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Fuzzy inference system towards safe fixed wing small-UAS operation

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Abstract

UAS (Unmanned Aerial Systems) are considered a hot topic operating in dark, fog, and difficult decreased visibility situations. Moreover, this low cost off-the self equipment combines computer vision that is sophisticated for aerial view in confined areas when manned helicopter cannot operate. A diverse array of these appliances includes aeronautical and engineering aspects while some others are capable to access structures using GPS systems. Bridging the gap with this lack of standardization to a certain degree dedicated to drones is like standing in front of the door of future since airworthiness Standards are not available, except for Federal Aviation Administration Modernization and Reform Act of 2012 and Code of Federal Regulations. The objective of this paper is to prioritize and quantify risk framework regarding safety constraints via a Fuzzy Inference System (FIS). This contribution is a brief and easily understood overview of drones and

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fundamental constraints that are being proposed. The upper goal of the paper is the defuzzification of safety requirements on the base of computer software as MATLAB, since we live in the century of information, with aim to succeed in overall hierarchy of mitigation efforts.

Mathematics Subject Classification: 93A30, 68M99

Keywords: Drones, standards, MATLAB, fuzzy, small-UAS, risk assessment.

1 Introduction

UAS are a system of systems that combines complementary fields of engineering to execute a specific task such as aerial photography and surveillance. Recent achievements of miniaturization of these platforms brought together intervention and surveillance, defending property intruders and especially against crime. Drones support protecting and mapping of area from natural disasters, transport and precision agriculture. They are finding increasing application in search and rescue field. Furthermore, they enhance management of hazardous conditions like tornado, flood, or forest fire (Figure 1). They assist in monitoring with proximity sensors to relocate human in wild areas while deliver goods and medical supplies. UAS are leaders in the organization of computer boards and the regulation of traffic in major cities using hybrid orientation system.

Figure 1: Drone assisting insurance claims monitoring
(source: http://www.top10drone.com)

Additionally, a harmonised certification debate towards safety of UAS including recent regulatory process and decisions is a proof of noteworthy initial work. A classification of civil UAS is provided and developed by ISO/AWI 21895 [10]. From the last to first, ISO progress combines ISO/TC 20/SC 16/WG 1, General [7], ISO/TC 20/SC 16/WG 2 Product [8] and ISO/TC 20/SC 16/WG 3, Procedure [9] are still developed by certain specific teams. Indeed, ISO/TC 20/SC 16/WG 1 [7] highlights the general specifications for civil drones. More specifically, ISO/-TC 20/SC 16/WG 2 [8] defines constraints for the design manufacture and continued airworthiness for every drone. Finally, ISO/TC 20/SC 16/WG 3 [9] aim at specifying the mitigation measures for drone operation.

2 Fuzzy Inference System using Matlab-Simulink

The objective of this study is the defuzzification of safety constraints and the respective hierarchy between them for fixed-wing small UAS (Table III). Risk is estimated counting severity of a harmful incident, population density, probability of harm occurring and operational complexity. As a result, in the Fuzzy Inference System, four variables are taken account. Parameter of “Severity” is described with five discrete levels: No safety effect, Minor, Major, Hazardous, and Catastrophic (Figure 2), parameter of “Population density”: Remote, rural, suburban, urban, congested parameter of “Probability”: No probability requirement, probable, remote, extremely remote, extremely improbable, parameter of “Operational Complexity”: VLOS (visual Line of sight), BVLOS (Beyond visual line of sight), single-multi UAS, autonomous-semi, collaborative multi UAS those are shown in Table I [7]. The output variable is risk and arranged within three levels: Low, Medium and High (Table II) [6].

Table 1: The discrete levels of input variables [6]

Severity	Population Density	Probability	Operational Complexity
1-No safety effect	1-Remote	1-No probability requirement	1- BVLOS
2-Minor	2-Rural	2-Probable	2. Single UAS
3-Major	3-Suburban	3-Remote	3. Multi UAS
4-Hazardous	4-Urban	4-Extremely remote	4. Semiautonomous
5-Catastrophic	5-Congested	5-Extremely improbable	5. Collaborative multi UAS

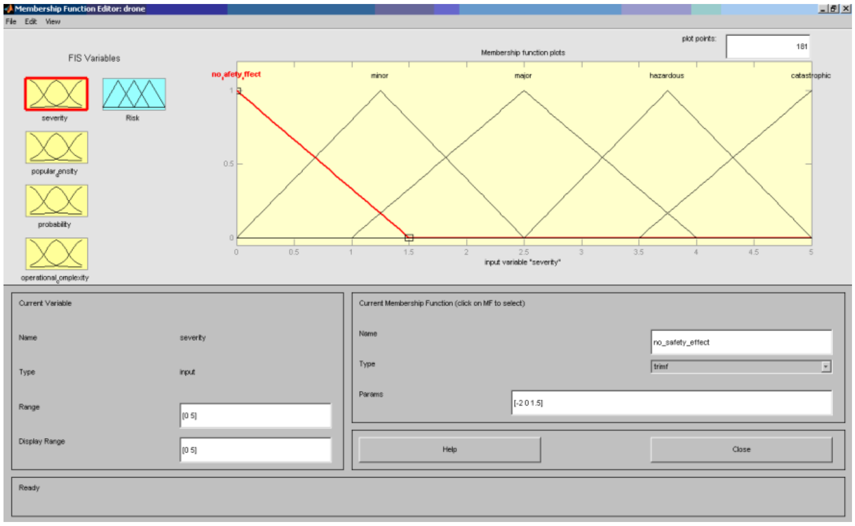

Figure 2: The first variable severity is arranged within [0 5] via Fuzzy Inference tool of MATLAB with 5 discete levels no safety effect/ minor/ major/hazardous/catastrophic while other 3 variables are arranged respectively.

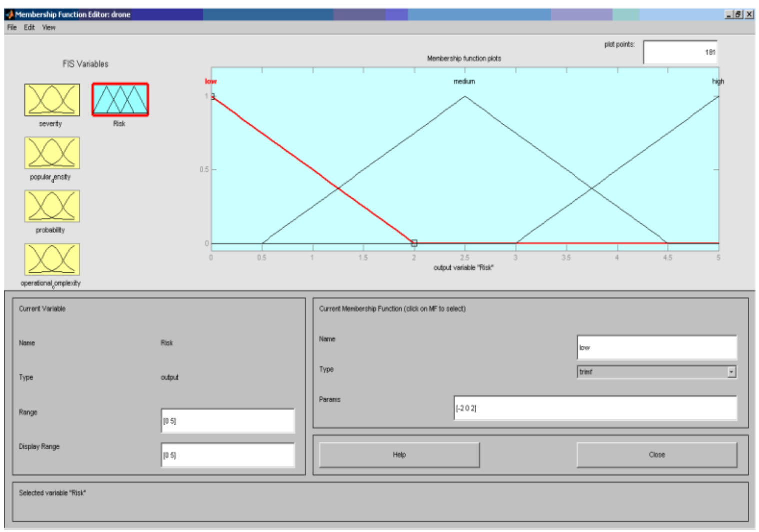

Figure 3: The output variable risk is arranged within a range [0 5] and 3 levels Low/ Medium/ High.

Table 2: Matrix towards severity and safety effect [6]

Likelihood		Severity: No Safety Effect 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
No Probability Requirement	A	Low	Medium	High	High	High
Probable	B	Low	Medium	High	High	High
Remote	C	Low	Medium	Medium	High	High
Extremely Remote	D	Low	Low	Medium	Medium	High
Extremely Improbable	E	Low	Low	Low	Medium	High* / Medium

*Risk is high when there is a single-point or common cause failure

Table 3: sUAS classification [6]

UAV Class	Weight, max [lb]	Velocity, max [knots]	Kinetic Energy, max [ft-lb]
A: Micro-UAS	4.4	60	704
B: Mini-UAS	20	87	6,727
C: Small UAS	55	87	18,498

Taking account of the estimation of output variable (risk) (Figure 3), rules and safety constraints are established in order to quantify the results of risk assessment and to achieve the safety of user and operational environment robot. The rules and safety requirements for every rule respectively are given below for a fixed wing-small UAS:

Hazard 1: Uncontrolled flight plan and/or undesired descent ends in collision with another aircraft.

Rule 1: If severity is catastrophic and popular density is rural, probability is extremely improbable and operational complexity is semiautonomous operation then:

- In the absence of airworthiness certification, the overflight of persons not under the control of the pilot is restricted and described in the conditions of the Permission issued by the CAA (Civil Aviation Authority). For drone’s operations over 20 kg, the overflight over congested areas shall not be prohibited taking account the assessment of UAS.

- The drone must incorporate emergency buttons which halt all mechanisms from the on-board power supply in case of danger. People may be exposed to dangerous situations and equipment may be destroyed if kinetic energy increases in very high levels [5].

Hazard 2: Uncontrolled flight plan and/or undesired descent ends in collision with airspace user resulting in injury or loss of human life.

Rule 2: If severity is hazardous and popular density is remote, probability is extremely remote and operational complexity is BVLOS then:

- Operator shall avoid the traffic on air operations. Drone shall operate over, or within 150 metres of, any congested area of a city, town or settlement
- Detect and avoid traffic (air and ground operations) according to the Rules of the Air.
- Detect and avoid all airborne users such as gliders, hang-gliders, paragliders, microlights, balloons, parachutists.

Hazard 3: Uncontrolled flight plan and/or undesired descent ends in possible crash with building/obstacle resulting in construction property damage or structures.

Rule 3: If severity is hazardous and popular density is remote, probability is extremely remote and operational complexity is BVLOS then:

- The remote pilot shall be able to keep direct, unaided VLOS with the UAS at all times that is adequate to observe the flight plan regarding other aircrafts, people, vehicles, obstacles avoiding collisions.
- The recommended distance from vessels is 500m horizontally and 400ft vertically.
- Detect and avoid terrain and other obstacles.
- The drone shall operate keeping distance of 50 metres of any person, vessel, vehicle or structure not under the control of the user except that during the take-off or landing the UAS must not fly above 30 metres of

any human being other than the airspace user in charge of the UAS or a person in charge of any other UAS or a person that remains in touch observing the operation of such a UAS.

Hazard 4: Uncontrolled crash on landing ends in drone break down, resulting in UAS debris and/or fire injuring people in congested ground

Rule 4: If severity is major and popular density is rural, probability is remote and operational complexity is single drone then:

- Drone's controller shall be equipped with an emergency stop switch.
- The operational area shall be well defined and operational contingencies detected shall be eliminated by the designer. Such operational contingencies include: inability to determine location using GPS; obstacles within its path.
- The manufacturer must check the ability of drone's safety features to shut-down the drone under all hazardous conditions should cause falling and tripping hazards to people.

Rule 5: If severity is major and popular density is remote, probability is remote and operational complexity is BVLOS then:

Recommendations for Preflight actions

- Understanding the fundamental control actions that need to be taken in case of an aircraft emergency or if a mid-air collision hazard happens during the flight.
- Monitoring a real-time look-out and keep the UAS within VLOS under all circumstances.

Hazard 5: Uncontrolled crash on landing ends in drone break down, resulting in UAS debris and/or fire injuring people on the ground or user

Rule 6 & 7: If severity is hazardous and popular density is suburban/ urban, probability is extremely remote and operational complexity is multi/single-drone then:

- The safety case for the overflight of people must include an assessment of the Kinetic Energy Limits and the method of flight termination [2].

Hazard 6: UAS breakdown from forced crash during landing in an unsafe ground, injures drone-user

Rule 8: If severity is minor and popular density is remote, probability is probable and operational complexity is single drone then:

- Operator of drone should be educated with theoretical courses and undertake skills and re-evaluation tests.

Hazard 7: Fire from UAS forced crash during landing in an unsafe terrain threatens wildlife and the environment

Rule 9: If severity is major and popular density is remote, probability is remote and operational complexity is BVLOS then:

- The operator shall take account the visibility in background conditions cloud and blue sky and real-time meteorological data.
- The operator shall take account the colour, size and markings of drone.
- The drone should assist the observer to detect it.
- Operation shall take place within Visual Meteorological Conditions suitable for VLOS in class E airspace.

Hazard 8: Uncontrolled emergency landing resulting in multi drone's collisions with terrain obstacles or loss of human life

Rule 10: If severity is catastrophic and popular density is suburban, probability is extremely improbable and operational complexity is semi-autonomous then:

- UAS users must take account of the possible reduction in operating range in an suburban environment due to the heavy use of communications equipment (mobile telephone, Wi-Fi) and other sources of electromagnetic spectrum/RF interference.
- Post-manufacture check of the full scale system, about its maximum, minimum, optimal speed and settings, start / end points, path, process.
- Speed mode should meet the performance criteria.

Hazard 9: UAS breakdown and/or fire from crash of uncontrolled emergency landing in unsafe ground, crashing with people on the ground

Rule 11: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is BVLOS then:

- Performing accurate and controlled flight maneuvers at representative heights and distances such as flight in ‘Atti’ mode (non-GPS assisted) or equivalent where fitted).

- Specific responsibilities for maintenance must be assigned to the airspace user. Manual/ user’s guide information must be written according the maintenance problems referred by the users in order to be complete. The manual must state that regular maintenance of cables/ wires is essential for optimizing the relevant efficiency.

Hazard 10: Crashing a manned aircraft or vehicle on the ground

Rule 12: If severity is catastrophic and popular density is remote, probability is extremely improbable and operational complexity is BVLOS then:

- Operate UAS on civil twilight (30 minutes before official sunrise to 30 minutes after official sunset local time) with appropriate Traffic Collision and Avoidance system and lighting. Daylight-only operations

- Three types of emergency stop states could be used according to the UAS type. Firstly, the user has control and decides to shutoff the operation. Secondly the system is combats a specific state that make it hard to continue to keep up with its tasking path. When this happens, the device will try to restart or enter and idle condition until the user manually restarts it. And lastly, the condition when all control attempts has failed.

- The remote emergency stop must be installed through a radio frequency receiver and relay positioned in series with the battery. When the receiver receives a signal from the remote RF transmitter, the relay shuts-off the power to the robot blocking any harmful incident. When power supply is on, the CPU will execute the command of the robot.

- Maximum groundspeed of 100 mph (87 knots).

Hazard 11: Uncontrolled landing crashing on the ground result in human injury or fatality

Rule 13: If severity is catastrophic and popular density is urban, probability is extremely improbable and operational complexity is single drone then:

- User shall pay extra attention if the area around the terrain is populated or congested. Always look for traffic when operating near roadways, walks or gravel drives.

- Perform equivalent functions, such as maintaining separation, spacing and sequencing that would be done visually in a manned aircraft.

- Small unmanned aircraft may not operate over any persons not directly participating in the operation, not under a covered structure, and not inside a covered stationary vehicle.

Hazard 12: Impact with structures or obstacles result in building damage, debris or fire from crashing with high voltage power lines

Rule 14: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is BVLOS then:

- Effective monitoring of drone status and endurance restrictions within a range of 3 miles.
- Camera view from the user may not satisfy "see-and-avoid" requirement but can operate since the guideline is fulfilled with other restrictions.

Hazard 13: Inability to control the drone from the ground result in collision with another airspace user

Rule 15: If severity is catastrophic and popular density is remote, probability is extremely improbable and operational complexity is single drone then:

- The internal connectors supplied with the robot must be waterproof and give a reliable electrical connection.
- User must be informed that regular test, calibration and maintenance of electrical components are essential.
- Sensors capabilities must not fail under dynamic conditions and sensor's reliability must be tested thoroughly.
- Enable the Remote Pilot to determine the in-flight meteorological conditions. Avoid hazardous weather.

Hazard 14: Inability to control the drone and monitor drone position from the ground result in crashing a person

Rule 16: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is multi drones then:

- Controlling a 'return-to-home' function following deliberate control-link transmission failure.

- In order to keep GPS signals free from interference, a common data link (CDL) is needed that connects the drone to the remote ground station and the pilot who controls it. Disrupted data links may happen maliciously and incidentally.
- The designer should design connectors so as to protect against separation of wires.
- Cords must be prevented from coming in contact with burrs, cooling fins or sharp edges, which might wore their insulation while the manual must warn the user that controller’s cords must be placed in the holder below the controller. User must not use the robot with damaged cord.

Hazard 15: Inability to control the drone and monitor drone position from the ground result in crashing a building or breakdown of drone

Rule 17: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is BVLOS then:

- Mission planning, airspace considerations and site risk-assessment.
- Aircraft pre-flight inspection and set-up (flight controller modes and power-source hazards).
- Disorientation of drone due to electromagnetic interference must be avoided.
- Shielding, regulating, filtering, grounding shall be provided to protect against control frequencies.
- Verification of use of separate EM radio frequencies through spectrum management.

Hazard 16: Inability to fly according to flight plan result in crashing another UAS or manned aircraft

Rule 18: If severity is catastrophic and popular density is remote, probability is extremely improbable and operational complexity is BVLOS then:

- Internet Protocol Security (IPsec) does not guarantee that packets are transferred in the exact order in which they are delivered, ensuring private policy of airspace users. It offers peer authentication and integrity including two security protocols, Authentication Header and Encapsulating Security Payload (ESP), Internet Key Exchange protocol and IP Payload Compression Protocol [4].

- Secure Sockets Layer (SSL) virtual private networks (VPN) facilitate safe remote access to the drone’s network. Because a VPN can be used over drone’s WEP/WPA encryption, it can provide the safer transport of private conversations through public resources.

Hazard 17: Inability to fly according to flight plan result in exit the assigned geo-fence crashing a person on the ground

Rule 19: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is single drone then:

- Internet Protocol Security (IPsec), that ought to be implemented, provides the typical used network layer security control for protecting against intruders. IPsec is a framework of open standards for ensuring private communications over IP networks [4].

- IPsec encrypts information using a cryptographic algorithm and a confidential value recognized by the persons who are communicating. The network information can only be decrypted by someone who has the confidential key.

Hazard 18: Inability to fly according to flight plan result in exit the assigned geo-fence crashing onto an obstacle resulting to injury from drone’s debris

Rule 20: If severity is hazardous and popular density is rural, probability is extremely remote and operational complexity is BVLOS then:

- The values of VLOS range from 100m to 500m whereas the authorities require VLOS up to 3 nautical miles. VLOS depends on the flight area altitude, meteorological conditions and other environmental factors, such as the duration of daylight. The range depends with drone’s battery power, radio range and visual capability of end-user [3].

- The flight altitude must be at least equal to the highest physical obstacle (trees, buildings, antennas) and authorities restrict drone flights to a maximum altitude and radius considering other programmed airspace activity [1].

- Prohibited areas include government buildings, nuclear factories and military bases [1].

3 Main Results

These are the main results of the paper.

After setting the rules and respective safety guidelines, the MATLAB simulink exports an output with the overall perspective of the rules (Figure 4) and the surface of the problem of risk assessment (Figure 5).

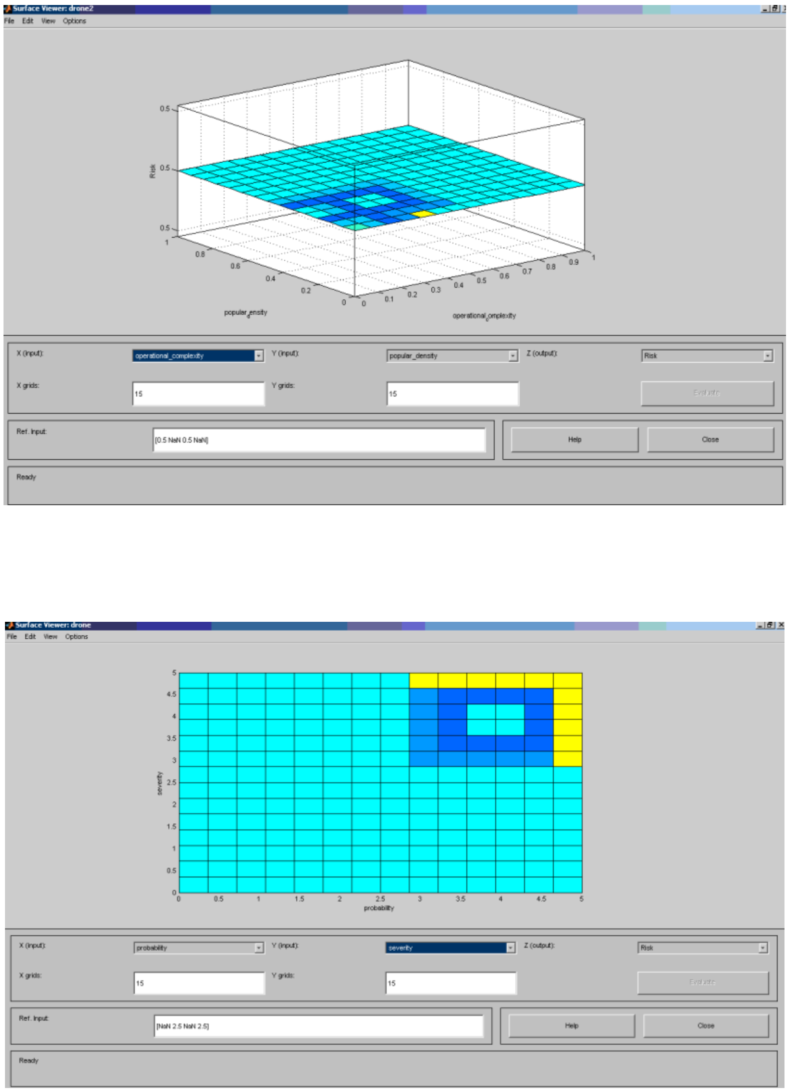

Figure 4: The surfaces of the problem as an export of MATLAB simulink.

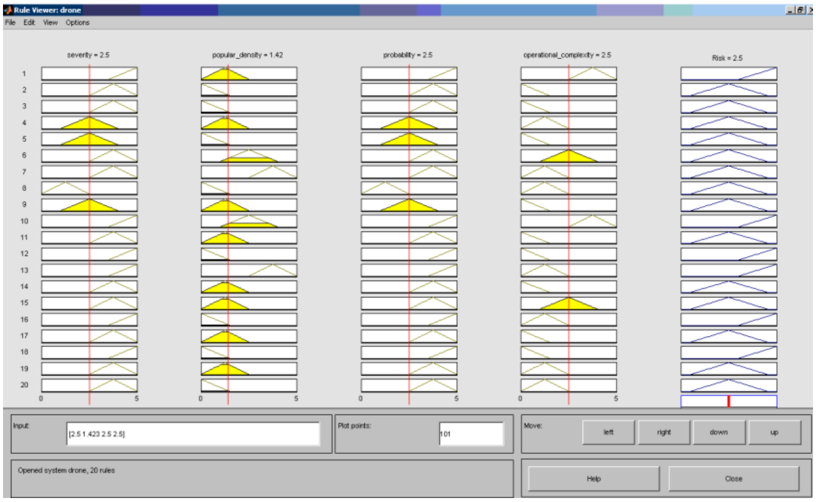

Figure 5: The overall perspective of the rules.

5 Conclusion

Fuzzy logic is an established scientific theory that focuses on optimized solutions to problems and it is considered effective on dealing with problems with high degree of fuzziness. In the last decades, theory and applications of fuzzy logic have presented a great success in many scientific fields. The fuzzy system is designed using many rules and parameters assisting in decision making. Through this research, the application of fuzzy logic has succeeded in defuzzification of safety guidelines via a fuzzy inference system. This system automates the decision making and quantifying the matter of risk counting four input variables: severity, population density, operational complexity and probability to avoid a hazardous condition to take place. The new framework support risk analysis in an optimized way reestablishing the work of standardization’s organization.

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