Assessment of the fuel efficiency of unmanned cargo aircraft, based on general aviation aircraft

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Abstract. This study was motivated by the globally increasing interest in unmanned cargo drones. It was focused particularly on cargo drones based on existing conventional general aviation airplanes and it should be regarded as a preliminary step towards the complex assessment of unmanned cargo aircraft transport systems. The aim was to estimate the fuel efficiency of such drones and to outline the optimums of some of their key design characteristics. A sample of 26 very light and light aircraft, and motorgliders was examined. The data was taken from open sources. The results outline that for best fuel economy the cargo drone should be a composite structure, piston engine airplane with wing aspect ratio of 10 to 12. Fuel efficiency estimation at distances of 500 to 2500 km shows that such cargo drones would be competitive with large piloted commercial cargo airplanes as well as with the road transport.

1. Introduction
Nowadays the introduction of unmanned autonomous transportation systems is expected to bring significant cost and environment benefits. These expectations cover also the air cargo, which is reflected in many strategic documents such as the IATA Cargo Strategy [1] and the European Commission Flightpath 2050 [2]. The initial interest by currier and e-commerce companies was focused on so called “last mile” delivery drones for small items. At the same time many start-ups emerged aimed at the creation of more heavy unmanned cargo aircraft (UCA) with longer range. This activity led eventually to the creation of organizations like the Platform for Unmanned Cargo Aircraft (PUCA). Most of the projects are for aircraft with payloads of 1 to 10 tons. Much practical work was conducted in China, creating cargo drones based on existing general aviation light aircraft like Staruas AT200.

An important step towards the realization of the cargo drone concepts is the estimation of their energy and transport efficiencies. A review of the problem of Unmanned Aerial Vehicles (UAV) efficiency, although not focused exactly on cargo drones is made by Amoiralis et.al. [3]. In [4] Valerdi reviews the cost metrics of UAV that can be used also for efficiency estimates.

Particularly for the case of “last mile” delivery drones efficiency analyses were performed by researchers funded by the U.S. Department of Energy [5] and RAND [6]. Regarding the larger UCA research has been undertaken under the auspices of PUCA [7, 8], trying to cover a broad area of the UCA commercial implementation aspects. At the same time there are no studies dedicated to the segment of UCA with range and payload corresponding to these of the very light class of general aviation aircraft (VLA), although there are start-ups aimed at the development of such UCA, including the Bulgarian company Dronamics.
The aim of this study is to estimate the fuel efficiency of such UCA, and to serve as a basis for further studies on their complex performance and efficiency as a transportation system. The approach used for this assessment is common with that of similar studies concerning the passenger aviation [9-12]. The difference is that the data used is for existing light and very light aircraft and some assumptions regarding the transformation of piloted aircraft to unmanned are applied. Also the study looks at the effect on fuel efficiency of some of the key design features of the aircraft such as the type of the materials used in the airframe and the wing aspect ratio. Finally a comparison with the efficiency of a contemporary mid-size air freighter and a panel van road vehicle is performed.

2. Assessment basis
It should be stated that the real performance of the future UCA will depend from a great number of their design features. The complexity of the UCA design challenge can be seen in works like [13], where different types of aircraft and rotorcraft layouts are compared, meeting different requirements. The aim of this paper is not to assess the variety of all the possible UCA, but to estimate the energy efficiency of UCA that can be easily developed from existing general aviation aircraft, using the same airframe and engine technologies.

2.1. Assumptions for the conversion of very light aircraft to UCA
The four main characteristics that have large effect on the energy efficiency of an aircraft are the weight, the aerodynamic properties, the power plant efficiency and the power consumption of the airplane systems. To assess correctly the UCA energy efficiency, using data for piloted aircraft it is essential to properly estimate how these characteristics will be affected by the UCA design requirements. In this paper the following changes in the design are suggested:

- The absence of a cockpit in the UCA will allow a better aerodynamic shape of the nose section of the body, and in the case of a single engine with tractor propeller – higher placement of the engine, resulting in shorter landing gear legs, which are lighter and create less drag;
- The absence of pilots and passengers equipment and furnishing as well as mechanical flight control system will save weight;
- The need of relatively large cargo volume, enforced cabin floor and suitable cargo door will have negative effect on the airframe weight and aerodynamic drag, compared to piloted VLA;
- The absence of cockpit flight instruments will probably compensate the addition of sensors and autopilot systems in terms of weight and energy consumption;
- The use of control surfaces actuators will add weight and energy consumption.

All of the considerations made above are very sensitive to the particular design and need separate investigations. For this reason in the present paper a ‘neutral’ scenario was suggested, assuming that the conversion of the airplanes to UCA will not affect significantly the empty weight and all available useful load will be divided between the fuel and the payload, and the aerodynamic properties will stay essentially the same.

2.2. Airplanes included in the survey
A sample of 26 very light and light aircraft, and motor gliders was examined, based on the performance data provided in Internet by the manufacturers and data from the corresponding Type Certificate Data Sheets. The airplanes with their manufacturers are listed in table 1. They can be divided in the following groups:

- VLA with aluminium alloy airframe, Rotax 912/914 gasoline engine (10 airplanes);
- VLA with composite airframe, Rotax 912/914 gasoline engine(9 airplanes);
- Motor gliders with composite airframe, Rotax 912/914 gasoline engine (3 airplanes);
- Motor gliders with aluminium alloy airframe, Rotax 912/914 gasoline engine (2 airplanes);
- Diesel powered light aircraft with composite airframe (2 airplanes);
- The AT200 turboprop UCA, based on PAC-750 utility aircraft was taken as a reference.
Table 1. Airplanes included in the survey.

| No. | Airplane Manufacturer | Airplane |
|-----|-----------------------|----------|
| 1   | Harmony LSA           | Evector  |
| 2   | EuroStar SL           | Evector  |
| 3   | DV-1                  | DOVA Aircraft |
| 4   | PS-28                 | Czech Sport Aircraft |
| 5   | P92js                 | Tecnam   |
| 6   | Skyleader 600         | ZALL JIHLAVAN |
| 7   | AC 4                  | Lightwing |
| 8   | AT 3                  | Aircraft technologies |
| 9   | SD 4                  | TOMARK, s.r.o. |
| 10  | P2008js               | Tecnam   |
| 11  | Sting S4              | TL-ULTRALIGHT |
| 12  | TL-3000               | TL-ULTRALIGHT |
| 13  | ATEC 321 Faeta NG     | ATEC     |
| 14  | DA20i                 | Diamond aircraft |
| 15  | KR-030                | Ekolot   |
| 16  | Virus SW              | Pipistrel |
| 17  | CTLS                  | Flight Design |
| 18  | WT 9                  | Aerospool |
| 19  | APM 30 Lion           | APM      |
| 20  | Europa XS             | Europa Aircraft |
| 21  | HK36                  | Diamond aircraft |
| 22  | Sinus                 | Pipistrel |
| 23  | SF 25 C Falke         | Scheibe Aircraft |
| 24  | Samburo AVO-68r       | M+D Flugzeugbau |
| 25  | Da40NG                | Diamond aircraft |
| 26  | DA50                  | Diamond aircraft |
| 27  | AT200                 | Star UAV System |

The VLA are the most popular nowadays category of general aviation aircraft that are widely used for pilot training and leisure flights. Most of these airplanes are relatively new designs and are equipped with Rotax 912/914 family engines, using automotive gasoline instead of more expensive aviation gasoline.

The motor gliders with thick airfoil, high aspect ratio wing are added in order to investigate the influence of the wing aspect ratio on the energy efficiency.

Diesel powered aircraft are interesting for their low specific fuel consumption. Their application in the general aviation was limited by the successful introduction of aviation piston engines certified for automotive gasoline, but diesel engines find applications also for military UAV.

3. Fuel efficiency assessment methodology

3.1. Metrics for cargo aircraft fuel efficiency

Publications [9-12] use a variety of different metrics to measure the environmental performance of commercial aircraft. In present paper as a metric, that is independent from the engine and fuel types the energy intensity is chosen. In the case of cargo aircraft the energy intensity is expressed in equation (1):

\[ Ei = \frac{m_{fuel} H_u}{1000 m_{pld} L_{flt}}, \]
where $m_{\text{fuel}}$ is the mass of the fuel spent for the flight in kg, $H_u$ – the net heat of combustion of the fuel that is used in MJ/kg, $m_{\text{payload}}$ – the payload in kg and $L_{\text{flight}}$ – the distance of the flight in km. The dimension of $E_i$ could be either MJ.(ton.km)$^{-1}$ or kJ.(kg.km)$^{-1}$.

3.2. Calculation of the fuel consumption

In most of the cases the available performance data of the examined airplanes is limited to the parameters described in table 2.

| No. | Parameter                          | Remarks                                                                 |
|-----|------------------------------------|------------------------------------------------------------------------|
| 1   | Empty weight of the airplane, kg   |                                                                         |
| 2   | Maximum allowed takeoff weight, kg |                                                                         |
| 3   | Capacity of the fuel tanks, litters| Assumed specific fuel weight is 0.74 kg/l for gasoline and 0.82 kg/l for jet fuel. |
| 4   | Maximum range with 30 minutes flight reserve, km |                        |
| 5   | Cruise speed, km/h                 | If the long range cruise is not known it is assumed to be 80% of the maximum horizontal speed. |

To overcome the absence of detailed performance data for the fuel-range calculations, an approach similar to that of Burzlaff [14] was applied. Instead of using the specific fuel consumption (TSFC) and the lift to drag ratio (L/D) in the Breguet equation:

$$L_{\text{flight}} = \frac{V_{\text{cr}} \cdot L/D \cdot \ln \left( \frac{m_{\text{TO}}}{m_{\text{TO}} - m_{\text{fuel}}} \right)}{\text{TSFC} \cdot g},$$

(2)

where $m_{\text{TO}}$ is the take-off mass of the airplane and $V_{\text{cr}}$ is the cruising speed, a Breguet factor is defined:

$$BF = \frac{V_{\text{cr}} \cdot L/D}{\text{TSFC} \cdot g}.$$  

(3)

The Breguet factor for each airplane now can be calculated using eq. (2) and the data for the maximum range and maximum usable fuel capacity:

$$BF = L_{\text{flight}\cdot\text{max}} \cdot \ln \left( \frac{m_{\text{TO}}}{m_{\text{TO}} - m_{\text{fuel}\cdot\text{max}}} \right) \cdot L_{\text{flight}\cdot\text{max}}.$$  

(4)

If the available data is for the maximum range with 30 minutes reserve ($t_R = 0.5$ h), than the maximum range without reserve is calculated using the assumption that the airplane will fly with its cruise speed:

$$L_{\text{flight}\cdot\text{max}} = L_{\text{flight}\cdot\text{max}} \cdot R + V_{\text{cr}} \cdot t_R.$$  

(5)

3.3. Calculation of energy intensity of the UCA at given flight distance

The energy efficiency at given distance is calculated at three steps:

- Calculation of the mass of the required fuel:

$$m_{\text{fuel}} = m_{\text{TO}} \cdot (1 - e^{-\frac{L_R}{BF} \cdot \text{BF}}).$$  

(6)

- Calculation of the mass of the reserve fuel:

$$m_{\text{fuelR}} = (m_{\text{TO}} - m_{\text{fuel}}) \cdot (1 - e^{-\frac{V_{\text{cr}} \cdot t_R}{BF} \cdot \text{BF}}).$$  

(7)
Calculation of the available payload and the energy efficiency:

\[ m_{\text{payload}} = m_{\text{TO}} - m_{\text{fuel}} - m_{\text{fuel\ TO}} \quad (8) \]

Energy efficiency is calculated using equation (1).

4. Results and discussion

The fuel efficiency assessment was divided in two tasks. First the Energy intensity of the airplanes was evaluated at 1000 km flight distance and the influence of the wing aspect ratio and the type of airframe structure on it was analysed. Secondly the Energy efficiencies of the best performing airplanes of each group described in p. 2.2 were calculated for distances between 500 and 2500 km and were compared with a narrow body cargo airplane and a hypothetical road cargo vehicle.

4.1. UCA fuel efficiency at 1000 km flight distance

The results of the calculations of the energy intensity at 1000 km as a function of the wing aspect ratio of the airplanes are shown in corresponding groups in figure 1.

![Figure 1. Energy intensity of UCA based on VLA and light aircraft at 1000 km flight distance.](image)

Figure 1 shows good relation between the energy intensity (fuel efficiency) and the wing aspect ratio of the airplanes. Only the older generation motor gliders with aluminium airframe stay out. The relation was approximated with third power regression curve, also shown on figure 1 (The two older motor gliders are excluded from the regression data). The results indicate that best fuel efficiency can be expected for airplanes with composite structure and wing aspect ratio in the order of 11 to 12. The poorer energy efficiency at lower wing aspect ratios is explained by the increased induced drag of such wings. At high wing aspect ratios the transport efficiency of the airplanes also is poorer because their wings are optimised for low speed soaring and not for covering long distances.

The energy intensity of the AT200 turboprop UCA is also shown on fig.1. Despite the larger size of the airplane and the difference in the power plant, it fits very well with the general tendency.

4.2. Comparison of UCA fuel efficiency with other types of cargo aircraft and ground transport

On figure 2 the “best performing” airplanes of each group are compared with Boeing 737-800 freighter and with a hypothetical panel van road vehicle. The data for Boeing 737-800 was taken from [10]. The energy intensity of the panel van is calculated with the assumption that it carries 400 kg of cargo with fuel consumption of 5 litters of Diesel fuel per 100 km.
Figure 2. Energy intensity of UCA based on VLA and light aircraft as a function of the flight distance.

The results show that at shorter distances up to 1000 km the best-performing VLA-based UCA will be comparable with the present generation of large piloted cargo aircraft. At longer distances the advantage of jet cargo airplanes is due to their greater cruising speed. At the same time the VLA-based UCA will be twice more efficient than the larger turboprop UCA (AT200), because of the much better specific fuel consumption of the small piston engines compared to the turbo propeller engines.

5. Conclusions
The results outline that for best fuel economy the VLA-based cargo drone with conventional airplane layout should have composite structure and wing aspect ratio in the order 10 to 12. Fuel efficiency estimation at distances of 500 to 2500 km shows that such UCA will be competitive with the present generation of large piloted commercial cargo airplanes, achieving energy efficiency in the order of 7-8 MJ/(t.km). This is a much better figure than 14-24 MJ/(t.km) of the utility turboprop-based UCA. To some extent and in particular cases such UCA will be competitive also with the road transport, which energy intensity is estimated around 4-5 MJ/(t.km).

This study should be regarded as a preliminary step towards the complex assessment and optimisation of UCA transport systems, including the airplane itself, the ground infrastructure, the operations, etc.

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