Conceptual Design and Control of Twin-Propeller Tail-Sitter mini-UAV

Conceptual Study of V-TS mini-UAV

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***Abstract*—This paper describes progress made on the design and analysis of a twin-propeller tail-sitter mini-UAV (named V-TS). Because the V-TS mini-UAV is a combination of airplanes and copters, high energy efficiency during the forward flight and VTOL capability in the hover flight are achieved. However, this configuration also brings new challenges and difficulties, especially in the case of control. Free software which was used in the design process is presented and described. AVIGLE Demonstrator is analyzed in SU^2 to verify correct settings of the aerodynamic analysis. Furthermore, 3D model of the V-TS mini-UAV with the Y-tail configuration and its basic geometrical parameters are shown. The results prove that it is aerodynamically efficient for our purpose. In addition, probably all control modes, transitional flight phases, and difficulties which appear in the control of the twin-propeller tail-sitter mini-UAV are defined and solutions are proposed. The transitional flight phases are determined as a combination of the control modes and sub-modes.**

Keywords*—conceptual study; duocopter; tail-sitter; twin-propeller; UAV; VTOL

List of symbols

C_D	drag coefficient
C_{D0}	zero-lift drag-coefficient
CG	center of gravity
C_L	lift coefficient
C_{L0}	zero lift coefficient
C_{L_max}	maximum lift coefficient
C_L/C_D	lift-to-drag ratio
CT (N)	center of thrust
LT (N)	left-propeller's center of thrust
MAC	mean aerodynamic chord
Re	Reynolds number
RT (N)	right-propeller's center of thrust
α (°)	angle of attack

I. Introduction

Unmanned aerial vehicles (UAVs) have been used for a wide variety of missions, such as surveillance and reconnaissance, search and rescue, border protection, surveying, agriculture, and meteorological monitoring. Generally, they have been used for both military and civil purposes. It is obvious that large and small UAVs are suitable for military applications; however, small UAVs are better candidates for civilian use because they require low operational costs, low human resources, and have high readiness. In contrast, large UAVs involve a considerable operational cost and many infrastructures.

Because of the increasing variety of missions and operation environments, a UAV should be both maneuverable (e.g. vertical takeoff, landing, hovering) and energy efficient (i.e. longer range or endurance). Tail-sitter UAVs offer unique capabilities which are not possible for conventional fixed-wing airplanes or rotary-wing aircrafts because they combine the desirable capabilities of both these configurations in a single platform.

Compared to fixed-wing airplanes, a tail-sitter UAV can take off and land vertically and hover. These capabilities are advantageous in urban, nature, and other constrained environments where limited access to a runway, catapult launchers or recovery nets is. Moreover, by nature of its design, fixed-wing airplanes need additional facilities and human involvement for safe takeoff or landing, which significantly complicate its fully automated operation.

Although helicopters have a great vertical take-off and landing (VTOL) capability, their cruise performances, such as flight speed, duration, and endurance are worse than those of fixed-wing aircrafts. On the contrary, tail-sitter UAVs can achieve long flight endurance and range which can extend the mission efficiency. As a result, tail-sitter UAVs are very suitable for a wide variety of missions and environments.

Historically, few manned tail-sitter aircrafts were researched and developed, for instance Convair XFY-1 "Pogo" [1], Lockheed XFV-1 [2], and Bachem Ba 349 [3]. The first two are Navy prototypes contracted as vertical take-off turboprop fighters. The pogo sat on outrigger wheels mounted on its cruciform delta fins; for comparison, the XFV-1's outrigger wheels were mounted on its cruciform tail. The Pogo made the successful transitions from the vertical take-off to the level flight and from the level flight to the vertical landings. On the other hand, the Lockheed never made the transitions despite application of the same engine which was used because the sufficiently powerful engine was only designed but never implemented. This difference results from application of the delta wing in Pogo which tolerates much higher angles of attack than straight wing in XFV-1. Consequently, the Pogo was capable to perform transition maneuver at much lower airspeed which means that it required much less powerful propulsion. Nevertheless, the Pogo's lightweight design, the lack of spoilers and air brakes caused the low ability to slow down and stop after moving at high speeds. Performance of both aircraft remained limited by the confines of the flight test regime which was not appropriate for fighter aircraft. Both projects were cancelled, the most due to very difficult handling during transition and landing, and also because of the engine problems.

In short, manned tail-sitter aircrafts have never been widely used in real missions due to the very difficult piloting, especially during landing, transition, and take-off. On the other hand, with the modern computing technology and improvements in sensor reliability, capability and cost, it is now possible to overcome the piloting disadvantages by using the concept of a UAV. With the pilot replaced by modern control systems, it should be possible to implement a usable tail-sitter configuration.

Among the various implementations of VTOL aircraft, a tail-sitter aircraft is probably the simplest one because it does not require any extra actuators (e.g. tilting mechanisms) for the VTOL maneuver. This is particularly useful for mini-UAVs in order to save weight and manufacturing complexity.

Tail-sitter UAVs, such as SkyTote [4] and GoldenEye [5], have been actively developed by a number of researchers. The SkyTote is equipped with coaxial counter-rotating rotors for the propulsion system. The GoldenEye is equipped with ducted propellers for the propulsion system and uses independently trimmed wing design in the main wings which are used in wing-borne flight. However, these commonly known tail-sitter UAVs have bigger size and higher weight than that which is usable for mini-UAVs. Furthermore, their complete solution is more complex than it is necessary for our purpose.

Several projects of tail-sitter mini-UAVs have been investigated too. Researchers have published information about their concepts or realizations, such as a mini-UAV with three fuselages and twin counter-rotating propellers [6], [7]. Despite the authors called it "tail-sitting VTOL UAV", it has to be propped to achieve the vertical position before takeoff. Moreover, during landing, it touches down with the tail gears at first but then it drops forward to touch down with the main gears. The tail was not designed for the full tail-sitting operations and three fuselages should not be aerodynamically effective for mini-UAVs.

In [8], a micro-UAV with two engines in a coaxial, counter-rotating configuration, and with an elevator and a rudder located in the slipstream was used. A quad-rotor tail-sitter mini-UAV without any control surfaces was shown in [9]. Another quad-rotor tail-sitter mini-UAV was presented in [10]. In fact, it is rather wing-sitter due to its flying-wing configuration; same as twin-propeller micro-UAVs described in [11], [12] and a pusher single-propeller mini-UAV developed in [13]. In [14] and [15], a progress made on the T-wing UAV with canard configuration and twin propellers was discussed. A conceptual design of a mini-UAV equipped with a ducted propeller, four actuated fins, as well as structural and landing support was proposed in [16] and very similar solution with small wings and tail was implemented in [17].

Of course, other VTOL solutions exist, such as mini-airplanes in [18], [19], [20], and [21] which have physically separated multi-rotors for hover flight and one or two propellers for the forward flight. Also tilt-wing mini-UAVs [22], [23] and tilt-rotor mini-UAVs [24], [21] are often designed. However, these concepts are more complicated than it is necessary; they need additional mechanical parts which increase weight and also structural requirements and control complexity. These mechanisms are not suitable for mini UAVs.

As can be seen, mostly tail-sitter UAVs with coaxial contra-rotating propellers, of flying wing or T-wing configuration, and with separated rotors for hover and cruise flight are used. However, a simpler design of a tail-sitter mini-UAV is possible. Twin-propeller tail-sitter mini-UAVs with Y-tail are not common and have not been satisfyingly examined and implemented, especially in the Europe.

Our proposed design has the following special features. Twin counter-rotating propellers on the right and left main wings cancel the rotating torques of the propellers; this configuration is simpler and more energy efficient than the other candidates, such as coaxial counter-rotating propellers/rotors. The complexity of the control system is mostly comparable or even easier; moreover, twin propellers also allow special maneuvers in the hover flight.

The ailerons and elevator immersed in the slipstream of the propellers are sufficient to enable attitude control even in the hover flight and a low-speed. No complicated control devices, such as the cyclic pitch control system of rotors, are required. Another advantage is the wide angular range of the forward view from sensors positioned in the fuselage; in some other tail-sitter designs, the center of the aircraft is occupied by the propulsion systems. In addition, the Y-tail should have sufficient weight distribution during tail-sitting and should generally be more effective than, for example, X-tail.

For the design and analysis of the V-TS mini-UAV, free software was used. In [25], parametric design, aerodynamic analysis and parametric optimization of a solar UAV were investigated using FreeCAD, and XFOIL. However, the aerodynamic analysis was performed by using commercial Star-CCM+ CFD. In [26], the work combines OpenVSP with OpenFOAM to create and analyze an aircraft. In [27], four types of reduced fidelity or degenerate geometric representations were defined and implemented in OpenVSP for the purpose of bridging the gap between conceptual design and analysis. In [28], tools, such as Digital DATCOM, AVL, and QPROP, were used for the conceptual design and engineering analysis of micro air vehicles. In [29], conceptual design tool was developed to assess electrochemically-powered micro air vehicles.

As can be seen, approaches when new design and implementation are achieved by using free applications are increasingly explored in the several last years. Nevertheless, the researchers also mostly use commercial software (e.g. Matlab, Star-CCM+ etc.) which negates the profits from the low financial costs. Moreover, they often use methods which are not appropriate for the precise analysis of the current small UAVs. For example, Digital DATCOM is not recommended for aerodynamic calculation at the low Reynolds numbers and AVL is based on simple CFD methods which constrain its applicability.

Despite the higher calculation costs, a better alternative is to use new, sophisticated, and accurate CFD software, such as SU^2. For selected 2D and 3D test cases, SU^2 solutions are shown to be in good agreement with both the available experimental data and numerical simulation results from other well-established computational tools as shown in [30], [31], [32], and [33]. Unfortunately, the results have been validated mostly for aircrafts and airfoils at high speeds. Probably only our previous paper [34] discussed the use of SU^2 on mini-UAVs; however, that work requires further extensions and research.

The aim of this work is to create and analyze a conceptual design and control of the twin-propeller tail-sitter mini-UAV which is currently developed in our faculty. This work builds on four technical objectives. The first is to propose the design of the mini-UAV, including the selection of wing and tail airfoils. The second is to perform aerodynamic analysis of the mini-UAV. The third is to define and evaluate the control modes for the cruise flight and the hover flight, including the technique using the adjustable center of gravity. The last but not least is to review possible transitional flight phases which can be applied on the mini-UAV.

This paper begins with the description of the free software which was used for the design and analysis of V-TS mini-UAV. New design of a tail-sitter mini-UAV is proposed, and its aerodynamics and feasibility are discussed. Finally, requirements and options of its control system are analyzed and described.

This UAV has been developed in response to meet demands for a more flexible surveillance and remote sensing platform than is currently available. Missions may include area monitoring, intelligence gathering, and border surveillance for civil or police use in an urban or natural environment. Because of its design, V-TS mini-UAV can be used without throwing or launching which is a suitable approach for universal UAVs.

II. SOFTWARE FOR DESIGN AND ANALYSIS OF MINI-UAV

In this section, software which was used for the design and analysis of the tail-sitter mini-UAV is described. The connections between the applications are illustrated in Fig. 1. Because all the software is free of charge and freely available, the financial cost was minimized.

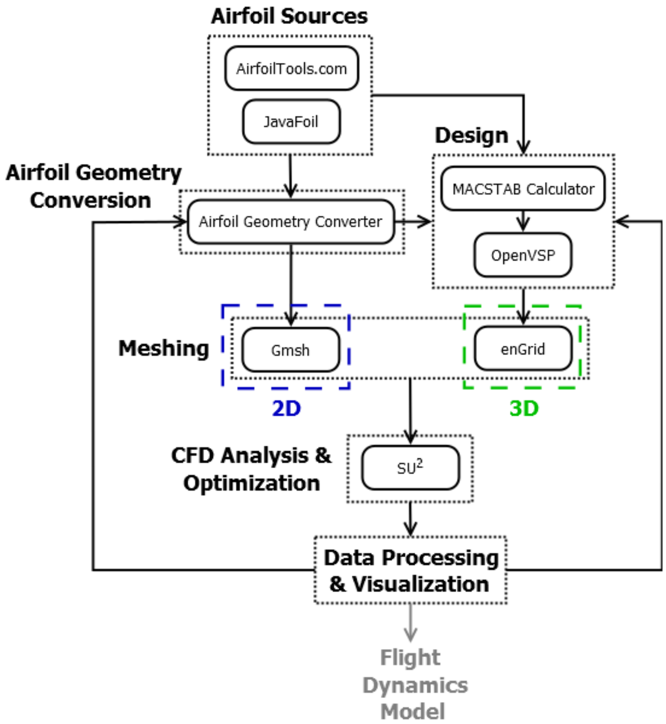

Fig. 1. Free Software for Design and Analysis of mini-UAV

The diagram shows two paths: one for 2D (airfoil) and the other for 3D (UAV, wing, tail). A feedback to the design process is also illustrated which emphasizes an option to improve the current mini-UAV and to create its new version. An advantage of this system is that all software can also be used for larger subsonic airplanes.

First of all, airfoil geometry data have to be obtained. It may be easily performed by using AirfoilTools [35] which can display and analyze airfoils from database or generate NACA 4-digit, NACA 5-digit, and user-defined airfoils.

Another option is to use JavaFoil [36]. JavaFoil may generate many standard airfoil types, e.g. 4-digit series, 5-digit series, 16-series, 6-series, EH series, symmetrical circular arc airfoils, user-defined airfoils, and others [37]. JavaFoil uses several traditional methods for airfoil analysis: the potential flow with a higher order panel method, and the boundary layer.

For aerodynamic analysis and optimization of airfoils in SU^2 CFD, a mesh process has to be performed. Airfoil Geometry Converter (AGC) [38] is a console utility which converts files with coordinates from/to the Selig and Lednicer formats. AGC can be used as a mesh file generator of airfoils for CFD software; e.g., in SU^2 and OpenFOAM. The files may be also converted back from the mesh file to a geometry file; for example, when an optimized airfoil should be applied to a wing in the real design of an aircraft. Then, the optimized airfoil can be easily used in CAD, or in a parametric application specialized on the aircraft engineering; such as OpenVSP. More information about AGC was published in [39].

In fact, AGC only converts geometry to GEO format, the mesh files are generated using Gmsh [40]. It is a finite element grid/mesh generator with a build-in CAD engine and post-processor [41]. It may export meshed geometry to SU2, MSH, STL and many others.

MACSTAB Calculator [42] is an application for the calculation of the Mean Aerodynamic Chord (MAC) of an arbitrary wing planform [43] and for the STABility estimation (in conceptual design) of a wing-tail aircraft configuration. The stability calculation is based on the tail efficiency, the position of Center of Gravity and Neutral Point which are set by user, and also on MACs, areas, and aspect ratios of a wing and tail. However, there is always compromise between good maneuverability and high stability. The entire geometry of the objects may be exported to VSP2 format which can be opened using OpenVSP 2.3.0, or imported to OpenVSP >=3.5.0. Then, the exported wing and tail may be used in design of an aircraft, or may be converted, modified, analyzed, and 3D printed.

OpenVSP [44] is a parametric aircraft geometry tool which allows the user to create a 3D model of an aircraft defined by common engineering parameters [45]. This model can be processed into formats suitable for engineering analysis, for example into STL, MSH, HRM, 3DM, FEL, etc.

enGrid [46] is open-source mesh generation software which is used predominantly for CFD applications. enGrid provides native export to SU^2 and OpenFOAM.

The Stanford University Unstructured (SU^2) suite [47] is an open-source, computational analysis and design software collection. SU^2 is being developed to solve complex, multi-physics analysis and optimization tasks using arbitrary unstructured meshes. All necessary information about methods and governing equations used in SU^2 may be found in [31], [32], [30], and [33]; and therefore they are not described in this paper.

More details about all the software can be found in [48]. It is important to emphasize that in the diagram (Fig. 1), no application for the structural analysis is included. The modelling and simulation usually do not need this kind of software; however, it is necessary during the following development. CalculiX [49] application can be used to perform the structural analysis.

III. Design and Aerodynamic Analysis of Tail-Sitter mini-UAV

The design of tail-sitter UAVs combines the capabilities of airplanes and copters. This approach includes advantages, such as VTOL and energy efficiency during forward flight, but also some difficulties and constraints. For example, the entire design has to be tailored to the specific flight modes and maneuverability, and at the same time has to be sufficiently aerodynamically efficient and stable.

The tail-sitter mini-UAV designed in this work should be able to operate at low altitudes (to 1 km) and velocities (approx. between 35 and 110 km/h). The geometry of the mini-UAV is shown in the first subsection and the description of the used wing and tail airfoils follows in the second. In the last subsection, the aerodynamic analysis of V-TS mini-UAV is compared with AVIGLE mini-UAV [23].

A. Design of Twin-Propeller Tail-Sitter mini-UAV

Fig. 2 illustrates the 3D model design of V-TS mini-UAV. The blue line directs to the aerodynamic center of the wings and the black line to the center of gravity of the mini-UAV.

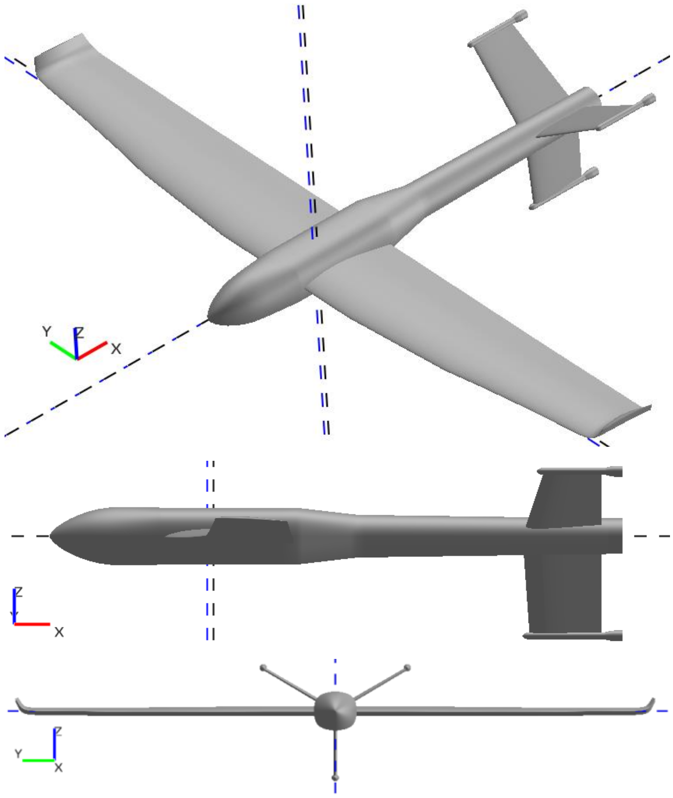

Fig. 2. 3D Model of V-TS mini-UAV (v1-532)

Basic geometrical parameters of V-TS mini-UAV are listed in Table I. The values indicate that the mini-UAV is designed for maneuverability in pitch but it should be also sufficiently stable.

TABLE I. Geometrical Parameters of V-TS mini-UAV

Parameter	Value
Fuselage Length	80 cm
Wing Span	138 cm
Wing Projected Span	135 cm
Wing Area	2172 cm^2
Wing Projected Area	2139 cm^2
Wing Aspect Ratio	8.768

Parameter	Value
Wing Projected Aspect Ratio	8.52
MAC Length	16 cm
25% of MAC (x)	22.023 cm
Horizontal Tail Span	35.5 cm
Horizontal Tail Area	337.25 cm^2
Horizontal Tail Effective Area	252.9375 cm^2
Horizontal Tail Aspect Ratio	3.737
Horizontal Tail Volume Coefficient	0.3514
Vertical Tail Span	14 cm
Vertical Tail Area	147 cm^2
Vertical Tail Aspect Ratio	1.333
Vertical Tail Volume Coefficient[a]	0.0302
Center of Gravity (x, y, z)	(22.900, 0, 0) cm
Neutral Point (x, y, z)	(24.963, 0, 0) cm

a. The horizontal V-tail contribution was considered.

The UAV weight with all necessary components should be around 1.5 kg and the maximum permissible takeoff weight is 2.0 kg. The thrust to maximum weight ratio should be at least 1.5 for safe and comfortable 3D flight, i.e. the thrust of at least 1.5 kg per propeller for our case.

The mini-UAV has 4 landing elements; due to the center of gravity, the weight acts mostly on the center element. On the other hand, the outer landing elements rather maintain balance. As can be seen, the tail areas are rotated around *x* axis by 120° to each other. This Y-tail is preferable to the X-tail because of its generally lower drag, lower weight, and higher effective area (when considering the same size of tails).

Compared to conventional airplanes, the center of thrust of tail-sitter UAVs has to be in the same point at *z* axis as the center of gravity is. Otherwise, the UAV would not remain in balance during the hover flight because it would be tilted towards the center of gravity as can be seen in the Fig. 3.

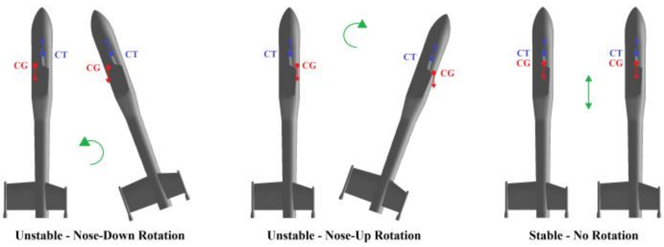

Fig. 3. Center of Thrust and Center of Gravity Interaction During Hover for Tail-Sitter mini-UAV

It should be noted, that during take-off, this effect may be minimized by using elevator; however, the aircraft would be unable to land or hover safely. Another option how to solve this problem could be the installation of tilt-propellers which would act against the tilt effect. On the other hand, there would be more design and structure requirements, higher weight, more complex control, and higher price; and therefore, fixed engines and propellers are assumed to be used in the designed mini-UAV.

Because it is advantages to have the uniform weight distribution on the landing elements and the center of thrust has to copy the center of gravity at *z* and *y* axes, the only simple and satisfactory solution is to use the mid wing configuration with no or very low dihedral/anhedral angle. Other solutions could be combinations of a high wing and an anhedral angle, or a low wing and a dihedral angle (examples are shown in Fig. 4); nevertheless, their usage would bring only insignificant benefits to our project.

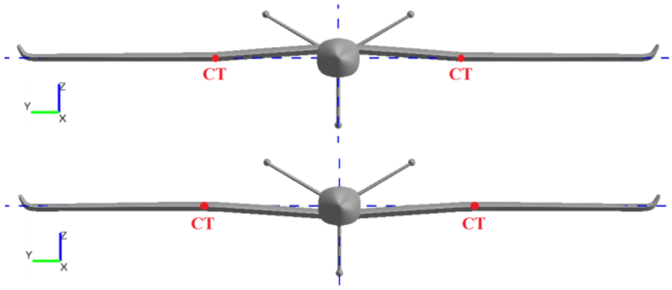

Fig. 4. Other Options of Wing Configuration for V-TS mini-UAV

A slight dihedral angle of 1° and twist angle of -1° is used at the wings of V-TS mini-UAV from 38 cm to 66 cm (measured from the centerline of UAV). At the end of the wings, blended winglets are placed with dihedral angle of 60°.

B. *Wing and Tail Airfoils of V-TS mini-UAV*

After a comprehensive aerodynamic analysis of 27 airfoils, the MH 38 airfoil was chosen due to its best lift-to-drag ratio. MH 38 airfoil has the maximum thickness of 9.7% at 31.6% chord and the maximum camber of 3.9% at 45.3% chord.

To improve the aerodynamic characteristics, the drag optimization was performed on the MH 38 airfoil by using SU^2 software – the adjoint method, and the Hicks-Henne bump functions. After these optimizations, new experimental wing airfoil was created; the working title is "MH 38-OPT D1.2". It has the maximum thickness of 8.9% at 36% chord and the maximum camber of 3.9% at 45.3% chord. This airfoil was used in designed wings of V-TS mini-UAV. The geometry comparison of the optimized and original airfoils might be seen in Fig. 5.

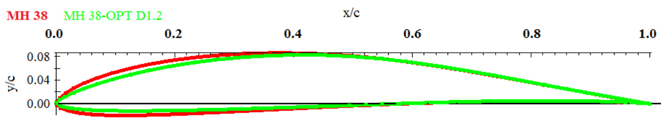

Fig. 5. MH 38 and MH 38-OPT D1.2 Airfoil Comparison for Wing

The symmetrical airfoil named S9033 was used for the tail parts. The S9033 airfoil has maximum thickness of 7.5% at 22.8% chord; its geometry is shown in Fig. 6.

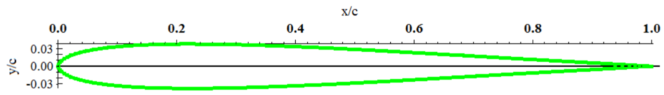

Fig. 6. S9033 Airfoil for Tail

C. Aerodynamic Analysis of V-TS mini-UAV

An aerodynamic analysis of the V-TS mini-UAV was performed in this section. Firstly, the accuracy of the used method had to be verified on a mini-UAV with similar proportions, mission, operating speed, and tested Reynolds number (Re).

We used AVIGLE Demonstrator mini-UAV [23] because it meets the requirements and the authors published enough information about its aerodynamic characteristics in a wind tunnel. The AVIGLE Demonstrator had actually half size in the tests than the designed version which is positive for our research. AVIGLE was analyzed at *Mach* speed of 0.0882 and *Re* of 3.68×10^5. Our first analysis in SU^2 software using ROE (Roe's Approximate Riemann Solver) method for computing convective fluxes was published in [34]; however, after upgrade to newer version (from 3.2 to 4.0), the results of the analysis changed.

Simplified comparison of differences between these versions is illustrated in Table II. It should be noted that the JST (Jameson-Schmidt-Turkel) flow gives exactly same results for both versions; in other words, the changes influenced only the ROE flow.

TABLE II. AVERAGE ABSOLUTE ERRORS FOR AERODYNAMIC COEFFICIENTS TESTED ON AVIGLE DEMONSTRATOR

Software (flow)	Average of Absolute Errors for C_L	Average of Absolute Errors for C_D	Angles of Attack
SU^2 (ROE v3.2)	*2.51 %*	11.59 %	-5° to 22°
SU^2 (ROE v4.0)	5.27 %	*8.61 %*	-5° to 22°

It is obvious that the lift coefficients seem to be less accurate; on the contrary, the drag coefficients are probably more accurate. It is surprising that the lift curve (see Fig. 7) for the 3.2 version is almost exactly same as for the wind tunnel test. Paradoxically, a combination of the drag curves (see Fig. 8) for both versions would be the most accurate solution.

Despite the version 3.2 has better results in this case, we preferred the newer version because it is not clear whether the results were really more accurate due to the different version of the algorithms, or whether there were other circumstances, such as the medium mesh quality, imprecise wind tunnel tests, designer's fault etc. and it just seems to be more accurate. In general, a new version usually means that bugs were fixed and methods were improved.

It should be also emphasized that because of some unpublished information about the geometry of AVIGLE, we was not able to create the exactly same 3D model and some properties had to be estimated. On the other hand, the results are very close to the wind tunnel tests; thus, the differences were probably not too high.

We used the Reynolds-averaged Navier-Stokes (RANS) equations with the compressible flow solver for the aerodynamic analysis. However, numerical discretization of the governing fluid dynamic equations using a conservative formulation often results in excess artificial viscosity at low Mach numbers. This degrades the performance of the compressible solver in regions of the low Mach number flow. Preconditioning techniques such as Roe-Turkel was developed in SU^2 for solving nearly incompressible flow problems using the same numerical methods developed for the compressible flows. This can be particularly useful when a part of a flow field is essentially incompressible. [31] [34] [48]

Fig. 7, Fig. 8, Fig. 9, and Fig. 10 show the aerodynamic characteristics of the V-TS mini-UAV analyzed in SU^2 (version 4.0). Other three curves in the graphs belongs to AVIGLE mini-UAV; there are CFD analysis performed by using SU^2 version 3.2 and 4.0, and the wind tunnel test data. These characteristics are here for both detailed accuracy comparison of the used method and settings and moreover, for brief comparison between V-TS mini-UAV and AVIGLE mini-UAV.

The aerodynamic characteristics of V-TS mini-UAV was analyzed for *Mach* speed of 0.0882 (i.e. 30 m/s) and *Re* of 3.34×10^5. This adjustment is probably clear; it was necessary to set similar conditions during the CFD analysis as for AVIGLE to achieve the appropriate comparison.

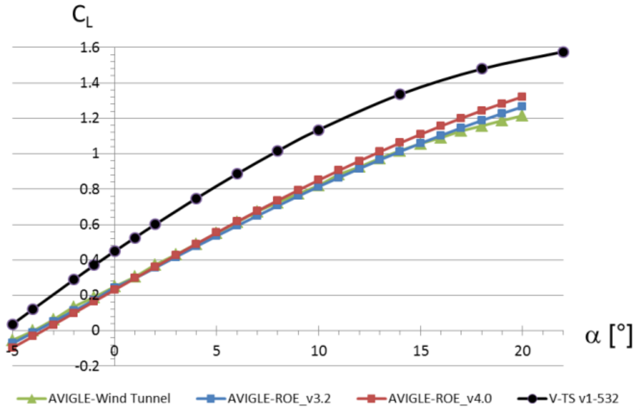

Fig. 7. Comparison of V-TS and AVIGLE mini-UAVs - C_L vs. α – (Mach = 0.0882, Re = 3.34×10^5)

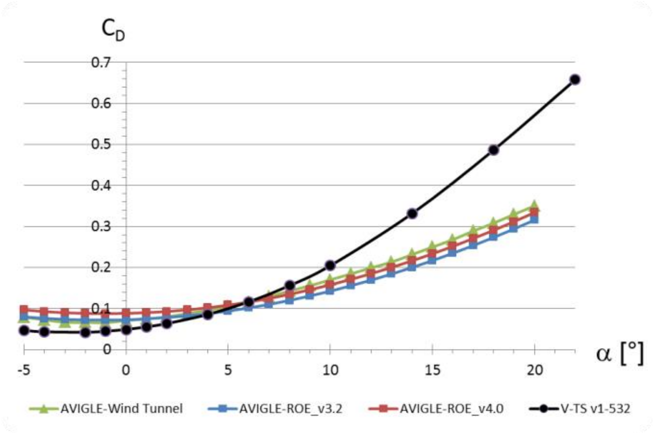

Fig. 8. Comparison of V-TS and AVIGLE mini-UAVs - C_D vs. α – (Mach = 0.0882, Re = 3.34×10^5)

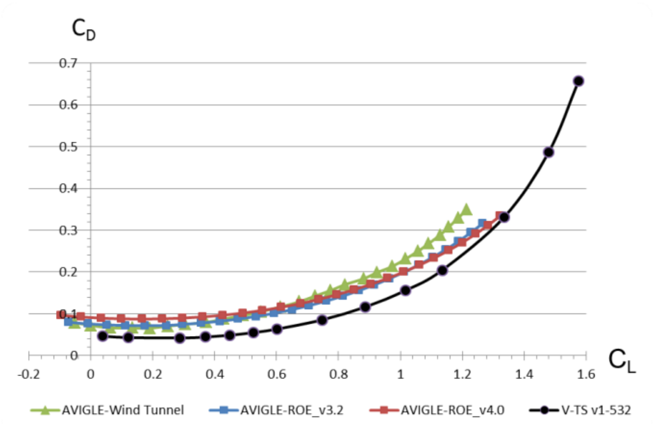

Fig. 9. Comparison of V-TS and AVIGLE mini-UAVs - C_D vs. C_L – (Mach = 0.0882, Re = 3.34×10^5)

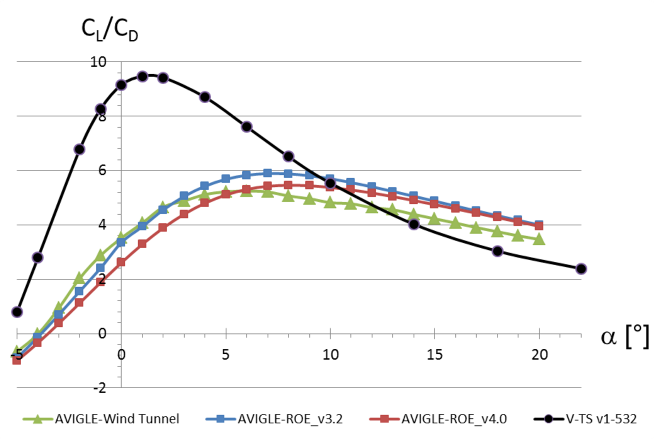

Fig. 10. Comparison of V-TS and AVIGLE mini-UAVs - C_L/C_D vs. α – (Mach = 0.0882, Re = 3.34×10^5)

The characteristics are very positive for V-TS mini-UAV, especially at angles of attack from -5° to 10° where the aerodynamic efficiency is approximately 3 times higher (0°) then for AVIGLE mini-UAV. This range is crucial because mini-UAVs usually fly at these angles for the longest time.

On the other hand, the very negative issue is lower lift-to-drag ratios at higher angles of attack (>10°) caused by rapidly growing drag coefficients. The V-TS mini-UAV is less aerodynamically effective by approximately 25 % (18°), and drag coefficient is by 67 % higher (18°) in comparison to AVIGLE.

In our case, the flight at the higher angles of attack is assumed only during the transitional flight phase for few seconds and consequently it is questionable whether it is the critical disadvantage. Nevertheless, an optimization process to solve this problem and maintain the benefits is planned in future work.

Furthermore, V-TS mini-UAV was analyzed at *Mach* speed of 0.0441 (i.e. 15 m/s) and *Re* of 1.67×10^5 which are proposed operating conditions. The results can be seen in Fig. 11, Fig. 12, Fig. 13, and Fig. 14.

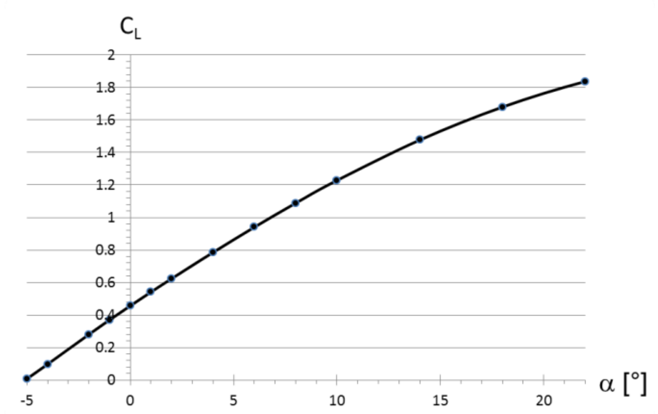

Fig. 11. Aerodynamic Analysis of V-TS mini-UAV - C_L vs. α – (Mach = 0.0441, Re = 1.67×10^5)

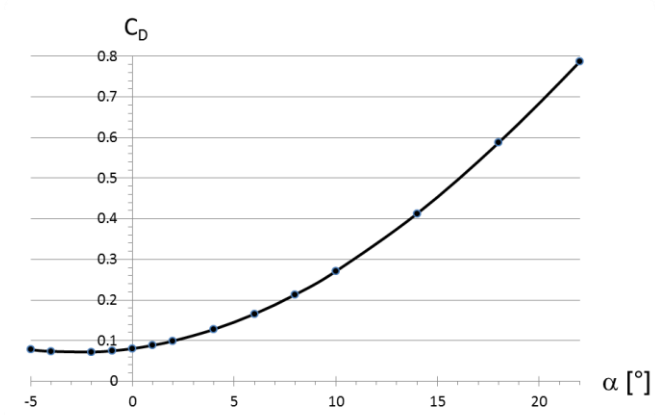

Fig. 12. Aerodynamic Analysis of V-TS mini-UAV - C_D vs. α – (Mach = 0.0441, Re = 1.67×10^5)

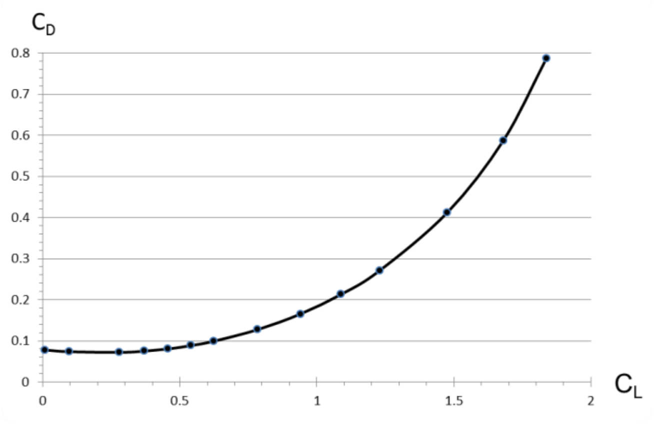

Fig. 13. Aerodynamic Analysis of V-TS mini-UAV - C_D vs. C_L – (Mach = 0.0441, Re = 1.67×10^5)

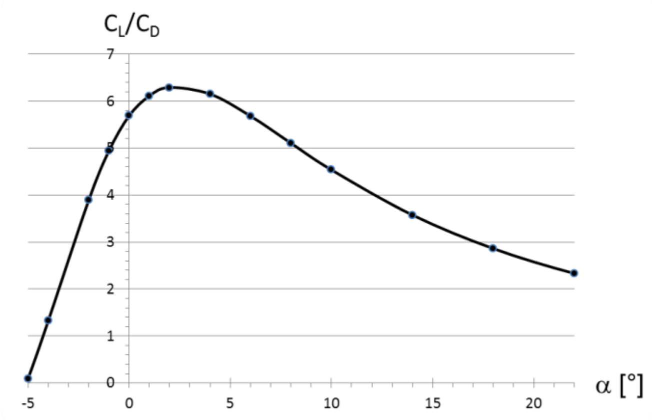

Fig. 14. Aerodynamic Analysis of V-TS mini-UAV - C_L/C_D vs. α – (Mach = 0.0441, Re = 1.67×10^5)

The graphs show very similar results to the previous characteristics – good aerodynamic efficiency but high drag coefficients at the higher angles of attack.

Zero lift coefficient (C_{L0}) is 0.457 which means the lift force of 13.428 N generated by wings for the design speed of 15 m/s. This force can lift about 1.369 kg of mass. The sufficient force for lifting of the predicted weight of the V-TS mini-UAV (i.e. 1.5 kg) should be generated around the angle of attack of 0.5° (C_L = 0.499). The enough force for the maximum permissible takeoff weight (i.e. 2.0 kg) is created at the angle of attack of 2.5° (C_L = 0.664), very close to the maximum lift-to-drag ratio. As a result, at the design speed, the mini-UAV should mostly operate at angles of attack between 0.5° and 2.5° with lift-to-drag ratios from 5.90 to 6.29.

The zero-lift drag-coefficient (C_{D0}) is 0.07776 which is satisfactory; furthermore, when we compare the CFD results of AVIGLE with the wind tunnel data, we may estimate that the wind tunnel value might be lower.

The maximum lift coefficient (C_{L_max}) was calculated as 2.05 at 36°; however, in comparison to AVIGLE for which this parameter was overestimated by around 25 % in SU^2, the real C_{L_max} of V-TS mini-UAV was estimated at approximately 1.57 at 16°. With regards to it, the estimated stall speed should be between 30.4 and 35.2 Km/h depending on weight. Nevertheless, it should be emphasized that the real value of the stall angle may be even lower which the sudden rise of the drag coefficient at the 10° indicates.

IV. Control Modes of V-TS mini-UAV

This section presents the control modes of twin-propeller tail-sitter mini-UAV. The entire control system of the mini-UAV must have capability to combine a control of a fixed-wing aircraft with a control of a duo-copter. As a result, main flight modes might be divided to the cruise (horizontal) flight and the hover (vertical) flight.

A. *Cruise Flight*

The cruise flight mode allows lower power consumption and longer flight duration. This mode copies the control of a fixed-wing airplane as illustrated in Fig. 15; because it is well known, it is not described in detail.

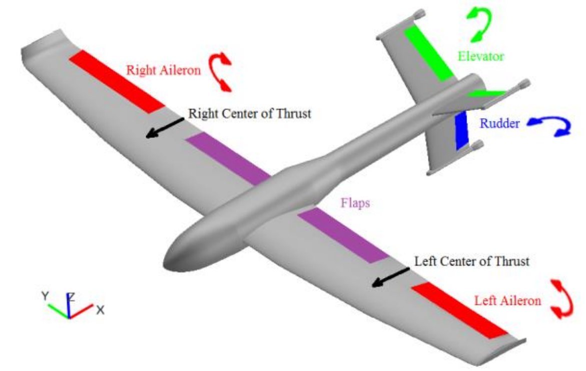

Fig. 15. Cruise Control of Fixed-Wing Airplane

The engines and propellers are used for a change of the velocity and attitude; of course, there is also collaboration with the elevator which sets the suitable lift coefficient using the adequate angle of attack adjustment. In the twin-propeller configuration, the thrust of both propellers must be synchronized to achieve a direct flight; otherwise, a rotation around *z* axis is generated.

In general, the rudder is used to control the position of the nose of the aircraft, mostly in cross-controlled flight. The ailerons are used to change the direction of flight or as wing leveler. They are used in the cross-controlled flight together with rudder. The last but not least is the elevator which is used for a change of the altitude or of the pitch angle; it is probably obvious that the elevator commands have to be applied in combination with an adequate engine power. In case of need, the flaps can be deflected to increase the lift and drag for low-speed flight.

It should be mentioned that the force which can be generated by the control surfaces is dependent upon the size, deflection and the speed of the airflow across the control surface.

B. Hover Flight

The hover flight mode allows vertical take-off and landing capabilities. For our special configuration, this mode is similar to the control of a tandem helicopter and of a multi-copter, but it is not exactly same.

For our purpose, the flight direction in hover is determined by the direction from the left wing to the right wing which means that the forward flight is directed to the right. The other logical option could be the orientation by the bottom of the mini-UAV; nevertheless, it is not practical to use this method with the twin-propeller configuration. To maintain simplicity, we use other parameters, such as the pitch angle in the same way as in the cruise flight. The Euler angles for the mini-UAV in the hover flight are illustrated in Fig. 16, Fig. 17, Fig. 18, and Fig. 19.

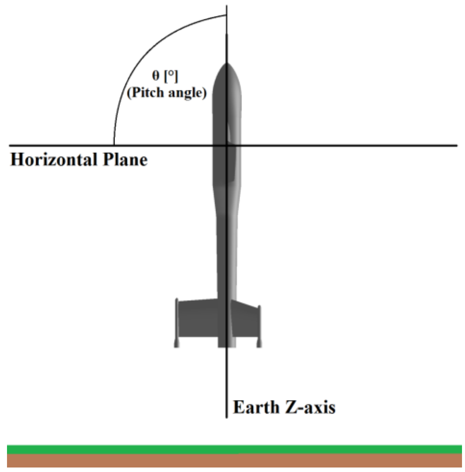

Fig. 16. Pitch Angle in Hover Flight

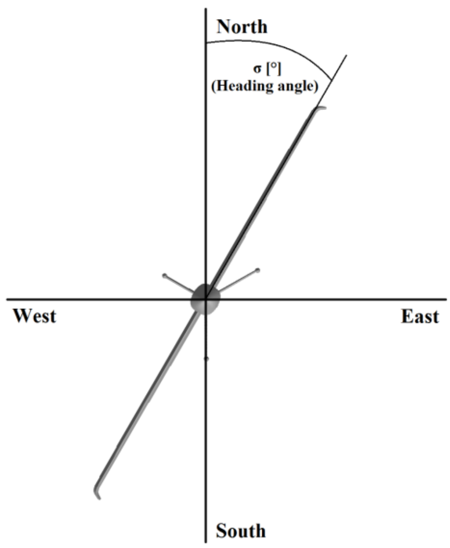

Fig. 17. Heading Angle (Direction) in Hover Flight

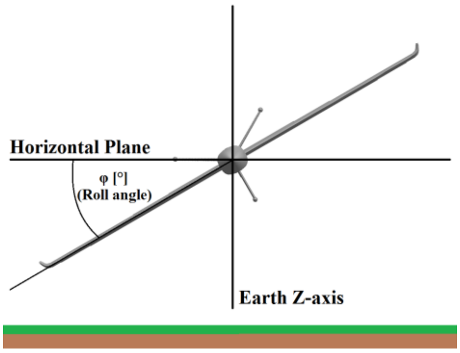

Fig. 18. Roll Angle of Aircraft with Pitch Angle between -90° and 90°

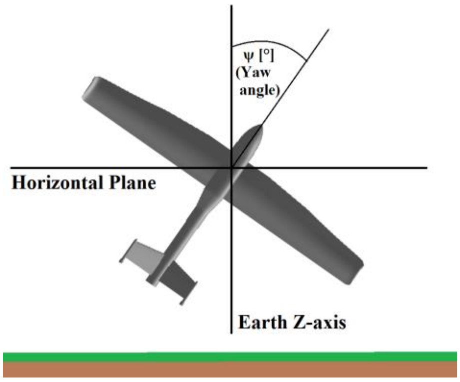

Fig. 19. Yaw Angle in Hover Flight

The control of the duo-copter is performed mostly by using engines. This applies to the control of the velocity, altitude, attitude, yawing, and, in limited range, to direction.

However, during this flight mode, it is also important to maintain a proper wing orientation using ailerons, the vertical (i.e. 90°) pitch angle using elevator, and an appropriate yaw angle using rudder. Obviously, it is only possible when the duo-copter moves, i.e. the engines have to be controlled together with the control surfaces. Unfortunately, this situation makes the control more complex; especially when the duo-copter hovers.

Fig. 20 demonstrates the principle of altitude change for the V-TS mini-UAV. It is performed by using the synchronized thrust of both propellers – if the total thrust is higher than the weight, the mini-UAV climbs; if they are same, the mini-UAV hovers; and if the thrust is lower, the UAV descends (or falls). It should be noted that, especially for descent, the minimum rotational speed of the propellers (i.e. minimum thrust) has to be specified to avoid fall.

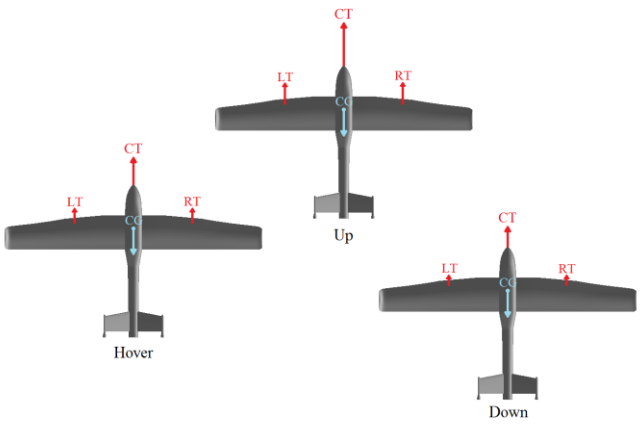

Fig. 20. Altitude Change of V-TS mini-UAV in Hover Flight

It should be emphasized that in our case, the change of thrust is provided by using the change of engine rotational speed. Another specialty of the mini-UAV is falling which is different from a helicopter or a multi-copter. When V-TS mini-UAV falls down, it has higher probability to recover, due to the natural aerodynamic behavior of airplanes and the control surfaces, and thus to continue with flight in the cruise mode. Consequently, unlike common copters, the fall can be partially controllable and thus safer.

Fig. 21 represents the change of the attitude by a thrust increase of the left propeller and subsequent thrust equalization by the right propeller. The left thrust causes a change of the yaw angle; on the contrary, the right thrust stops the rotation and moves the mini-UAV forward.

The thrust rise can be achieved by using a higher propeller rotational speed. Because of a temporarily different torque of propellers, a small change of the direction is created; nevertheless, it can be negated during the flight. This problem could be also solved by using a change of the blade pitch angle to provide both the higher thrust and an identical rotational speed of propellers. However, we are limited to use fixed pitch propellers to keep the mini-UAV design as simple as possible.

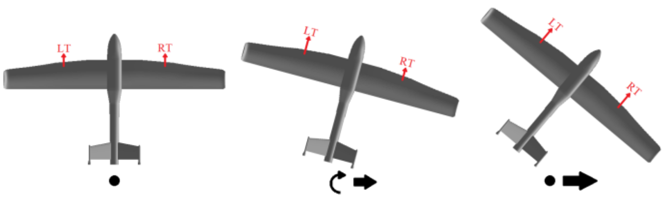

Fig. 21. Attitude Change of V-TS mini-UAV in Hover Flight

The big difference between the control of V-TS mini-UAV and multi-copters is the direction change using the torque of propellers (see Fig. 22). When this method is used, an attitude change must be taken into account; hence, only slight increase and decrease of a propellers' rotational speed is allowed. The parasitic change of the attitude is unpleasant because it cannot be simply negated. A solution might be a change of the blade pitch angle to provide the identical thrust together with a higher rotational speed of a propeller.

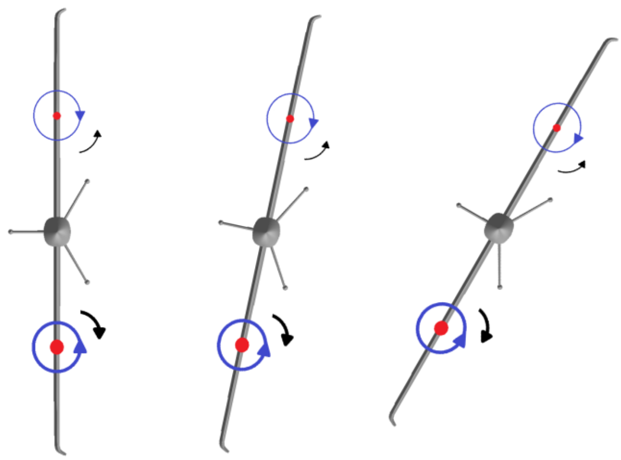
Fig. 22. Direction Change of V-TS mini-UAV in Hover Flight by using Propeller Rotational Speed

As shown in Fig. 23, the direction change may be performed during the attitude change using elevator. This technique seems to be safer than the previous due to the controlled attitude change.

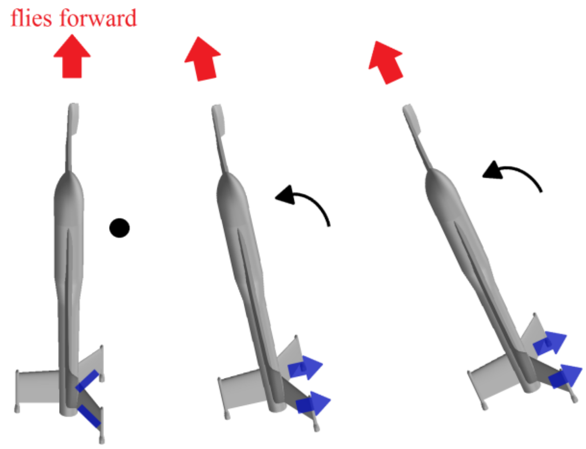

Fig. 23. Direction Change of V-TS mini-UAV in Hover Flight by Using Elevator Deflection

However, when a constant attitude has to be maintained, the third option illustrated in Fig. 24 can be used. In this approach, the direction is changed during climb by using ailerons. Once the desired direction is reached, the mini-UAV may descend back to the initial altitude. The last two control sub-modes can be used in most cases and because of their higher safety, they should be preferred. It should be noted that the ailerons immersed in the slipstream of the pull-propellers could be able to change direction without the climbing.

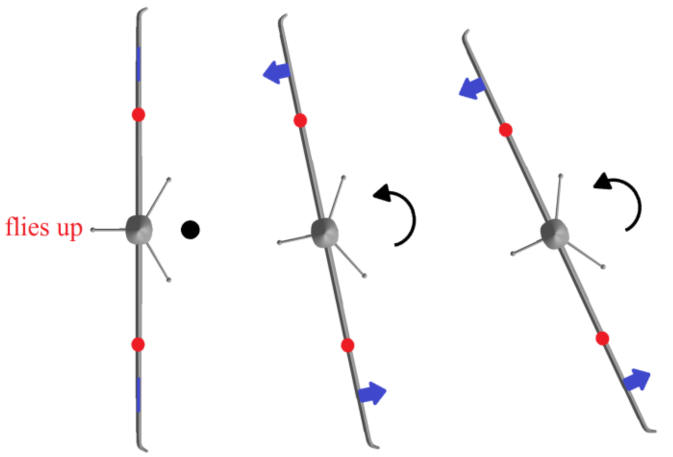

Fig. 24. Direction Change of V-TS mini-UAV in Hover Flight by Using Ailerons Deflection

The yaw angle is another parameter which has to be controlled. Fig. 25 and Fig. 26 describe two ways how to do that. The first uses a thrust increase of one propeller to stabilize the mini-UAV which is more suitable during hovering. In contrast, the second method uses rudder, and thus it works better when the mini-UAV changes altitude or attitude. The reasons are probably evident; rudder cannot be used when the mini-UAV does not move (i.e. during hovering). On the contrary, the propellers are not able to generate enough thrust when engine power is close to maximum power (e.g. during climb); moreover, a rudder deflection is usually more energy efficient than a thrust increase and in this case, a little bit safer.

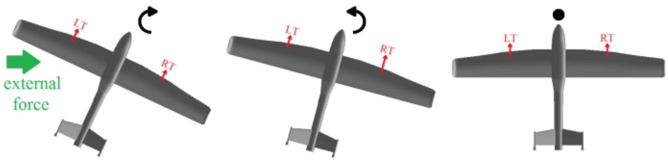

Fig. 25. Yaw-Angle Change of V-TS mini-UAV in Hover Flight by Using Propeller Thrust

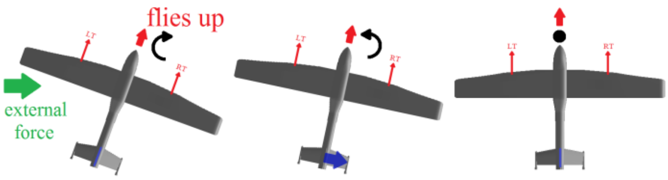

Fig. 26. Yaw-Angle Change of V-TS mini-UAV in Hover Flight by Using Rudder Deflection

Probably the most serious problem of our duo-copter is the pitch control. One solution is to use elevator and synchronized thrust as can be seen in Fig. 27. Nevertheless, using this method, the mini-UAV usually cannot be stabilized in pitch for a long time when hovers. Tilt-propellers could solve this problem; however, because of the disadvantages mentioned in the previous section, and because the hover flight should primarily be used only for VTOL in our project, we want to keep this option as the last choice. It should be also noted that the elevator immersed in the slipstream of the propellers could be able to change the pitch without the climbing.

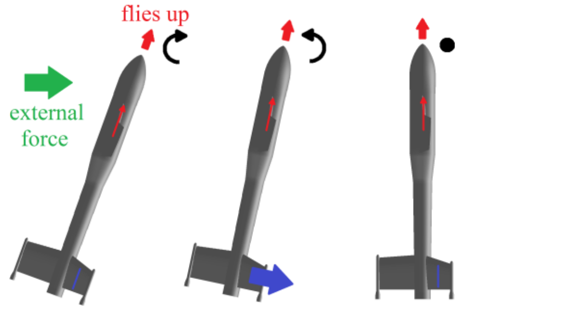

Fig. 27. Pitch-Angle Change of V-TS mini-UAV in Hover Flight

An external destabilization in pitch may be minimized when the wing orientation are turned to the biggest source of the destabilization as shown in Fig. 28. After that, the destabilization can be negated by using the thrust of propeller as illustrated in Fig. 25. Unfortunately, it is not always easy and possible to find the direction of the destabilization during flight; furthermore, the direction may change, or there can be more sources than one. This is probably the major disadvantage of this configuration.

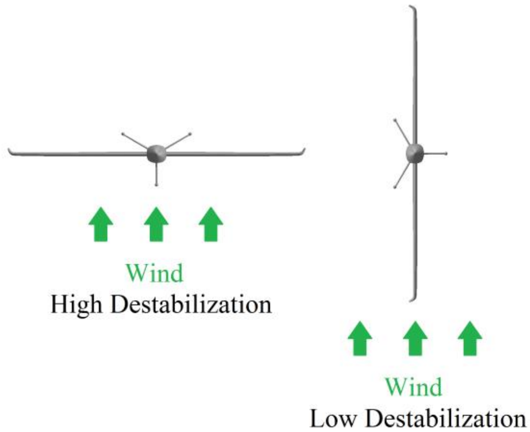

Fig. 28. Minimization of Pitch Destabilization of V-TS mini-UAV in Hover Flight

The last but not least is the control of wing orientation. It is most usable during transitional phase when an initial wing level should be maintained. The elemental principles are described in Fig. 29; the wings are pushed back to the initial state by using ailerons regardless of the pitch angle. We named this control sub-mode as “wing orientator”.

The function of the wing orientator is similar to the function of the wing leveler; nevertheless, the realization is different. The wing leveler only maintains the bank of the plane neutral. Consequently, if the pitch angle is higher than 90°, the wings will rotate from the roll angle of ±180° back to 0° which may cause endless rotation as Fig. 30 indicates. It follows that the roll angle in the hover flight must be converted into an angle which refers to the north, not to the ground.

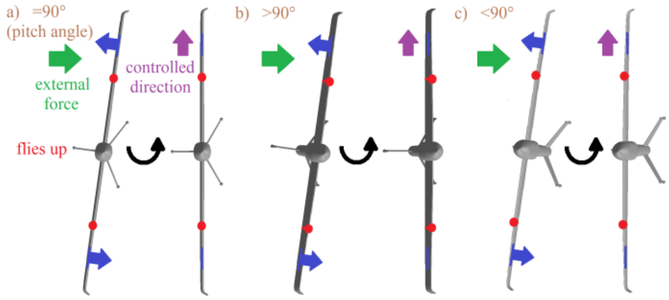

Fig. 29. Wing Orientator Behavior of V-TS mini-UAV in Hover Flight

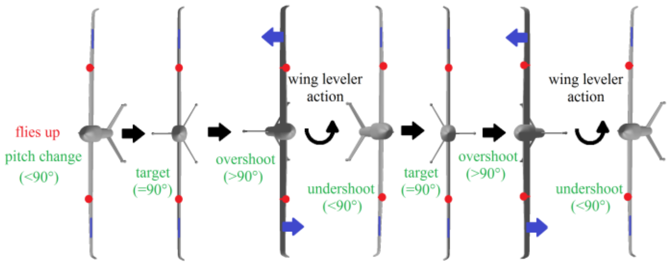

Fig. 30. Wing Leveler Behavior in Hover Flight

1) Adjustable Center of Gravity

The adjustable center of gravity can be another approach which can solve some problems of the duo-copter. This technique is not commonly used in mini-UAVs; a similar exception was described in [50]. Disadvantages of this method are a limited range of the center of gravity adjustment, additional components, and thus higher weight, more complex UAV design, and more complicated control system requiring the use of very fast servo motors to achieve dynamic stability. Nevertheless, all possible options should be included in a conceptual study; moreover, the advantage should be lower overall complexity than in case of a swash plate application.

First use is to move the center of gravity close to a wing as can be seen in Fig. 31. This causes a rotation of the mini-UAV and a change in the yaw angle. When the center of gravity is back at the initial position, only the attitude is changed. It is obvious that this method may be used for the stabilization of the yaw angle as well. The rotational speed of both propellers can increase but also it may remain synchronized which negates the parasitical direction change during this maneuver.

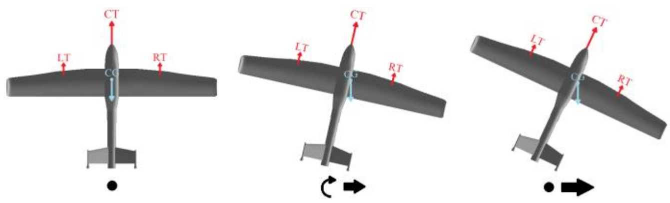

Fig. 31. Attitude Control by Using Center of Gravity Change in Hover Flight

Second application is similar; when a direction change is performed by using an increase of the rotational speed of a propeller, the center of gravity is moved close to the propeller to balance the thrust forces (see Fig. 32). It does not result in any parasitical attitude change but only in a change of the direction caused by the higher torque.

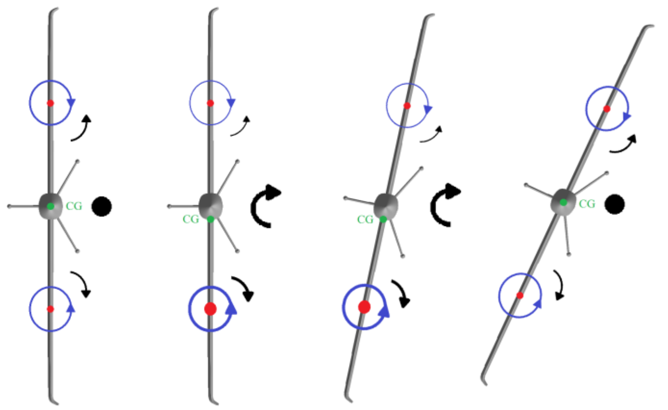

Fig. 32. Direction Control Correction by Using Center of Gravity Change in Hover Flight

Finally, the center of gravity may be moved close to the lower or upper side of the fuselage to maintain pitch stability. The center of gravity should act against the direction of an external force to compensate the destabilization pitch moment as illustrated in Fig. 33.

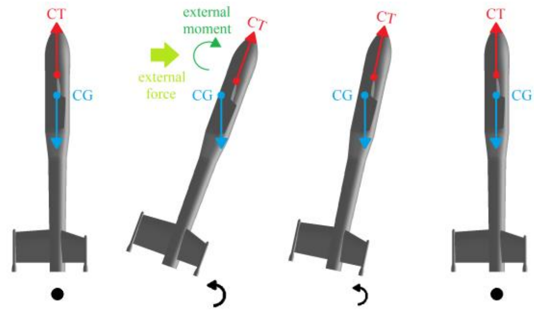

Fig. 33. Pitch Stabilization by Using Center of Gravity Change in Hover Flight

V. Transitional Flight Phases

It is necessary to solve the problem of transitional flight phases for the control of the tail-sitter mini-UAV. The transitional flight phases should be composed of the known control modes and sub-modes in order to maintain simplicity. In any case the angle of attack has to be very carefully measured and controlled to avoid stall.

Nevertheless, it is also important to determine the states between the different ways of flight and define when the control modes should be automatically switched. There are two possible transitional ways: to use pitch change or yaw-roll change.

A. Pitch Transition

The pitch transition of the flight phases is the most used method in the projects of tail-sitter mini-UAVs [6], [7], [8], [51], [52]. It can be performed by using the control sub-mode for the change of the pitch angle and total velocity. It is also necessary to maintain wings in a constant level/orientation using wing leveler, or wing orientator, respectively.

Fig. 34 shows take-off and hover-to-cruise transition. Firstly, the mini-UAV has to achieve a sufficient altitude using the altitude-change sub-mode for the hover flight; moreover, the wing leveler has to be turned on. After that, it should increase the total velocity at value higher than the stall speed. Then, it may start to change the pitch angle from 90° to 0°. The flight modes of the control system have to be switched during this maneuver, for example when the pitch angle is lower than 45° (i.e. half of 90°).

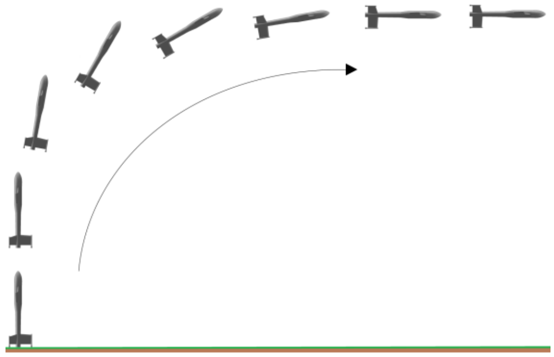

Fig. 34. Pitch Hover-to-Cruise Transition of Tail-Sitter mini-UAV

The cruise-to-hover transition and landing which can be seen in Fig. 35 require a similar process. The desired total velocity should be set at value higher than the stall speed; moreover, the wing orientator has to be turned on. After that, it may start to change the pitch angle from 0° to 90°. The flight modes of the control system have to be switched again during this maneuver, for example when the pitch angle is higher than 45° (i.e. half of 90°). Then the mini-UAV may start to land using the altitude-change sub-mode for the hover flight.

The mini-UAV should also descend to a low altitude before the cruise-to-hover transition because the downward vertical speed during landing has to be low to avoid fall. If the altitude had been high, it would have taken more time to land which would have been less energy efficient.

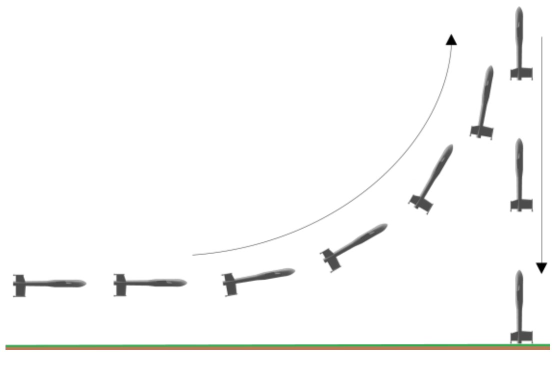

Fig. 35. Pitch Cruise-to-Hover Transition of Tail-Sitter mini-UAV

This method is simple, nature, and commonly used. Furthermore, it is less dangerous and easier-to-control in comparison to the following transitional methods; on the other hand, it might be less energy efficient and slower.

B. Yaw-Roll Transition

The yaw-roll transition is not typically used for tail-sitter mini-UAVs; in fact, it is rather unknown or omitted. This maneuver can be performed by using the control sub-mode for the change of the yaw angle and for wing leveler/orientator. First of all, it is necessary to generate enough lift and achieve enough total velocity.

As can be seen in Fig. 36, the hover-to-cruise transition starts with yaw change and after achieving of 45° and less, the control sub-mode switches from the wing orientator to the wing leveler which decreases the bank angle to 0°.

As described in the previous section, the yaw angle may be controlled using the rudder or thrust of one propeller. The first option does not seem to have noticeable advantages compared to the conventional pitch transition. In contrast, the higher thrust of one propeller can very quickly turn the mini-UAV around yaw axis from yaw angle of 0° to 90° (in view of hover flight). Moreover, the higher rotation of one propeller will rotate the wings to level if the rotation direction is same as illustrated in Fig. 22.

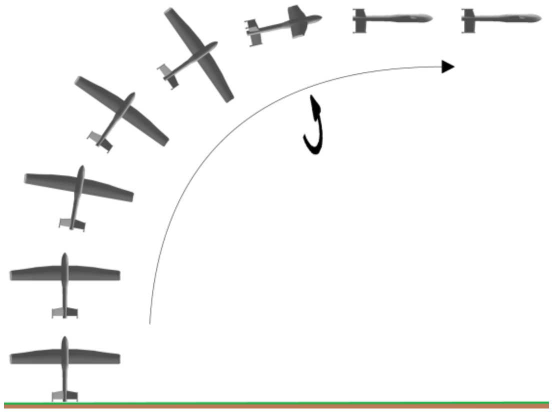

Fig. 36. Yaw-Roll Hover-to-Cruise Transition of Tail-Sitter mini-UAV

The cruise-to-hover transition which is shown in Fig. 37 has to perform the opposite actions. Firstly, enough velocity/thrust should be achieved, the bank angle should be changed to 90° and then, yaw angle may start to increase up to 90° – from 45° and more, the control sub-mode switches from the wing leveler to the wing orientator. We should also calculate with the direction change which is provided by roll-angle change.

Because the mini-UAV moves forward before this maneuver and the higher rotation of one propeller also changes the roll angle, it can be more dangerous and complicated to use asymmetrical thrust of propellers to change the yaw angle than in the hover-to-cruise transition. Consequently, the better option is to use the rudder.

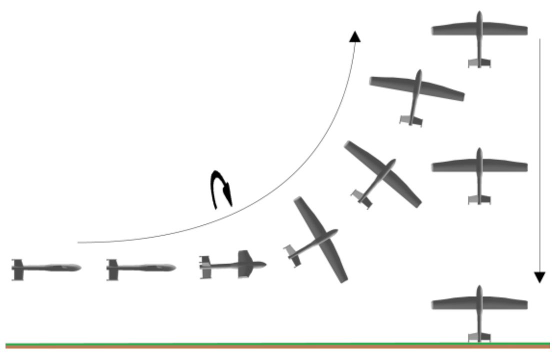

Fig. 37. Yaw-Roll Cruise-to-Hover Transition of Tail-Sitter mini-UAV

The advantage of the yaw-roll hover-to-cruise transition by using the asymmetrical thrust is the faster change to cruise flight mode in comparison to pitch transition. The disadvantage is lower safety during this maneuver, including a possible loss of the altitude. Moreover, it is not commonly used and thus not verified in practice.

On the contrary, the cruise-to-hover transition does not seem to have more advantages than disadvantages; furthermore, there are probably no benefits in comparison to the pitch cruise-to-hover transition method. Last but not least, new control sub-mode for the specific roll-angle change would have to be designed.

C. *Stall Hover-to-Cruise Transition*

This method can be used in hover-to-cruise transition only. Fig. 38 shows an approximate process of this approach; the real maneuver mostly varies. The autopilot of the mini-UAV should be prepared to solve this situation because it may happen during an incorrectly performed pitch transition; e.g. with low speed and high pitch angle.

The first action is to reach the stall; when we want to initiate it, we can move the elevator up without sufficient increase of thrust, or we can significantly reduce the engine power in the hover flight, and turn-off the control sub-modes which influences the ailerons, elevator, and rudder. This is actually desirable during unwanted stall too because the nose of the mini-UAV may start to turn around. When the sufficiently low angle of attack and a sufficient airspeed margin above the stall speed are achieved, the wings can be balanced using wing leveler, the engine power may be increased again, and the pitch angle can be changed to 0°. Unfortunately, because the mini-UAV behavior during the stall might be always different depending on conditions (e.g. the mini-UAV may also start to spin), it is hard to predict the best autonomous process to the recovery, and thus, this process may fail sometimes.

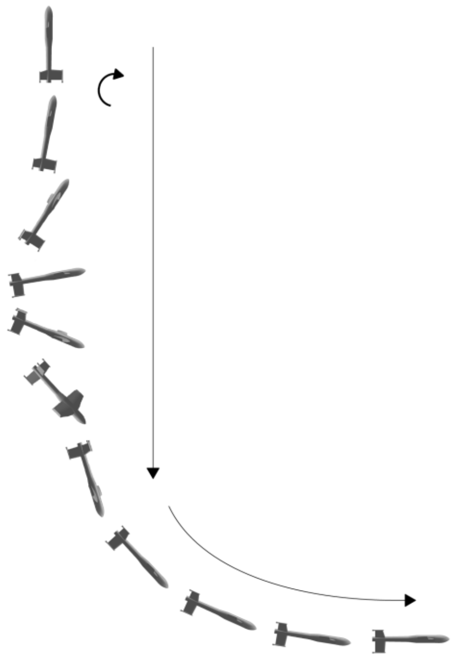

Fig. 38. Stall Hover-to-Cruise Transition of Tail-Sitter mini-UAV

Because the engine power is reduced during this approach, it should be the most energy-efficient transition but only when the lower altitude is also requested. It is obvious that this transition will lose a lot of energy when the aircraft has to climb back to the original altitude. Furthermore, if the mini-UAV includes a control system which is able to solve the problems after the stall, the general safety of the flight is higher.

However, this maneuver needs enough altitude and time to recover, and can be initiated and usable only in special cases (e.g. when a fast altitude descent is requested). Moreover, it is probably the slowest and the most dangerous transition with hardly predictable situations after stall which makes the autonomous control more complex.

VI. Conclusion and Discussion

The main goal of this paper was to design and analyze a twin-propeller tail-sitter mini-UAV (V-TS v1-532). The V-TS mini-UAV combines two different ways of flying; consequently, it was also necessary to describe and solve challenges and difficulties of this concept, especially in the case of control.

The software which was used for the design and analysis of the V-TS mini-UAV was presented and the connections between the applications were illustrated. Because all the software is free of charge and freely available, the financial cost was minimized. The applications can be used for wide range of the design tasks, such as airfoil, wing, tail, or entire mini-UAV optimizations. Moreover, as we proved, they can be useful in the projects of UAVs with both conventional and several unconventional configurations.

3D model of the V-TS mini-UAV and basic geometrical parameters were shown. Because the V-TS mini-UAV is a combination of airplanes and copters, high energy efficiency during the forward flight and VTOL capability in the hover flight are achieved. The Y-tail was preferred over the X-tail due to its generally lower drag, lower weight, and higher effective area.

We applied new optimized airfoil for the wings with maximum thickness of 8.9% at 36% chord and the maximum camber of 3.9% at 45.3% chord (MH 38 was the original airfoil). For the tail parts, the symmetrical S9033 airfoil with maximum thickness of 7.5% at 22.8% chord was used.

AVIGLE Demonstrator was analyzed in SU^2 to verify correct settings of the aerodynamic analysis. This mini-UAV was selected due to its similar proportions, mission, operating speeds, and Reynolds numbers to our designed V-TS mini-UAV. Nevertheless, different conditions may lead to different results.

Unfortunately, differences between results of SU^2 software in version 3.2 and 4.0 distort trustworthiness of this application; however, the values are still sufficiently accurate. On the other hand, wind tunnel tests of V-TS mini-UAV are planned to re-verify the accuracy of this analysis.

The characteristics are very positive for V-TS mini-UAV at angles of attack from -5° to 10° where the aerodynamic efficiency is very high, with the maximum of 9.476 at 1°. On the other hand, the very negative issue is lower lift-to-drag ratios at higher angles of attack caused by rapidly growing drag coefficients. As mentioned before, the flight at the higher angles of attack is assumed only during the transitional flight phase for few seconds; nevertheless, an optimization of the V-TS mini-UAV is planned to solve this problem and maintain the benefits. In conclusion, the results proved that the V-TS mini-UAV could be sufficiently aerodynamically efficient for our purpose, only with the minor drawback.

In the second main part, the conceptual control system was defined. There were illustrated probably all control modes, transitional flight phases, and difficulties which may appear in the control of the twin-propeller tail-sitter mini-UAV. The entire control system must have capability to combine a control of a fixed-wing aircraft with a control of a duo-copter.

Because the control of fixed-wing airplanes is well known, it was not described in detail. In contrast, the hover flight was described in detail in order to include all options of our special configuration. This mode is similar to the control of a tandem helicopter and of a multi-copter, but it is not exactly same.

The control of the duo-copter is performed mostly by using engines but in our case, also ailerons, elevator, and rudder are applied. This is probably the biggest difference between the V-TS mini-UAV and tandem helicopters, or multi-copters.

Because it is possible to use the control surfaces only when the duo-copter moves, there are several challenges: the pitch-angle and yaw-angle stabilization, and the direction and attitude change. Our proposed solutions contain probably all variants including the mention about tilt-propellers and swash plates. Another rarely used technique is the adjustable center of gravity which may increase the quality of the stabilization process. It is simple method which could almost completely replace the control surfaces in the hover flight. The disadvantages might be demands on a moving component with sufficiently weight and the lowest size as possible, and of course, on the moving system with the lowest weight and complexity as possible.

As a part of main problem, the transitional flight phases which can be composed of the known control sub-modes were defined and solved. Pitch transition is simple, nature, commonly used, the safest, and easy to control. As can be seen from the study, it is the only one which should be used for the cruise-to-hover transition.

However, for faster, and thus more energy efficient option of hover-to-cruise transition, the yaw-roll transition by using of asymmetrical thrust can be used. The disadvantage is lower safety during this maneuver, including a little loss of the altitude.

The proposed stall hover-to-cruise transition is not recommended for general use despite it could bring the highest kinetic energy efficiency and the fastest altitude descent. The mini-UAV needs enough altitude and time to recover. Furthermore, it is probably the slowest and the most dangerous transition with hardly predictable situations after stall which makes the autonomous control more complex. Nevertheless, the autopilot of the mini-UAV should be prepared to solve this situation because it may happen, for example during an incorrectly performed pitch transition. Consequently, the main reason why this method was discussed is that if the control system is able to solve the problems after the stall, the general safety of the flight is higher.

In short, this conceptual study of the design and control of the twin-propeller tail-sitter mini-UAV revealed several new approaches and ways of its development. In addition, a novel experimental mini-UAV, which airworthiness will be modelled and simulated in our future work, was created.

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