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Automated Control Surface Design and Sizing for the Prandtl Plane

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This paper presents a methodology for the design of the primary flight control surfaces, in terms of size, number and location, for fixed wing aircraft (conventional or unconventional). As test case, the methodology is applied to a 300 passenger variant of the Prandtl Plane. This box wing aircraft is deemed to have low induced drag compared to conventional aircraft. The methodology is completely physics based and includes an aerodynamic analysis, followed by a control allocation algorithm and an analysis of the flight mechanics. The design has to fulfill a set of handling qualities requirements with a minimum total control surface area. An optimization algorithm is used to find the best design. Results indicate that this is possible with ailerons outboard on both wings, elevators inboard on both wings and conventional rudders in the vertical tail. The configuration allows for pure torque control and also direct lift control in the longitudinal axis. These features can potentially enhance airfield performance.

Nomenclature

B	=	aerodynamic effectiveness matrix [Nm/rad]
CA	=	control allocation matrix
H_{app}	=	altitude during approach [m]
H_{cr}	=	cruise altitude [m]
H_{rot}	=	altitude at take-off rotation [m]
L	=	aerodynamic roll moment in body axes [Nm]
m_d	=	desired moment vector [Nm]
M	=	aerodynamic pitch moment in body axes [Nm]
N	=	aerodynamic yaw moment in body axes [Nm]
V_{app}	=	airspeed during approach [m/s]
V_{cr}	=	cruise airspeed [m/s]
$\mathrm{V}_{\mathrm{rot}}$	=	speed at take-off rotation [m/s]
X_A	=	lateral stick input [-]
X_B	=	longitudinal stick input [-]
X_P	=	pedal input [-]
δ	=	vector of all control deflections [rad]
δ_i	=	deflection of i-th control surface [rad]

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I. Introduction

Back in 1924, the famous Ludwig Prandtl developed a theory that calculated drag on sets of multiple wings[1]. The theory describes how a larger vertical spacing between the wings further decreases induced drag. Furthermore, Prandtl discovered that when keeping the total amount of lift constant, the larger the amount of wings that are located above each other to create this lift, the more efficient the total system becomes. The most efficient system therefore is the theoretical situation where an infinite amount of wings is situated on top of each other. The most efficient system from a practical point of view is a box wing design with two horizontal wings connected to each other with vertical elements. The horizontal wings should have a constant plus elliptical lift distribution and the vertical wings should have a butterfly shaped lift distribution. This design is called the best wing system. Several civil aircraft designs, incorporating the best wing system, were developed by a consortium of five Italian universities[2-4]. In honor of Ludwig Prandtl, these are designated as Prandtl Planes (Fig. 1).

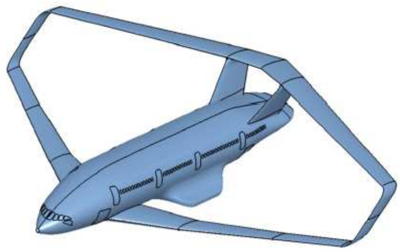

Figure 1. 300 passenger variant of the Prandtl Plane Aircraft[3]

Primary flight control surfaces are not yet defined for this aircraft. The aim of this research study is to develop a methodology for the automated design of flight control surfaces in terms of number, size and location. This method should be applicable to any fixed wing aircraft type (conventional or unconventional). The Prandtl Plane is considered to be an appropriate and relevant test-case since conventional design methods that rely on statistical information cannot be applied to this aircraft.

The outline of this paper is the following. First, the design process is described (Section II). This design process starts with an initial design, which is presented in Section III. The various tools used in the design process are elaborated in Section IV. A summary of the main results is presented in Section V and finally conclusions and recommendations are made

II. Design Process

The overall design process, which is depicted in Fig. 2, consists of two distinct phases. First, an initial design must be developed, which is done by an engineer through a systems engineering process. The second phase of the design process is automated. The initial design is first defined in a parametric aircraft model, after which the input for the aerodynamic analysis tool is then created based on this aircraft shape. An aerodynamic dataset is then constructed. In principle, it is possible that there are a redundant number of control surfaces. Furthermore, they can have combined functionalities; e.g. a control surface on the front wing can be used both for pitch and roll. A control allocation scheme must therefore be derived that determines which control surfaces deflect and to what extent, following a pilot input. This is done via a direct method[5, 6]. Finally, the aerodynamic data and control system data, as well as some structural data and propulsion system information is combined in a flight mechanics modeling toolbox[7]. The handling qualities of the design are assessed with this toolbox. An optimizer can then be used to find the design with a minimum control surface area, thereby minimizing aircraft weight, which fulfills all requirements.

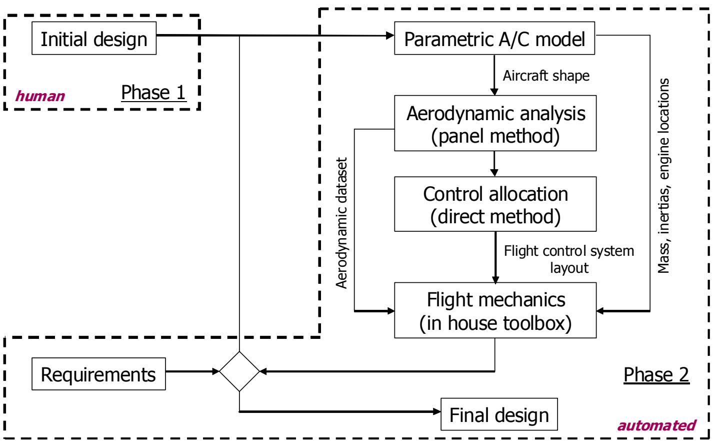

Figure 2. Design process

The set of requirements which the design must comply with is summarized in Table 1. These requirements are considered to be the most essential. However, the list can easily be extended.

Table 1. Handling qualities requirements overview

	Take-off rotation speed Sea level		*Approach speed Sea level*		*Cruise speed Cruise altitude (10500 m)*	
Requirement	**No crosswind**	**Crosswind**	**No crosswind**	**Crosswind**	**No crosswind**	**Crosswind**
Aircraft trim	√	√	√	√	√	√
Take-off rotation[8] (7 deg/s^2)	√	√				
Push pull maneuver[9] (0.5 to 2.0 'g')			√	√	√	√
Minimum time to bank[9] (2.3 s to 30 deg)			√		√	
One engine inoperative[9, 10] (trimmed flight)			√	√		
Steady turn			√	√		

III. Initial Design

The basic aim of the control surfaces is to provide pitch, roll and yaw control. There are many design options for the placement of the primary flight controls of the Prandtl Plane. One can place elevators on the front wing, on the rear wing, or both. The same holds for the ailerons. Furthermore, it is possible to combine functionalities; surfaces that are used both for pitch and roll control. Yaw control can be achieved with conventional rudders or by placing drag rudders in the vertical wing connections. All the design options are summarized in Fig. 3. Note that 'virtual drag rudders' are also listed as a design option. In principle, the elevators and ailerons or elevons can be deflected such that no resulting pitch or roll moment is created but a drag difference between the left and right wing is created. This drag difference causes a yawing moment just like a real drag rudder would do, hence the name 'virtual drag rudder'.

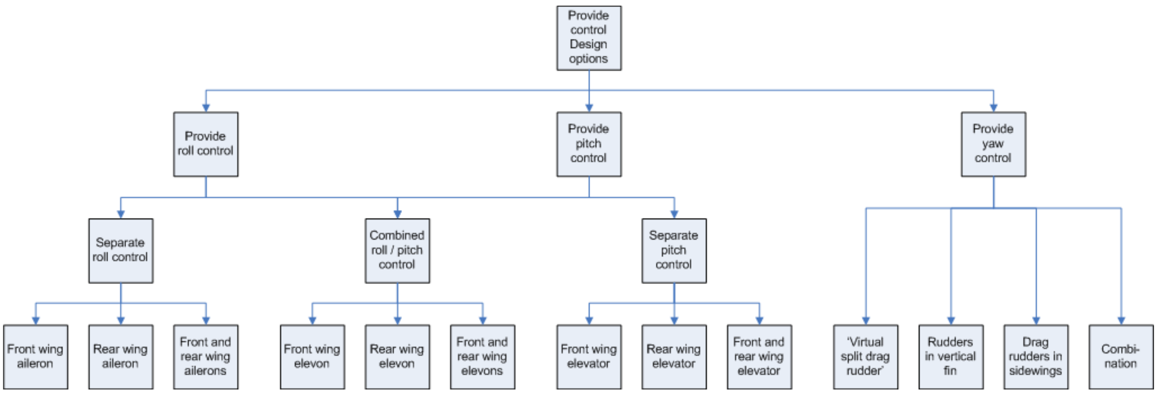

Figure 3. Control design option tree

Two trade-off studies were conducted to determine the most suitable option. The first trade-off was made to determine whether separate or combined control surfaces for pitch and roll should be used. Results are presented in Table 2. Five factors were taken into account. The control effectiveness is largest for the separate option because elevators can be placed inboard and ailerons outboard, which maximizes the moment arm. The complexity of the separate controls is considered to be lowest because no combined functionalities have to be created in the actuation of the flight control system. On the other hand, it does imply that more control surfaces must be created. The unintended control influences are smaller for the separate surfaces. When the remaining space is considered for placing high lift devices, then the combined surfaces are the best option because it is likely that more space is available, in particular at the inboard section of the wing where flaps are most efficient. After applying weights to the influencing factors, it can be determined that the separate roll/pitch control option is slightly preferred over the combined roll/pitch surfaces.

Table 2. Trade-off separate versus combined controls

	Scores		*Weight*	*Weighted scores*	
	separate roll/pitch	**combined roll/pitch**		**separate roll/pitch**	**combined roll/pitch**
control effectiveness per control function (large = good)	3	1	3	9	3
total control effectiveness per unit control surface (large = good)	1	3	2	2	6
complexity (low = good)	3	2	2	6	4
unintended control influence (small = good)	3	1	2	6	2
space for high-lift devices (large = good)	1	3	3	3	9
				26	24

Scores: *1 = bad*, *2 = fair*, *3 = good* **Weights:** *1 = less important*, *2 = moderately important*, *3 = very important*

The second trade-off study (Table 3) was made to determine whether pitch and roll control surfaces should be placed on the front wing, the rear wing or on both wings. Several factors were taken into account in the trade-off. First, a design with low complexity is preferred. Second, the aircraft should be controllable in stalled conditions. The front wing of this aircraft stalls first due to the fact that the rear wing is in the downwash of the front wing. Third, it is beneficial if a pure moment can be created by the controls and if they are in their most effective position. With a conventional tail, a pitch up rotation is preceded by a slight downward motion due to a negative force on the tail plane. If elevators are placed on both wings, then this effect can be eliminated. Finally, it was checked whether direct lift control can be created with the control configuration. The trade-off study clearly shows that controls on both wings are preferred for both pitch and roll.

Table 3. Trade-off between roll- and pitch controls on one or both wings

		Scores						*Weight*	*Weighted scores*					
		roll			*pitch*				*roll*			*pitch*		
		front	rear	both	front	rear	both		front	rear	both	front	rear	both
control effectiveness	pure couple/torque? (yes = good)	-	-	-	1	1	3	3	-	-	-	3	3	9
	double moment arm? (yes = good)	1	1	3	-	-	-	3	3	3	9	-	-	-
produce negative lift @ pitch-up? (no = good)		-	-	-	3	1	3	3	-	-	-	9	3	9
complexity (low = good)		3	3	1	3	3	1	3	9	9	3	9	9	3
unintended control influence (small = good)		1	1	3	2	2	3	2	2	2	6	4	4	6
loss of control after stall? (no = good)		2	3	3	1	3	3	2	4	6	6	2	6	6
Best Wing System (symmetry) (yes = good)		1	1	3	1	1	3	3	3	3	9	3	3	9
direct-lift possible? (yes = good)		-	-	-	1	1	3	1	-	-	-	1	1	3
									21	23	**33**	31	29	**45**

Scores: *1 = bad*, *2 = fair*, *3 = good* **Weights:** *1 = less important*, *2 = moderately important*, *3 = very important*

The outcome of the trade-off studies results in the 'initial design' displayed in Fig. 4. So, separate elevators are placed inboard on both the front and rear wing. Ailerons are present outboard on both wings. Conventional rudders are located in the vertical tails. In short, this configuration is most effective due to the large moment arm to the center of gravity. Furthermore, a pure torque moment and direct lift can be created. A trade-off study was also conducted to determine the best option for yaw control. This study is not included in this paper for the sake of brevity. Results show that conventional rudders are preferred over drag rudders because they are a proven design (low risk). Now, the optimum size for the controls must be found through an automated design process.

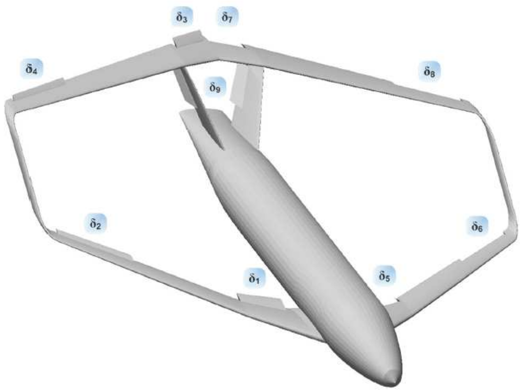

Figure 4. Initial design

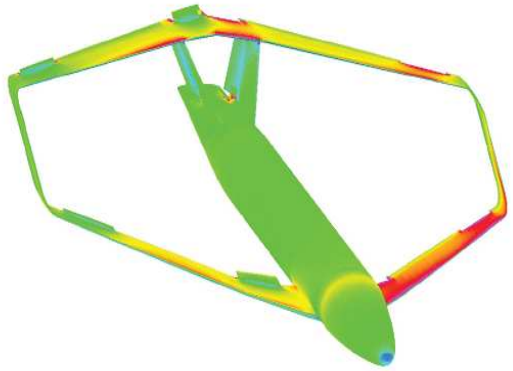

Figure 5. Aerodynamic analysis

IV. Analysis

The parametric aircraft model is created by a Matlab routine in which all the geometric design parameters can be defined. This includes parameters such as the wing position, the chord length, wing sweep, airfoil type, control surface location, etc. The basic aircraft shape is kept constant in this study. The only design variables are related to the control surfaces. Based on this information, an input file for the aerodynamic analysis is created. The commercial off the shelf software package VSAERO[11] is used in this study. This is a first order panel method with viscous boundary layer integration. The computation time of this method is relatively low when compared to CFD methods with a higher accuracy. The main reason to choose this method is that many different configurations must be analyzed and thus computation time should be kept low. An impression of the resulting pressure distribution on the aircraft with asymmetrically deflected control surfaces is presented in Fig. 5. An aerodynamic dataset is constructed by analyzing the model in various flight conditions. Mach number, angle of attack, angle of sideslip and control surface deflection angles are varied accordingly.

Subsequently, a control allocation scheme must be derived, to determine a relationship between the three pilot inputs (longitudinal stick X_B, lateral stick X_A and pedals X_P) and a deflection of the control surfaces (Fig. 6).

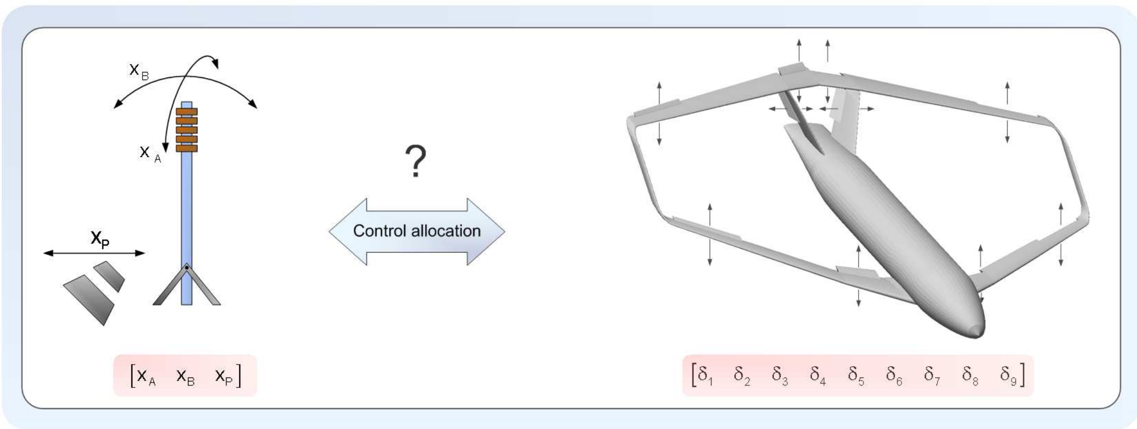

Figure 6. The control allocation problem

Many theories and allocation methods for managing multiple, redundant control effectors exist. The general control allocation problem can be defined with Eq. 1.

$$m_d = B\vec{\delta} \tag{1}$$

Here m_d is the desired moment vector, B is the aerodynamic effectiveness of the controls and δ is the control deflection vector. The control deflection limits are assumed to be ±30 deg for all controls. So, in fact this is a constrained control allocation problem. For the current application, there is an infinite amount of solutions to this equation. In this study, it is merely the objective to create a simple and constant gearing ratio between the pilot inputs and the control deflections. It is decided to use a direct method as described in Refs. 5 and 6.

The direct method[5] is derived by assessing the moments created by the individual control surfaces. In short, a control allocation routine[6] uses the aerodynamic effectiveness matrix and the control surface deflection limits to create the maximum attainable moment subset (all possible control deflection combinations within the limits, multiplied by the aerodynamic effectiveness matrix). The routine is subsequently used to evaluate what the minimum required control surface deflections are to generate a unit moment in each of the three principal moment directions (roll moment *L*, pitch moment *M* and yaw moment *N*). The relative magnitudes of the required control surface deflections per principal moment direction are then related to the individual entries in the control allocation matrix per pilot input. The result is one constant control allocation matrix (*CA*) representing the relation between the pilot inputs and the control surface deflections. A simple gearing ratio is subsequently added to scale the required pilot inputs to obtain maximum control surface deflections to a unit input.

$$\begin{bmatrix} \delta_1 & \dots & \delta_9 \end{bmatrix}^T = \begin{bmatrix} X_A & X_B & X_P \end{bmatrix}^T CA \tag{2}$$

This control allocation can easily be implemented in a mechanical flight control system. It is a recommendation for future work to find the best control allocation scheme for each flight condition and to make a comparison between the various control allocation methods available. For example, the weighted pseudo-inverse method[12] can also be considered. This however, should be done after the design of the flight control surfaces in terms of size and position is completed and is therefore not part of this research study. Now the control allocation is determined, the flight mechanics analysis can be conducted.

The flight mechanics modeling toolbox used for the analysis is based in Matlab / Simulink. It is a generic and modular toolbox that can handle any fixed wing aircraft type. The aircraft model is automatically constructed based on user input such as the number, type and location of the engines. Relevant data has to be provided subsequently. The structure of the toolbox is such that it can be implemented in a multi-disciplinary design optimization. Once the aircraft model is created, then various routines can be executed for analysis. For example, a trimming algorithm is present to find the aircraft attitudes and control inputs for a prescribed flight condition. Linear aircraft models can be derived based on the full nonlinear model. Handling qualities analysis can be done in both the linear and nonlinear domain. For example, complete maneuvers can be simulated with the nonlinear model, whilst the linear model can be used to identify the aircraft Eigen motions. A more detailed description of the toolbox is given in Ref. 6.

V. Results

Once the design process was implemented, an exhaustive search through the design space was conducted to obtain a clear understanding of the problem. Results are presented in Fig. 7. The green area shows the feasible design space. The numbers in the green boxes indicate the total control surface area. The numbers in the red boxes indicate which requirements are not satisfied. This gives the engineer a powerful insight in how the physical aircraft design influences the aircraft controllability and handling qualities. The engineer can easily investigate what the effects of resizing the control surfaces or relaxing certain requirements will be. A simple example; the infeasible designs with a large aileron span width and small elevators do not comply with the push – pull requirement (6 and 11). In the interpretation of the results, one must realize that the control allocation scheme allows the ailerons to be used partially as elevators and vice-versa. So they cannot be seen as pure ailerons or elevators. Nevertheless, the inboard surfaces are designated as elevators and the outboard surfaces as ailerons.

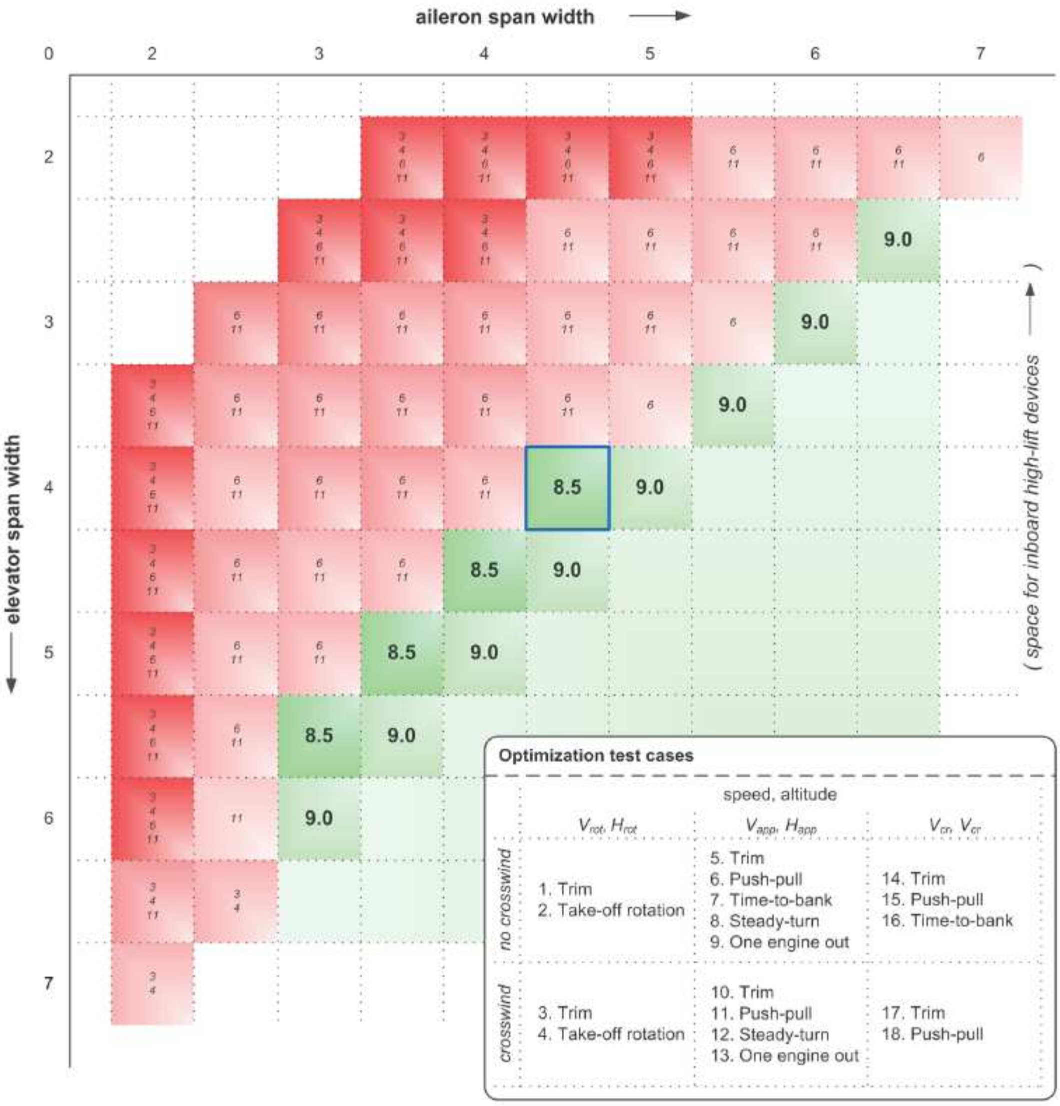

Figure 7. Results

Clearly it is not always possible to perform an exhaustive search throughout the design space. An optimizer can also be linked to the process to find the best solution. This was also tested successfully. It depends on the initial design, which solution is found. For example, if an initial design with large ailerons and small elevators is used, then the solution will be on the Pareto front in the region with large ailerons and small elevators. The current study is not focused on optimization techniques however. The exhaustive search is therefore seen as a good validation of the control design method. The highlighted cell in Fig. 7 is chosen as the final design because it is the element of the set of optimal solutions with the smallest elevator. Elevators are located inboard and ailerons outboard, therefore adding elevators on the wing has a larger negative effect on aerodynamic performance of the wing than adding ailerons (high lift devices which could be placed instead of elevators/ailerons have a better performance inboard. The smaller the elevator, the better. The resulting final design which was selected is presented in Fig. 8.

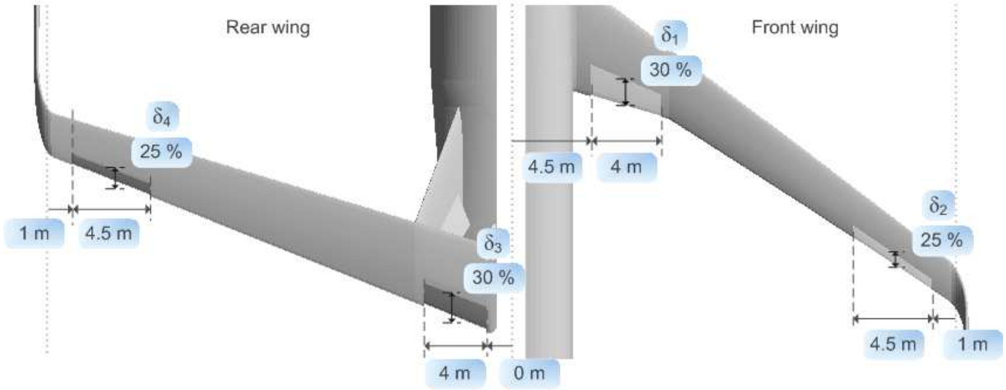

Figure 8. Final design

VI. Conclusions and Recommendations

A methodology is presented that allows the automated design of primary control surfaces for all types of fixed wing aircraft, in terms of number, size and location. The method is purely physics based which makes it particularly suited for unconventional aircraft. The automated part of the design process includes an aerodynamic analysis, control allocation and a flight mechanics analysis. As a test case, flight control surfaces are designed for a 300 passenger variant of the Prandtl Plane, a box wing configuration. This aircraft is deemed to have a low induced drag compared to conventional aircraft. Elevators are placed inboard, both on the front and rear wing. Ailerons are located on the outboard portions of both wings. Conventional rudders are placed in the vertical tails. Results indicate that the controls are most effective at these locations. The aircraft must be able to fulfill a set of handling qualities requirements with these control surfaces. Furthermore, the total surface area is minimized to reduce aircraft weight.

The overall aircraft design has been kept constant in this research. In future work, the flight dynamics of the Prandtl Plane will be evaluated in detail, as well as the influence of design variables such as wing sweep on the flight dynamic behavior. Furthermore, the design will be evaluated with a detailed aerodynamic method (CFD) and the complete aircraft flight mechanics should be evaluated through a piloted simulator trial. Furthermore, the potential that direct lift control and pure moment control (or a combination of both) offer will be exploited in the design of an automatic flight control system.

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