UAS operational risk

Is it an obstacle on the way towards civilian applications?

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Outline

UAS Regulation

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FAA EASA CASA TC Canada

US DoD CAA-UK ASTM AOPA

DFS INOUI ICAO CAA-NL

RTCA NASA NMSU Air4All JAXA

ACUO DLR

DGA UNITE JUAV EDA NATO

EUROCONTROL UAVNET ASTRAEA JARUS

ARCAA UVS International SAE EUROCAE

Europe – Brief History I

- 1999 After a joint EUROCONTROL/NATO workshop the JAA is contacted to prepare a document on UAS certification.
- 2001 UAVNET an EU sponsored program is created to coordinate research efforts on UAS technology and policy.
- 2002 The CAA-UK published “CAP 722 Unmanned Aerial Vehicle Operations in UK Airspace — Guidance”.
- 2004 The JAA/EUROCONTROL UAS Task Force issues the report.
- 2004 The CAA-UK published a “Policy for light UAS systems”.
- 2004 ParcAberporth a technology park that provides facilities for UAS operations is founded in the UK.

Europe – Brief History II

- 2004 USICO a program under UAVNET is completed. The goal was to investigate regulation, procedures and technology to improve operational safety.
- 2005 EASA adapts the report as an A-NPA, titled "Policy for Unmanned Aerial Vehicle (UAV) certification".
- 2005 CAPECON also under UAVNET is completed. The goal was to identify safe and cost-effective civil applications and UAS configurations.
- 2005 DLR tested UAS operations in controlled airspace.
- 2006 EUROCAE launches workgroup 73 to assist in the development of minimum airworthiness requirements.
- 2006 Autonomous Systems Technology Related Airborne Evaluation & Assessment (ASTRAEA) is launched in the UK.

Europe – Brief History III

- 2007 EASA publishes a Comment Response Document (CRD) based on feedback from the A-NPA.
- 2007 The European Commission launched the INnovative Operational UAS Integration (INOUI) program to develop requirements for insertion of UAS into non-segregated civilian airspace.
- 2007 EUROCONTROL published "Specifications for the use of Military UAVs as Operational Air Traffic"
- 2007 The CAA-NL received a UAS certification request for an unmanned rotorcraft weighing 80 kg. Soon after the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) group was formed to assist with harmonization of regulation of Light UAS.

Europe – Brief History IV

- 2008 EDA awarded a contract for the development of "UAV Air Traffic Insertion Roadmap".
- 2008 EUROCONTROL simulated UAS interaction with ATC to determine ATM requirements.
- 2008 The CAA-UK revised CAP 722 and renamed it to "Unmanned Aircraft System Operations in UK Airspace — Guidance"
- 2008 The Light Unmanned Aircraft System Scheme (LUASS) for operating Light UAS in the UK was launched and is currently run by EuroUSC.
- 2009 EASA published a policy statement regarding UAS certification.
- 2010 EUROCAE is preparing a concept document on airworthiness certification and operations of UAS in non-segregated airspace.

UAS certification avenues in the US

Currently there are only two avenues for UAS certification:

- Public UAS: Certificate of Authorization (COA)
- Civil UAS: Special airworthiness certificate based on Order 8130.34.

Under both avenues, there are several operating restrictions imposed that impede commercialization.

Current certification paths are counter-productive for the FAA as well, because it is forced to allocate resources for thoroughly investigating each application instead of producing the required regulation.

FAA aims to publish a proposed rule for small UAS in 2013

Other Countries

- Australia All commercial UAV operations require an operating certificate. Additionally for large UAVs operator certificates are also required. By 2009 there were 8 certified UAS operators in Australia.
- Canada UAS operations are possible with a Special Flight Operation Certificate. Transportation Canada convened a working group to develop a regulatory framework on UAS operations. In 2007 the final report was issued that proposed a 5 year roadmap.
- Japan Large fleet of unmanned helicopters for agricultural applications has been operating for two decades. Recently UAS certification procedures have become available, although operations are restricted to unpopulated areas.
- Other countries with active UAS industry and/or regulation development programs include Brazil, China, Israel, Russia, South Africa.

Light UAS

- EASA states that airworthiness certification for lighter (less than 150 kg) vehicles remains with national authorities.
- In the UK, Light UAS are divided into three categories with different operational and certification requirements. For UAS above 20 kg systems must be certified to be airworthy. CAA-UK waives airworthiness requirements for UAS with weight less than 20 kg, but maintains a range of operational restrictions. Finally for vehicles less than 7 kg most of the requirements are waived.
- In Australia, CASA exempts only ultra light UAS (less than 0.1 kg) and imposes operational restrictions from the rest of the light UAS.
- Japan restricts the maximum altitude for the Rmax to 150 m.
- In the US, the recommendations of the sUAS ARC divide UAS up to 25 kg into 4 categories with different operational requirements.

Outline

Manned vs unmanned aircraft

The pilot is physically removed from cockpit:

- The pilot of an aircraft is aware of the surroundings as well as of the performance of the aircraft. On the other hand a UAS operator is limited to the information provided by the instruments.
- Communication lag may impede timely UAS response.
- In some cases UAS operators may operate more than one vehicle and/or may not be fully qualified pilots.
- The UAS operator may not have full control of the aircraft.
- Lack of life-threatening situations may increase operator error frequency.
- Ground control station and communication link safety becomes important.

Manned vs unmanned aircraft

- Applications The vast majority of manned aircraft are employed in point to point operations of transporting goods and people, while UAS are also used for applications that require them to loiter over a specific area for several hours, even days.
- Maximum take-off weight Manned aircraft have an MTOW of at least 100kg (more for powered vehicles) and up to 600 metric tons (Airbus A380). On the other hand UAS span the entire spectrum from a few grams and up to 12 metric tons.
- Sacrificability A manned aircraft crash is considered a catastrophic accident that should be avoided as much as possible. In the case of UAS it is acceptable to allow the UAS to crash to minimize risk to people and property.

Elements of current UAS regulation

- Primary goal is ensuring the safety of the public.
  - Increased reliability.
  - Effective sense-and-avoid.
- Operation rules same or similar to current.
  - Compliance with right-of-way rules.
  - Communication with ATC and compliance with instructions.

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  - Communication with ATC and compliance with instructions.
- No disruption of current manned aviation operations.
- Same set of regulations applicable to all UAS may impose unreasonable requirements.
  - At least two and possible several classes of UAS can be expected, each with different requirements.
- Separation of pilot and aircraft may lead to increased accidents due to human error.
  - UAS operator training and certification requirements.
  - Fully qualified pilot will be required when UAS fail-safety is based on manual pilot override.

Fail-Safe Design Concept I

FAR Part 25 airworthiness standards are based on the fail-safe design concept:

- Failure of any single element, component or connection should not prevent continued safe flight and landing or significantly reduce the capability of the airplane to cope with failure conditions.
- Subsequent failures, detected or latent and combinations thereof should also be assumed unless extremely improbable.

"The capability for continued controlled flight and landing at a suitable airport, possibly using emergency procedures, but without requiring exceptional pilot skill or strength. Some airplane damage may be associated with a failure condition, during flight or upon landing" *, FAA AC25.1309*

Fail-Safe Design Concept II

- Designed integrity and quality
- Redundancy
- Isolation of systems, components and elements
- Proven reliability (multiple, independent failures unlikely)
- Failure warning or indication
- Flight crew procedures
- Checkability
- Designed failure effect limits
- Designed failure path
- Margins or factors of safety
- Error-tolerance

Outline

Equivalent Level of Safety

Principles of UAS regulations

- Fairness: No exceptions, no waiving of requirements, no additional restrictions
- Transparency: UAS should be transparent to airspace operations
- Accountability: No pilot on-board, but someone should be responsible

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How do we compare stringency?

- Accident rate
- Fatality rate
- Casualty[1] rate
- Expected cost of damages (life and property)

[1] Casualties are people suffering injuries that are not life threatening

Manned Aviation Risk Reference System

Aircraft class	Minor	Major	Hazardous	Catastrophic
Part 25				
	$> 10^{-5}$	10^{-5}	10^{-7}	10^{-9}
Part 23				
Class I (<2,720 kg, SRE)	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Class II (<2,720 kg, STE, MRE)	10^{-3}	10^{-5}	10^{-6}	10^{-7}
Class III (>2,720 kg, SRE, MRE, STE, MTE)	10^{-3}	10^{-5}	10^{-7}	10^{-8}
Class IV (commuter)	10^{-3}	10^{-5}	10^{-7}	10^{-9}

Source: FAA AC 23.1309, 25.1309

So, how safe is manned aviation?

	Air Carrier	Commuter	General Aviation
Accident	$2.43 \cdot 10^{-6}$	$2.37 \cdot 10^{-5}$	$8.05 \cdot 10^{-5}$
Fatalities aboard	$8.68 \cdot 10^{-6}$	$1.64 \cdot 10^{-5}$	$2.77 \cdot 10^{-5}$
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In-flight collision with terrain or water only			
Accident	$2.06 \cdot 10^{-7}$	$9.33 \cdot 10^{-6}$	$2.84 \cdot 10^{-5}$
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Mid-air collision with another aircraft only			
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Ground fatalities	None	$1.91 \cdot 10^{-8}$	$2.86 \cdot 10^{-8}$
Total fatalities	None	$7.15 \cdot 10^{-7}$	$1.07 \cdot 10^{-6}$

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Mid-air collisions only			
Accident	$1.34 \cdot 10^{-5}$	$3.48 \cdot 10^{-6}$	$1.38 \cdot 10^{-5}$
Total fatalities	$9.73 \cdot 10^{-7}$	$3.42 \cdot 10^{-6}$	$7.40 \cdot 10^{-6}$

Estimated injury, casualty and fatality rates from different sources or activities

Activity/Source	Injuries	Casualties	Fatalities
Motor vehicle accidents (all)	$1.35 \cdot 10^{-5}$	$1.13 \cdot 10^{-6}$	$1.40 \cdot 10^{-7}$
Motor vehicle accidents (occupant)	$8.80 \cdot 10^{-6}$	$6.73 \cdot 10^{-7}$	$5.89 \cdot 10^{-8}$
Collision of pedestrian with motor vehicle	$5.10 \cdot 10^{-7}$	$8.92 \cdot 10^{-8}$	$1.04 \cdot 10^{-8}$
Unintentional Falls	$2.45 \cdot 10^{-5}$	$2.20 \cdot 10^{-6}$	$6.06 \cdot 10^{-8}$
Natural Environment	$1.31 \cdot 10^{-7}$	$1.44 \cdot 10^{-8}$	$7.59 \cdot 10^{-9}$
Bicycles & accessories	$1.50 \cdot 10^{-6}$	$8.98 \cdot 10^{-8}$	
Household appliances	$4.23 \cdot 10^{-7}$	$1.81 \cdot 10^{-8}$	
Baseball, basketball and football combined	$2.59 \cdot 10^{-5}$	$3.44 \cdot 10^{-7}$	
London Blitz (civilian only)	N/A	$1.04 \cdot 10^{-6}$	$6.22 \cdot 10^{-7}$
Aviation (all accidents)			10^{-5}–10^{-7}
Aviation (ground impact)			10^{-7}–10^{-8}
Aviation (mid-air collision)			10^{-6}–10^{-7}

Outline

Risk modeling

$$f_F = N_{\mathrm{exp}} \; P(\mathrm{fatality}|\mathrm{exposure}) \; f_{\mathrm{GIA}}$$

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- f_{GIA} is the rate of ground impact accidents.
  - If this is known or can be estimated, it can be determined whether the UAS poses an *equivalent* risk with respect to ground impact accidents.
  - If the other terms are known, f_{GIA} can be calculated and used to design the UAS and its equipment.

Risk modeling — Expected accident frequency

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The accident frequency f_{GIA} can be estimated:

- From previous accident statistics, if sufficient flight hours have accumulated.
- Assuming an exponential accident distribution for new vehicles without accidents so far.
- As one crash per flight or per flight hour (conservative).
- Based on the results of a formal UAS reliability assessment.

Risk modeling — Number of people exposed

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$N_{\mathrm{exp}} = A_{exp} \cdot \rho$ (Assuming a uniform population density ρ)

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- The population density ρ is estimated:
  - as the average population density in the area of operations.
  - using the standard density of 200 ppl/km^2 proposed by EASA.
  - assuming an impact at the most densely populated part around the area of operations (worst-case).
- The exposed area can be estimated by:
  - The area presented by the aircraft perpendicular to its path and augmented by the width of an average person.
  - The aforementioned area, including the area the aircraft traverses on the ground until it stops.

Risk modeling — Probability of fatality

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- 1.0 (worst-case)
- Using a threshold of kinetic energy, e.g. 34 kJ
- Using a vulnerability model, e.g. Feinstein et al.
- Using a vulnerability model that also takes into account sheltering, e.g. Weibel et al., Dalamagkidis et. al.

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  The *kinetic energy* can be estimated from:
  - Kinetic energy at terminal velocity (worst-case)
  - Kinetic energy at VNE (velocity not to exceed)
  - Kinetic energy at 140% operational velocity

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  - Kinetic energy at VNE (velocity not to exceed)
  - Kinetic energy at 140% operational velocity
    - The difference between kinetic energy at impact and kinetic energy remaining post-impact
    - Kinetic energy at impact reduced by the energy required to penetrate

Adding Detail

The department of Aeronautics & Astronautics of the University of Washington has created an online UAS Risk Calculator (still under development). These are the factors taken into account:

- UAS Properties: Mean speed, frontal area, wingspan, length, glide angle, failure rate, effectiveness of collision avoidance, effectiveness of in-fleet collision avoidance.
- Operating Area (more than one can be defined): Number of UA, max. operating altitude, min. operating altitude, total flight hours, operating area, structure density, structure size, average structure height, in-structure fatality rate (fatalities per strike), average pedestrian density, pedestrian fatality rate (probability of fatality).
- Transient Aircraft (more than one can be defined): Density (over area), mean speed, frontal area, passenger load, collision avoidance effectiveness.

Outline

Injury Types and Severity I

Injury Types

Blunt trauma	High acceleration and/or loading to a body part
Crushing injury	When body movement is constrained
Penetrating trauma	Caused by small-sized fragments
Laceration	From fragments with sharp edges
Overpressure	From the shock wave of an explosion
Burns	From explosion and/or fire
Poisoning	From toxic/radioactive payloads

Injury Types and Severity II

AIS	Severity	Type of Injury
0	None	None
1	Minor	Superficial
2	Moderate	Reversible injury: medical attention required
3	Serious	Reversible injury; hospitalization required
4	Severe	Life threatening; not fully recoverable without care
5	Critical	Non-reversible injury; not fully recoverable even with medical care
6	Virtually unsurvivable	Fatal

Vulnerability Modeling I

Important considerations:

- Injury depends on the impacting object, its size, shape, mass, density, frangibility, deformability, velocity and angle of impact, etc.
- It also depends on the person, posture, clothing, weight, height, age, health, sex, etc.

Note

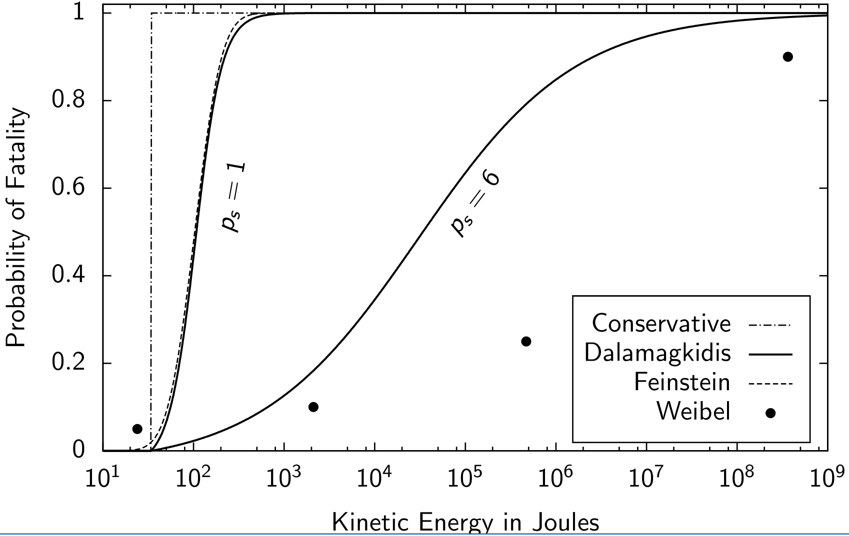
Although very accurate biology-based models are available, they are seldom used because they require information that is not typically available.

Vulnerability Modeling II

Assumptions/Limitations

- Multiple strikes and some injury mechanisms are not considered.
- Strikes after fragment bouncing off of other objects are not considered.
- The casualty/injury probability is averaged over the different body parts.
- The casualty/injury probability is averaged over the possible body postures.
- An “average” person is considered.
- A model of the form mv^2 is assumed.

A comparison of blunt trauma vulnerability models



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$$f_F = N_{\mathrm{exp}} \; P(\mathrm{fatality}|\mathrm{collision}) \; P(\mathrm{collision}|\mathrm{CT}) \; f_{CT}$$

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- $P(\mathrm{collision}|\mathrm{CT})$ is the probability of a mid-air collision given that two aircraft are on conflicting trajectories.
- f_{CT} is the rate of ground impact accidents.
    - The last two terms together correspond to the expected frequency of mid-air collisions. If the latter is known then the f_F can be determined.
    - If the other terms are known, f_{CT} can be calculated and used in the design of the sense and avoid system.

Risk modeling — Expected number of fatalities

$$f_F = N_{\mathrm{exp}} \; P(\mathrm{fatality}|\mathrm{collision}) \; P(\mathrm{collision}|\mathrm{CT}) \; f_{CT}$$

- N_{exp} can be assumed to be the number of people on-board all involved aircraft.
- $P(\mathrm{fatality}|\mathrm{collision})$ can be assumed to be 1 (conservative) or taken from historical data.

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- $N_{\text{exp}} P(\text{fatality}|\text{collision})$ as a product, can be estimated from historical data (0.02–1).
- The effects of debris falling on the ground and/or one or more of the aircraft crashing post-collision must also be considered.

Risk modeling — Collision probability

$$f_F = N_{\mathrm{exp}} \; P(\mathrm{fatality}|\mathrm{collision}) \; P(\mathrm{collision}|\mathrm{CT}) \; f_{CT}$$

For the value of the term $P(\mathrm{collision}|\mathrm{CT})$ the following options exist:

- The number 1 (conservative).
- An estimate based on analysis of the S&A system (a large number of scenarios may need to be considered).
- An estimate based on the presence of other means of collision avoidance, e.g. observers.

Risk modeling — Frequency of conflicting trajectories

$$f_F = N_{\text{exp}} \; P(\text{fatality}|\text{collision}) \; P(\text{collision}|\text{CT}) \; f_{CT}$$

The frequency of conflicting trajectories f_{CT} can be determined based on:

- The gas model of aircraft collisions using actual traffic data.
- Worst-case air traffic density based on historical data. For example Weibel et al estimated $4 \cdot 10^{-5}$ CT/hr at FL370.

Note!

Air traffic is very dynamic. Moreover, in lower altitudes there are collision hazards that are not included in typical air traffic data (parachutists, tethered balloons, etc.). On the other hand in many airspace classes separation is provided by ATC.

The gas model of aircraft collisions

The expected number of conflicting trajectories can be calculated based on the gas model of aircraft collisions as:

$$E(\mathrm{CT}) = \frac{A_{exp} d}{V \cdot t}$$

where,

- A_{exp} is the exposed area of the threatend aircraft.
- d the distance travelled.
- V is the airspace volume.
- t is the time required to travel the distance of d.

Outline

Fatality probability

UAS Model	$P(\text{fatality}\|\text{exposure})$ Vulner. model[1]	Vulner. model[2]	34 kJ limit[2]
RQ-4 Global Hawk	100.0%	100.0%	100.0%
MQ1 Predator	100.0%	100.0%	100.0%
RQ-2 Pioneer	99.5%	99.9%	100.0%
Aerosonde	93.6%	96.6%	100.0%
Rmax type IIG	61.7%	95.4%	100.0%
Maxi Joker	30.3%	63.6%	100.0%
Mosquito	0.0%	0.0%	0.0%

[1] Vehicle kinetic energy estimated by using 140% of operational velocity.

[2] Worst-case vehicle kinetic energy estimate.

Assuming a population density of 200 ppl/km^2 and a sheltering factor of 3.

Required reliability

UAS	Required hours between ground impact accidents			
Model	Vul. model[1]	Vul. model[2]	34 kJ limit[2]	$P = 1$
RQ-4 Global Hawk	1,120,073	1,120,074	1,120,080	1,120,080
MQ1 Predator	315,066	315,128	315,180	315,180
RQ-2 Pioneer	69,177	69,504	69,540	69,540
Aerosonde	24,184	24,949	25,840	25,840
Rmax type IIG	13,967	21,607	22,643	22,643
Maxi Joker	2,774	5,816	9,140	9,140
Mosquito	0	0	0	4,032

[1] Vehicle kinetic energy estimated by using 140% of operational velocity.

[2] Worst-case vehicle kinetic energy estimate.

Assuming a population density of 200 ppl/km^2 and a sheltering factor of 3.

Outline

Questions

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3. What can we do to improve their performance?

Aeronautics vs Robotics

Aeronautics

Priority: Safety
- Redundancy
- Reliability
- Determinism
- Regulations

Robotics

Priority: Performance
- Intelligence
- Low cost
- Segregation

Unmanned Aircraft Systems

New failure modes and new things to learn
but also new capabilities and opportunities.

Some troubling news – Crashes

- 1999 – United States: Two Global Hawk UAS are destroyed due to wrong commands: first was sent a self-terminate signal, the second was instructed to taxi at $287\,\mathrm{km\,h^{-1}}$.
- Apr. 2006 – Arizona, US: Predator crashes due to wrong procedures being followed when switching console. The first console locked-up.
- Oct. 2006 – Kinshasa, DRC: Belgian Hunter-B crashes after pilot mistakenly switches off engines (two deaths and two injuries).
- Dec. 2006 – Nevada, US: P-175 Polecat UAS crashes after unintentional activation of its flight termination system due to GCS failure.
- February 2010 – Aigburth, UK: Small police UAS crashes into water due to loss of power. It was not found.

Some troubling news – Security Issues

- Oct. 2007, Jun. 2008, Jul. 2008, Oct. 2008: Terra AM-1 and Landsat-7 satellites were accessed by unauthorized parties.
- Summer 2009 – Iraq: U.S. forces discover drone footage on the laptops of Iraqis. A $26 piece of software allowed them to capture the video.
- March 4, 2011 – Border of North and South Korea: Jamming signal disrupts GPS sensors of S. Korean navy vessels and of U.S. Army RC-7B reconnaissance plane.
- October, 2011 – Creech AFB, USA: News come out that the GCS software of UAS operating over Iraq and Afghanistan has been infected with malware.

New capabilities: Sensor failures and decision making

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In manned aircraft, the pilot is another “on-board system” that fuses sensor information and can provide redundancy.

New capabilities: Sensor failures and decision making

In manned aircraft, the pilot is another "on-board system" that fuses sensor information and can provide redundancy.

- Optimal decisions are not always obvious and can be counter-intuitive
- Contradictory or contradictory-appearing information can lead to confusion
- Providing the causal chain for each warning or lack thereof is not always possible

New capabilities: Sensor fusion and intelligence decision making

Intelligent/Cognitive decision support systems

- Learn from experience
- Can balance speed, computational power and precision
- Can deal with missing, noisy and contradictory sensor data
- Retain situational awareness
- Robustness

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- Natural language processing
- Can explain a problem or situation in “layman” terms

New capabilities: Main- or Tail- rotor failure in helicopters

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If continued safe flight is not possible, safely terminate flight.

Under loss of power, a helicopter can use the main rotor as a parachute and land safely. The goal is to develop a controller that can perform this autonomously without violating performance and safety requirements.

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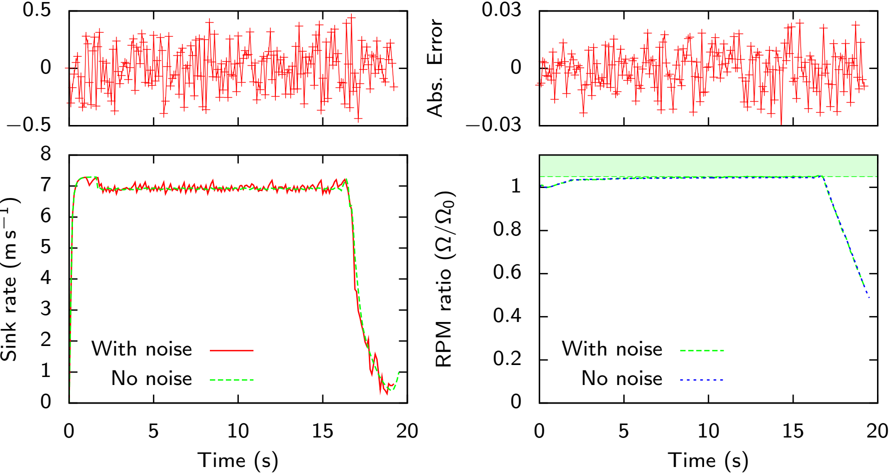
Autorotation

A maneuver usually performed when the engine shuts down due to power loss or malfunction. During this maneuver the helicopter is left to glide downwards. As it moves the air passing through the rotor disk is utilized to maintain rotor rpm. Just before touchdown the rotor rpm is exchanged for a reduction in the descent rate thus allowing the helicopter to land safely.

Simulation results (Raptor 30v2)



Raptor 30, with and without noise.

Possible enhancements

- Emergency landing system: The autorotation controller can be integrated into an emergency landing system with the following components:
  - Fault detection and identification.
  - Controller bank.
  - Landing site identification (using GPS and/or vision).
  - High-level planning under failures.

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- Emergency landing system: The autorotation controller can be integrated into an emergency landing system with the following components:
  - Fault detection and identification.
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  - High-level planning under failures.
- Autorotation assistant for manned helicopters
  - Need to overcome pilot's resistance.
  - Adapt the controller to provide guidance rather than assume control.
  - Handling of non-vertical trajectories.
  - Different levels of assistance depending on the helicopter's state.

New capabilities: Mid-air collision avoidance

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Different sensors

- Electro-Optics
- Infrared
- Acoustic
- Lidar
- Radar

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- Tracking of multiple threats
- Robustness with respect to weather and lighting conditions
- Higher range and wider field of “view”

Conclusions

- Go back to what we know works:
  - Redundancy
  - Certifiable, purpose-built equipment
  - Verifiable code
- Take advantage of existing and upcoming technologies
  - High performance control systems
  - Intelligent decision support systems
  - Multi-modal sensing
- Match application requirements
  - UAS should not be a solution looking for a problem
  - One size does not fit all

Thank You