Description of “Aquila” UAV design

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1. INTRODUCTION

We are students of Mechatronic Engineering at AGH University of Science and Technology in Krakow, Poland. UAVs is the field that combines mobile robotics - area that is covered by our studies programme with aviation, to which we both share passion. Thanks to the participation in this competition we’ve greatly increased our knowledge about the unmanned aerial systems. We think the main theme - building of a cargo drone - is so interesting that we both plan to continue this project as our Master Thesis. We strongly believe that it is the future of small-scale transportation.

2. MAIN IDEA

The design was inspired by existing cargo airplanes, and professional heavy-duty drones (like MQ-9 Reaper). According to [1], the conventional wing-tail configuration is hard to beat. It is well understood, simple to analyze, and offers good performance. A vast experience base exists for the conventional wing configuration, making it a relatively low risk configuration option. Unusual configurations might possess undesirable characteristics that are not immediately apparent. Any new configuration should be considered as high risk until proven on multiple flight vehicles. That’s why we propose the configuration, that have worked well on other successful UAVs and meets the main requirement - to keep the design super simple: one wing in high configuration. Such solution provides no surfaces ahead of the wing generating undesirable downwash on the wing or a turbulent wake, and in consequence - lower aerodynamic efficiency (for example, the tandem wing configuration might experience poor stall behavior). On the other hand, the major benefit of a high wing is that it allows placing the fuselage closer to the ground and allows safe unloading the cargo. This solution enables also inserting the cargo from the side. There are few drawbacks, e.g. the fuselage will be flattened at the bottom which will be heavier than the optimal circular fuselage, however, they will not outweigh the profits.

3. WINGS & WINGLETS

Based on the information provided in [2], we have chosen the most important parameters of the wing. First is aspect ratio which is one of the key parameters for the performance of the aircraft. In our case it is equal to 16.2.
Based on the figures in [2], e.g. 4.19, 4.22 the wing:

- without sweep,
- with .4 taper ratio ([2]: “Most wings of low sweep have a taper ratio of about 0.4-0.5”)
- without twist,
- with 2 deg incidence,
- with 0 deg dihedral ([2]: “Roughly speaking, 10 deg of sweep provides about 1 deg of effective dihedral.”)

has been selected.
At the tips of the wings the winglets will be mounted. They will serve the function of vertical stabilizer as well as drag-reduction device by preventing the escaping of higher-pressure air at the bottom of the wing around the wing tip to the top of the wing. A properly designed winglet can

potentially provide an effective span increase up to double that bought by adding the winglets' height to the wing span.

3. AIRFOIL SELECTION

According to [2], in early conceptual design it is not important to pick exactly the “right” airfoil - later trade studies and analytical design tools will determine the desired airfoil characteristics and geometry. During this phase of the project, the selected airfoil is
important mostly for e.g determining the thickness available for structure. Thus, we have chosen the NACA 23015 profile for the main wing and NACA 0010 for the tail.

4. TAIL

While the wing carries the substantial amount of lift, the tails is a key element of stability, acting much like the fins on an arrow. We have decided to use the "T-tail". Heavier than a conventional tail, the T-tail provides compensating advantages in many cases. It lifts the horizontal tail clear of the wing wake and propwash, which makes it more efficient and hence allows reducing its size. It can be found in [2], that the exact planform of the tail surfaces is actually not very critical in the early stages of the design process. The tail geometries are revised during later analytical and wind-tunnel studies.

5. MODULARITY, ADAPTABILITY

According to [1], a truly modular UA has interchangeable modules that can be replaced over the life of the UA. In this case, these modules are wings and landing gear - parts especially exposed to fatigue or the possibility of damage.
However, minor structural repairs should be supportable in the field. UAV composite structures can become cracked, delaminated, or crushed. This damage can be repaired with tools and materials provided in a field composite repair kit, including composite cloth, shears, epoxy,
sandpaper, and gloves.

Landing gear is one of the most crucial subsystems of the UAV. It should be able to absorb the energy of the impact with ground. Our idea is to add in each of three parts of the landing gear a mechanical damper, e.g. a spring. It will provide additional support to make landing smoother.
For the safety reasons, we do not use vertical stabilizers as the parts of the landing gear. In case of any sudden impact with the ground and, in consequence, damage to the stabilizers, the UAV would be unable to continue that particular flight, or would require a complex repair. This choice is also caused by the fact that composites are not as damage-tolerant as metals.
There will be also possibility to adapt the landing gear from the conventional tripod into tricycle with wheels or articulated skis, depending on the area where the UAV will be operating. The tricycle configuration is by far the most common for unmanned aircraft because of the simplicity for takeoff, landing, and ground handling.

As the jet engines are mounted outside the fuselage and are not it’s integral parts, there will be possibility of dismounting them. Combined with conventional tricycle landing gear, this solution will make possible the transition of the UAV into motor glider mode and conventional takeoff and landing.

There will be sometimes need to transport the UAV to the point of operation and then en-site assembly. [1] says that good objective is to minimize the number of parts that must be detached. Thus, during transport, the UAV will be divided into four parts: fuselage with engines, two wings and the tail, all of them having suitable handling points that are easy to lift and can withstand the human grasp. It will provide the modularity of the aircraft for the sake of easy handling and transportation. When fuselage is treated as one integral part during transport, there is no need of disconnection all the electronics, responsible for e.g. control of the engines. Avionics and other replaceable units that require frequent removal will be installed one deep - no other components would have to be removed to provide access. This will reduce the time to perform maintenance. For even faster turnaround time, batteries can be easily replaced by exchanging whole battery compartment for fresh one.

6. MATERIALS

It is planned to make outer skin of the UAV of molded composite material, preferably CFRP. As can be found in [1], molded structures permit unitizing of the structure (building a
large structural component as a single unit), compound curvature, yielding greater design flexibility and elimination of many fasteners, such as rivets. Composite materials offer also the potential for significant weight savings. An additional benefit is improved corrosion resistance.
In the places requiring higher strength and/or stiffness, the sandwich construction can be used, with the face sheets of CFRP and the phenolic honeycomb material or rigid foam core.

Composites have also drawbacks - e.g. low conductivity relative to metals, which poses challenges for electromagnetic interference (EMI), lightning protection, and electrical grounding. Composite structures might need conductive layers to provide these functions.

For areas that are relatively small , have complex geometry, and are not subjected to high loads (e.g. electronic board holders), the 3D printing technique can be used.

7. CONTROL SYSTEM

As main Flight Control Computer (FCC), Raspberry Pi 3 with Navio 2 add-on board was chosen. This solution combines high processing power of ARM processor with real time control of RC I/O coprocessor. The result is reliable and very stable, while at the same time being cost-effective and having very low power consumption. Built-in triple power supply basically eliminates possibility of power loss in drone electronics. The system incorporates a dual GPS/GLONASS receiver, providing precise position and altitude. There are also two IMUs built-in, providing backup sensor data in case of main IMU malfunction. Electronics can operate in various weather conditions - in hot environment, cooling is realised by air flowing in and out through designed inlets and outlets. In colder areas circuits can be heated by additional electric heating wire. Water is prevented from entering by securing all openings with waterproof mesh.

Raspberry Pi 3 runs full Linux operating system which makes it easy to prepare advanced control programs and algorithms, enabling fully autonomous operation, automatically correcting orientation based on sensor data. It also contains WiFi and Bluetooth transceivers, that allow wireless control program update when in close range to vehicle.

8. SENSORS

Main Inertial Measurement Unit consists of iMAR iμVRU-01, a system that calculates internally drone orientation, offloading main FCC and allowing it to do other operations at the same time. It is placed just above centre of gravity, to ensure best possible accuracy.

For vision system, dedicated Raspberry Pi camera was selected. Its main advantages are very small and lightweight form factor, low power consumption and good integration with main FCC. The no-infrared variant allows to use UAV at night.

As air data system Air Data Unit from Advanced Navigation was chosen. It is used to measure pitot airspeed and barometric altitude. It features high accuracy temperature calibrated pitot and static air data sensors. The Air Data Unit allows a Spatial GPS/INS to maintain significantly higher position, velocity and orientation accuracy when GPS is not available — with position error growth as low as 0.1% distance travelled.

9. COMMUNICATION SYSTEMS AND MODEMS

Communication system consists of two parts. First allows fully manual drone control — Turnigy 9X 9Ch Transmitter for movement, and Helistar 8 Channel 500mW 5.8GHz Wireless Audio/Video Transmitter for FPV. However, it only works in close proximity to vehicle (several kilometres). When longer distances are needed, drone can be used in semi-autonomous mode, controlled through GSM network with A-GSM GSM/GPRS/SMS/DTMF Shield. This allows control station to be located virtually anywhere.

Sage tech XPG-TR transponder was chosen to fulfil ADS-B requirement. This particular model contains Mode S and ADS-B output, as well as integral GPS receiver, making it a self-contained unit. It can be used even in critical situations, when main flight control computer has crashed. This improves safety drastically, allowing to broadcast vehicle position in all circumstances.

10. PAYLOAD

Payload is secured in container by non flammable foam, cut out specifically for that cargo. If the cargo is smaller, foam will be designed to keep it in the center. Whole container is secured in place by aluminium frame, that can be moved to sides to enable bottom loading/unloading, possibly automated. Manual loading can be also done from the side, which is much easier and more comfortable for people. The container is a simple box that can be easily changed with another.
If an unobstructed view is required (for example in case of sensor payload) bottom double doors can be left open - otherwise, during cargo flight they are closed. Opening and closing of these doors can also be realised automatically or manually.

11. PROPULSION

Mostly due to beneficial payload integration options, we decided to to use one pusher propeller. Other advantages of such solution are: unobstructed forward field of regard and no payload contamination in flight. Pusher propellers provide also pitch and yaw stabilizing effects.
An aft propeller can create challenges for balance, where the powerplant aft location tends to make the UA tail heavy. A weight in the nose is needed to balance the aircraft - which in this case will be satisfied by avionics and communications systems.

a) PROPULSION - HOVER MODE

Typical multicopter design uses standard two-blade or three-blade propellers, which provide thrust needed for hovering and manoeuvring. However, in case of such heavy vehicle, the propellers have to be very big (more than 70 cm). An UAV’s open rotors can pose ground handling safety hazards. Adding safety rings around them would be impractical - the rings would have to be either very fragile, or add a lot of mass to the design. This means it is basically impossible to ensure safety of nearby people during take-off and landing — and that is unacceptable for vehicle operating surrounded by unqualified civilians (for example during disaster relief missions). That is why this design proposes alternate propulsion system, based on four high-power, high-speed EDFs - Schuebeler DS-94-DIA HST, with DSM6745-700 motor. It has only 12 cm diameter, which allows to mount it directly on aircraft fuselage. Full engine enclosure ensures safety even when engines are spinning. Yaw control is possible due to slight turn - one pair is slightly turned clockwise and one anti-clockwise from fully vertical position. 520 Newtons of thrust make it possible to take off very quickly, and in very rough weather conditions. To operate such powerful motor, Turnigy Monster-2000 200A 4-12S Brushless ESC was selected. Power is supplied by heavy-duty MaxAmps LiPo 9000XL 12S 44.4v battery pack. One of it's advantages is that it's 100% waterproof, resulting in safe operation in rain. This system also supplies power to main flight computer and other electronics.

b) PROPULSION - CRUISE FLIGHT

For forward flight propulsion, one Cheetah A5345-7 motor with 21 x 9.5 carbon fibre two-blade propeller is used. The main reason for this choice is efficiency — this motor must work for over an hour. This motor is very effective, while keeping desired power, allowing flight even in 10 m/s headwind and crosswind. Two-blade propeller is preferred due to lowest air turbulence of all possible configurations. Carbon fibre ensures safe and stable operation, while keeping weight minimal. Power is controlled by T-Motor Flame 80A ESC. To maintain longest possible flight time, instead of standard LiPo pack, Panasonic NCR18650B batteries are used. They have much lower maximum discharge rate (only 1C constant/2C max), but have much higher capacity to weight ratio.

12. SAFETY

Galaxy GRS GBS10/350 Flight Termination Parachute is included for safe descend in case of engine failure. It's preferred over the suggested XL96 Skycat/X55-CF Skycat combination for several reasons. Most importantly, it consists of only one device (in the suggested system there are two), which makes it more reliable — there are less parts that can break. It also makes it smaller and lighter. Second advantage is very low minimal deployment altitude — only 5 meters above ground (instead of 25 meters - 5 times lower!). This means it is possible to use at basically any flight stage — even take off and landing. This system also supports weight up to 35 kg, which gives safe margin for dynamic forces when deployed in high speed.

For deployment Galaxy GRS Extended Controller was chosen. It has several safety features built in — for example, it does not allow to take off with parachute system disabled. It also kills engine power when parachute is deployed, ensuring safe descent. There is also an integrated buzzer, that makes loud noise during descent, warning people that could be standing on a landing site. This way risk of catastrophic crash is minimised.

Safety system is supplemented with anti-sink device (Bell Outfitters H2O Gear Pro), which allows to recover drone after failure over lake or sea. The device releases highly visible buoy, that has line attached to it. It makes it possible to just pull vehicle out of the water.

13. APPLICATIONS

- long, repetitive, monotonous missions
- flying through environments contaminated by chemical and biological agents or radioactive environments.
- Scientific missions seek to gather data or perform experiments to advance the state of knowledge, in situ atmospheric measurements (Air pollution, temperature and humidity profiles)
- risky operations without risk to human life,
- aerial mapping and surveys,
- aerial pesticide spraying, fertilizer application,
- forest fire monitoring/firefighting,
- Public services support (e.g. monitoring land vehicle speed, UASs can be fitted with loudspeakers to communicate with people on the ground - survival instructions, safety procedures)
- emergency support ->establish communication networks, deliver emergency supplies to survivors (food, water, medicine, live jackets and other survival gear),
- dropping supplies with a parachute/land vertically and place the supplies directly on the ground.

14. REFERENCES

[1] - Gundlach, J. *"Designing Unmanned Aircraft Systems: A Comprehensive Approach"*, American Institute of Aeronautics and Astronautics, Reston, Virginia 2012

[2] - Raymer, Daniel P.: *"Aircraft Design: A Conceptual Approach"*, American Institute of Aeronautics and Astronautics, Washington, DC 1992