Design of a tilting mechanism for a VTOL flying wing UAV

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Abstract. In this paper, the detailed design of a mechanism for the transition from vertical to horizontal flight of a Vertical Take-off and Landing (VTOL) fixed wing Unmanned Aerial Vehicle (UAV) is presented. The UAV, which is being developed in the framework of the MPU research project, under the designation MPU RX-4, is a lightweight, all electric driven UAV with a flying wing layout. The MPU RX-4 is capable of performing both conventional flight, like a regular fixed wing aerial vehicle, as well as vertical hovering, like a multicopter, adapting on different operational demands. To achieve that, the development of a robust transition procedure from one flight phase to the other is required. This procedure is based on mechanisms capable of altering the flying characteristics of the UAV. More specifically, these mechanisms should be designed in order to change the orientation of the thrust vectors from horizontal to vertical and vice versa. MPU RX-4 uses a configuration of three electric motors (two mounted on the canards, and one in the main body) in order to perform both flight phases. For the transition from the hovering phase to the level flight, the two frontal motors have to be tilted from the vertical position to the horizontal, and the rear motor to be nested in its proprietary position, using four external hatches. Two separate mechanisms are designed, one for the canards’ tilting movement and another one for the extension and retraction of the rear motor hatches. Finite Element Analysis is carried out for the structural sizing of the mechanism (i.e. internal loads, linkages cross-section, joints sizing). The aerodynamic loads, acting on the mechanisms, are derived from Computational Fluid Dynamics analysis performed for the various flight phases (hovering, level flight and transition) of the UAV. Finally, the designed mechanisms are presented as integrated parts of the prototype UAV.

1. Introduction

Fixed wing Unmanned Aerial Vehicles (UAVs) have been largely developed through the ending decades of the 20th century, initially for military, and later for civilian operations and scientific applications. In recent years, the number of civilian Unmanned Aerial Systems (UAS) in use has been drastically increased [1], with applications ranging from security and border monitoring, to emergency transports and/or search and rescue operations. Nowadays, many companies facilitate UAVs on applications regarding cartography, real estate and precision pharming. The UAVs are robotic platforms that, if equipped with appropriate flight control and environment perception algorithms, can operate
autonomously and collect the desired data. As a result, a great number of UAS systems are currently available in the market. Modern commercial UAVs can be classified in to two main categories regarding their geometry, e.g. fixed wing and multicopters. Fixed-wing UAVs offer the advantage of reduced drag, which can be translated into increased payload capability, endurance and/or cruise speed, due to its more efficient aerodynamic design. Multicopters, though, offer the capability for vertical take-off and landing (VTOL), access to areas that are not easily traversable, hovering and in some cases increased portability [2]. Their significant disadvantage lies in their limited flight time, and low maximum speed, due to the very high-power consumption of their motors [3] because of their non-aerodynamic design.

The present study is performed on the framework of the Multirole Portable UAS “MPU” research project, that aims to develop a portable small UAS, under the designation RX-4 (Figure 1), which is designed to be of fixed wing configuration but with hybrid flight capability, thus incorporating also some of the advantages of multicopters [4]. The UAV will be a multirole platform, equipped with various electro-optical equipment (RGB, Thermal, Multispectral). RX-4 will be capable of performing VTOL and will carry a useful payload of 0.5kg. The mission requirements of the MPU RX-4 drive some basic design choices, i.e. its VTOL configuration for a rapid deployment and the flying wing configuration for larger internal volume and enhanced flight performance characteristics [5]. These two disruptive design choices push the RX-4’s operational capabilities to the maximum. Indicatively, flight endurance can be stretched beyond the limits of a state-of-the-art conventional layout fixed-wing UAV or a multicopter and agility beyond the limitations imposed by the need of a paved runway or special launching and arresting equipment (catapults, wires, nets, etc.). The RX-4 aims to integrate the best of both worlds, allowing a fast a deployment with the maximum flight endurance during its mission. In Table 1, the basic mission requirements of the UAV are presented.

| Table 1. RX-4 Technical specification |
|--------------------------------------|
| Mission                            | Surveillance and mapping |
| Take-off and landing                | Vertical                 |
| MTOW                               | 4.5 kg                   |
| Payload                            | 0.5 kg                   |
| Wingspan                           | 1.8 m                    |

Figure 1. RX-4 Basic dimensions
Wing loading (W/S) 6.15 kg/m²
Cruise speed 65 km/h
Maximum speed 125 km/h
Stall speed 25 km/h
Endurance 120 min
Cruise altitude 125 m

One of the most critical design aspects of the MPU RX-4 is its portability and ease of deployment, thus its overall dimensional limitations are present throughout the whole design procedure. It was decided for the RX-4, to be divided into 3 major components, i.e. the center body and the two wings.

2. Aim of the study
The aim of this study is to design two different types of mechanisms, allowing the MPU RX-4 to transition from the hovering flight phase to the leveled flight phase and vice versa. The configuration of the MPU RX-4, before and after the transition mechanisms deployment, is depicted in Figure 2, along with two simplistic free body diagrams of the UAV, indicating the forces equilibrium, both in the flying phase and the hovering phase. In every fixed wing VTOL application, there is a common method of rotating the thrust vector from the horizontal to vertical position [6], in order to change flight direction of the aircraft. The RX-4 uses three electric motors for its propulsion, powered by two independent battery sets. The first motor is positioned in the back, operating as a fan for VTOL and hovering legs of the mission. However, during the horizontal flight segments of the mission, the rear electric motor remains inactive. The two frontal motors have a dual purpose, at first, they provide the necessary thrust for the horizontal flight segments and secondly, they supplement the rear motor for the phases of VTOL and hover. Noting in this point that, during a vertical take-off, the UAV’s weight is not the only load that has to be taken into consideration, due to a heavy presence of inertial loads and drag forces in the vertical axis. Moreover, the contribution of the frontal motors, during vertical movement or hovering, is not limited only in adding extra thrust when it is necessary, but also by providing a crucial control authority, enabling the autopilot to keep the UAV stable during its ascent and descent (note that the control surfaces have no authority during hovering). In case of the RX-4, to achieve a safe and quick transition after a successful vertical take-off, the thrust vectors of the frontal motor should rotate from the vertical position to the horizontal and the rear fan bay should be sealed from the flow around the UAV. The first is achieved by mounting the frontal motors on two tilting canards, powered by electric servo actuators. In
order to reduce the drag generated by the fan bay, a two-set closing-system of the hatches is used, one positioned on the pressure side and one on the suction side of the UAV. The operation of the hatches is also controlled by electric servo actuators. For the opposite transition, during landing, the rear fan hatches open, and the frontal motors are tilting from the horizontal position to the vertical. When the transition is complete, the three motors cooperate, being controlled by the autopilot, to lower the UAV safely to the ground.

3. Mechanisms design tools and methodology

The core of the tilting mechanisms design methodology lies on its basic kinematic model, the calculation of the loads and the practical implementation and realization to the UAV. The proposed methodology initiates with the listing of the design requirements and constraints which leads to the first mechanisms concepts. These concepts are then evaluated, regarding their total weight, complexity, consistency and safety. When the concepts reach an adequate level of development, the external loads are calculated. Some static loads, such as the moments on the canards, caused by the motor’s thrust, are calculated analytically. Residual more complex loads, like the torsional loads around the moving axis of the rear motor hatches are calculated using computational fluid dynamics (CFD) simulations. When the maximum external loads are calculated, simple kinematic models are being set up, aiming to the sizing of the servo actuators along with the estimation of the mechanisms’ responses throughout their working cycle. Finally, the detail design takes into consideration the manufacturing constrains of each mechanism, by introducing the final integration tweaks, and provide the manufacturing drawings for each part of the designed and sized mechanism.

3.1. Conceptual mechanism design

For the conceptual design of the mechanisms regarding the transition of the MPU RX-4, many initial concepts had been conceptualized. Each of the concept had to follow a list of requirements and constraints, some of these requirements are presented in the following Table 2.

| Table 2. Mechanisms requirements and constraints |
|-----------------------------------------------|
| **Canards**                                        | **Fan hatches**                                |
| Min. weight                                      | Min. weight                                    |
| Min. Number of moving parts                      | Min. Number of moving parts                    |
| Durable enough to support ½ MTOW at 2g           | Durable enough for the aerodynamic loads        |
| Small enough to be fitted into the stationary part | Small enough to be mounted around the fan      |
| Powered by electric servo actuators              | Powered by electric servo actuators            |
| Low complexity                                   | Low complexity                                 |

As far as the rear fan hatches mechanism is concerned, three concepts are proposed. The first one is about facilitating a planar mechanism, embedded into the skin of the MPU RX-4, which controls two rotating hatches on both sides (upper and lower) of the UAV, opening them during transition in a way resembling the aperture mechanism on a camera. This mechanism was soon dropped due to high weight and complexity. The next two concepts are about the four fan hatches, which are rotating around a longitudinal axis of the UAV, as shown in Figure 3. The difference between these two concepts is the
number of servos actuators used. The design using two servo actuators, each of them connected to a pair of hatches through a complex linkage system, was soon dropped due to lack of available space and high complexity. The concept of favor turned to be the most simple and robust one, with four independent servo actuators connected to the four hatches. The hinge supports are directly connected to the servo axis, minimizing the number of necessary parts for each mechanism and the movement of the hatch is directly controlled by the servo actuator with no gear ratio. Regarding the canard mechanism concepts, the selection procedure is more straightforward, since the only design choice is about rotating only the motors on the canard tips or the whole canard around a certain axis. Due to the limited available space near the canard tips, the second concept was selected.

3.2. Load calculation
For the load calculation on the selected mechanisms concepts, two simplified CAD files are generated respectively, in order to provide the basic geometry and dimensions of them. The certain loads, such as inertial loads, weights and static forces and moments are calculated analytically. For example, the bending moment around the axis of the canard, due to motor thrust, is easily reached by multiplying the maximum motor thrust times the span of the canard. For the more complex loads, i.e. the aerodynamic loads, high fidelity Computational Fluid Dynamics (CFD) computations are performed, solving the Reynolds Averaged Navier-Stokes (RANS) equations. More specifically, the computational grid is generated, using the commercial BETA ANSA pre-processing software (v19.1.0). The grid consists of both structured and unstructured regions. Special care is given in areas with strong pressure gradients and/or where flow separation is most likely to appear (e.g. around the main motor hatches). Above the UAV’s external surface, a structured region exists with 20 hexahedral cells in the normal to the wall direction and appropriate first cell height to ensure a value of $y^+$ bellow one, since a low-Reynolds turbulence model is adopted for an accurate representation of the boundary layer development, very close to the UAV’s surfaces. The final computational grid that was used, is the result of extensive grid independency studies performed at cruise conditions. All cases were solved with the ANSYS Fluent software (Release 18.2), using a pressure-based solver, and employing the SIMPLEC scheme for the pressure-velocity coupling and a second order spatial discretization scheme for all the discretized transport equations. The Low-Reynolds Spalart-Allmaras (S-A) turbulence model is adopted, a widely used turbulence model in external aerodynamics applications. The model can accurately predict turbulent or transitional external flows with imposed external adverse and favorable pressure gradients, such as the ones imposed on airfoils and wings [7].

3.3. Detail mechanism design
The final detailed design for the canards’ mechanism (Figure 4) was based on a hybrid carbon fiber reinforced plastic (CFRP) structure. The moving part of the canard was designed as a carbon component with a plastic 3D printed core, which is simultaneously working as an inner mold, enabling the carbon layers to maintain an adequate geometrical accuracy around it. The canard shaft is machined on the aluminum canard moving core. This canard region is considered a high stress area, thus the plastic core is replaced by an aluminum one.

On the other side of the canard, where the stationary part is located, a similar manufacturing technique is implemented. In this case, a milled aluminum component is used as core, being welded to rest of the carbon structure by a heavy duty two component epoxy glue. This aluminum insert, called the canard stationary part, is housing the canard shaft using two ball bearings. The aluminum canard shaft is one of the most crucial elements of the mechanism, having a dual role, by supporting the whole moving canard with the electric motor on it and by transferring the servo motion for the canard rotation around the shaft’s axis. On the inner end of the shaft, a coupler (transmission hub) is connecting it to the servo actuator, completing the power transmission system. The axial loads, of this mechanism, are counteracted by a fixation on the servo mounting base, through the servo actuator itself.
Regarding the fan hatches mechanism, as stated previously, the simpler and lighter mechanism concept is selected. Once again, the power transmission system has the main structural role, supporting the fan hatches both in the closed and the opened position. The mechanisms for the lower and the upper fan hatch are essentially mirrored but, due to some minor geometrical deviations their parts are not quite interchangeable. In order to avoid unnecessary repetition, these mechanisms are going to be explained as one.

As being shown in Figure 5, the whole mechanism, including the hatch itself, is supported by the fixed servo base, through the servo actuator. The main structural element is the steel rod that supports the carbon hatch and rotates it by transferring the motion from the servo actuator, through a metal servo horn. These steel rods bear the maximum stresses during the mechanism’s operation, especially in the area near the servo horn where a severe 3D stress state is present. More specifically, the rod is subjected to bending and torsional strains in the three normal directions, due to inertial and aerodynamic loads.

It is chosen not to use a complex actuating mechanism, via hinges along the diameter of the fan bay, due to strict spatial constraints in this area and to avoid adding extra weight to the MPU RX-4. The design philosophy for this mechanism is rather simplistic, focusing on using one structural element (the steel rod) both for the structural support of the fan hatches and for power transmission. This approach is compromising the steel rods, of each fan hatch, as the one and only critical component, under a 3D stress state. Dedicated structural analyses, being presented in the next chapter, are validating that the “weakest link in the chain” is in fact capable enough to withstand the working stresses for this mechanism.

For the integration of the designed mechanism into the composite structure of the RX-4, some critical skin modifications to the carbon fiber monocoque are needed. These skin regions are altered to accommodate the necessary mechanism parts but also reinforced with extra carbon layers to withstand
the higher regional loads, occurring by the supported mechanisms. The skin modifications are primarily focused on two regions, the canards and the servo wells around the fan bay, as shown in Figure 6.

![Skin modifications](image)

**Figure 6.** Skin modification for the mechanisms’ integration

4. Results

The most crucial component for both designed mechanisms are analyzed, using finite element analysis methods (FEM), for their structural integrity to be ensured, given that these two mechanisms are critical for the MPU RX-4’s safe operation. For these simulations, the BETA ANSA 19.1 software is used, coupled with the impeded BETA Epilysis solver (Nastran based). The results post-processing is executed using the BETA META software. More specifically, all models are solved as linear static problems (Nastran SOL 101), providing safe results for time independent loads causing minor elastic deformations. For an initial stress analysis, these assumptions are considered safe, if the stresses which are developed on model are well below the maximum tensile strength of the material used.

The model, including the canard moving part and the machined canard shaft, constitutes of around 200K solid elements and it is solved in the highest torsional stresses state. The bending loads are also taken into consideration. The material used is the aluminum alloy 6061-T6 and the maximum Von Mises stresses developed are about 70MPa (Figure 7a), a value well below the maximum tensile strength at 276MPa [8]. The maximum deformation occurred is 1.2mm.

Regarding the fan hatches mechanism, the steel rod which supports the carbon hatch and connects it to the servo actuator, is the element bearing the maximum working loads. The hatch rod model constitutes of around 130K solid elements and it is solved in the highest bending stresses state. The torsional loads are also taken into consideration. The material used is a typical steel alloy and the

![FEM models](image)

**Figure 7.** FEM models for the canard stationary part and the steel rod for the fan hatches
maximum tensile strength of 350MPa [9]. For the examined steel rod, the maximum Von Mises stresses developed are about 180MPa (Figure 7b). The maximum deformation observed is 4.3mm.

5. Conclusions
The current study presents the design approach and methodology for the transition mechanisms, allowing the MPU RX-4 to transition between a level flight state to a vertical hovering state and vice versa, namely, the canards rotation mechanism and the fan hatches mechanism. At first, a conceptual design for both mechanisms takes place, followed by the concepts’ evaluation over the initial design requirements and constraints. As the best concepts are selected, a first CAD model for each one is created, providing the necessary geometrical data for the external loads’ calculation. Finally, a detail mechanism is developed, taking into consideration the analyses around the parts sizing and other manufacturing constraints. The mechanisms design procedure for the MPU RX-4 indicates that it is possible, for a small UAV, to be designed as a VTOL platform, without adding an unacceptable amount of extra weight to its structure.

For the future steps of these analyses, the authors expect to develop a detailed kinematic model of the two presented mechanisms, in order to calculate the stresses on every link and joint of them, allowing a further optimization of the designed mechanisms, with the critical goal of their overall weight reduction. Time depended models of the mechanisms are also required, allowing a fatigue simulation for the sized parts. The last step of the current analysis is the integration of the designed mechanisms to the actual UAV, followed by a testing campaign, including fully functional flight tests.

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