Ground Impact Study:
Experimental analysis of the severity of a sUAS impact with a human being

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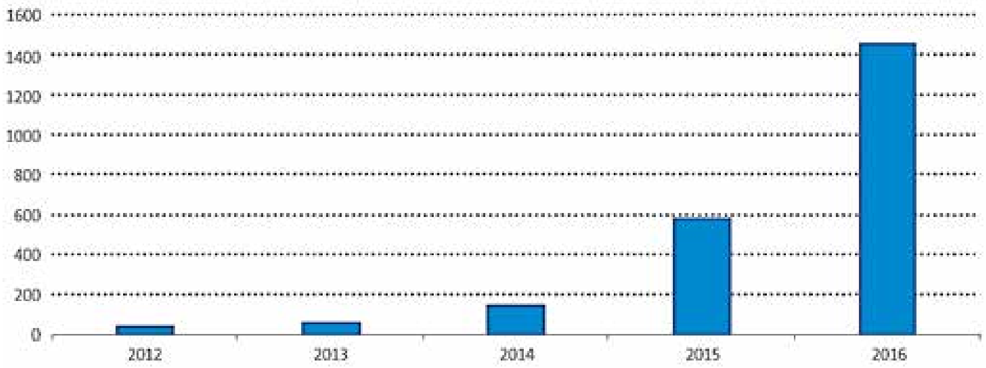
March 17th 2021 – AMUSE 2021 Conference

Accidental miscellaneous events



UAS incident occurrences per year 2012-2016 (EASA)

Year	Profile	Reasons	Consequences
2013	19 years old	Operator loss of control	Death (decapitation)
2013	Adult	Collision with a building	Minor contusions
2014	Adult	Operator loss of control	Minor contusions
2015	18 month old	Collision with a tree	Enucleation
2017	**13 years old**	**Race accidents**	**Skull fracture**

- UAS weight: between 500g and 800g
- Impact localized on the skull vertex
  → loss of consciousness and skull fracture

- Fatal accidents are only related to the use of semi-professional drones
- 80 % of non-fatal accidents refer to leisure drones between 1 and 3 kg
- 96.7% of accidents involved quad-rotor drones

Major concern of the surgical community

Forces between 14.1 to 68.5 J, which can be produced by a 500g drone traveling approximately 17 to 37 mph, are enough to fracture adult human skulls in cadaveric studies [*Chung et al. 2017*]

European regulation

OPEN category - Low risk

NO-PRE APPROVAL

LIMITATIONS: 25 kg, VLOS, height <120m, system of zones

3 Sub-categories: fly over, close, far from people

General public

Model Flying

Photographers

Operation		Remote pilot competency (age according to MS legislation)	UAS				UAS operator registration
Subcategory	Area of operation (far from aerodromes, maximum height 120 m)		class	MTOM/ Joule (J)	Main technical requirements (CE marking)	Electronic ID/ geo awareness	
A1 Fly over people	You can fly over uninvolved people (not over crowds)	Read consumer info	Privately built	< 250 g	N/a	No	no
			C0		Consumer information, Toy Directive or <19 m/s, no sharp edges, selectable height limit		
		• Consumer info • online training • online test	C1	< 80 J or <900 g	Consumer information, <19m/s, kinetic energy, mechanical strength, lost-link management, no sharp edges, selectable height limit.	Yes + unique SN for identification	yes
A2 Fly close to people	You can fly at a safe distance from uninvolved people	• Consumer info • online training • online test • theoretical test in a centre recognised by the aviation authority	C2	< 4 kg	Consumer information, mechanical strength, no sharp edges, lost-link management, selectable height limit, frangibility, low-speed mode.		
A3 Fly far from people	You should: • fly in an area where it is reasonably expected that no uninvolved people will be endangered • keep a safety distance from urban areas	• Consumer info • online training • online test	C3	< 25 kg	Consumer information, lost-link management, selectable height limit, frangibility.		
			C4		Consumer information, no automatic flight	if required by zone of operations	
			Privately built		N/a		

Ground Impact Study

End of 2018:

→ Specific study founded by the DGAC (French Civil Aviation Authority) dedicated to the category C1 defined by EASA

Objective & problematic

To assess the potential of lethality generated by a 900g UAS impact with human being on the ground

Proposed approach

State of the art → World wide regulations / Impact criteria / UAS impact tests

Experimental investigations

→ UAS Free-fall tests

→ UAS to dummy impact tests

Summary

- Introduction and context
- **Literature review on UAS impact**
- Experimental investigations
- Conclusions and outlooks

Review of experimental studies

In 2018, only 4 research centers have performed dedicated campaigns for the experimental study of human body impacted by UAS

Research center	Drones	Experimental Setup	Analysis / Criteria
NIAR/UAH	Phantom 3	Frontal and vertical impact Launching ramp	KEimp, HIC_{15} / AIS, g
Polytecnico di Torino	**Home-made** quadcopter and flying wing	5 configurations with a launching ramp	HIC_{36}, F_{xyz}/M_{xyz}
Virginia Polytechnic	Phantom 3, Inspire and S1000+	Frontal impact manually piloted Free fall vertical impact	HIC_{15} / AIS, F_x, N_{ij}, g
ATMRI Singapour	**Home-made** quadcopter and flying wing	Guided free fall	KEimp, HIC_{15} / AIS

+ Ohio State University: UAS impact tests on PMHS (*Starck et al. 2019*)

Review of experimental studies

	NIAR/UAH 12 m / 1,2 kg	Polytecnico di Torino 12 m / 1,9 kg	Virginia Polytechnic 10 m / 1,2 kg	ATMRI Singapour 10 m / 1,4 kg
E_{imp}	105 J	156 J		122 J
HIC_{15}	40	2988	12	693
P AIS 2/3	0%		0%	0%
g	70		32	121
F	3500 N	6900 N	1936 N	

Severity of impact of a 900g drone

Very difficult to consistently conclude regarding with the already published results

Summary

- Introduction and context
- Literature review on UAS impact
- Experimental investigations
- Conclusions and outlooks

Experimental investigations: UASs of the study

Parrot Anafi Classic

Weight	320 g
Velocity Max angular velocity	15m/s (55km/h) 200°/s
Battery	Lipo High density (2 cells) Capacity : 2700mAh Voltage : 7.6V Puissance max. : 24W Weight: 125 g
Autonomy	25 minutes
Resistance	Wind (50km/h) Wind burst (80 km/h)
Dimensions	Folded arms: 244x67x65mm Extended arms : 175x240x65mm

DJI Mavic Pro

Weight	837 g
Velocity Max angular velocity	20 m/s (72 km/h) 200°/s
Battery	Lipo (4 cells) Capacity : 3850mAh Voltage : 17.6V Puissance max. : 80 W Weight : 297 g
Autonomy	31 minutes
Resistance	Wind (29km/h) Wind burst (38 km/h)
Dimensions	Folded arms: 214 x 91 x 84 mm Extended arms: 322x242x84 mm

GIS's experimental tests:

#1: Preliminary free-fall tests
#2: Impact tests with HIII dummy

Free-fall experimental tests

Experimental protocol

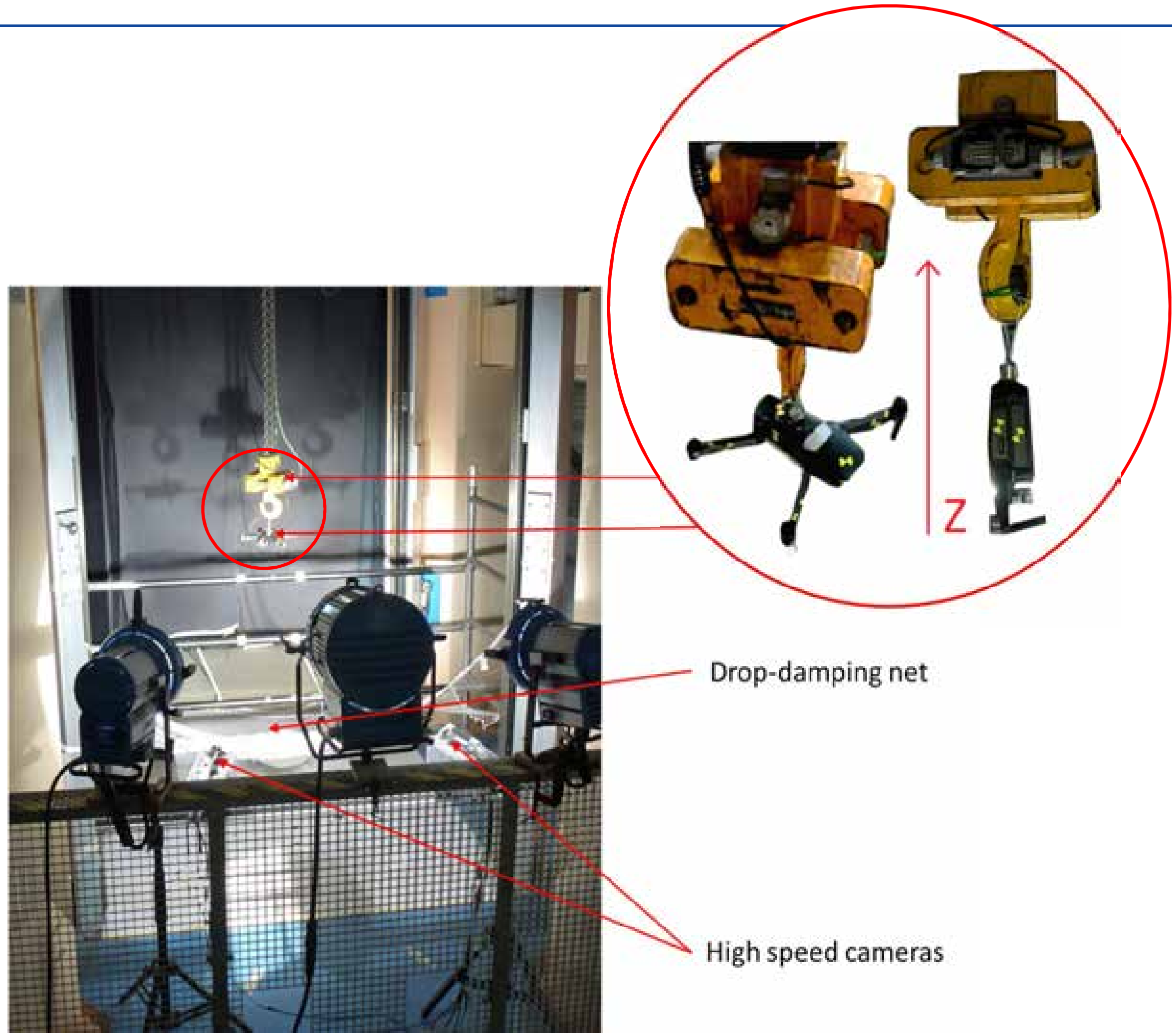
- Tested drop altitudes:
8 m, 10 m, 12 m and 13.7 m

- Wind influence minimized

- Tracking of the fall :
$0.48 \times 0.8 \times 0.6\ m^3$ / f = 1 kHz

- Tested initial fall-orientations:
"flat" & "nosedive" configurations

- Repeatability:
3 tests w/r to configurations and altitudes



Free-fall experimental tests

Comparison results

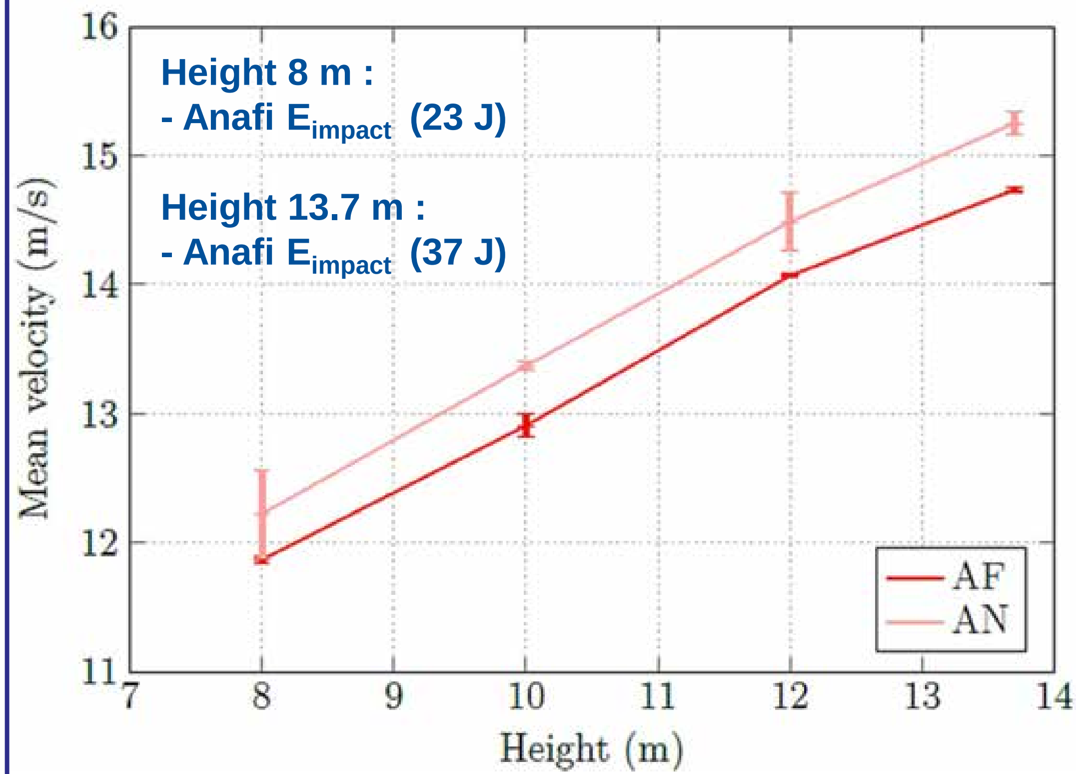
AF: Anafi Flat configuration
AN: Anafi Nosedive configuration

MF: Mavic Flat configuration
MN: Mavic Nosedive configuration

Equilibrium of forces not reached →Fall altitude too low

Rotations during the fall: delicate comparison

Arrival orientation: Battery towards the ground



Free-fall experimental tests

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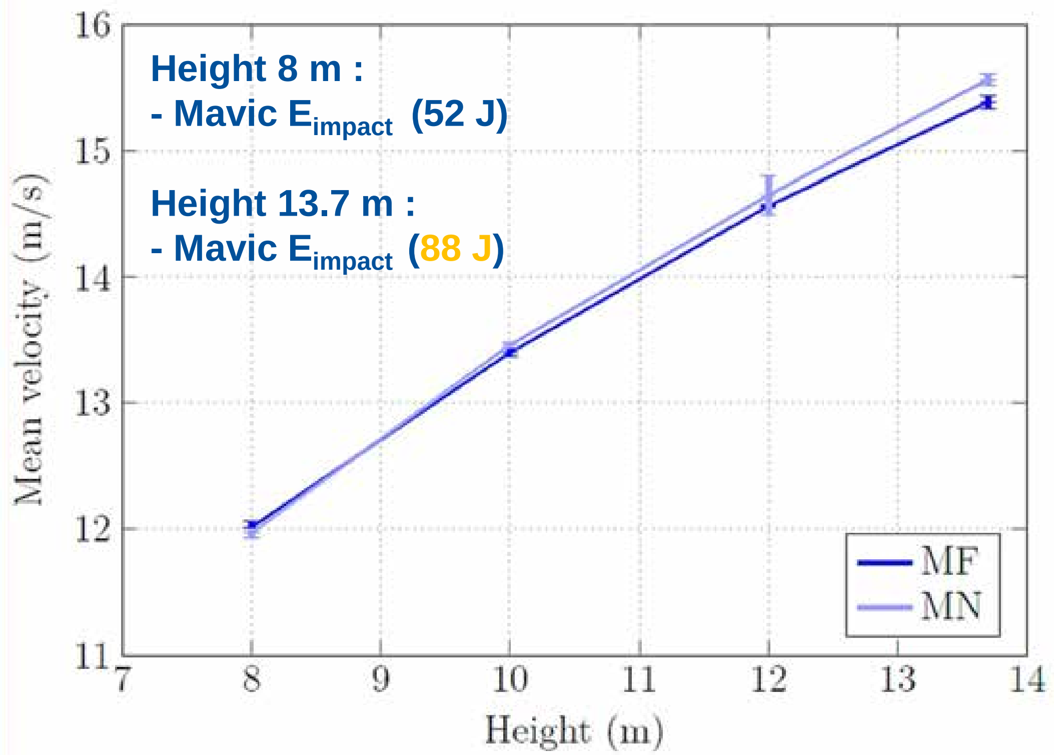
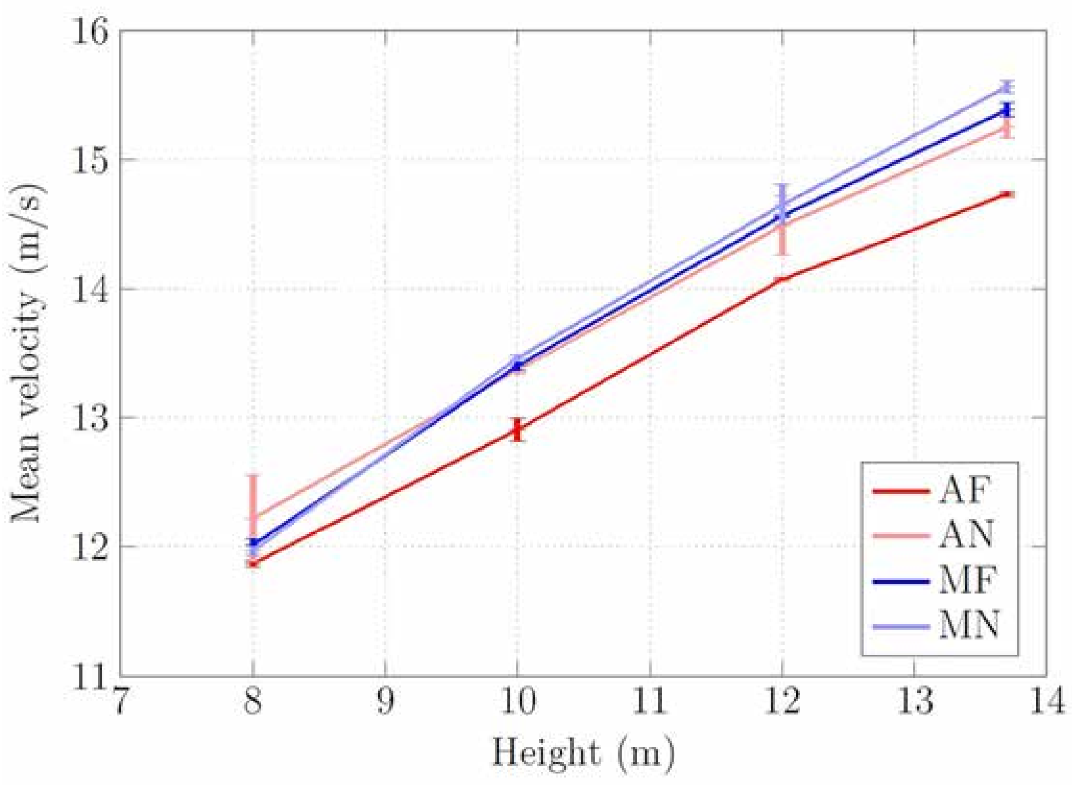


Free-fall experimental tests



Drawbacks & conclusions

Drop altitude not sufficient to reach terminal velocity

Rotations of the drones during the fall to be taken into account:

- → comparisons of configurations not very reliable
- → need for full height measurements

$\text{Drone}_{400\text{ g}}$ → ~14 m → 15.25 m/s → E_{impact}: 36 J
$\text{Drone}_{800\text{ g}}$ → ~14 m → 15.56 m/s → E_{impact}: 88 J

➔ Input: velocity for impact tests

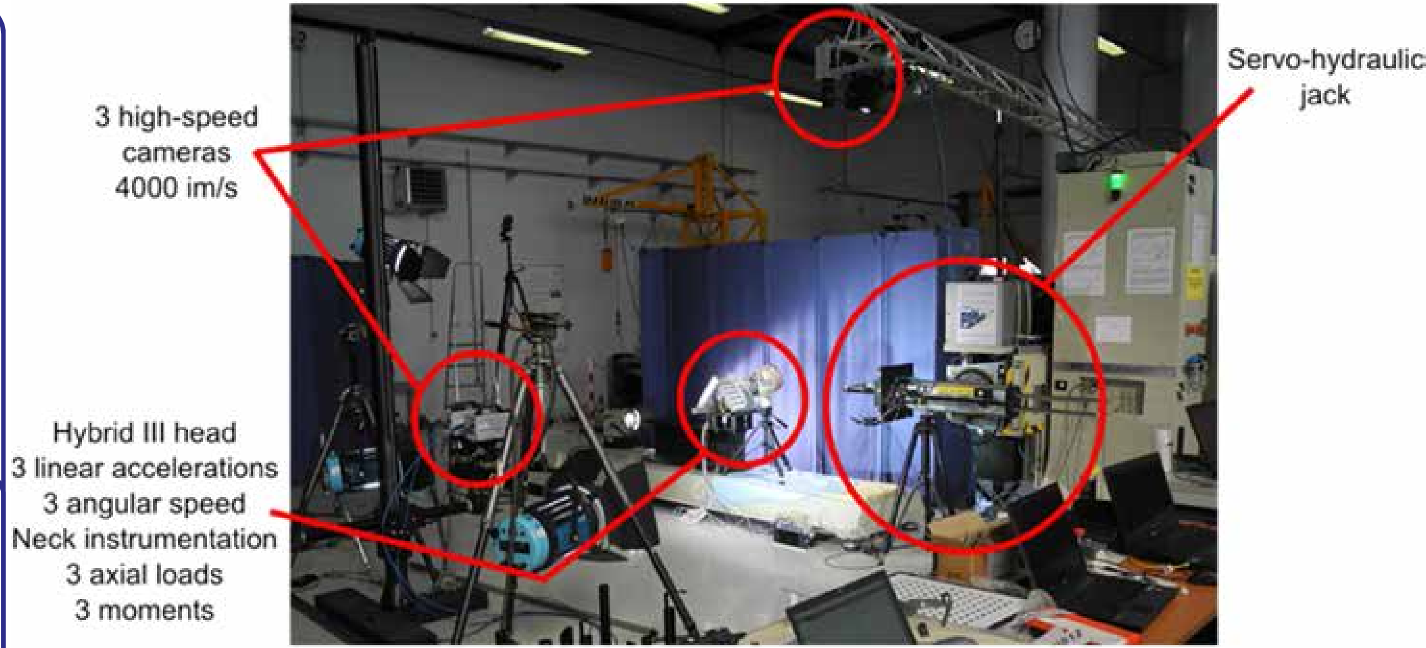
UASs impacts to dummy head

Impact tests protocol

- Velocity: ~15.5 m/s
- 9 impact configurations
- 3 impact location on the head
- CG to CG impacts
  → Worst case scenario

Impact tests injury criteria

- HIC *(Eppinger et al., 1999)*
- BrIC *(Takhounts et al., 2013)*
- Nij *(Eppinger et al., 1999)*



SAE J211 standard data processing

Accelerations and neck forces ⇔ CFC1000
Angular velocity ⇔ CFC60 (NHTSA NCAP)
Neck moments ⇔ CFC600

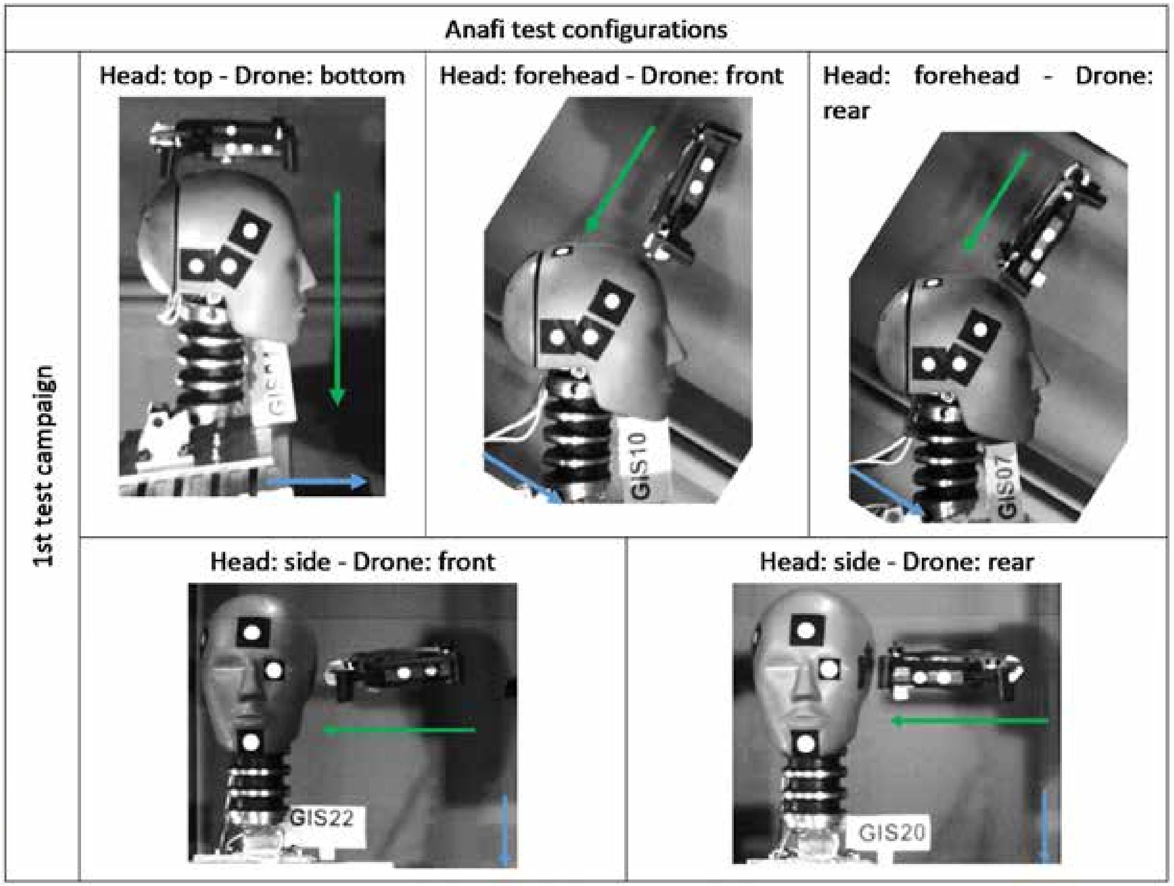
UASs impacts to dummy head

1st Impact tests configurations: Anafi

UAS bottom surface to the top of the head

UAS front to the forehead (58° oriented)
UAS rear to the forehead (58° oriented)

UAS front to the side of the head
UAS rear to the side of the head



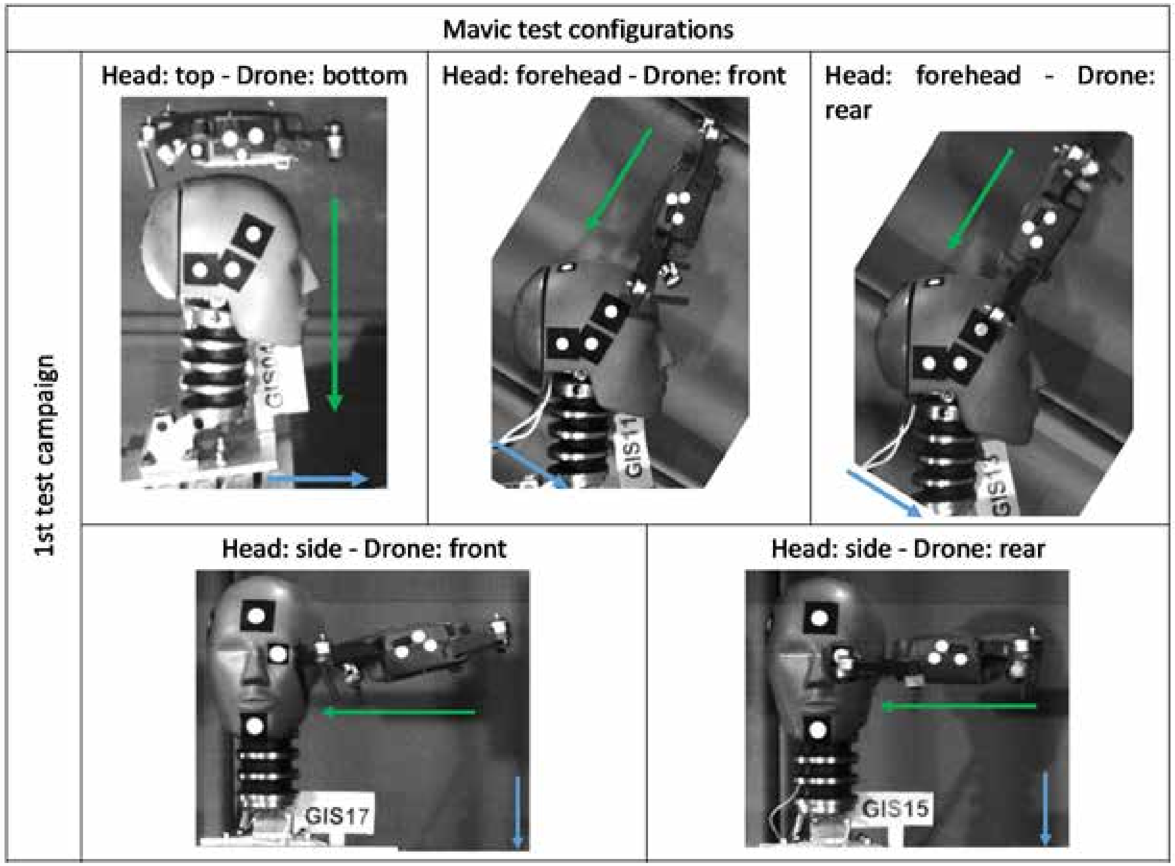
UASs impacts to dummy head

1st Impact tests configurations: Mavic

UAS bottom surface to the top of the head

UAS front to the forehead (58° oriented)
UAS rear to the forehead (58° oriented)

UAS front to the side of the head
UAS rear to the side of the head

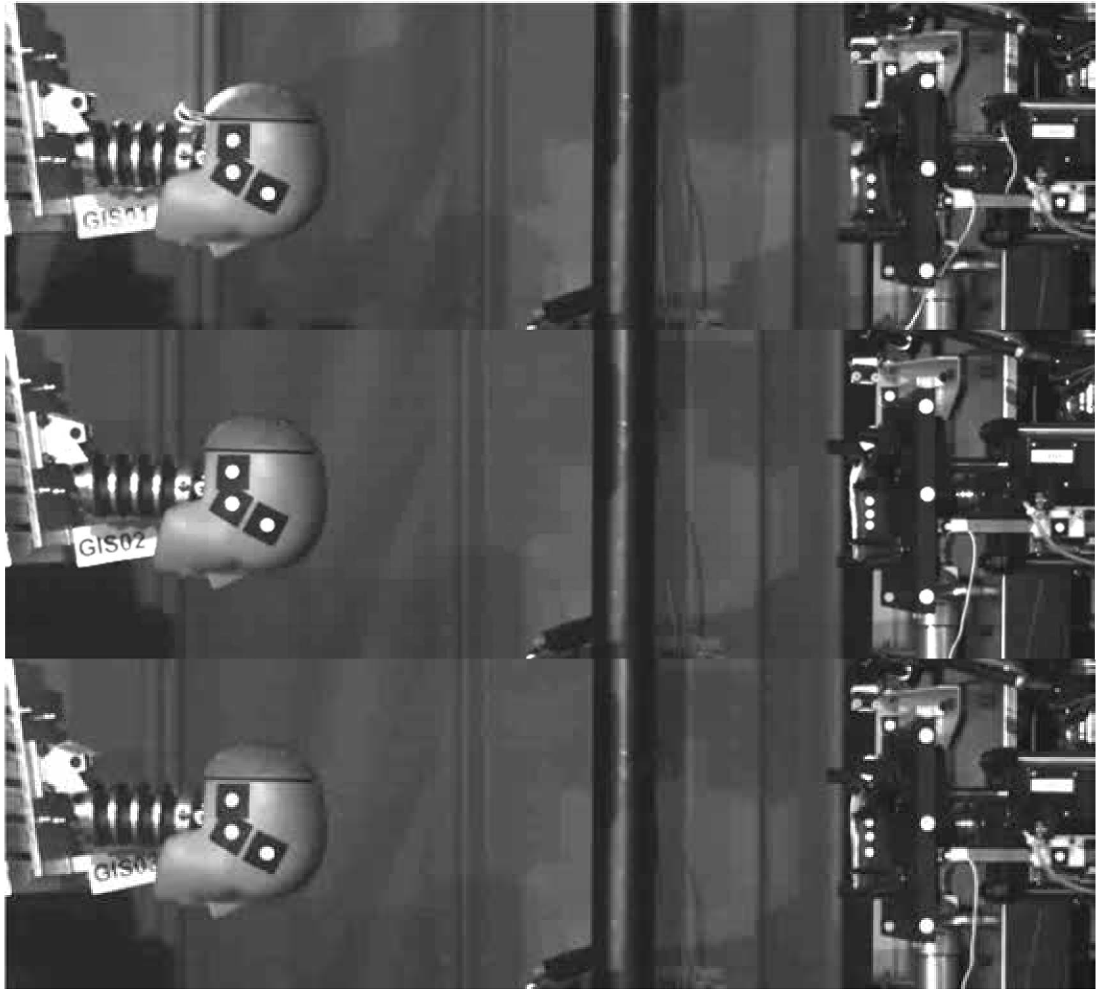


UASs impacts to dummy head

Test configuration: Vertex impact

- Anafi

Test	Head pos	Drone	Drone pos	Speed (m/s)	Side CG dev. (mm)	Top CG dev. (mm)
GIS_01		Anafi		15.65	1.3	Low*
GIS_02				15.63	-0.9	
GIS_03	Top		Bottom	15.64	1.2	

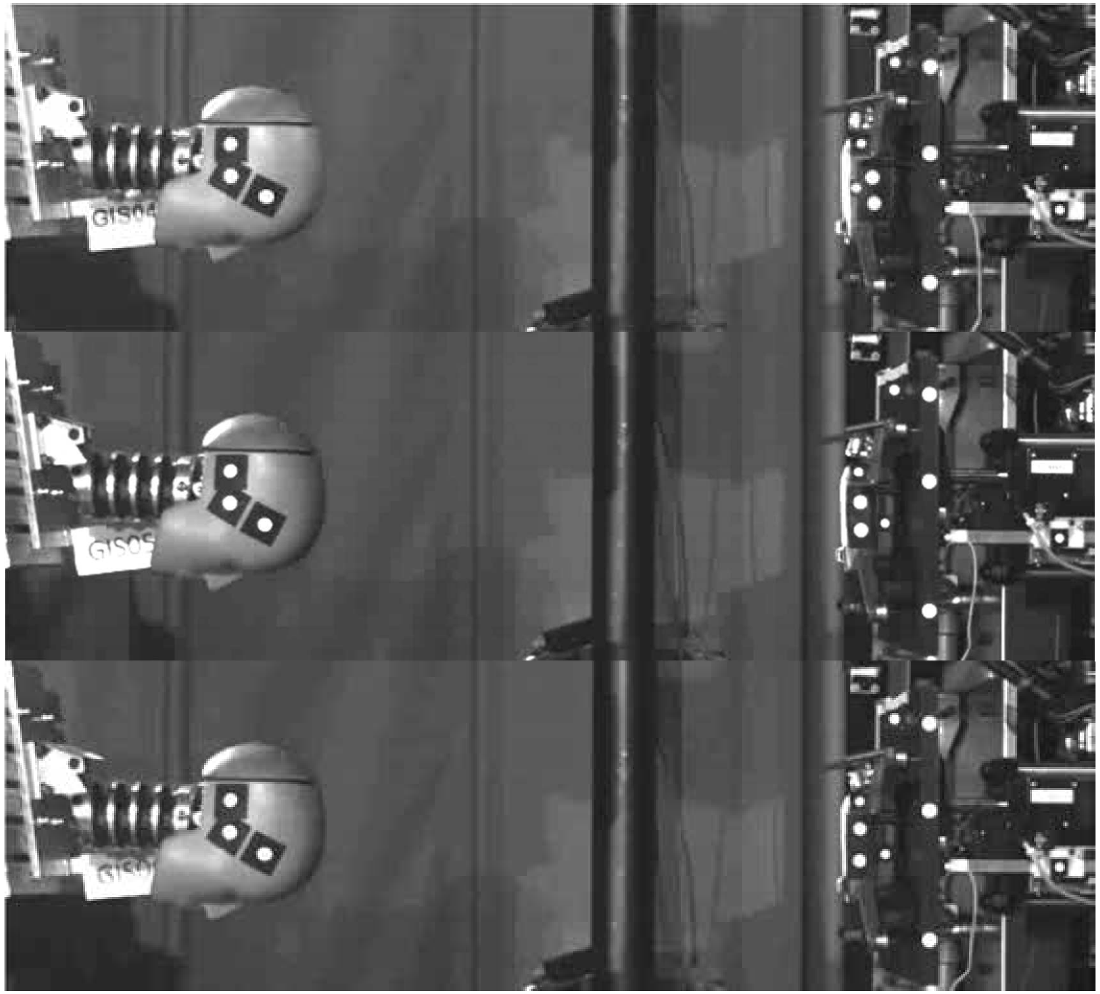


UASs impacts to dummy head

Test configuration: Vertex impact

- Mavic

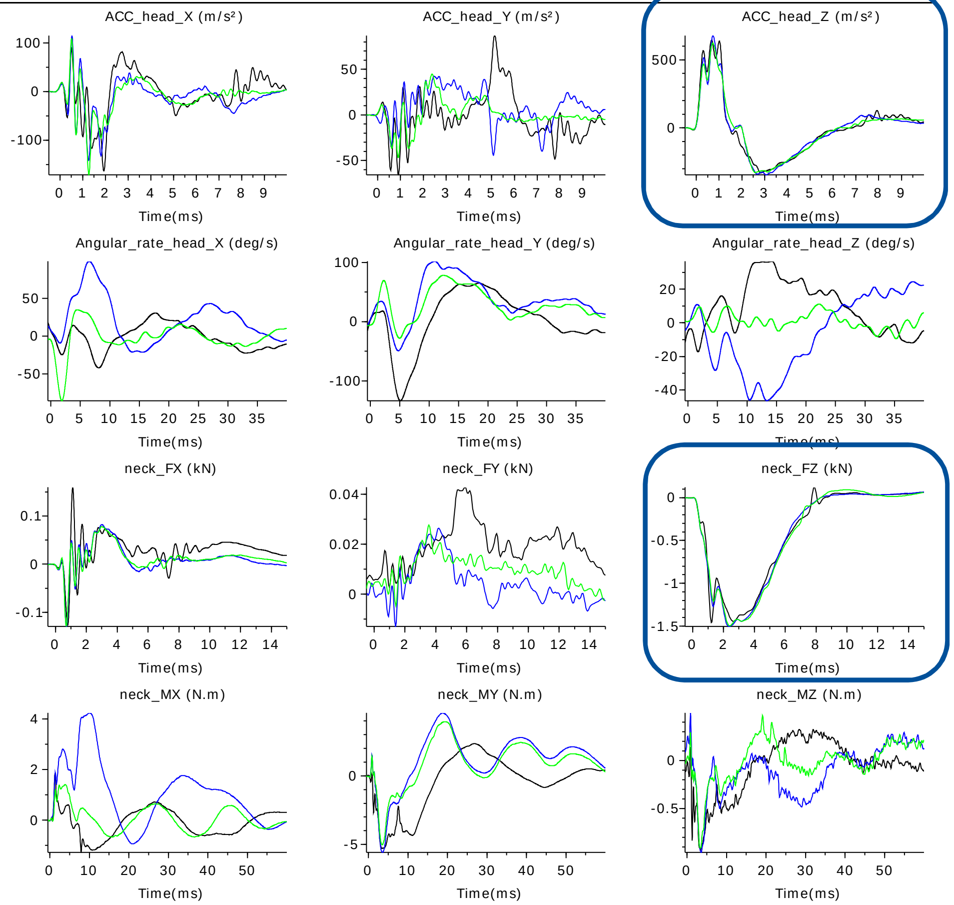
Test	Head pos	Drone	Drone pos	Speed (m/s)	Side CG dev. (mm)	Top CG dev. (mm)
GIS_01	Top 90 deg	Anafi	Bottom	15.65	1.3	Low*
GIS_02				15.63	-0.9	
GIS_03				15.64	1.2	
GIS_04		Mavic		15.88	-2.9	5 to 10*
GIS_05				15.80	-0.4	
GIS_06				15.84	0.1	



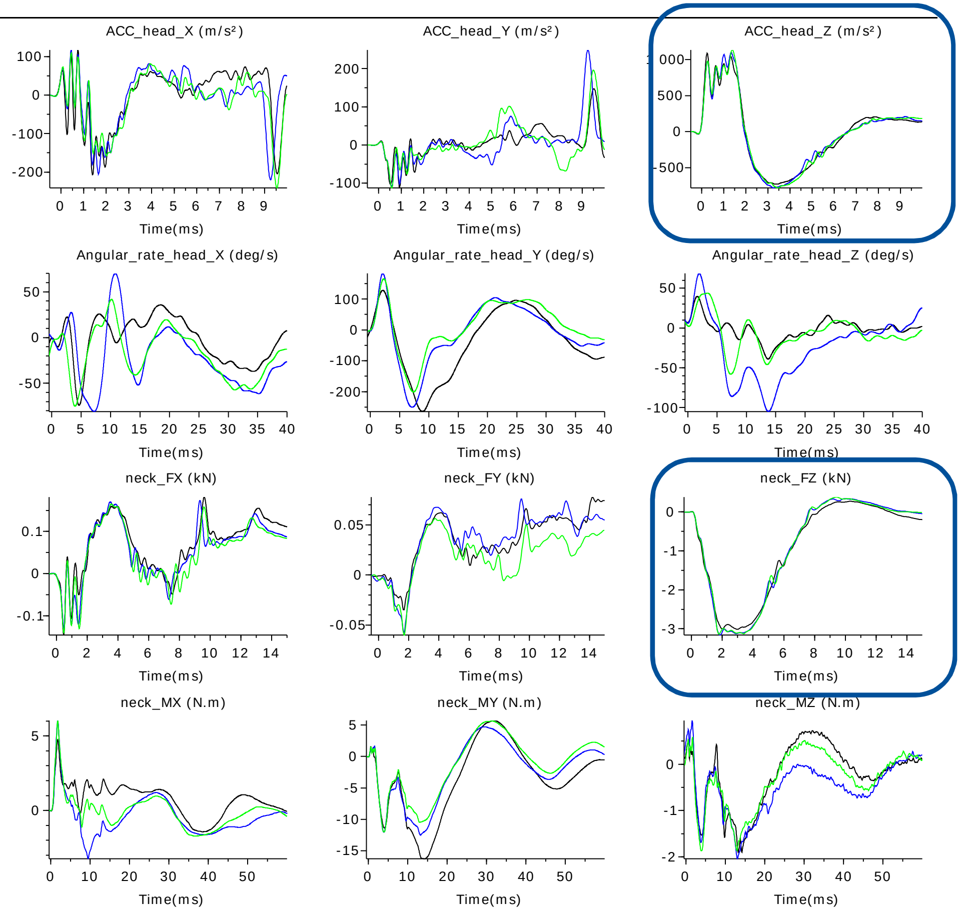
UASs impacts to dummy head

Test configuration: Vertex impact

Anafi



Mavic



UASs impacts to dummy head

Test configuration: Vertex impact

A significant influence of the drone weight:

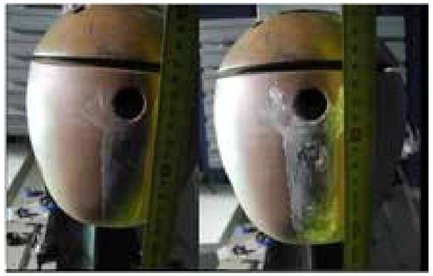
- Head and Neck Compressive force

- Significant higher HIC values

- -

- BrIC were small for all (less than 0.1)
  → rotations are limited
- Nij values : lower than 1

Test	Head pos	Drone	Drone pos	Speed (m/s)	HIC15	BrIC	Nij
GIS_01	Top 90deg	Anafi	Bottom	15.7	23	0.04	0.35
GIS_02				15.7	20	0.04	0.36
GIS_03				15.7	19	0.03	0.36
GIS_04		Mavic		15.9	182	0.08	0.74
GIS_05				15.9	190	0.08	0.77
GIS_06				15.9	187	0.05	0.78



UASs impacts to dummy head

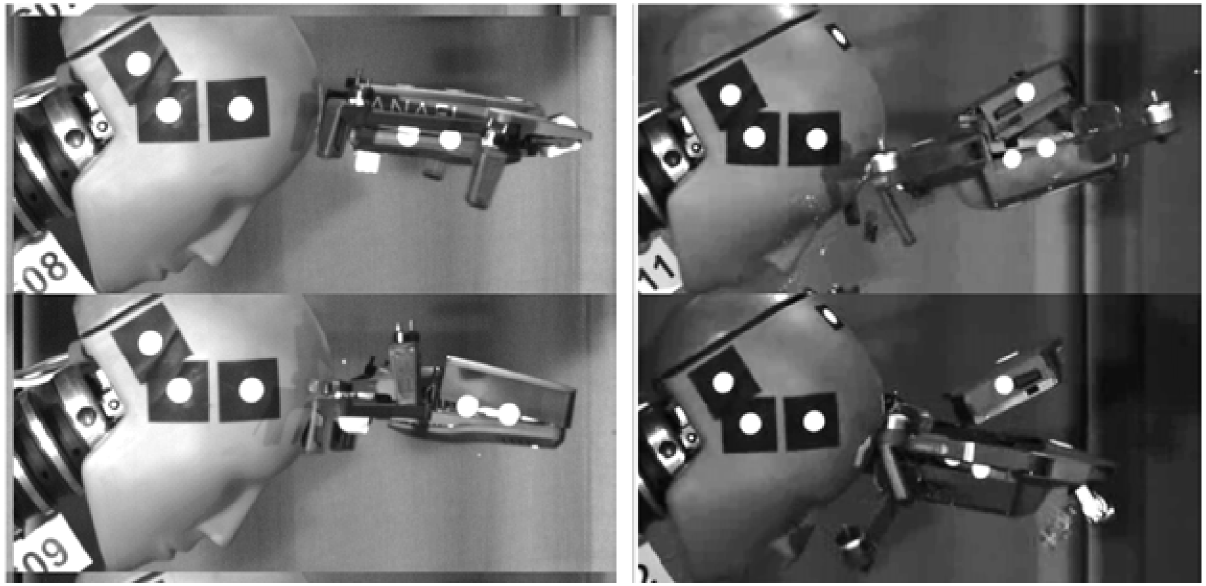
Test configuration: 58° forehead impact

Drone weight influence is limited:

- Anafi Front and Rear : very different
  → Design influence (local rigidity)

Test	Head pos	Drone	Drone pos	Speed (m/s)	HIC15	BrIC	Nij
GIS_07	Front 58deg	Anafi	Rear	15.8	72	0.09	0.38
GIS_08				15.7	60	0.09	0.38
GIS_09			Front	16.3	9	0.10	0.29
GIS_10				16	9	0.11	0.33
GIS_11		Mavic	Front	15.5	45	0.22	0.65
GIS_12			Rear	15.5	83	0.19	0.63
GIS_13				15.2	67	0.18	0.61

Anafi Mavic



UASs impacts to dummy head

Test configuration: Side of head impact

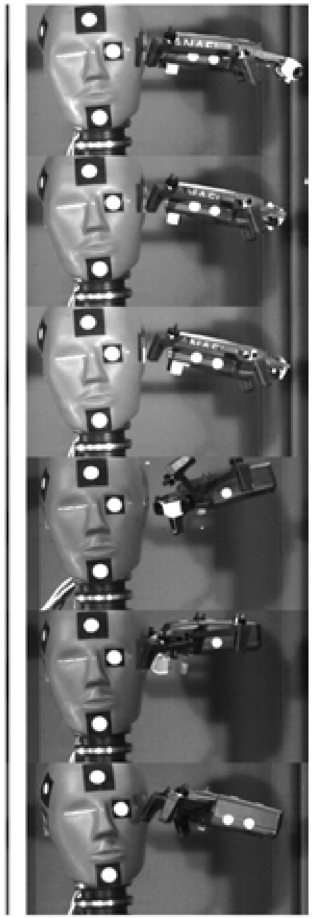
Severity of impact :

→ Weight : 1st order parameter

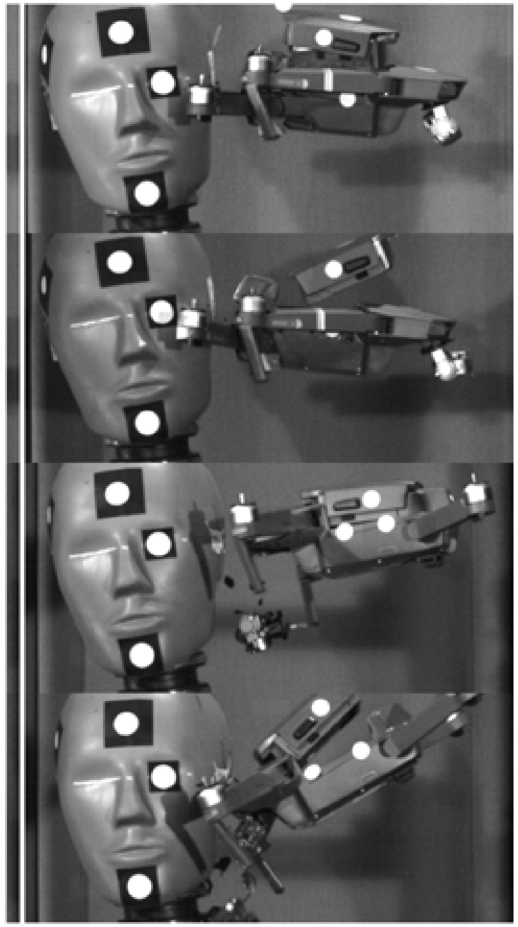
→ Design influence : 2nd order parameter (not to be neglected)

Test	Head pos	Drone	Drone pos	Speed (m/s)	HIC15	BrIC	Nij
GIS_14	Lat. 0 deg	Mavic	Rear	15.2	167	0.28	0.07
GIS_15				15.3	177	0.27	0.07
GIS_16			Front	15.4	113	0.30	0.05
GIS_17				15.4	45	0.28	0.06
GIS_18		Anafi	Rear	15.2	116	0.13	0.04
GIS_19				14.9	102	0.13	0.04
GIS_20				15.4	113	0.14	0.04
GIS_21			Front	15.4	18	0.16	0.04
GIS_22				15.4	12	0.15	0.05
GIS_23				15.7	19	0.13	0.03

Anafi



Mavic

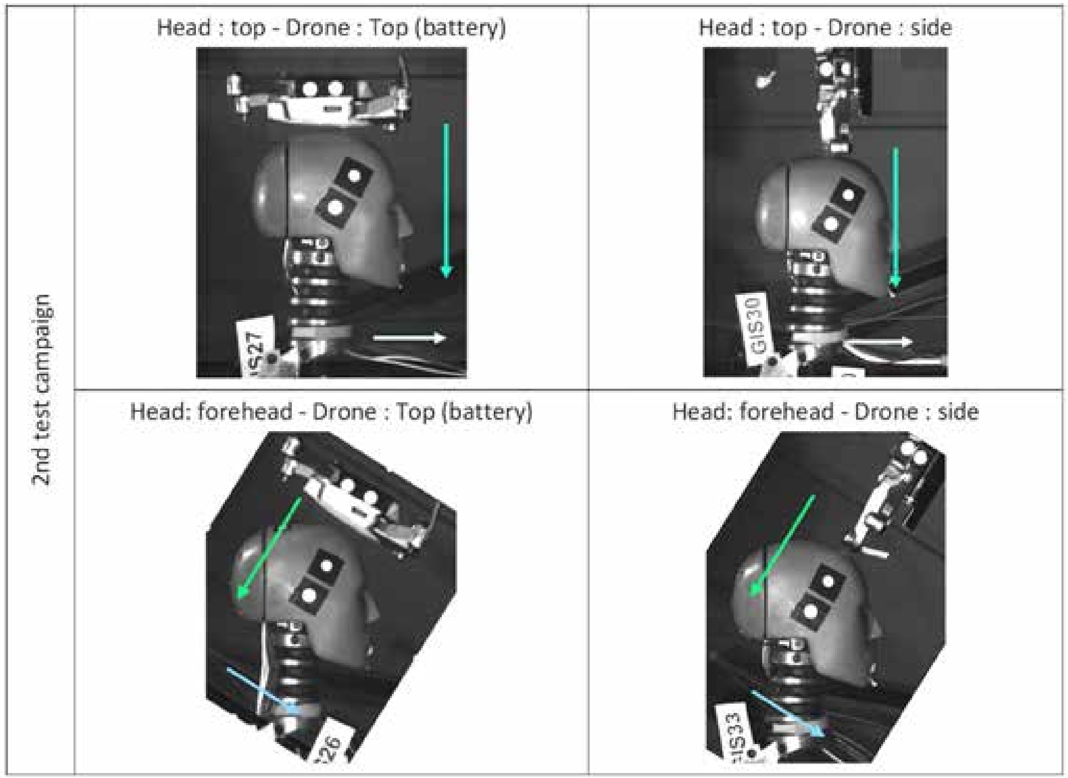


UASs impacts to dummy head

2nd Impact tests configurations: Mavic only

UAS Top battery surface to top of the head
UAS Top battery surface to the forehead (58° oriented)

UAS Side battery surface to top of the head
UAS Side battery surface to the forehead (58° oriented)



UASs impacts to dummy head

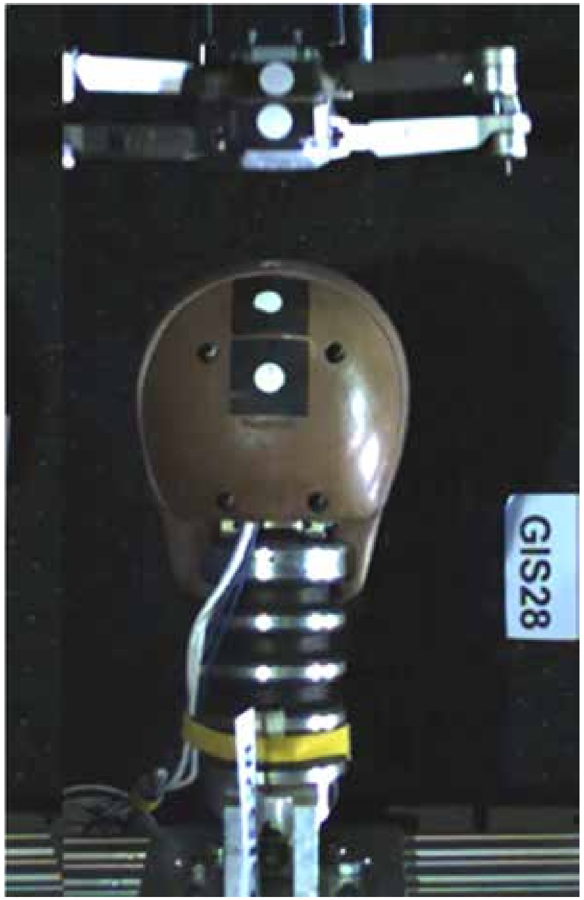
Test configuration: Forehead & Vertex

- Highest HIC values of the study

Test	Head pos	Drone	Drone pos	Speed (m/s)	HIC15	BrIC	Nij
GIS_24	Front 58deg	Mavic	Top Battery surface	14.19	171	0.16	0.68
GIS_25				14.87	192	0.13	0.69
GIS_26				14.84	201	0.16	0.69
GIS_33			Side	14.11	253	0.20	0.77
GIS_34				14.85	311	0.20	0.81
GIS_35				14.89	333	0.21	0.81

Test	Head pos	Drone	Drone pos	Speed (m/s)	HIC15	BrIC	Nij
GIS_27	Top 90deg	Mavic	Top		167	0.03	0.75
GIS_28					195	0.04	0.77
GIS_29					217	0.04	0.79
GIS_30			Side		381	0.07	0.99
GIS_31					490	0.07	1.07
GIS_32					452	0.08	1.05

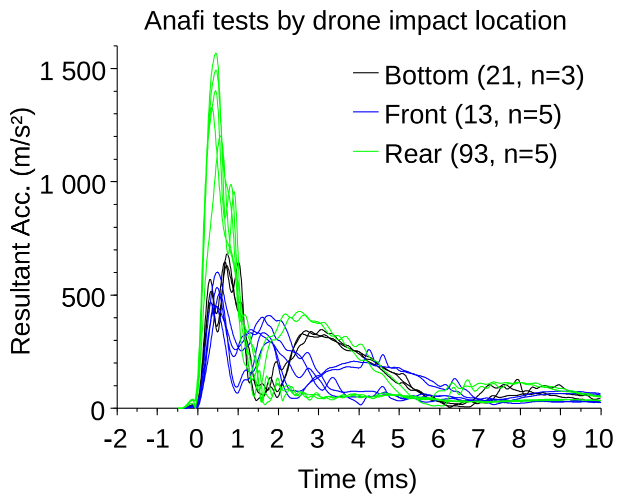
Top

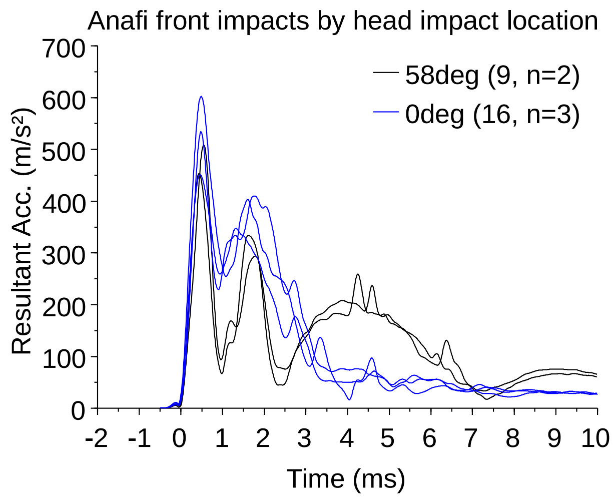


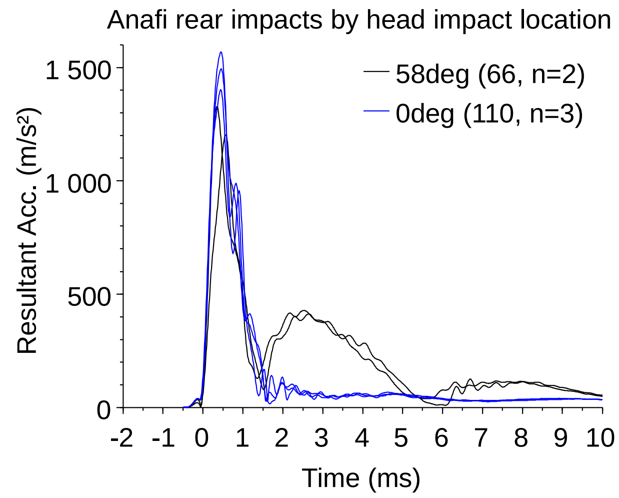
Side

UASs impacts to dummy head

Anafi tests comparison: Dummy measurements





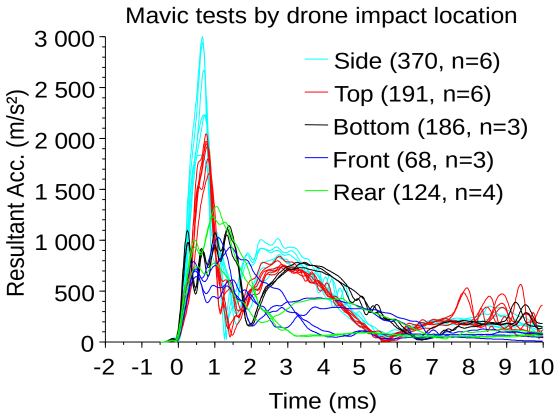


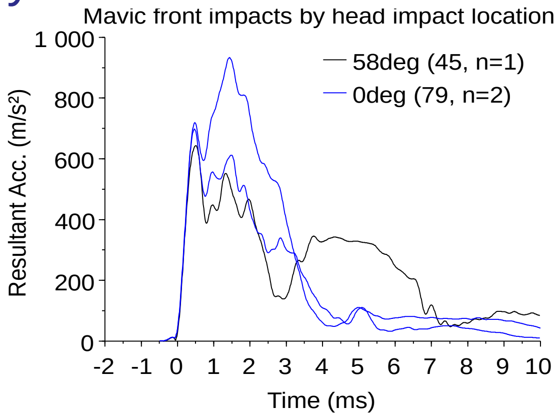
→ High influence of the drone impact location

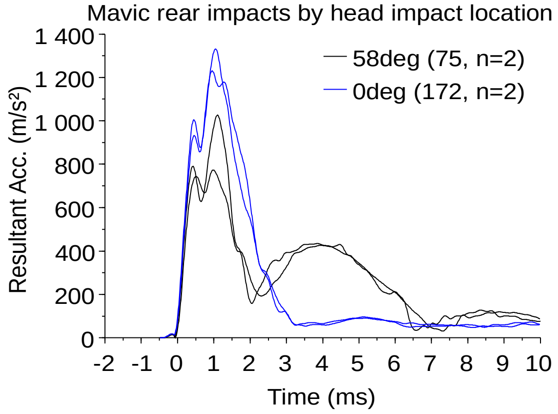
→ Difficult to conclude on the head impact location

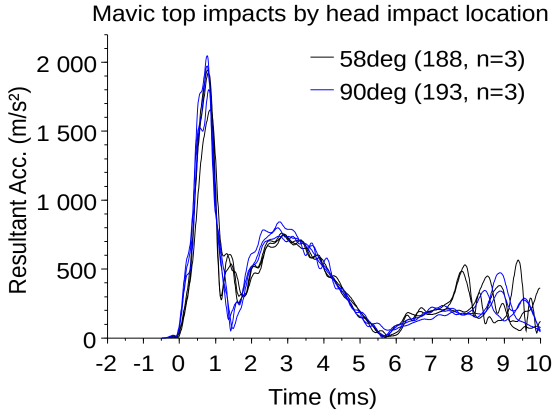
UASs impacts to dummy head

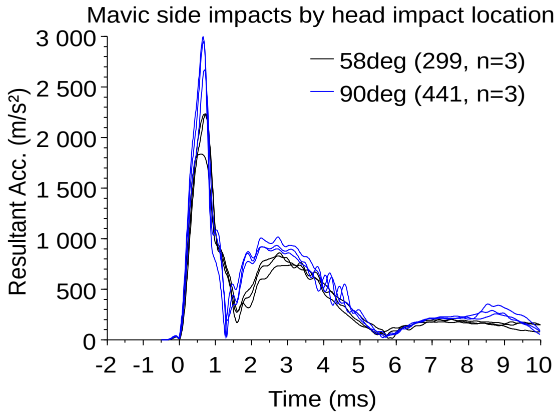
Mavic tests comparison: Dummy measurements







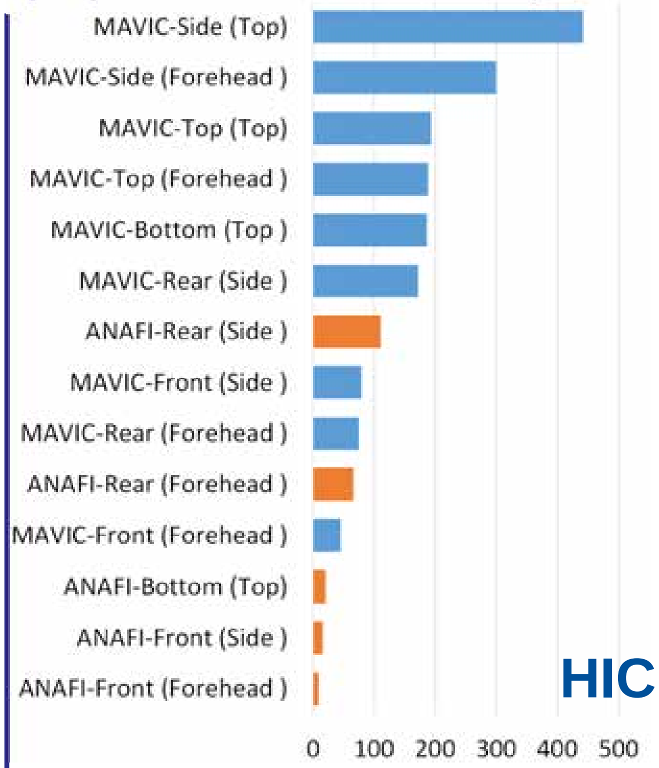


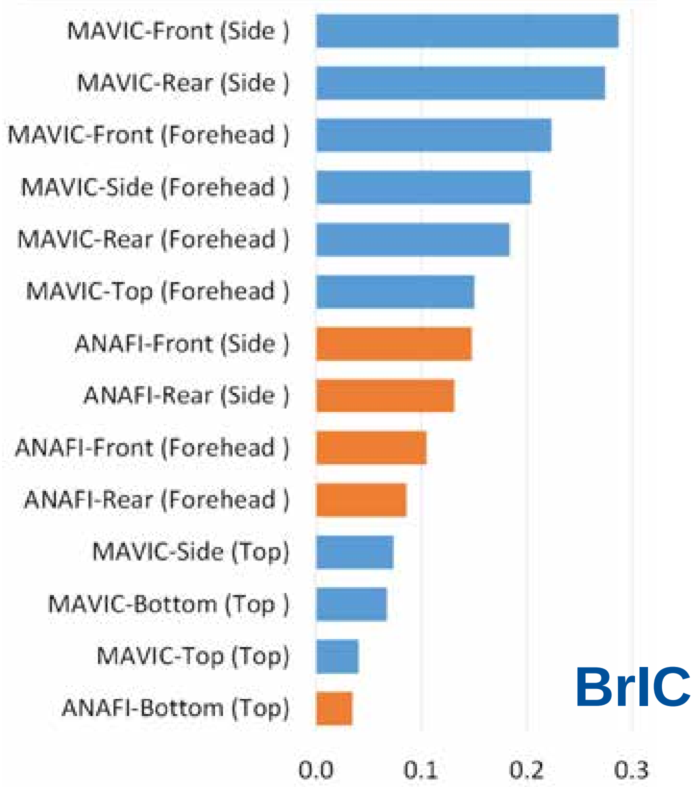


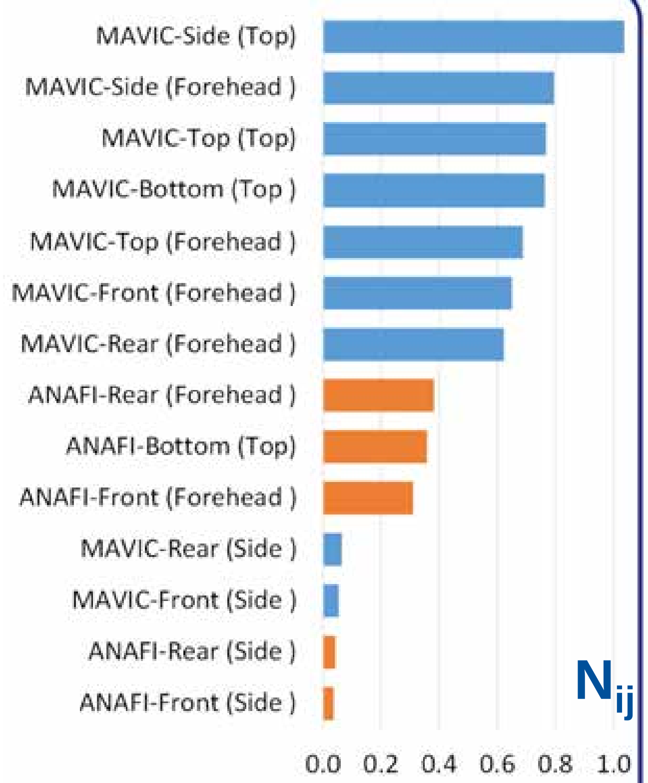
→ High influence of the drone impact location
→ Difficult to conclude on the head impact location

UASs impacts to dummy head

Injury criteria: Tests comparisons







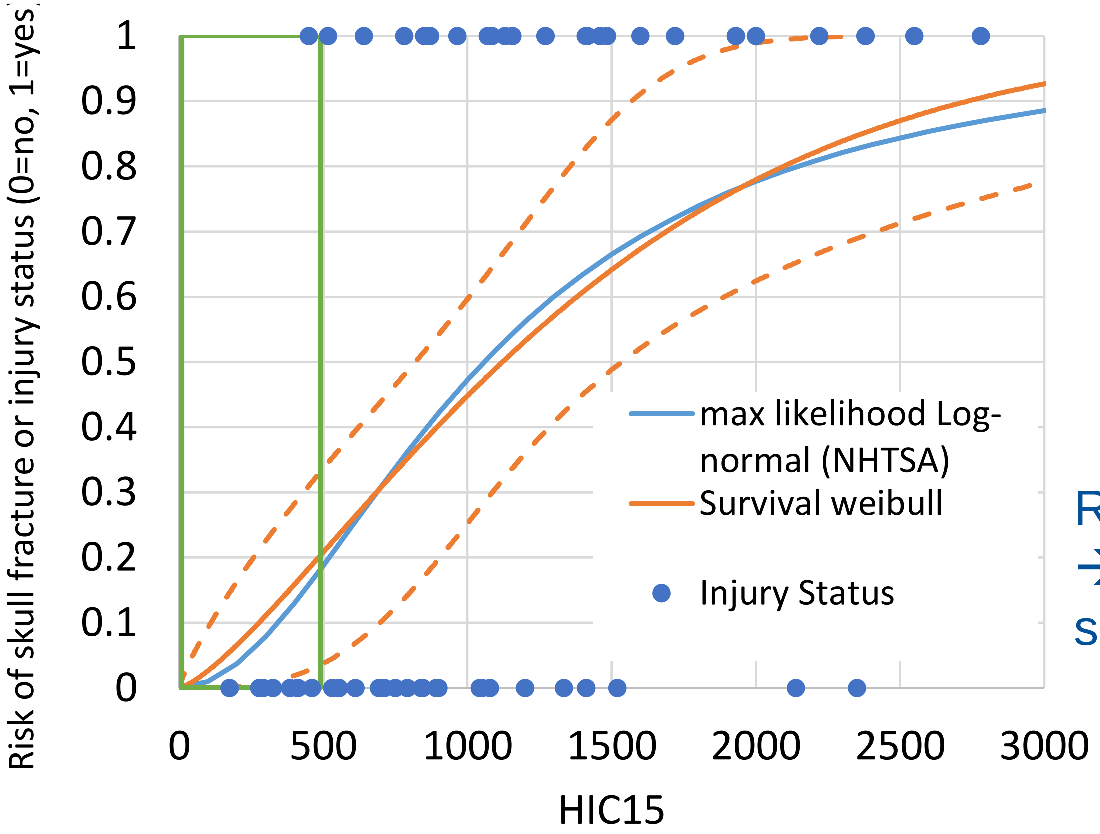
Critical head impact location:
Vertex & forehead

Critical head impact location:
Side & forehead

Critical head impact location:
Vertex & forehead

UASs impacts to dummy head

HIC analysis & limitations



NHTSA skull fracture risk curves

Lowest configuration HIC = 9
→ risk of skull fracture ~ 0 %

Highest configuration HIC = 490
→ risk of skull fracture ~ 20.3%
(consistent with OSU's study)

Risk results should be considered cautiously
→ the confidence in the risk prediction for such low HIC values is questionable

Summary

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Conclusions

- 2 "open" category drones tested
- 35 tests performed
- Various drones orientations tested
- Good repeatability of the different tests

- Some differences with the point of impact head
- Large differences (HIC) depending on the point of impact drone → Weight is not everything

Limitations/open questions:

GIS I ⇔ 100% experimental approach

- Only one impact velocity
- Only 2 drones of small weights
- Is Hybrid III consistent for drone impact tests ?

Max average per configuration :
HIC : 441
BriC : 0.284
Nij : 1.04

Repeatability :
HIC:15%
Bric: 7%
Nij: 5%

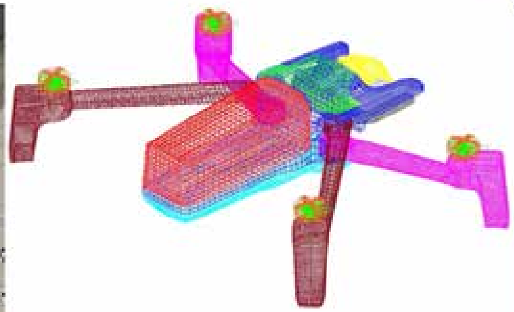
Head pos	Drone	Drone pos	HIC15	BrIC	Nij
Top	MAVIC	Side	441	0.073	1.04
Forehead	MAVIC	Side	299	0.204	0.79
Top	MAVIC	Top	193	0.040	0.77
Forehead	MAVIC	Top	188	0.150	0.69
Top	MAVIC	Bottom	186	0.068	0.76
Side	MAVIC	Rear	172	0.275	0.07
Side	ANAFI	Rear	110	0.131	0.04
Side	MAVIC	Front	79	0.287	0.05
Forehead	MAVIC	Rear	75	0.184	0.62
Forehead	ANAFI	Rear	66	0.086	0.38
Forehead	MAVIC	Front	45	0.223	0.65
Top	ANAFI	Bottom	21	0.035	0.36
Side	ANAFI	Front	16	0.148	0.04
Forehead	ANAFI	Front	9	0.105	0.31

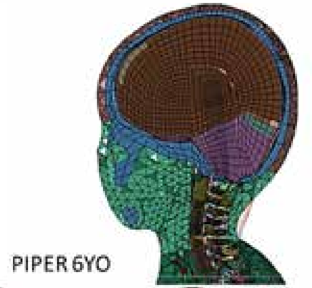
Outlooks

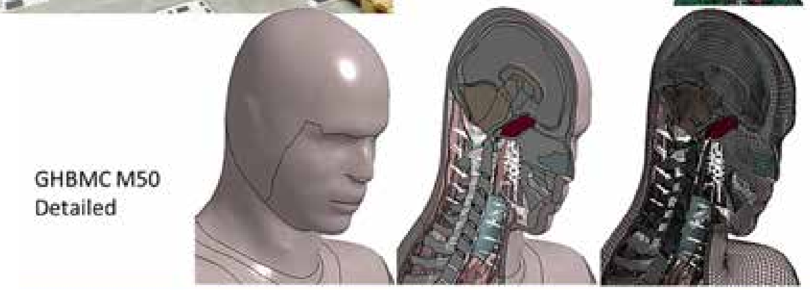
Ground Impact Study II (2021-2024)

ONERA To predict the impact severity by the potential energy transmitted by the drone
→ study mechanical criteria (local stiffness, interfaces, weights, velocities, orientations, surface)

EIFFEL To estimate the risk of injury for a drone impact on the head
→ study of specific lesion criteria, human substitute (mannequin), human variability







Thank you for your attention

The authors would like to thank the french Direction Générale de l'Aviation Civile (DGAC) for the financing of the GIS studies

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