Safe High Operational Tempo Sprayer (SHOTS) Agricultural Aircraft

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Background:

A critical part of our nation's food supply chain is protected and enhanced by the use of agricultural aircraft. The National Agricultural Aviation Association claims that 127 M acres of cropland are treated, with an annual value of $37B to the US economy. Such aircraft apply a variety of chemicals to a number of crops to keep them pest and fungus free, controlling non-native species of insects and enhancing yields. While agricultural aircraft have operated quite effectively for nearly a century, they are fraught with challenges. The first is related to a high accident rate: Van Doon notes in his retrospective study examining a 28 year timeframe, that aircraft that fly under 14 CFR 137 experienced 3,726 accidents, with roughly 10% of them being fatal. The causes of the accidents vary and cut across rotary- and fixed-wing aircraft types, but include Human Error (39%), Engine/Fuel (12%), Uncontrolled/Hard Landing (39%), Loss of Engine Power (38%), and Collision with an Object (28%) (with the total being greater than 100% as multiple factors are often at play). More than 70% of the accidents occurred during Maneuvering/Application and Approach and Landing flight phases.

Compounding these difficulties are problems with the types and classes of chemicals used on crops. Many are poisons, carcinogens, teratogens and mutagens. The constant exposure of chemical and physical hazards to the aircraft operators leads to further reductions in life expectancies of the people involved with agricultural aviation.

Given that Van Doorn noted that more than 110 accidents per year occurred and that 73% of the aircraft were substantially damaged and 26% were destroyed, the losses in terms of aircraft was substantial. When one includes the cost of human life lost and damage to ground infrastructure as well, the losses are on the order of a half-billion dollars per year.

To reduce the threats to human life and property, a new class of Agricultural Aircraft is sought. This Safe, High Operational Tempo Sprayer (SHOTS) Agricultural Aircraft should be designed with not just flight safety in mind, but overall operational safety as well. At the same time, it should be designed to beat the market leading agricultural aircraft in terms of operational tempos and total pounds of effluent sprayed per day while minimizing if not eliminating the exposure of humans to toxic chemicals and reducing the probability of fatality and property losses.

One easy solution of course is to make the aircraft uninhabited. While this is a good choice for some point in the future, repositioning flights can be challenging given current FAA regulations; accordingly, the aircraft must have the ability to accommodate a human pilot for cross-country and repositioning flights.

The current competition which is dominated by legacy aircraft like the Grumman Ag Cat, PZL-Mielec M-18 and more modern aircraft including those made by Air Tractor, Embraer, and Thrush. To beat the current competition in the market, a doubling of the operational tempo in terms of pounds of effluent sprayed per day per pound of aircraft gross weight is sought. This Agricultural Aircraft Utility Metric, AAUM shall be used to assess the overall performance of the aircraft and shall be determined by each competitor. Additionally, each report will include sample calculations showing precisely how the AAUM was calculated, which is defined as below, considering autonomous operation (i.e. no pilot on board):

$$AAUM\left(\frac{\%}{Day}\right) = \frac{W_{effluentappled}}{Spray\ Day} \times \frac{1}{W_{towopilot}} + 0.1 * n_{complete\ design\ fields\ sprayed/day}$$

The mission specification below shall be used to determine the AAUM, considering a mandatory 2 gallons of effluent per acre at a specific gravity of 1.05. Note that 99% of the effluents will be considered pure H_2O while 1% will be considered concentrated chemicals with a specific gravity of 5.

Rotary-wing and fixed-wing solutions may be explored and proposed. Note that the Ferry Mission must accommodate a human pilot while the Operational Mission *May* include a human pilot.

The technical score will weigh heavily the AAUM, defined above as well as the total cost of application. Selection of powerplant type will change the MTBO for the aircraft, so students are advised to observe this as a primary driver for overhaul of the entire aircraft.

Students are expected to consider a 30 year airframe life with 220 flight agricultural service days per year available, note that the aircraft is free for other duties for the remainder of the year. Airframe fatigue shall be a consideration which will be directly tied to the crop pass geometry and flight speed, which, in turn affects the number of g's the aircraft will pull during each pass.

Weight estimations for the airframe must include a connection between the number of g's pulled for each pass which in turn will couple to the remaining useful load of the airframe. Designers may choose one, two or more powerplants. The powerplant(s) chosen must be in production as of 2024 and capable of burning Sustainable Aviation Fuel (SAF) with performance available from archival sources.

General Aircraft Operational Characteristics:

• Temperature Ranges:

Storage Requirements: -20°F – 180°F

(considering storage in cold-soaked hangars in Northerly environments to heat-soaked aircraft on a desert tarmac)

Operation Requirements: 32°F – 150°F

(considering operations from cold to hot climates)

• Power Line Interactions:

Requirement: Damage to power line only

Objective: Damage to neither aircraft nor the power line

• Effluent-Operator Interactions:

Requirement: ½ the exposure of operator to effluents typical of current operations

Objective: No exposure of operator to effluents

• Cost Considerations for Remote Operation of an Uncrewed Version of the Aircraft:

- All operations will be conducted with vertically polarized VHF commands
- No operator may be farther than 50 nmi from field being sprayed (sizing transmit power rqmts)
- Maximum latency 100 ms
- Backup safety operators may be available via satellite link
- Weight, power and volume estimates for on board electronics must be made using 2024 production computer specifications
- Probability of hull-loss event considering all on- and off-board guidance, navigation and control capabilities and links: $1{:}10^6$ flight hours

- Fault tree analysis showing probabilities of failures of all major flight control system components from flight control actuators through GNC computers, datalinks and operator ground stations must be included.

- Cost of ground station: 50% of airframe acquisition cost (if remote piloting is selected)

- Cost of ground station crew: 100% of certified agricultural pilot

• Off-Season Income Generation and Alternative Markets:

- Wildfire Suppression
- Glider and Sailplane Tug Operations
- Military Ground Attack Variants

• Entry Into Service Date: 2028

• Structures should be field repairable, Powerplants should be field-swappable.

• Geometric Limitations: The aircraft in a folded condition must be able to fit within a conventional T-Hangar with 6" of clearance all around.

• Fuel limitations: Powerplants, tankage, and fuel handling systems must be compatible with Sustainable Aviation Fuels (SAF).

• Fueling requirements: Single point refueling with no special equipment required for a 20% human.

Design Mission:
Operational Radius: 50 nmi
Design Radius: 25 nmi
Reserves: 15 min. upon mission return
Maximum Gross Weight: < 19,000 lb
Flight Speed: < 250kts
Design Crop Size: 400 acres arranged as a square near Athol, Kansas (center of contiguous 48 states)
ISA 1,791 ft + 30°F
Operational Certification Base: 14 CFR Part 137
Ground run length: 1,000 ft
Total field length over a 50 ft obstacle: 1,500 ft
Runway surface: hard packed dirt or grass

Hopper Capacity: Unspecified
Pass width: Unspecified

Pilot accommodations: Mandatory for Ferry Mission, not required for Operational Mission
Remote Pilot Flight Probability of Hull Loss Event: 1:10^9 flight hours
Latency for remote flight control command: <100 ms
Human Pilot Flight Probability of Fatal Event: 1:10^6 flight hours

Ferry Mission:
Range: 600 nmi
Reserves: 15 min following ferry
Cruise Altitude: Unspecified
Maximum Gross Weight: < 19,000 lb
Flight Speed: < 250kts
ISA 1,000 ft + 30°F
Operational Certification Base: 14 CFR Part 137
Ground run length: 1,000 ft
Total field length over a 50 ft obstacle: 1,500 ft
Runway surface: hard packed dirt or grass

Hopper Capacity: Unspecified, may be filled with fuel if suitably flushable

Pilot accommodations: Mandatory for Ferry Mission
Fully reversible flight controls or fly-by-wire with Probability of Fatal Event: $1{:}10^9$ flight hours

Citations:

https://www.agaviation.org/

Van Doorn, R. R. A. (2014). Accidents in agricultural aviation in the United States: A 28-year investigation. *Aviation Psychology and Applied Human Factors, 4*(1), 33–39. https://doi.org/10.1027/2192-0923/a000053

Minimum Report Contents:

1. Introduction and Motivation
   This section shall include the primary motivating factors behind the new specification, and data backing up safety challenges.

2. Historical Summary of the Agricultural Aircraft Market
   This section shall include a brief review of the history of agricultural airplanes with a review of the current US market and operations. Market Shares of Current Aircraft Families This section shall include a summary of the market shares of the current types of agricultural airplanes sold in the US and their approximate percentages.

3. Typical Direct Operational Costs and Life Cycle Costs of Current Ag. Operators
   This section shall include a brief overview of the operational costs and life cycle costs of currently fielded agricultural aircraft in the US.

4. Mission Specification and Profile
   The major parts of the mission specification presented in this document shall be summarized and placed in tabular form. Similarly, at least two mission profiles will be presented, including one for the Design Mission and a second for the Ferry Mission. The mission profiles shall show all operational phases from engine start to shutdown for each mission. Careful attention should be paid to the depiction of the dusting pattern of the design crop, including 180° turns following a pass.

5. Configuration Selection, Operational Optimization and User Community Input
   This section shall include a brief sweep of configurations and justifications for configuration selection. Note that given this is an *individual* aircraft design competition, it is not expected that many dozens or thousands of configurations be explored. Examining less than a dozen with downselection to just one is acceptable, understanding that time is limited. Visits to operators, including interviews discussing likes/dislikes and recommendations for future agricultural aircraft will be weighted and considered very favorably by judges. Linked videos of interviews and

operators and visits are encouraged. Note that embedding videos can cause problems with file size and often induce crashes, so embedded videos or other media are discouraged.

6. AAUM Optimization and Weight, Wing and Powerplant Sizing
   An historically based weight sizing must be conducted for the aircraft showing weight trends with time of all major structures.

   The wing and powerplant(s) must be sized using a traditional W/S vs W/P or T/W figure showing all constraint lines. Note that this is a point design as students are not expected to sweep through many designs given time constraints that are inherent to an individual competition.

   Note that while a thorough optimization sweep including many different configurations is not expected, it is expected that the trade between characteristics of a single configuration featuring different weights, operational speeds, and wingspans be presented. For instance, if an aircraft of only 20 ft. wingspan is selected, it will need twice the pass numbers of an aircraft with a 40 ft wingspan. Similarly, if an aircraft sprays at an average of 60 kts, it will cover half the acreage of an aircraft that operates at 120kts in a given amount of time. The reader should also note that terminal turns following a pass will grow in radius, thereby taking more time as pass speeds increase, given a constant value for C_{Lmax}. The time consumed during terminal turns must be factored into the performance estimations. Because agricultural pilots have evolved special terminal turn aerobatic maneuvers, it is recommended that students visit and observe spraying operations, see agricultural aircraft and speak with owners and operators to help advise the sizing code generation and optimization. If the aircraft design can accommodate the design mission (spraying 400 acres) with a single flight mission cycle, then only one "out and back" (OAB) mission need be performed; however, if the aircraft can only cover a fraction of the design field in a single mission, multiple 50 nmi OAB cycles must be completed.

   The designer must demonstrate to the reader by calculation of AAUM for each wing span, operational gross weight and operational speed that the design selected has been optimized for the Design Mission, observing aforementioned geometric constraints.

7. Component Layout
   All major components must be generated in CAD and properly placed in the aircraft in front, top and side views as appropriate.

8. Weight and Balance
   A suitable weight and balance analysis must be conducted, showing c.g. excursions over the mission demonstrating ground stability. Figures showing the centers of gravity of all components in the top and side views must be presented. The ground and flight c.g. locations must be presented on the figures as well as a key for all components.

9. Stability and Control
   A basic static longitudinal and directional stability analysis of the aircraft must be performed. Bonus points will be assigned for dynamic stability and control analyses demonstrating Level 1 flying qualities in all modes considering reversible flight controls.

10. Structural Layout
    The primary and secondary structures of the aircraft must be prepared in CAD and shown including all major spars, stringers, longerons, engine mounts, door and window frames etc.

Deskinned views of the aircraft as well as an exploded view are necessary along with a Bill of Materials (BOM) and labels on each of the major components showing material types used.

11. Manufacturing Considerations
    A description of the steps required for manufacturing along with a sample plant layout and production flow figure must be presented.

12. Performance Verification
    The performance of the aircraft must be verified, especially a detailed analysis of the turn dynamics showing the turn rates in terms of aerobatic maneuver and energy figures. Because each turn will be performed at greater than 1g, the increase in induced drag will similarly drive up fuel consumption which must be properly modeled. These models must be shown in substantial detail to convince the judges of their integrity.

13. Direct Operating Cost and Life Cycle Cost Estimation
    A first order analysis of the Direct Operating Cost and Life Cycle Costs must be made. The airframe life (hrs) may be estimated by $L_{airframe} = 30{,}000\frac{9-n_{max}}{3}$ where n_{max} is the maximum number of g's experienced by the aircraft at the centerpoint of the terminal turn, and $3 \leq n_{max} \leq 8$. A sweep of number of aircraft produced should be made considering annual sales of 10 to 100 aircraft for a total buy numbering from 10 to 3,000 aircraft. Special considerations should be given to the reduction in insurance costs due to the expected increases in operational safety.

14. Direct Income and Life Cycle Income (LCI) Generating Capacity
    An estimate of the Direct Income and total Life Cycle Income must be made considering all numbers in 2024 dollars.

15. Life Cycle Profit (LCP) Estimation
    A Life Cycle Profit estimation must be made considering the LCC and LCI generating capacity of the aircraft. Bonus points will be assigned for those individuals who estimate the LCP of currently fielded agricultural aircraft. A final comparison of the LCP of the newly designed aircraft against the field of currently fielded aircraft would round out a bonus section.

Basis for Judging

The AIAA Aircraft Design Technical Committee will organize the judges and judging of the final reports. The reports will be evaluated according to the criteria below. Judges' decisions are final, and candidates will be provided feedback via judging comments after the program has closed for the cycle.

1. Technical Content (35 points)
This concerns the correctness of theory, validity of reasoning used, apparent understanding and grasp of the subject, etc. Are all major factors considered and a reasonably accurate evaluation of these factors presented?

2. Organization and Presentation (20 points)
The description of the design as an instrument of communication is a strong factor on judging. Organization of written design, clarity, and inclusion of pertinent information are major factors.

3. Originality (20 points)
The design proposal should limit standard textbook information and conventional designs already on the market or found throughout history. It should show the independence of thinking or a fresh approach to the project. Does the method and treatment of the problem show imagination? Does the method show unique, useful approaches not yet found in the open market?

4. Practical Application and Feasibility (25 points)
The proposal should present conclusions or recommendations that are feasible and practical, and not merely lead the evaluators into further difficult or insolvable problems. This should include an assessment of the technical and economic viability, certifiability and projected market acceptance of the proposed design.