference of velocity in the impact process is less than:

$$\Delta v = g\Delta t = 9.8 \text{ m/s}^2 * 0.005\text{s} = 0.049 \text{ m/s} \quad (57)$$

where 0.049m/s, compared to the relative velocity where UAV hits Dummy head in our test (4m/s to 7m/s), is ignorable.

2) Information on Test Equipment

The impact platform is CADEX Twin Wire Impact Machine, as shown in Figure 3.29. It is freefall guided impact machine for impact attenuation evaluation, the full motorized system[50].

Figure 3.29: CADEX Twin Wire Impact Machine

The CADEX Impact Machine has following sensors:

- Accelerometer: 0-1000g mounted on hamper
- Force Sensor: 0-40 KN mounted on base

The machine could reach maximum dropping height at 3.5 meters with maximum dropping weight at 5.5kg (including fly arm). The dropping objective (UAV in this case) must be fixed with the fly arm of the machine which has weight 0.969 kg. This weight of fly arm must be considered in the calculation of dropping mass.

The experiment is in the range:

- Initial Impact Velocity: 4m/s to 7.5m/s
- Dropping Mass: 1.5 kg to 5 kg
- Dropping height: 1-3.5 m
- Rotor and Arms: Depends

3) Potential Error

Despite the error caused by gravity, due to the space limitations of impact machine, the arm and rotors are removed in this test. Therefore, absorbed energy in the shake of arms and rotors were not considered.

Furthermore, due to the lack of reliable human neck dummy, the neck is absent in this experiment. The absorbed energy by dummy neck is not considered as well.

4) Redesign of the Impacting Equipment

As shown in Figure 3.30, there is a fly arm in the CADEX impactor to fix and carry the impact “hammer”, in this case, the “hammer” is replaced by UAV frame. The original adjusting frame connects the hammer to fly arm is a spherical set, which is not suitable for the flat UAV platform. To fix the UAV frame with the fly arm, an adjusting frame is designed, as shown in Figure 3.31:

Figure 3.30: Original Fly Arm and Adjusting Frame

Figure 3.31: Design of New Adjusting Frame

In the new adjusting frame, the arm with a hole is to connect with the original fly arm, the hole is for lightening of the whole frame. There are two flat round plates with a screw hole, the upper plate is to connect with the arm, the lower plate is to fix the UAV flat body. In between the two plates are weight, to help to vary the dropping mass. Each of the weight is 0.5kg. Another important function of the adjusting frame is to fix the accelerometer stably. Details of accelerometer house are shown in Figure 3.32.

Figure 3.32: Detailed Design of Accelerometer House

A support frame to fix the dummy head on the base of impactor machine is designed as Figure 3.33.

Figure 3.33: Detailed Design of Supporting Frame

5) Utilization of High-Speed Camera

The impact machine provides a dropping/impacting platform. To measure the impact velocity, a high-speed camera is introduced.

We use a high-speed camera to record the impact process. Initial impact velocity v_n^0 and relative velocity v_n^i when objectives separate could be calculated by:

$$v_{imp} = \frac{h_2 - h_1}{t_2 - t_1} \quad (58)$$

where h_2 and h_1 are the height of UAV in the two frames before impacting on the dummy head, t_2 and t_1 are the time of two captured frame. The high-speed camera used in this test could capture at 240 frames per second with 720p HD solution.

The camera must be calibrated to ensure the accuracy of measurement. The calibration setting is shown in Figure 3.34.

Figure 3.34: Calibration of High-Speed Camera

Figure 3.35: Vision from Camera

The scale on the protection cage is calibrated with the distance between UAV and dummy head at ratio 1:2. For example, in Figure 3.35 when the UAV drops at scale marked 2, its real distance with dummy head is 4cm.

The measured velocity is compared with theoretical impact velocity. The error includes the friction system which is about 0-5% of the theoretical velocity.

Table 5: Velocity Measurement Error Calculation

Dropping Mass	height	Δh before impact (cm)	Estimated v_n^i (m/s)	Theoretical v_n^i (m/s)	Error
1.6kg	1m	1.733	4.16	4.4229	5.9%
	2m	2.3	5.52	6.2488	11.6%
	3m	2.5	6	7.6458	21.5%
2.1kg	1m	1.75	4.2	4.4239	5.1%
	2m	2.25	5.4	6.2516	13.6%
	3m	2.6	6.24	7.6508	18.4%
3.1kg	1m	1.7	4.08	4.4249	7.8%
	2m	2.3	5.52	6.2546	11.7%
	3m	2.73	6.56	7.6564	14.3%
5.2kg	1m	1.67	4	4.4258	9.6%
	2m	2.45	5.88	6.2571	6.0%
	3m	3.05	7.32	7.6610	4.5%

3.5.3 Results from Experiment

From above calculation to find the damping coefficient, we can define d/e_{eff} as the damping factor coefficient ratio, which can be used directly for calculation. Thus the result of damping factor coefficient ratio is shown in the last column of Table 6.

Table 6: Result of Damping Factor Coefficient Ratio

Dropping Mass	height	$\Delta h_{\text{before impact}}$ (cm)	Estimated v_n^i (m/s)	Δh after impact (cm)	Estimated v_n^o (m/s)	e_{eff}	d	d/e_{eff}
1.6kg	1m	1.733	4.16	0.83	2	0.48	0.77	1.6
	2m	2.3	5.52	1.07	2.56	0.46	0.78	1.69
	3m	2.5	6	1.07	2.56	0.43	0.82	1.92
2.1kg	1m	1.75	4.2	0.8	1.92	0.46	0.79	1.73
	2m	2.25	5.4	0.95	2.28	0.42	0.82	1.95
	3m	2.6	6.24	0.95	2.28	0.37	0.87	2.37
3.1kg	1m	1.7	4.08	0.7	1.68	0.41	0.83	2.027
	2m	2.3	5.52	0.8	1.92	0.35	0.88	2.53
	3m	2.73	6.56	0.8	1.92	0.29	0.91	3.12
5.2kg	1m	1.67	4	0.57	1.36	0.34	0.88	2.60
	2m	2.45	5.88	0.7	1.68	0.28	0.92	3.21
	3m	3.05	7.32	0.75	1.8	0.25	0.94	3.82

Analysis of the damping factor coefficient ratio is shown in Figure 3.36. The figure shows the relationship of between damping factor coefficient ratio and impact velocity (dropping height) and mass of the impact objective.

Figure 3.36: Analysis of Distribution of Damping Factor Coefficient Ratio

From the distribution of damping factor coefficient ratio, we can find the coefficient is not a constant but varies with the objective mass (UAV mass) and impact velocity (depends on dropping height) in this UAV-dummy head case. When the impact velocity increased, we can see the increase of the damping factor coefficient ratio, as well as when we increase the objective weight, this will also show an increase in the damping factor coefficient ratio. The reason for changing of coefficient might be the special structure and material of dummy and UAV as explained previously, where the dummy head structure is a composite of silicone rubber and steel.

To compare with WeTS experiment, in which the UAV and dummy head impacting velocity is between 7m/s to 11m/s, the damping factor coefficient ratio coefficient is chosen as at the 3-meter dropping. The coefficient ratio at 2.6kg is estimated by calculating the mean value of coefficient ratio at 2.1kg and 3.1kg.

Table 7: Selected Damping Factor Coefficient Ratio at 3-meter Dropping

Weight	1.6kg	2.1kg	2.6kg	3.1kg	5.1kg
d/e_{eff}	1.92	2.37	2.745(estimated)	3.12	3.82

4 RESULTS AND ANALYSIS

4.1 Realization of UAV-Dummy Head Impact Model

The simulation program is developed to realize the proposed mathematical model in this research. The simulation is named Improved Dynamic Contact Simulation (IDCS), refers to the Dynamic Contact Simulation (DCS). The mathematical model results are verified and compared with FEM and DCS simulation results and real UAV impact experiment results in following sections.

With the mathematical model in Section 3.3 and measurement results of key parameters k_v and d/e_{eff} in Section 3.4 and 3.5, the real-time impact force in impact process could be calculated. The simulation program builds up the geometry model of the UAV and dummy head based on Section 3.3, then it defines and updates the key parameters. After this preparation, the program enters the impact acceleration calculation loops.

The inputs of this step are the mass of UAV, dropping height of UAV. The output of the simulation is acceleration curve of the dummy head, HIC level, and AIS level of the impact. This process is repeated in 100KHz. The software environment is Matlab. The process flow of volumetric contact algorithm is shown in Figure 4.1.

Figure 4.1: Process Flow of Improved Dynamic Contract Simulation Algorithm

4.2 Results from Improve Dynamic Contact Simulation

From the IDCS, we can obtain the impact process in terms of time versus acceleration. The results of estimation of specific dropping height or weight are shown in Figure 4.2 and Figure 4.3. The horizontal axis represents impact time (second), the vertical axis represents impact acceleration (g).

Figure 4.2: Estimation of Impact Acceleration at Height of 10ft, 20ft, 30ft, 50ft, and 100ft

Figure 4.3: Estimation of Impact Acceleration at Weight 1.4kg, 2.1kg, 2.6kg, 3.1kg, and 5.1kg

From the estimation results, the impact time and acceleration level increases as the weight of UAV and dropping height are higher. The acceleration curves are not perfectly smooth. It is because the estimation could reflect the break of carbon fibre in the impact. When the carbon fibre breaks, it absorbs energy from the impacts, the force working on dummy head will decrease immediately. The carbon fibre breaks follow the breaks measured from k_v in the UAV-Dummy Head combination situation in Section 3.4.

4.3 Comparison of Improved Dynamic Contact Simulation Results with Other Methods

In this section, the UAV-Dummy Head impact process is estimated and compared with other method results. The four methods compared are:

- 1) WeST Experiment: UAV dropping experiment data
- 2) ANSYS: ANSYS Simulation
- 3) DCS: Dynamic Contact Simulation (From Hertz Theory)
- 4) IDCS: Improved Dynamic Contact Simulation (main research of this thesis)

The comparison includes the acceleration curve over entire impact time, the HIC level, and AIS level of each impact. The results of UAV-dummy head impact experiment and ANSYS are cited from the internal report of project “Weight Threshold Study(WeTS) for safety UAV Operation in Singapore”[1]. A brief of experiments in WeTS could be found in APPENDIX A. The results of DCS is cited from[43].

4.3.1 Comparison of Impact Acceleration

Comparisons of impact acceleration on human dummy head from 4 methods are shown in Figure 4.4 to Figure 4.8. The horizontal axis represents impact time (second), the vertical axis represents impact acceleration (g). Data at 1.4kg 50ft and all weights at 100ft from ANSYS are not available. The length of acceleration curves is not the same due to the original data obtained has some differences. In some figures, the acceleration curve from WeTS has more than one peak or ripples, it is because of the vibration of the accelerometer.

Figure 4.4: Comparison of Impact Acceleration at 10ft for Weights of 1.4kg, 2.1kg, 2.6kg, 3.1kg, and 5.1kg

(a) 1.4 kg

(b) 2.1 kg

(c) 2.6 kg

(d) 3.1 kg

(e) 5.1 kg

Figure 4.5: Comparison of Impact Acceleration at 20ft for Weights of 1.4kg, 2.1kg, 2.6kg, 3.1kg, and 5.1kg

(a) 1.4 kg

(b) 2.1 kg

(c) 2.6 kg

(d) 3.1 kg

(e) 5.1 kg

Figure 4.6: Comparison of Impact Acceleration at 30ft for Weights of 1.4kg, 2.1kg, 2.6kg, 3.1kg, and 5.1kg

(a) 1.4 kg

(b) 2.1 kg

(c) 3.1 kg

Figure 4.7: Comparison of Impact Acceleration at 50ft for Weights of 1.4kg, 2.1kg, and 3.1kg

Figure 4.8: Comparison of Impact Acceleration at 100ft for Weights of 1.4kg, 2.1kg, and 3.1kg

From the previous Figure 4.4 to 4.8, IDCS could estimate the impact process both in time and acceleration level and obtained good performance. Compared to the other three methods, it shows a significant advantage in predicting the break or cracks of material in the impact (sunk in the peak area, obvious in 5.1kg 30ft and 1.4 kg 50ft). However, in the cases of 1.4kg, the error in acceleration is obvious. It might be because that in the experiment of measuring coefficient d/e_{eff} the rotors of UAV were removed. Thus the effect of rotors and arms shaking, which absorbed energy, was dismissed. In the cases of 1.4kg, the peak of acceleration value is small, the error from UAV shaking becomes significant. A comparison of UAV-dummy head impact UAV with arm vs UAV without an arm is carried out in Figure 4.9.

Figure 4.9: Comparison of Impact Acceleration UAV with and without Arm

From the comparison, the acceleration of dummy head in the same situation (10ft 1.4kg UAV) are quite different. The IDCS result is more closed to the impact with UAV without an arm.

4.3.2 Comparison of Injury Levels

Injury levels in different impacts are calculated and shown as follows. In some method, the HIC and AIS are not available in the original reports. The threshold for harmless UAV operation is chosen as HIC=1000 or AIS level 3.

Table 8: Comparison of HIC

No.	Dropping Height	Weight	HIC from WeTS	HIC from ANSYS	HIC from IDCS
1	10ft	1.4kg	9.04	11	220.40
2		2.1kg	157.81	279	361.38
3		2.6kg	362.24	436	462.37
4		3.1kg	608.84	712	576.36
5		5.1kg	1448.2	1738	990.28
6	20ft	1.4kg	32.26	36.2	377.24
7		2.1kg	443.89	516	589.83
8		2.6kg	838.12	942	794.52
9		3.1kg	1072	1632	994.84
10		5.1kg	2246.9	5272	1933.47
11		1.4kg	69.73	61.13	586.52
12		2.1kg	684.55	752	1257.01

13	30ft	2.6kg	942.19	1709	1625.92
14		3.1kg	1531.3	3238	2100.52
15		5.1kg	4151.8	10363	4075.48
16	50ft	1.4kg	170.91	142.86	1290.03
17		2.1kg	1237.5	2658.92	2855.82
18		3.1kg	3222	7221.54	4978.22
19	100ft	1.4kg	NA	NA	2161.64
20		2.1kg	NA	NA	5028.47
21		3.1kg	NA	NA	11297.31

Table 9: Comparison of AIS

No.	Dropping Height	Weight	AIS from WeTS	AIS from ANSYS	AIS from IDCS
1	10ft	1.4kg	0.18	0.23	1.17
2		2.1kg	0.96	1.37	1.65
3		2.6kg	1.66	1.91	2.00
4		3.1kg	2.51	2.86	2.39
5		5.1kg	5.39	6.39	3.81
6	20ft	1.4kg	0.52	0.54	1.71
7		2.1kg	1.94	2.19	2.44
8		2.6kg	3.30	3.65	3.14
9		3.1kg	4.10	6.02	3.83
10		5.1kg	8.14	18.54	7.06
11	30ft	1.4kg	0.65	0.62	2.43
12		2.1kg	2.77	3.00	4.73
13		2.6kg	3.65	6.29	6.00
14		3.1kg	5.68	11.54	7.63
15		5.1kg	14.69	36.04	14.42
16	50ft	1.4kg	1.00	0.91	4.84
17		2.1kg	4.67	9.55	10.23

18		3.1kg	11.49	25.24	17.52
19	100ft	1.4kg	NA	NA	7.84
20		2.1kg	NA	NA	17.69
21		3.1kg	NA	NA	39.24

As is clear in the results, the HIC and AIS result from IDCS are consistent with the result obtained from the simulation. IDCS method could predict the potential head injury in UAV-dummy head impact. In some cases, IDCS provides more strict safety threshold. In this public safety topic, over protection to people is acceptable while less protection is not allowed. Generally, IDCS has comparable, even better estimation performance the ANSYS.

5 CONCLUSION AND FUTURE WORKS

In this thesis, a new mathematical model (IDCS) on UAV-dummy head impact was formulated up and verified. The model was based on volumetric contact theory. To customize the model for UAV-dummy head cases, two significant coefficients were measured in a series of experiments. The simulation result was verified by compared with WeTS measured results and results from two other simulation methods, DCS and ANSYS. Some summary of the comparison of results are as follows:

1) Compared to the WeTS experiment result

The real UAV dropping experiment is the closest to the real incident situation, thus its result is most reliable. The result of IDCS shows strong consistency with the WeTS while changing both the weight and dropping height of impacting objectives. It has good performance in the estimation of impact time, impact acceleration, HIC and AIS.

2) Compared to the DCS and ANSYS results

From a comparison of the three simulation methods, IDCS and ANSYS have good performance in estimating the entire acceleration curve. The IDCS has error in the 1.4kg cases, which should be improved in future work. However, from the WeTS, the 1.4kg case injuries are much lower than threshold AIS level 3. 1.4kg is not the decision weight level according to AIS 3.

3) Capability in reconstructing wider impact range

The real UAV dropping experiment is the most reliable method. However, it could not reconstruct all the situations, such as cases when UAV's flight height is over 150ft, or when the UAV hit human head from a slant angle. Also, the setting up and preparation of experiment cost large human resource and budget. In this IDCS, it took a 10-person team more than 5 months to conduct the experiment.

4) Advantage in processing time

The FEM simulation result provides not acceleration curve but the UAV and head motion in the crash. Due to the mass calculation, its process

time is too long (more than 90 minutes for each drop). And the modification of UAV model needs knowledge of ANSYS, it is also time-consuming. For instance, in our team, a trained ANSYS designer needs more than 10 hours to redesign and test a new UAV model. In IDCS, the calculation is controlled within 3 minutes.

5.1 Contributed Results

The contributions of this research are summarized as follows:

1) Validation of simulation method in UAV-dummy head impact

Compared to the other simulation methods and actual drop experiment, IDCS is a better estimation method. It could accurately predict the impact process in both impact time and acceleration level, even the breaking of materials during impact. It could reach larger mass and height range in impact problems, which could not be realized in actual drop experiment. The calculation time is short.

2) Application and verification of volumetric contact theory in higher impact velocity problems

The volumetric contact theory(VCT) is a new theory first proposed in 2002. It is initially proposed and utilized in solving robot gripper problems[49], when the relative impact velocity between gripper and objectives are within 0.01m/s to 0.1m/s. There are few references utilized or demonstrated VCT could solve higher relative velocity (more than 1m/s) problems. Results in this research proved VCT has good performance on analysing contact cases with impact velocity from 4m/s to 11m/s.

3) The measurement method and result of coefficient k_v and e_{eff}

The accuracy of IDCS is due to the scientific measurement of k_v and e_{eff} . This research designed many planes to measure and test the property of the two coefficients. By scientific design and analysis of the measurements, the changing trend and properties of the two coefficients were found, so as the most reliable value of them. A possible reason to explain the changing trend was analyzed as well. The design of

measuring experiment and the value of k_v and e_{eff} will be shared to the researchers who are interested in impact or UAV safety problems.

5.2 Future Works

The current achievement of this research proved the direction of using mathematical models, simulation and experiment, that we are following is correct and the results are repeatable and closely matching the real UAV crash cases. The research was conducted under some assumption and condition. For example, all the UAV-dummy head were assumed to be perfectly free fall crash. The future work will be based on this mathematical model method to reconstruct and mimic as closely as the real crash situation. There are some errors obvious in this research, such as the 1.4kg cases. Further research to reduce the error should be carried out.

Some future works are listed as follows:

- 1) Side-way UAV-dummy head impact simulation: In real UAV crash incidents, the UAV always hits human on the sideway. Thus, side-way impact models are more closed to real situations. To verify the side-way impact model, it is suggested to carry out a series of real UAV crash experiments as the WeTS. Furthermore, in the side-way crash, the injuries on facial features and neck becomes significant, the injury level standard should vary as well.
- 2) Application on UAV in other materials: This research used carbon fibre UAV as a specimen. There are UAV made of plastics and other materials available in the market. Some of these materials are not as fragile as carbon fiber, which will have a different result on the injury level.
- 3) Improvement on the measurement of coefficient e_{eff} : In this report, the measurement of e_{eff} caused come error due to the restriction of impact machine. In the improved e_{eff} measurement experiment, the impact platform is to be horizontal, which could reduce the effect of gravity. The rotors and arms of UAV should be fixed with the UAV in the impact, the vibration effect must be considered in the measurement.

- 4) Research on safer material on UAV: Since the material of UAV body has a significant influence on the head injury, finding safer materials to replace current UAV body frame will be an inspiring researching area. The bottom of UAV especially the undercarriage and payload which touch the human firstly in the impact will be the focus of this future research.

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APPENDIX A UAV-Dummy Head Impact Experiment [1]

A real UAV-dummy head impact experiment was conducted in the project “Weight Threshold Study (WeTS) for safety UAV Operation in Singapore”[1]. The experiment reconstructed the free-falling crash of UAV. The aim of the experiment is to achieve the acceleration curve of the human head in the impact and to get the HIC and AIS level in different weight and height UAV crash.

In the experiment, two parameters were chosen to be varied, the dropping height and weight of the UAV. A range of values was chosen for the variables of height (10 to 100ft) and weight (1.4kg to 5.1kg). For each set of experiment, a minimum number of four repetitions were carried out.

A Hybrid III crash test dummy head is used to replace human cadaver due to its high bio-fidelity and instrumentation capability. Three one-axis accelerometers are fixed in the dummy head to detect acceleration in the X, Y and Z direction as shown in Figure A1. The UAV was configured to attain a different weight. Weights were placed in the centre of the UAV to achieve various weights.

Figure A1: Hybrid III Dummy Head and Accelerometer [1]

Figure A2: Basic Configuration of UAV [1]

In the experiment, UAVs are held under the mobile hanging platform by an electromagnet, and two steel ropes are hanged to ensure that UAVs will impact on the centre of the dummy head. A mobile barrier is provided to prevent any fragmentation of the UAVs after impact. The impact process is recorded by the high-speed camera. A sample of the photo is shown in Figure A4.

After ensuring all the devices are operational, the operator would cut off the power to the electromagnet. The UAV drops along the steel ropes until hits on the dummy head. Frictions of ropes would influence the final impact velocity of UAV and dummy head.

Figure A3: Experiment Setup

Figure A4: Impact Moment