# AN INTEGRATED SYSTEM FOR BORDER SURVEILLANCE AND MONITORING BASED ON VERY LIGHT MALE UAV

**Zdobyslaw Goraj**
**Warsaw University of Technology (goraj@meil.pw.edu.pl)**

**Keywords**: *UAV, design, surveillance, comtutational aerodynamics*

## Abstract

*VL MALE UAV and MINI UAV airplanes were designed for surveillance missions, especially for state border monitoring and sending the images in LOS range (~250 km). Aircraft are built both either in classic or tailless configurations with either pushing or pulling propellers. Sensor suit consists of FLIR, SAR (optionally SATCOM for VL MALE configuration). FLIR and SAR containers are optimised for best visibility. Professional software (UNIGRAPHICS, VSAERO, ANSYS and others) are routinely used in design process.*

## 1 General Introduction

Nowadays UAVs are widely accepted for various civilian missions [1] including highway patrol, security patrol, urban traffic monitoring, pipeline monitoring, power line monitoring, maritime surveillance, mapping of mineral distribution, border surveillance and many others. In Poland and other New Member States of European Union there is a big interest in border surveillance. Polish Eastern border is long enough in order to be monitored from air and creation of an efficient surveillance system being able to work 24 h a day is important, Fig.1. Moreover, according to the vision presented in European UAV Roadmap the technology development will offer a special chances just to New Members allowing them to avoid a skills gap and avoid a brain drain to other parts of the world. Development of UAVs technology will create chances for overall progress in science and technology, will boost inexpensive investment, will stimulate a high level of interdisciplinarity (avionics, MDO, new materials, sensor's technology, wireless communications, software development, etc.) and will offer a well defined application areas and as a result will bring numerous benefits for societies.


*Fig.1. Possible scenario of operation over eastern Polish border*

Design and research effort devoted to UAVs has started in the Institute of Aeronautics and Applied Mechanics in the beginning of nineties [2,3,4,5]. One of the first projects in this area, focused on a HALE surveillance UAV was HARVE [2], submitted for consideration to DARPA in 1995 and then published in 1999 [5]. An important influence on UAV activity in IAAM have had international projects called UAVNET [6,7,8,9] and CAPECON [10], supported by European Union within the V Framework. CAPECON project, lunched in May 2002 was devoted to developing new configurations of MALE, HALE and Rotary and accentuates some universal aspects and features of all aerospace designs, namely design, new materials, aeroelastic phenomenon, safety, reliability, cost and economical competitiveness. A special emphasis was put on selecting the platform best suited for the planned mission. The trade-off between aerodynamic efficiency, performances, flight stability, selection the flight control system, payload and sensor's volume, reliability and safety was reviewed. Within CAPECON project IAAM was responsible both for MALE [11,12] powered by single piston engine (called as PW-103), HALE [13,14,15] powered by two turbofan engines (called as PW-114) and for critical technologies necessary for successful design of MINI UAV. Experiences gained within CAPECON project were important in planning and realization the successive projects [16,17,18]. In this paper two of such projects will be presented, namely a very light MALE to be used for border surveillance missions and called PW-126 and MINI UAV called PW-141. Both projects are in very early stage of conceptual design.

## 2 PW-125 –a surveillance MALE class UAV design project

This chapter describes a very early beginning of design activity devoted to developing an MALE UAV, undertaken at the Department of Airplane & Helicopter Design of Warsaw University of Technology and based both on the experience gained in the past during the successful designing of PW-5 and PW-6 glider family and the more recent current experience obtained from the participation in the international programs devoted to UAV optimization and development, gained first of all under the CAPECON program. That time the situation related to the application of UAVs in Poland could be briefly described as follows:

- As a consequence of the accession of Poland into the European Union in May 2004 there will arise a necessity of undertaking some venture, where unmanned aircraft could be used. Among various applications the most important for Polish economy & security will be the following: (1) border surveillance. Polish eastern border, almost eight hundred km long – must be carefully protected against the smuggling of goods and people; (2) highways development and monitoring; (3) powerlines and gaslines inspection and (4) air pollution monitoring, forestry surveillance and establishing the anti-fire, early warning protection system.
- No civilian Polish entities have in their disposal any Unmanned Aerial Vehicles now for routine operation (situation in July 2004). Selecting the system of UAV for civilian purposes and a decision-making process in this area will undoubtedly influence on a similar decision undertaken in the military sector in the future.
- Taking into account a great Polish aeronautical tradition before and during the WW2 and a decline of aerospace sector in Poland in the last years there is a very strong expectation and social desire in order the future unmanned aerial vehicle was a Polish airplane (of course it does not include sensors, communication unit, control software etc).
- In our opinion there is no chance to buy a complete UAV system now or even in the nearest future. Not only because of the cost, but first of all because of the psychological reasons. Society and the

decision-makers should look themselves into the advantages the UAVs could offer in the civilian service and the fact that such airplanes will contain Polish components and Polish engineering effort can essentially help and boost this undertaking.

- Warsaw University of Technology has designed and developed very successful composite glider, known as PW-5 – the winner of the World Class Glider international competition. Now we are looking for a partner to establish a joint venture between Warsaw University of Technology and an industrial company with experience in sensors, data link, communication and the ground control station technology.
- The main goal of such a venture would be a development of unmanned aircraft family of MALE class, well suited for specific Polish conditions. WUT could design the unmanned platform (basing on our experience and even some parts and templates ready to use). A foreign company could propose and integrate the on-board and the ground equipment, including communication, control and sensor systems. At the beginning such an UAV could be equipped with EO/IR sensor only. The commercial proposal offered to Polish authorities would be prepared and submitted jointly by WUT and a foreign company.
- One of the statutory aims of university is increasing its research and design ability and standards. For WUT taking part in the design and development of a new series of unmanned airplanes would be a great scientific, research and publicity success.
- There is a big chance that such an unmanned airplane could be accepted by civilian authorities and that it could establish a standard in Poland. For a foreign company it would be an occasion to make a good business in Poland and very probably that also in the whole Central and Eastern Europe.

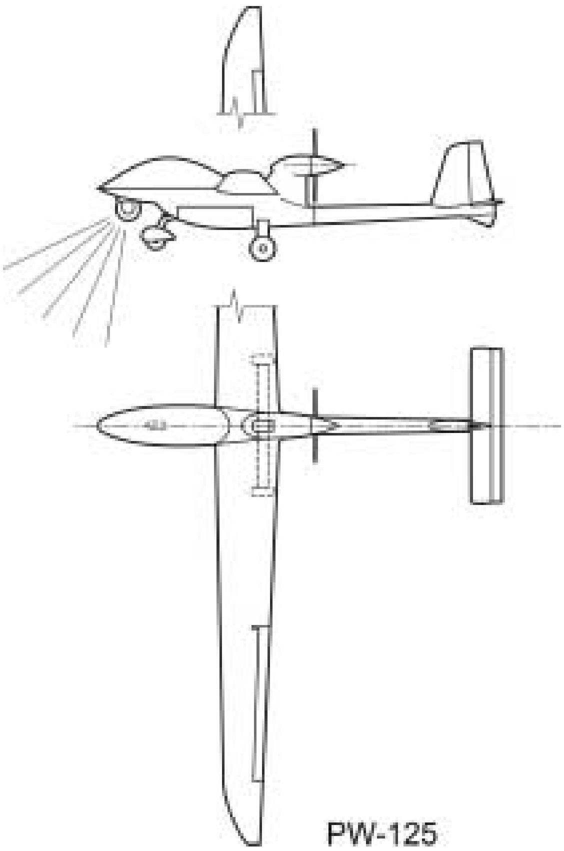


*Fig.2. Surveillance, MALE class UAV project, based on PW-5 glider layout*

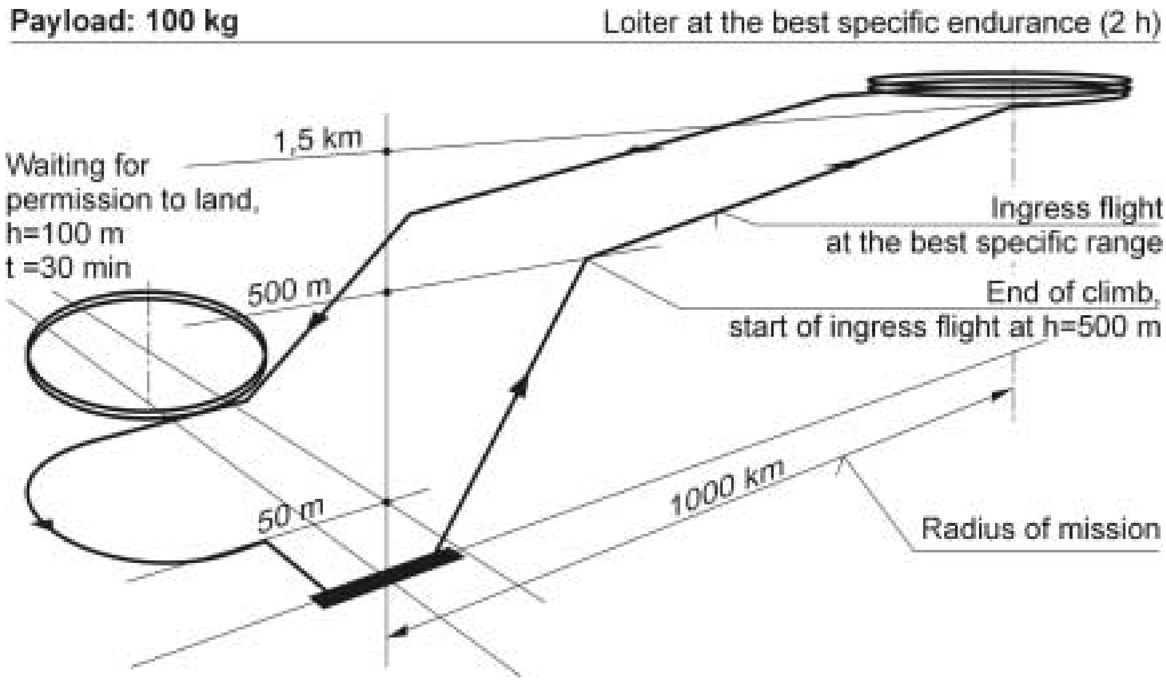


*Fig.3. Typical mission of PW-125*

Conceptual Project of PW-125 was developed and critically reviewed. However, considering various advantages and drawbacks we came to the conclusion that glider-based structure, its dimensions and weights will create numerous difficulties and that it will be much better to design a specialized the platform from the scratch. Project was cancel and replaced by the idea of PW-126.

## 2 Very Light MALE UAV

PW-126 VLUAV class airplane is designed for surveillance mission, especially for state border monitoring and sending the images in LOS range (~250 km). SATCOM could be a possible option on the customer request. Aircraft is built in tailless configuration with pushing propeller powered by Rotax 112 engine of 90 bhp. Sensor suit consists of FLIR, SAR (optionally SATCOM). FLIR,SAR & SATCOM containers are optimised for best visibility.

Tailless architecture was based on Horten, Northrop and PW-114 (HALE class UAV developed within CAPECON program sponsored by European Commission) design experience. Front undercarriage leg is retracted (to improve sensor's visibility, main undercarriage is fixed. No one element of aircraft structure limits the sensor's visibility. All payload systems are put into separate modular containers of easy access and quickly to exchange, so this architecture can be consider as a „modular".

Main dimensions of the platform are as follows: Wing span: 11.8 m; Length: 4.65 m; Height: 1.71 m; Lifting area: 11.6 $m^2$; Aspect ratio: 12.0. Weights are as follows: MTOF: 450 kg; Empty weight: 200 kg; On-board equipment weight: 100÷150 kg; Fuel weight: 150÷100kg. Wing loading: 38,8 kg/$m^2$; Power loading: 5,6 kg/hp.

The design process was an interdisciplinary approach, and included a selection of thick laminar wing section, aerodynamic optimisation of swept wing, stability analysis, weight balance, structural and flutter analysis, many on-board redundant systems, reliability and maintability analysis, safety improvement, cost and performance optimisation. Presented paper focuses mainly on aerodynamic, wing design, longitudinal control and safety issues. Aerodynamic calculations were made using the

VSAERO program. The program uses the potential incompressible flow model (subsonic) coupled with boundary layer.

Predicted performance are: Max speed: 280 km/h; Cruising speed: 200 km/h; Min speed: 63 km/h; Rate of climb: 9.5 m/s; Ceiling: 8 km; Endurance (depending on sensors weight & speed): 10¸35 h; Range: 3200 km; Landing run/take-off run: 80 m.

Scenario of operation is adjusted to Polish conditions and based on the following assumptions: One return flight (2000 km) lasts 10 h; 10 aircraft fly simultaneously, each behind its predecessor at the distance of 200 km, i.e. each aircraft flies 1 h after the other one; Each aircraft scans the border strip on 10 km deep from both sides; People illegally crossing the border need at least 2 h to go through the border strip (It means that there is no chance to cross the border unnoticeable).

Sensor's suit should be adopted to the local conditions (flight altitude, necessary image resolution, local environment (forestry, necessity to look through the foliage etc.). One of possible option could be a high resolution SAR/GMTI I-MASTER™ radar of the following parameters: Single LRU configuration; Lightweight (30 kg); Diameter of 370 mm; Height 470 mm; Low power consumption (no more than 500 W); Multi-channel; Ku-band; Very wide bandwith; $360^{o}$ azimuth rotation; Elevation tilt $+10^{o}/ -55^{o}$; On-board processing; SAR including Strip, Spot and GMTI modes (In Strip mode the range up to 20 km, sub-metric resolution and very large swath; in Spot mode the range up to 15 km, sub-metric resolution and scanning up to 1.5 x 1.5 km; in GMTI mode the range up to 20 km, $360^{o}$ coverage + spotlight, Scanning speed $3^{o}$/s to $12^{o}$/s, accurate geo-location and a very low speed vehicle detection).

Successful design, testing and operation of this kind UAV can open a new very profitable business, important for security of European Union. Only Polish external border is more than 1500 km long, East European border is about 3000 km long and the whole Europe around is longer than 8000 km.

*Fig.4. Very light MALE UAV – PW-126*

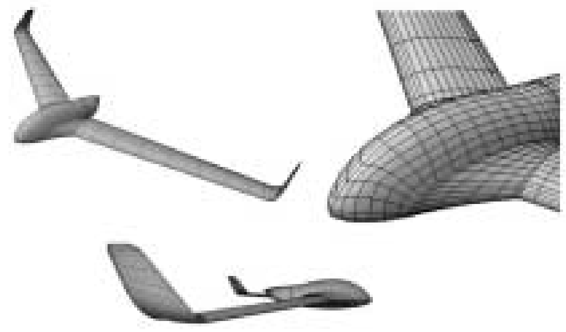

*Fig.5. Meshes for panel methods calculation*

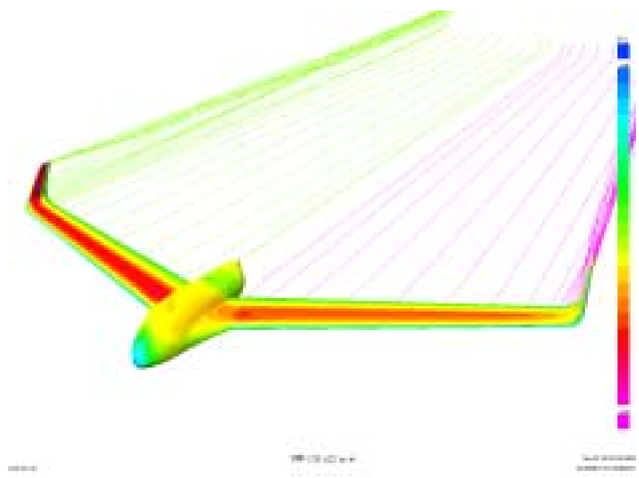

*Fig.6. Pressure distribution computed by VSAERO software*

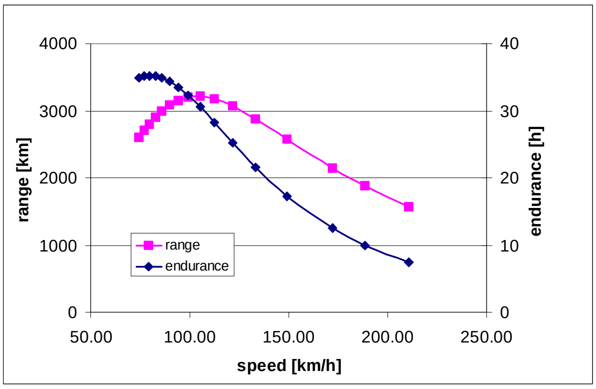


*Fig.7. Range and endurance computed at altitude 1 km*

*Fig.8. PW-126 – manned version (design to speed-up flight tests)*

## 4 PW-141 – MINI class UAV

PW-141 was inspired by Israeli K-70 [10] being developed and optimized under the CAPECON programme. K-70 is light weight (about 70 kg), modular configuration, with fuselage decoupled from wing and tail, with aft end of fuselage free for parachute deployment, a very reliable design (MTBUL > $10^5$; many redundant subsystems) and a very low target price (one airplane with sensors will cost less than $50 000). It must be emphasized that MINI UAV can now replace MALE [19,20] in various missions because of very rapid sensors miniaturization we are observing during recent years. K-70 will be equipped with the EADS mini SAR (resolution:0.5x0.5 m, weight: 4 kg; volume: 0.3x0.3x0.3 m, power consumption: less than 100 W). In both K-70 and PW-141 a mini EO/IR will be employed – TAMAN mini POP of 0.3 milli rad resolution, 6 kg of weight and diameter of 0.2 m. Both aircraft will have a very impressive endurance: 9 h in case of K-70 and more than 20 h in case of PW-141.

Below the design assumptions taken for PW-141 are presented.

Weights (in kg) of main elements have been assumed as follows:

1. sensor's container 3,5
2. wing 5,4
3. fuselage beams 1,2
4. empennage 1,2
5. undercarriage 3,5
6. **structure (total) 14,8**
7. power unit (2 engines 3W-35M plus 2 propellers 19x12") 6
8. fuel system 0,4
9. **structure plus power unit (total) 21,2**
10. on-board systems: 5,8
    a. electrical (generator, battery, transducer, wires)
    b. navigation
    c. communication
    d. control (6 ÷ 8 servo)
    e. antennas
    f. Video camera (pilot view TV)
11. emergency system (parachute) 2
12. empty weight(total) 29
13. mission payload 14
14. fuel (for 24 h endurance) 24
15. maximum take-off weight 67
16. maximum take-off weight including 3kg reserve fuel 70

<u>**straight wing configuration (total weight) Q=70 kg**:</u>

<u>Other assumptions:</u>

wing section: FX66-17AII-182/20; thickness 18,4%; aileron 20%

Loitering Reynolds number:

$$Re = \frac{40 \; x \, 0,35}{16 \, x 10^{-6}} = 0,875 * 10^6$$

$C_{L,max}$ for Re=0,7 x $10^6$ is equal to 1,4

Wing span and wing chord: b=4; c=0,35

Wing area S=1,4 $m^2$

Wing aspect ratio A=11,43

Stall speed:

$$V_S(H=0)=\sqrt{\frac{2Q}{\rho S C_{L,\max}}}=$$

$$\sqrt{\frac{2x700}{1{,}225x1{,}4x1{,}4}}=23{,}9\,m/s=86\,km/h$$

Landing weight (after typical mission):
$Q_L$ = 70 – 20 = 50 kg
and corresponding landing speed is equal to:

$$V_S(H=0)=\sqrt{\frac{2Q}{\rho S C_{L,\max}}}=$$

$$=\sqrt{\frac{2x500}{1{,}225x1{,}4x1{,}4}}=20{,}2\,m/s=72\ \ km/h$$

**Analysis of a typical surveillance mission:**
Power unit: 2 engines 30W-60i; power of one engine– 6 bhp; revolutions 1300 ÷8500 rpm; Q=2,42 kg; one engine cost: 427 euro.

It was assumed that mission (patrol) will take place at altitude H=0, with flight speed equal to 150 km/h = 41,7 m/sek. Lift coefficient is equal to

$$C_{L,patrol}=\frac{2Q}{\rho S V_{patrol}^2}=\frac{2x700}{1{,}225x1{,}4x41{,}7^2}=0{,}4601\ ,$$

and drag coefficient is equal to

$$C_D=0{,}025+\frac{0{,}4601^2}{\pi 11{,}43}=0{,}025+0{,}0059=0{,}0309$$

Lift to drag ratio can be computed as

$$E=\frac{0{,}4601}{0{,}0309}=14{,}89\ .$$

Thrust required for level flight at altitude H=0 is equal to:

$$T_{patrol}=\frac{1}{2}\rho S C_x V^2=$$

$$\frac{1}{2}x1{,}225\ x1{,}4x0{,}0309x41{,}7^2=41\,N=4{,}7kg$$

Power required for patrol is:

$$N_{patrol}=\frac{TV}{\eta_{propeller}75}=\frac{4{,}7015x41{,}7}{0{,}7\,x\ 75}=3{,}7\,bhp$$

Available power is equal to: $N_{available}$ = 0,7 x 12 = 8,4 bhp
Coefficient of power consumption:
$N_{patrol}/N_{available}$ = 0,44

The following figures show details of configuration of PW-141.

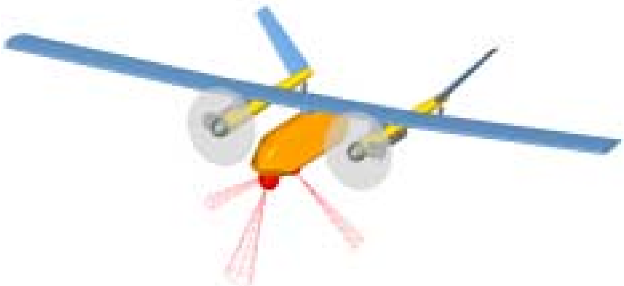

*Fig.9. PW-141 – a general configuration*

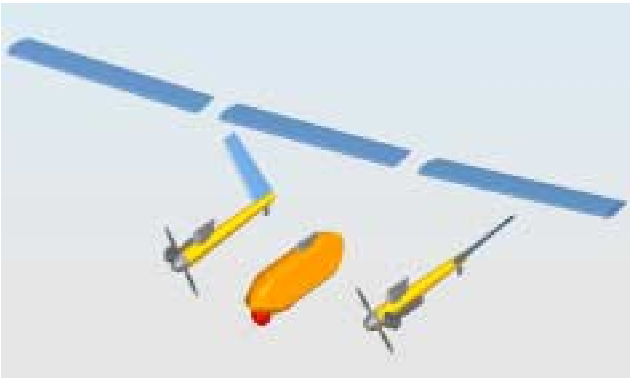

*Fig.10. Main design subsystems of PW-141*

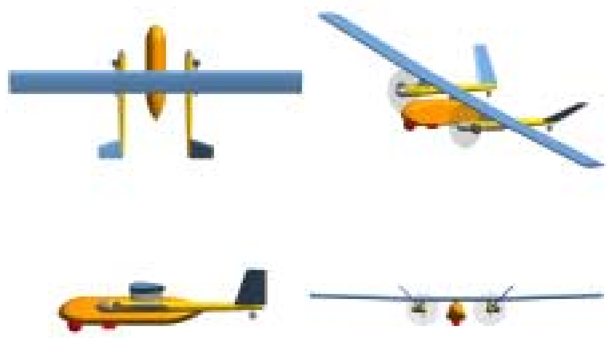

*Fig.11. Top, side and front views of PW-141*

*Fig.12. Front view – main container with FLIR (yellow)*

*Fig.13. Front-bottom view of PW-141 – main landing gear and tail wheel is well shown*

*Fig.14. Frames of main container and wing spars*

*Fig.15. A modified version (PW-141B) with nose wheel and redesigned wing attachment*

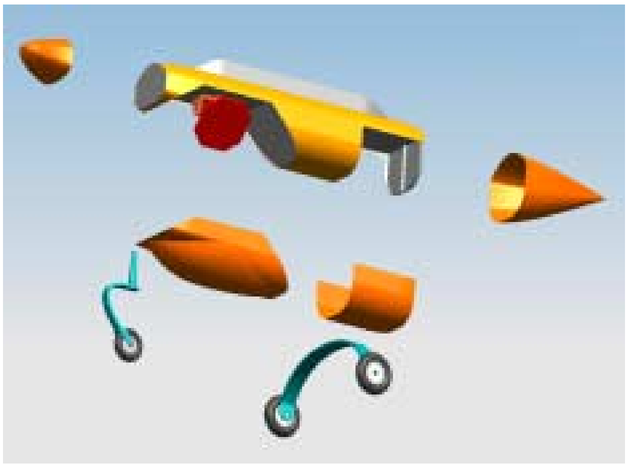

*Fig.16. Details of main container*

*Fig.17. Flying wing version (PW-141C)*

*Fig.18. Flying wing with container attached (micro SAR is visible)*

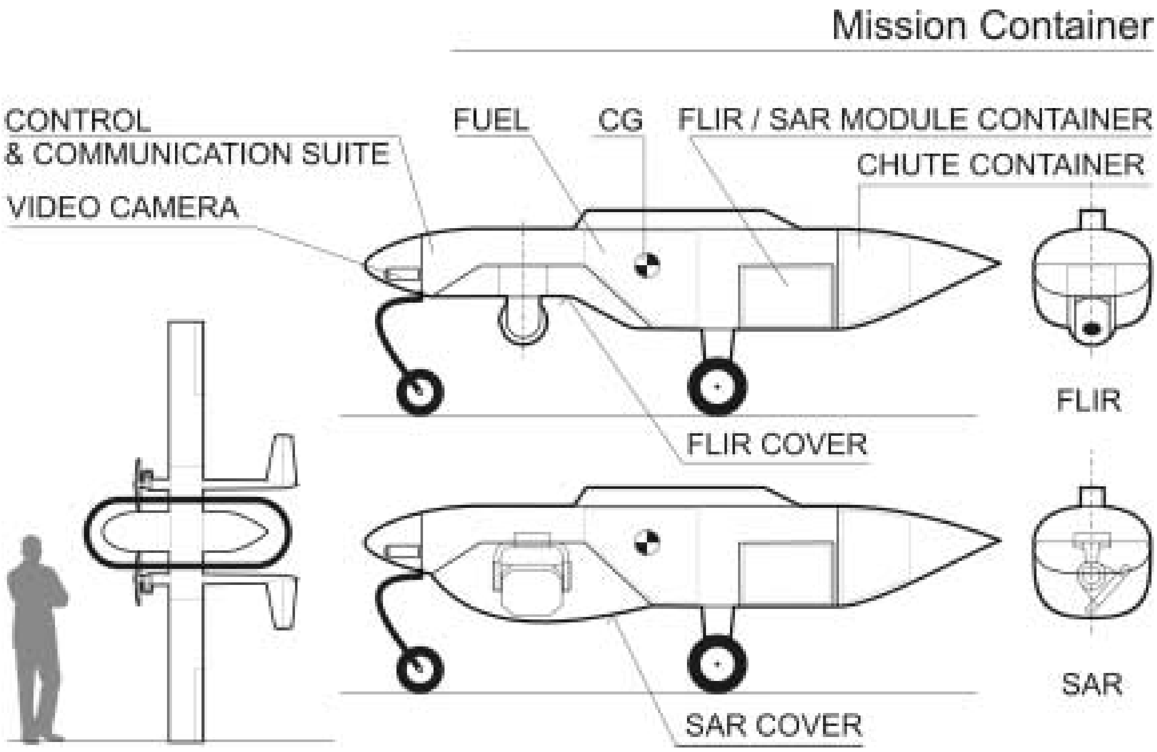


*Fig.19. Version B: FLIR can be replaced by micro SAR*

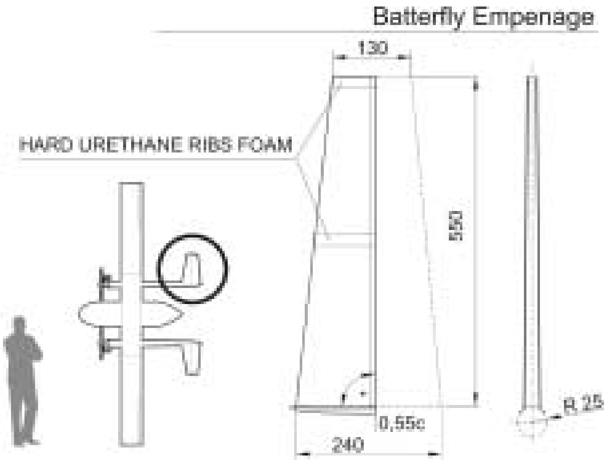


Fig.20. Selected design details of batterfly empennage

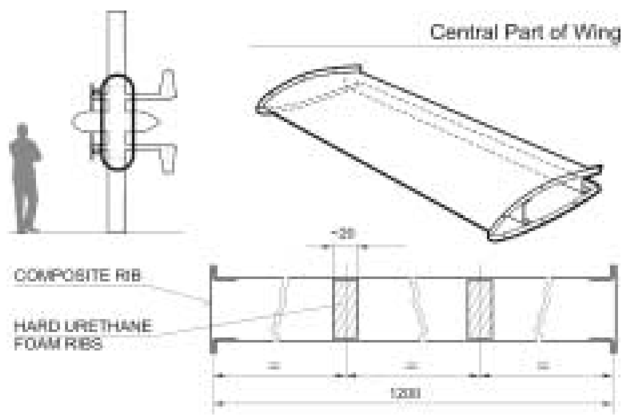


Fig.21. Central segment of main wing

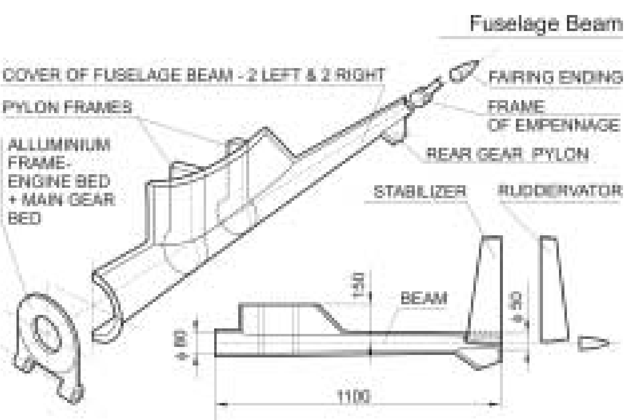


Fig.22. Design details of fuselage beams

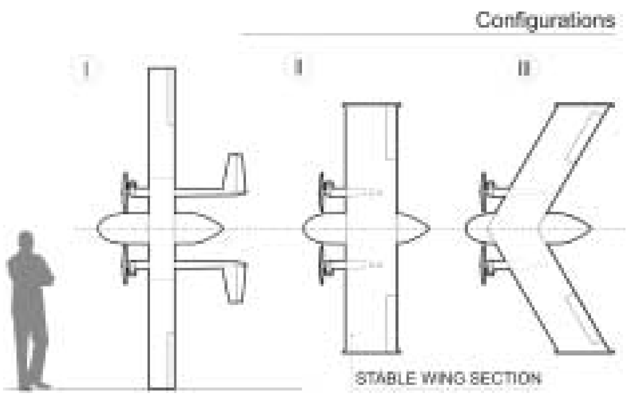


Fig.23. Configurations being considered in the project

## 5 Aerodynamic calculation

Digital geometry of an arbitrary aircraft generated within UNIGRAPHICS software can be easily transferred to VSAERO software using IGES file format. PW-126 and PW-141 UAV aircraft have been designed to be used in civilian missions including surveillance and monitoring. Important goal to be achieved in design effort was cost reduction, mainly by higher aerodynamic efficiency, lower fuel consumption and better performance. VSAERO software is used first of all for computing the main steady aerodynamic characteristics (lift versus angle of attack, induced polar drag, pitching moment, gradients of tailplane lift versus angle of attack and elevator deflection and many other static characteristics) of initial aircraft configuration, both for 2D and 3D flow. It is also used for modification and optimization of initial configuration [18,19] (i.e. a result of small geometrical changes introduced in UNIGRAPHICS can be estimated in VSAERO and performance software. It is usually an iterative process, to be completed when performance, stability and maneuverability are consistent with those in accepted preliminary requirements!). VSAERO software is based on classical panel method [18] (derived from the mathematical solution of Laplace equation) and is coupled with viscid boundary layer. Such an approach is widely used in aeronautical engineering practice and in most of cases guarantees a sufficient accuracy in acceptable time to be spent for aerodynamic and dynamic analysis.

The model of unmanned aircraft was built in Unigraphics system. The geometry was translated from it to the VSAERO pre-processor by the IGES translator. Building a mesh was the next step to build a model for aerodynamic analysis. The mesh is the point pattern, which describes the geometry of unmanned aircraft. The mesh consists of two main elements. The first is a flat rectangular panel. This panel is a basic element of computing mesh. The second element is the so-called ‘patch’. The ‘patch’ is a group of panels and the main division of aircraft surface. The ‘patch’ is also the main element used in a patch strategy.

The patch strategy is a technique of division aircraft’s surface into patches. This technique allows to change some patches if results of aerodynamic calculation are disappointing or some changes in geometry of aircraft were made. Wing’s patches might be replaced by wing’s patches with different span, for example.

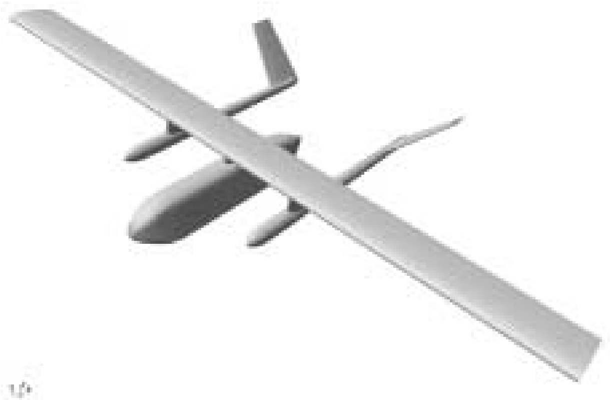

*Fig.24. Computational model prepared for aerodynamic analysis*

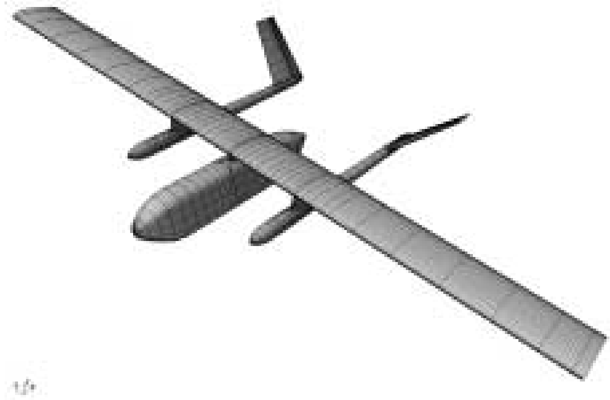

*Fig.25. Mesh over the aircraft surface*

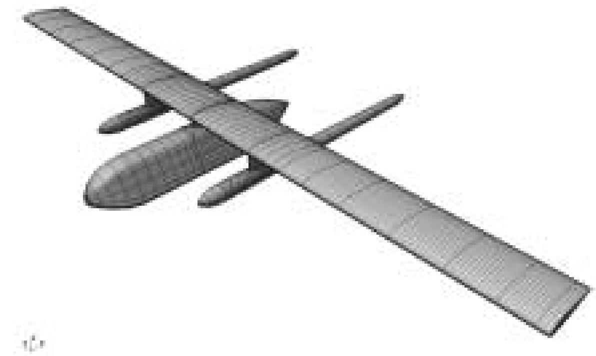

*Fig.26. Mesh over the aircraft surface – empennage excluded*

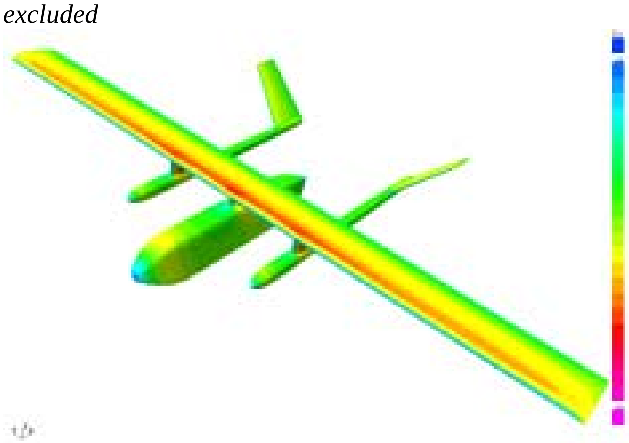

*Fig.27. Pressure distribution computed in VSAERO*

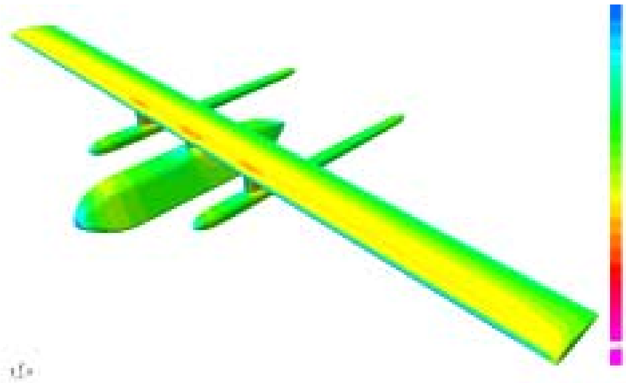

*Fig.28. Pressure distribution computed in VSAERO, empennage excluded*

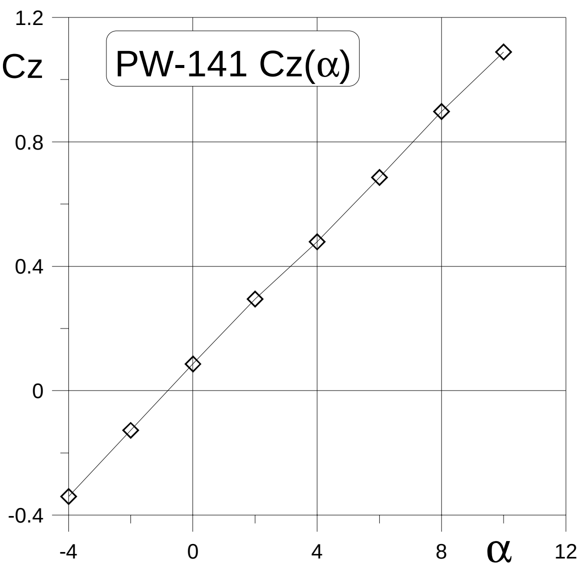


*Fig.29. Lift coefficient versus angle of attack (version PW-141A)*

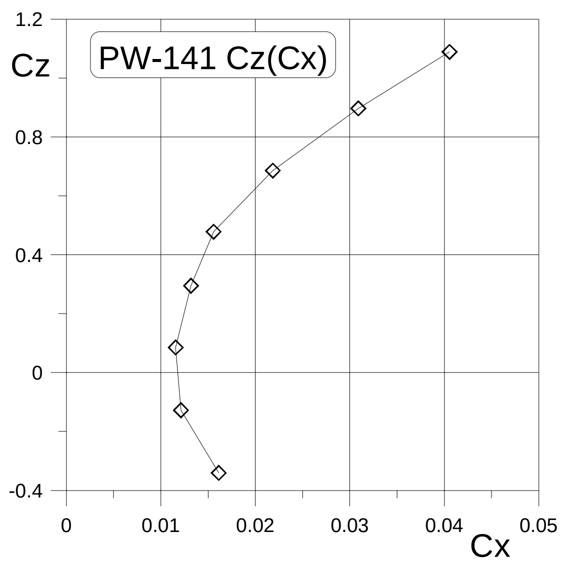


*Fig.30. Polar drag (version PW-141A)*

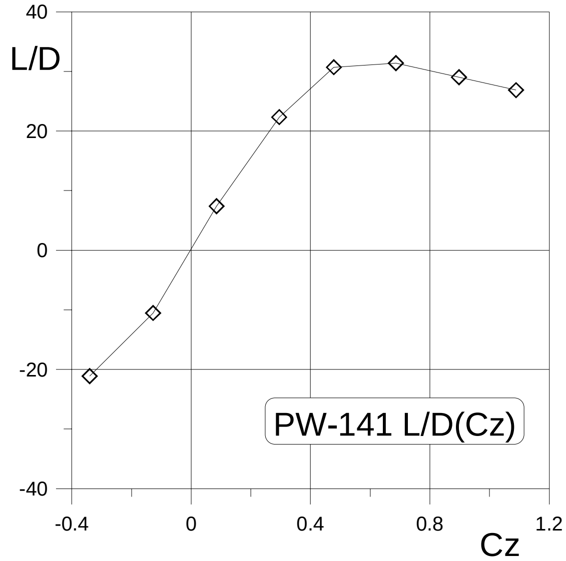


*Fig.31. Arerodynamic efficiency (version PW-141A)*

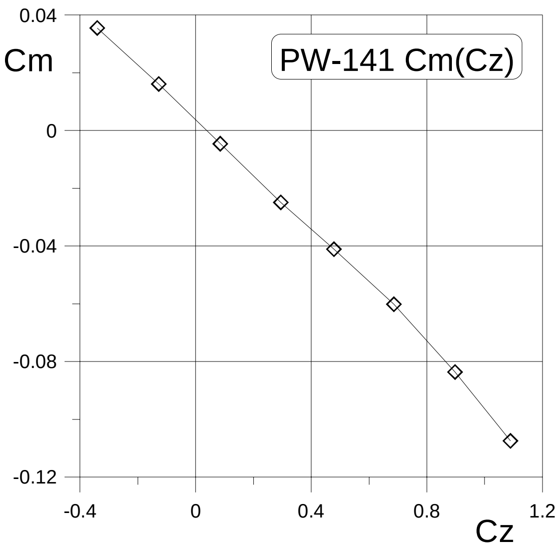


*Fig.32. Pitching moment versus lift coefficient (version PW-141A)*

## 6 Conclusion

MINI UAV called PW-141 (versions B and C) presented in this paper are still in the design phase. Tremendous progress in miniaturization of sensors enables to design a very small, light and cheap monitoring aerial system being able to deliver high resolution images through 24 hours a day. Redundancy and high quality reliable subsystems guarantee a safe operation and creates a new chances for users. Technology development offers a new opportunity for research and the whole economy, especially for New Member States.

## 7 References


1. European Civil Unmanned Air Vehicle Roadmap, www.uavnet.com
2. Wortman, A., Wyszkowski, C., Frydrychiewicz, A. and Goraj, Z., "High Altitude Reconnaissance Vehicle Enterprise". Design Conceptual Project submitted for DARPA, Santa Monica, 1995, unpublished.
3. Goraj Z.,: "Dynamics of a High Altitude Long Endurance UAV", ICAS Congress 2000, England, Harrogate, paper 362.
4. Goraj Z., Ueda T., "Ultra Light Wing Structure for High Altitude Long Endurance UAV", ICAS Congress 2000, England, Harrogate, paper 476.
5. Goraj Z., Frydrychewicz A., Winiecki J., "Design Concept of a High Altitude Long Endurance Unmanned Aerial Vehicle", Aircraft Design - An International Journal, Vol.2, No.1, (1999), pp.19-44.
6. Website: www.uavnet.com
7. Goraj Z., "Civilian Unmanned Aerial Vehicles – Overview of European Effort and Challenges for the Future". Aviation Journal, Vilnius 2003, Aviation, Vol.VII, No 2, pp.1-18, 2003.
8. Tsach Sh., "Advanced Technologies for Civil Applications UAV's". Rochester UAVNET meeting, July 2002, www.uavnet.com
9. Morag A., "Aurora Flight Sciences Corporate Overview". Eilat UAVNET meeting, Oct. 2002, www.uavnet.com
10. CAPECON Project No GRD1-2001-40162 ("Civil UAV Applications & Economic Effectivity of Potential CONfiguration Solutions"), Technical documents 2002-2004. V FR of European Union.
11. Goraj Z., Ransom Ph., Wagstaff P., "Dynamics and design aspects of future UAV's", Aviation, Vol.VII, No 3, pp.20-36, 2003.
12. Goraj Z., Frydrychewicz A., „Development Approach of the PW_103 - An Increased Reliability MALE UAV - Under the CAPECON Project Within the V FR of EU", Proc. Of 24th ICAS Congress, Yokohama 2004, Paper 443.
13. Goraj Z., Frydrychewicz A., de'Tallec C., Hermetz J., "HALE UAV platform optimised for a specialized 20-km altitude patrol mission", Proc. Of 24th ICAS Congress, Yokohama 2004, Paper 285.
14. Goraj Z., Frydrychewicz A., Świtkiewicz R., Hernik B., Gadomski J., Goetzendorf T., Figat M., Suchodolski S., Chajec W., "High Altitude Long Endurance Unmanned Aerial Vehicle of a New Generation – a Design Challenge for a Low Cost, Reliable And High Performance Aircraft", Bulletin of Polish Academy of Sciences, Vol.52, No.3/2004, pp.173-194.
15. Tsach S., Yaniv A., Avni H. and Penn D., "High Altitude Long Endurance (HALE) UAV for Intelligence Missions", 20th ICAS Proceedings, Vol.I, Sept. 1996, 368-379.
16. Z.Goraj, PW-125 MALE UAV design project developed in Warsaw University of Technology. AIAA 3rd conference "Unmanned Unlimited", Chicago, Sept. 2004, AIAA paper 6326.
17. Z.Goraj, Civilian Long Endurance UAV – a Design Challenges. Aviation, Vol.IX, No 2, pp.3-9, 2005.
18. M.Figat, T.Goetzendorf-Grabowski, Z.Goraj, Aerodynamic Calculation of Unmanned Aircraft. Aircraft Engineering and Aerospace Technology, Vol.77, No. 6, 2005, pp.467-474.
19. Z.Goraj, Design Challenges associated with development of a new generation UAV. Aircraft Engineering and Aerospace Technology, Vol.77, No. 7, 2005, pp.361-368.
20. J.Gadomski, B.Hernik, Z.Goraj, Analysis And Opimisation of a Male UAV Loaded Structure. Aircraft Engineering and Aerospace Technology, Vol.78, No. 2, 2006, pp.120-131.