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Aerodynamic design analysis of a UAV for superficial research of volcanic environments

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ABSTRACT

When volcanoes manifest unusual signs of activity, real-time data aids for evaluating and communicating reports about volcanic hazards. For this reason, the present research aims the aerodynamic design of a low-cost unmanned aerial vehicle (UAV) able to perform aerial surveillance of volcanic environments. Its main mission is to transmit real-time volcanic data to a remote location, in order to aid to forecast volcanic eruptions, as well as avoiding the exposition of pilots and scientists to these dangerous flight conditions. During the conceptual design phase, classical and new design procedures were developed in order to determine the vehicle design requirements, in relation to its flight in a hard scenario like an active volcano. Likewise, the main geometric, aerodynamic, stability and performance parameters of the UAV were calculated and assessed through theoretical/analytical presizing and Computer-aided Design (CAD) methods. After obtaining the final concept, the aerodynamic design was carried out considering the constraints found in the previous design phase. In this way, an accurate estimation of the aerodynamic coefficients was developed, through analytical simulations, Computational Fluid Dynamics (CFD) simulations and wind tunnel testing. Results showed that the entire design process was consistent because the analytical, numerical and experimental results were greatly similar in the Lift (C_L) and Drag (C_D) coefficients. Furthermore, the UAV characteristics are within the limits of the design requirements, presenting several aerodynamic and performance advantages in comparison to other vehicles used in the same mission. This suggested that, on a large scale, the aerodynamic behavior of the UAV is suitable for performing the mission for which it was created. However, actual-environmental studies are still necessary in order to validate the reliability of the designed UAV.

1. Introduction

The study of volcanoes continues to be of vital importance to society, because these have caused many disasters over time, generating an imminent danger to the nearby towns [1]. In a geographical context, the Pacific ring of fire is a large zone around the Pacific Ocean, where there is a high level of seismic and volcanic activity. It extends over more than 40000 kilometers, from New Zealand to the west coast of South America, through the coasts of East Asia and Alaska and Northeast North America and Central America [2]. This zone contains the volcanoes that have generated the greatest human losses, due to large volcanic eruptions. Among the most important volcanoes are: Tambora Volcano (2850 m a.s.l.), located in Indonesia ($8°14'43''S, 117°59'34''E$), whose eruption caused 82000 deaths; Ruiz Snow-capped Volcano (5311 m a.s.l.), located in Colombia ($4°53'33''N, 75°19'25''O$), whose eruption caused 24800 deaths; Mount Unzen Volcano (1500 m a.s.l.), located in Japan ($32°45'24''N, 130°17'40''E$), whose eruption caused 15000 deaths, among others [1,3], such as the ones presented in Fig. 1.

The aforementioned catastrophes all have something in common; they could have been avoided, if the gases composition and the surface deformations suffered by these volcanoes had been previously known [4]. Fortunately, recent advances in technology have resulted in an array of volcano monitoring systems, that can provide suitable warning prior to volcanic eruptions.

Based on the experience of Patterson et al. [5], besides the risk for populations near to volcanoes, there is another hazard in relation to volcanic eruptions, which is the injection of large quantities of volcanic ash into the air in a relatively short period of time, taking only five minutes for an ash plume to rise to a height of 10 km. This represents a threat to commercial airliners, because the volcanic ash particles are abrasive and can melt at high temperatures

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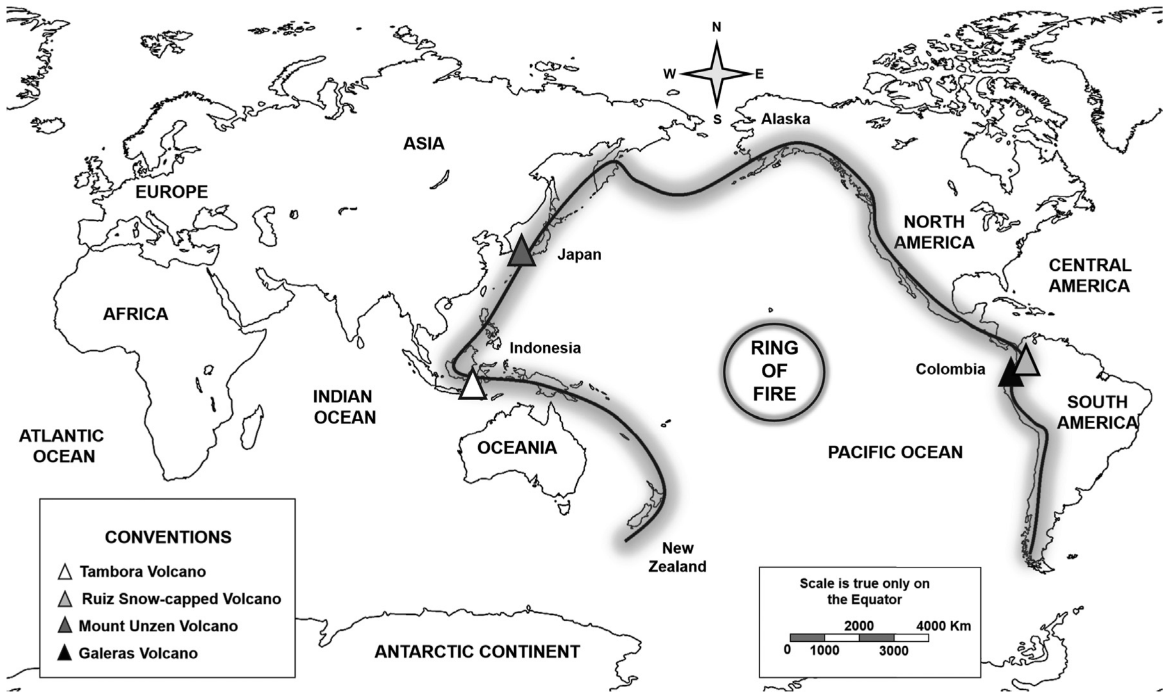

Fig. 1. Pacific ring of fire.

within jet engines, clogging the turbines and causing engines to flame out. According to data obtained by Guffanti et al. [6], 129 incidents have been reported, in which: 94 incidents are confirmed ash encounters, with 79 of those having various degrees of airframe or engine damage, including 9 encounters with the engine shut down during flight; 20 are low-severity events that involve suspected ash or gas clouds and 15 have data that are insufficient to assess severity.

Most of these encounters occurred within 24 hours of the ash production onset, and at distances less than 1000 km from the volcanoes source. For that reason, a periodic monitoring of the atmosphere around the volcanoes craters could avoid this kind of incident, because, in case of any air composition change, the airport controller could be informed, in order to modify the flight route and keep airplanes far away enough from the volcanoes craters.

Regarding the previously mentioned problem, gas emissions with unusual chemical composition and geographical deformations in volcanoes are warnings of a possible eruption. Specialized research centers in forecasting volcanic eruptions have developed different procedures for analysing the behavior inside and outside the craters. One of these procedures involves performing continuous flights over the volcanic domes, with the intervention of manned aircraft. I.e., the aircraft are equipped with instruments for in situ analysis the geographical, chemical and thermal changes over the volcano surfaces. However, the highly unfavourable flight conditions can affect the aircraft performance, risking the lives of the crew aboard [7–9] That is the reason why NASA satellite images are used to analyze the surface deformations of volcanoes. However, it is not possible to know more important details and may even generate false alarms [8,10–12].

Under these limitations, the removal of the crew from the aircraft, combined with remote sensing technology of Unmanned Aerial Vehicles (UAVs) appears as a viable solution to this issue.

In the present study is reported the design methodology for a commercial low-cost UAV named URCUNINA (meaning Fire Mountain), whose mission is to harvest volcanic data (pictures, videos and gases samples), in order to aid scientists figure out the possible types of volcanic activity and the associated real-time hazards to prevent loss life.

In-depth exploration of the operational field of the URCUNINA-UAV was performed, aiming to identify the Design Requirements and Objectives (DRO) for the aerodynamic design of this vehicle [13,14]. The geographical features of the Galeras Volcano (4276 m a.s.l.), located in San Juan de Pasto – Colombia ($1°13'31''N, 77°21'68''W$) (Fig. 1) were selected [15,16]. Hence, the URCUNINA-UAV must be able to fly up to 4300 m a.s.l. i.e., it requires a high service ceiling. At this great altitude, the wing lift is reduced due to the rarefaction of the air. Therefore, the choice of the wing airfoil was emphasized to obtain a sufficiently high lift coefficient (C_L). A powerful propulsion system is also required because of the mass flow rate decrease at the operating altitude. Thus, the selected engine/propeller must reach this performance requirement, keeping sufficient Thrust to Weight Ratio (T/W) during each phase of the mission profile.

In the vicinity of volcanoes, the ground is often very rocky, so, the take-off phase must be performed a few kilometers away from the foot of the volcano. In our case, the base station is located in the premises of the "Servicio Geológico Colombiano (SGC)" in San Juan de Pasto – Colombia, at an altitude of 2527 m a.s.l. and, 9 km in a straight line until reaching the top of the volcano [17], i.e. the URCUNINA-UAV requires sufficient endurance and range capabilities. Moreover, an aircraft catapult was also considered, as a form of assisted take off, for mission initiation closer to the crater, i.e. from the top o a car.

Regarding the constraints of the volcano monitoring phase, for an adequate and complete assessment of the volcanoes behavior, the URCUNINA-UAV must be able to maintain low flight velocities, close to 20 m/s (Low Reynolds Number), in order to enable taking pictures, videos and gas samples in real time over the crater's surface [10,18]. An additional drawback has to be considered; the presence of strong turbulence due to wind speeds greater than 25 m/s [19,20]. Therefore, the wing and empennage configurations were selected to overcome the possible stability and performance reductions.

Finally, Von Glasow [21] suggested a fast thermodynamic equilibrium between the high-temperature of volcanic gases and the atmospheric temperature might be applicable, at those altitudes. Hence, the URCUNINA-UAV must withstand temperatures lower