Preliminary design of a BWB UAV for highway traffic monitoring

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Abstract. The current work presents the preliminary design procedure of a small-scale, fixed-wing Unmanned Aerial Vehicle (UAV), incorporating the novel Blended-Wing-Body (BWB) layout configuration. The UAV is designed to support a Cooperative-Intelligent Transport System (C-ITS), for monitoring traffic conditions at large national highways. The presented UAV design procedure emphasizes on both aerodynamic and stability behavior, aiming to a high aerodynamic efficiency and the satisfaction of the mission requirements. The design is supported by CFD analyses, to determine the aerodynamic and stability coefficients. Following the CFD modeling, the performance parameters of the platform are calculated. Furthermore, an internal layout study is conducted to integrate all the necessary internal components, determining the center of gravity. Finally, the overall UAV design concludes to an optimum configuration of the UAV-ITS, satisfying all the aerodynamic, stability and mission requirements.

1. Introduction
The increase of population around the globe has led to the increase of vehicles on roadway networks and to the urgency for development of improved means of traffic monitoring. Currently, there are several technologies in use for traffic sensing at modern roadways, such as radars, video cameras, detectors embedded in pavements and pneumatic tubes stretched across the roads [1]. These technologies provide useful information and collect data regarding traffic flow, vehicle speeds and emergency situations at specific points. Along with those benefits there are also some drawbacks, as these means tend to have high installation and maintenance costs, while they cannot move through the transportation network. As a result, they are not able to provide information regarding traffic flows over space and routing. Moreover, most roadways lack complete surveillance systems, resulting in many “blind” spots and in the loss of valuable time in case of emergencies.

There is currently a plethora of on-going research projects focusing on new technologies that will improve surveillance techniques for traffic management. Aerial view provides a better perspective and the advantage of covering a wider area. Satellites were initially considered as an alternative for traffic surveillance, but the transitory nature of satellite orbits makes it impossible to provide the right imagery to address continuous problems, such as traffic tracking [2]. Moreover, the quality of satellite imagery is relatively poor during overcast days. Another alternative that provides aerial view and has been
examined for traffic surveillance is flying manned aircraft although this option is ineffective regarding its operational costs. Having these in mind, Unmanned Aerial Vehicles (UAVs) are considered as a suitable choice for this type of mission as they can overcome all the aforementioned drawbacks.

UAVs have been in use for many decades and are widely used for military and civilian purposes. Intelligence, Surveillance and Reconnaissance (ISR), border patrol, mapping, fire detection search and rescue, telecommunications, agriculture and delivery of goods are just a fraction of all the different missions that UAVs perform today [3]. UAVs may as well be employed for a wide range of transportation operations and planning applications such as, emergency response, monitoring of highway conditions, coordination among a network of traffic signals, traveler information, emergency vehicle guidance, track vehicle movements in an intersection, measurement of typical roadway usage and monitoring of parking lot utilization [4]. Also, a key advantage of UAVs is that they can move faster than ground vehicles, as they are not restricted by the road network. Unmanned vehicles have also significant advantages when compared to manned vehicles.

The concept of employing UAVs for traffic surveillance and control is not a new idea [1,5]. There are numerous researches exploring the potentials and the advantages of such missions [6,7]. In [8] a real-time detection algorithm for a vision-based monitoring system on a UAV is presented. The author of [9] proposes a traffic monitoring system using UAVs to overcome the limitations of Saudi Arabia’s existing SAHER system, while [10] and [11] provide information in airborne video traffic surveillance systems. Additionally, an intelligent monitoring drone system for highway speed measurement based on deep learning is presented in [12] and finally references [13] and [14] propose intelligent, UAV-enabled traffic systems for the smart cities of the future.

All the aforementioned works provide valuable information and insight concerning the models and the algorithms behind the intelligent transport systems. However, there are no information regarding the characteristics, sizing and design of the UAV platforms. In the current work the preliminary design of a small-scaled UAV aiming to support an ITS is presented. The UAV incorporates the novel Blended-Wing-Body (BWB) layout as it provides large internal space for the mission payload and avionics and has significant aerodynamic advantages compared to the conventional wing-and-tube configuration [15]. Figure 1 presents the concept of the mission of the UAV. Its purpose is to fly above large national highways in Greek territory and to search for accidents and road obstructions in order to provide warning messages for the vehicles nearby.

![Figure 1. UAV concept of operation](image-url)
2. Initial platform requirements

The current work is a part of DROMEAS research project, and its purpose is the design of a UAV platform able to support a C-ITS for highway traffic-monitoring. The platform should be able to reach the operation area as fast as possible, thus, short takeoff and landing is considered necessary and a relatively high maximum speed is desired. All the initial requirements that govern the design procedure are summed up in table 1.

| Initial platform requirements   |   |
|--------------------------------|---|
| GTOW                           | 25 kg |
| Max Wingspan                   | 3 m   |
| Cruise speed                   | 130 km/h |
| Max speed                      | 160 km/h |
| Operating altitude             | 50-1000 m |
| Endurance                      | 6 h   |

The mission profile of the UAV is presented in figure 2. The mission includes 7 segments, starting with takeoff and climb then cruise, loiter around a point of interest, then cruising back to its base and finally the phases of decent and landing, where the operation ends. The UAV cruises across the selected highway and receives information, through the electrooptical payload, regarding the condition of the road, accidents or road blockages and weather conditions such as rain, fog, snow and ice accumulation. The UAV then processes all the input data and then relays the information to nearby vehicles. If there is a certain area of interest the UAV will perform loiter over it to provide information and assistance for a longer extent of time.

![Figure 2. UAV mission profile](image)

3. Methodology

3.1. Sizing and performance analyses

For the sizing of the UAV platform and the performance analysis, an in-house tool is employed, based on textbook methods [16-19]. The existing methods have been modified to be applied on the novel BWB configuration according to similar studies [20,21]. The tool is used to provide guidelines for the layout design, to make weight estimations and to conduct performance analysis. Indicatively, Equation (1) is a formula used for weight estimation and Equation (2) is a formula used to calculate the maximum velocity of the UAV.

\[ \frac{W_e}{W_0} = A W_0^C K_{WS} \]

\[ V_{max} = \left\{ \frac{[(T_A)_{max}/W](W/S)\sqrt{[(T_A)_{max}/W]^2 - 4C_{D,0}K}}{\rho\omega C_{D,0}} \right\}^{1/2} \]

More specifically, Equation (1) estimates the empty weight fraction \( (W_e/W_0) \) of a UAV during the early design phases, when very few information is available regarding its layout. Note that \( W_e \) and \( W_0 \) denote the empty and the gross takeoff weight of the aircraft, respectively, whereas the \( A, C \) and \( K_{WS} \) are coefficients based on statistical data and trends. For the performance parameters calculations, a 6 hp EFI engine is used coupled with a propeller for the thrust generation. As the design proceeds and the
available information about the UAV increases, more complicated expressions are employed, consequently increasing the fidelity of the performance calculations.

It must be noted that throughout the sizing procedure all the critical design parameters of the UAV (appropriate airfoil sections, quarter-chord sweep, aspect ratio, wing twist, wingspan, etc.) are selected and reevaluated. The goal of the design procedure is to find the optimum combination of those parameters that will enhance the aerodynamic and stability behavior and will satisfy the initial requirements.

3.2. Aerodynamic analysis
To extract the necessary aerodynamic performance data accurately, an extensive campaign of high-fidelity analyses was performed using the ANSYS CFX commercial software (ANSYS® Scientific Research, Release 18.2). The Reynolds-Averaged-Navier-Stokes (RANS) equations are solved, coupled with the Spalart-Allmaras (S-A) turbulence model [22], a model widely used in aeronautical applications thanks to its accuracy in predicting turbulent or transitional external flows around airfoils and wings. A second order upwind scheme was used for both the discretized momentum and turbulence model equations, whereas the inlet turbulence boundary conditions were based on [23]. A steady-state approach was employed due to computational resources limitations. An unstructured mesh of approximately 9,500,000 nodes, depicted in figure 3, is generated around the BWB geometry, whereas several inflation layers are generated on the walls of the model, to accurately model local, low Reynolds boundary layer phenomena in the wall region. The turbulence inlet conditions are selected to represent typical flight conditions. The geometry used for the analyses is generated using existing parametric 3D CAD tools.

![Computational mesh around (left) and in the surface (right) of the UAV](image)

**Figure 3.** Computational mesh around (left) and in the surface (right) of the UAV

3.3. Internal layout design
The position and orientation of all the internal systems is the main objective of the internal layout studies. The UAV flight and mission requirements introduce a list of systems to be integrated to the platform, including, among others, structural elements, fuel system, mission electronics and avionics, fuel and electrical lines, payload and engine parts. Having populated the systems’ components list, each component is represented in a CAD model that includes its basic dimensions and its weight. On one hand, it is apparent that components-off-the-shelf (COTS), like payload, avionics and engine, are easier to be represented as their dimensions are already known. On the other hand, systems that follow an in-house design and development procedure (e.g., structural elements, fuel system, etc.), have their dimensions initially estimated and, as the overall design progresses, the fidelity level of their CAD representations increases. The internal layout studies have to follow a set of spatial, functionality and stability constraints, presenting a problem that may initially seem overly complex, as the number of feasible, non-optimal configurations is effectively unlimited. In order to bypass this, a number of designer’s choices is necessary regarding some major components. For example, the engine position is fixed in the back of the main body, as the pusher configuration dictates and the fuel tank should be positioned somewhere in the middle of the main body, close to the desired center of gravity (CG) position, to minimize the CG movement during flight. Accordingly, the mission electronics are to be positioned in the frontal bay for ease of maintenance. Finally, through the UAV structural studies, the structural elements are designed with respect to the defined positions of these major components.

As the internal layout studies conclude, a systems assembly, including the skin and the structural elements, is created in a 3D CAD environment, in which the overall CG position and the principal...
moments of inertia (MoI) matrix are calculated. The CG position and MoI matrix are parameters that heavily affect the overall stability of the platform and the control surfaces sizing calculations. Moreover, at each design loop, the external geometry is updated, thus components rearrangements arise, or some systems are substituted, hence, the overall CG position and MoI matrix should be constantly recalculated.

4. Results
Following the methodology described in Chapter 3 the final optimum configuration is extracted, which satisfies all the initial requirements of the DROMEAS research project taking into concern all the aerodynamic and stability restrictions. Table 2 sums up some of the geometrical and performance characteristics of the UAV configuration. whereas figure 4 presents a 3D CAD representation of the UAV configuration at the end of the preliminary design.

| Table 2. UAV configuration geometrical and performance characteristics |
|---------------------------------------------------------------|
| **GTOW** | 25 kg |
| **Wing loading** | 33.5 kg/m² |
| **Cruise speed** | 130 km/h |
| **Loiter speed** | 130 km/h |
| **Max speed** | 170 km/h |
| **Stall speed** | 75 km/h |
| **Takeoff runway** | 137 m |
| **Loiter endurance** | 6 h |
| **Rate of climb** | 5.2 m/s |
| **Weather conditions limit** | 8 beaufort |

Figure 4. UAV external layout and dimensions

Concluding, some of the most important information about the UAV design characteristics are presented in figures 5-8. More specifically, figure 5 presents two indicative flow visualizations from CFD modelling. The left side of the figure depicts streamlines and a u-velocity contour on a plane intersecting the leading edge of the UAV, while the right side depicts streamlines around deflected control surfaces of the UAV. In figure 6, the corresponding aerodynamic coefficients, as extracted from CFD calculations, are shown in two diagrams, the drag polar and the trim diagram. The black dotted line at the trim diagram indicates the lift coefficient at mid-cruise. Note that at this point the platform is trimmed without any control surfaces deflection. This design characteristic keeps the platform stable
and minimizes the trim drag penalty. The final internal layout assembly is presented in figure 7. The engine and its auxiliaries are positioned in the back of the main body while the mission electronics and avionics are in the frontal bay area. The payload (EO/IR gimbal) is positioned in the middle of the frontal bay as it is deemed the safest position in case of an incident. The fuel tank is arranged on the desired CG position offering a minimum CG movement during the mission. Finally, in figure 8 at the left side the required thrust of the UAV (Drag) and the available thrust, generated by the engine-propeller combination, are presented as a function of the flight velocity, both at sea level and the height of 1 km, whereas at the right side the rate of climb of the UAV as a function of the flight velocity is presented.

**Figure 5.** CFD results in the form of velocity contours and streamlines around the UAV (left) and around the UAV with the control surfaces (elevons) deflected (right)

**Figure 6.** Drag Polar as calculated from CFD (left) and Trim Diagram (right)

**Figure 7.** Positioning of the avionics, electronics, payload and propulsion components inside the UAV
Figure 8. Thrust available and thrust required as a function of velocity at sea level and 1 km (left) and rate of climb as a function of velocity at sea level and 1 km (right)

5. Conclusion and future steps
The current work emphasises on the preliminary design phase of a UAV platform that supports a Cooperative-Intelligent Transport System for highway traffic-monitoring. This system is intended to be used in Greek national highways, to collect information about the road and weather conditions across the highways and to inform nearby vehicles. Text-book methods along with in-house sizing tools were employed for the design of the UAV platform, while CFD modeling was used for the purposes of all aerodynamic analyses. Effort was given for the design to meet all the initial mission requirements. The internal components were positioned into the platform without violating any spatial constraints or center of gravity constraints, hence the platform is stable and the trim drag is kept to the minimum.

The study so far has covered a significant amount of work, however there are some steps that have to be concluded. As a future step, the complete structural analysis of the designed platform will be conducted along with a detailed internal layout design loop for the determination of the mounting bases for the internal components. Moreover, the detailed drawings to open the way for the manufacturing of the prototype will be produced. The final step will be the integration of the components and test flights that will assess the platform and, as a consequence, the overall design itself.

6. References
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[13] Acknowledgements
The work presented in this paper is a part of the research program DROMEAS: Unmanned Aerial Vehicle – Cooperative Intelligent Transport System. It has been co - financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH - CREATE - INNOVATE (project code: T2EDK-02794).