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Energy-optimal path planning for Solar-powered UAV with tracking moving ground target

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ABSTRACT

This paper presents the novel use of receding horizon control (RHC) with particle swarm optimization (PSO) to generate the energy-optimal trajectories for Solar-powered Unmanned Air Vehicle (SUAV) with the mission of target tracking. Firstly, an integrated model is presented that accounts for the couplings, such as kinematics, energetics and mission. The model can formulate the relationship between the aircraft's position or attitude and the solar time or angle at anytime and anywhere in the world. Next, the mission of tracking moving ground target is studied in this paper, which is unique relative to past work about the SUAV. At the same time, to collect more energy and track the moving ground target, the optimization method of RHC with PSO is used here. To evaluate optimization performance, some performance indexes are put forward, and the definitions of them are given. Finally, several numerical simulations demonstrate that this method is feasible and flexible to generate the energy-optimal route for solar-powered UAV online with tracking ground moving target. The analysis of simulations results indicates that it's possible to carry out the task of tracking maneuvering target for a longer time for SUAV.

1. Introduction

In recent years, researchers have increasingly focused on improving the endurance performance for the HAVE/UAV (High Altitude Very-long Endurance/Unmanned Air Vehicle). And Solar-powered UAV (SUAV), e.g. Sky Sailor and Helios, has proved to be an effective solution with high energy utilization efficiency. In Ref. [1], a solar-powered helicopter prototype is designed and developed. It was equipped with solar cell on top of its wings, and the consumed energy by the aircraft can be derived from the solar cell and battery. In [2–9], the application of optimization techniques plays a decisive role in increasing the required energy utilization efficiency for SUAV. However, there are still some big challenges. For example, a suitable mathematical model is difficult to obtain, which can show the relationship between the attitudes of aircraft and the solar radiation intensity at any time and any place. In addition, it is challenging to generate the energy-optimal target-tracking trajectories, as there are some complex couplings among SUAV aerodynamic model, the solar energy harvesting and the mission constraints.

There has been great progress in the recent studies on the solar powered aircraft. In Ref. [10], the research progress about photovoltaic cells, rechargeable batteries, maximum power point tracking and so on for aircraft has been reviewed, and some guidance principles for designers in the design of UAVs are also provided. A review of the general history and existing literature on the analysis and design of solar-powered vehicles and trajectory planning is provided in [4,5,8,9,11–19]. In [20], implications of longitude and latitude on the size of solar-powered UAV have been studied. It is concluded that solar-powered UAVs can be utilized more effectively in the places closer to the equator, where smaller and lighter solar-powered UAV can be designed. Spangelo et al. [5] put forward a method to plan a smoother and energy-optimal path in a three-dimensional space. In [21], an active power management method for path planning has been investigated. The usefulness, advantages, and disadvantages of this method over a passive method are analyzed. To fulfill the power requirement with weight constraint of rechargeable batteries, the method of energy stored by gravitational potential for solar-powered aircraft has been put forward in [22,23]. And the equivalence of gravitational potential and rechargeable battery for aircraft on energy storage has also been analyzed.

However, for the definition of energy collection model, the previous studies usually assumed that the solar position and radiation is invariable and known. Consequently these models may not correctly reflect the genuine relationship between solar and SUAV during the long-time flight. In addition, the SUAV must be designed

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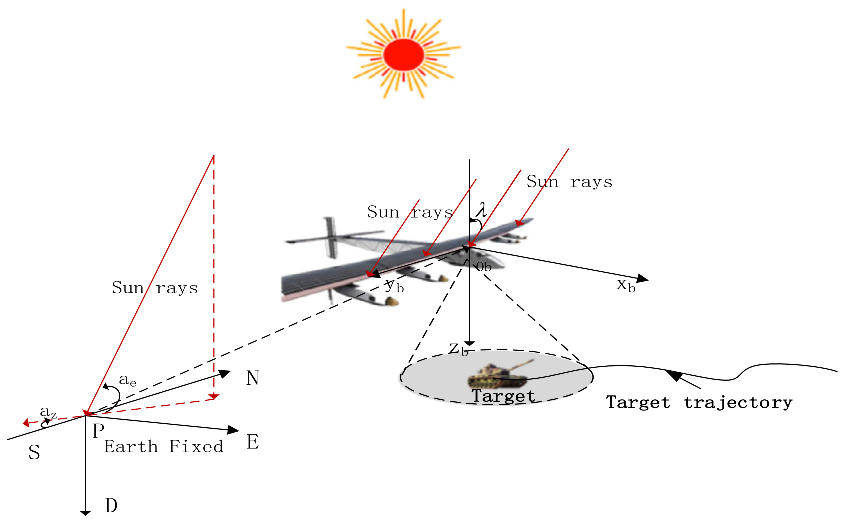

Fig. 1. Overall view about sun and aircraft.

based on executing the variety of required missions, and the typical tasks include the intelligence, surveillance and reconnaissance missions. But in most of literatures such as [3,16,22,23], the optimal path planning of solar aircraft is only based on the simple mission such as flying from the start position to the final position. The energy-optimal path is planned off-line in known static environments, and it may be inapplicable to the dynamic tasks e.g. the target tacking. To the best of our knowledge, the receding horizon control (RHC) has been used and proved to be an efficient on-line optimization method in a dynamic environment, which is based on the simple idea of repetitive solution of an optimal control problem and state updating after the first input of the optimal command sequence [24,25].

Based on the above analysis, to achieve the mission of tracking moving ground target for the SUAV for a long time, an integrated model is presented and the energy-optimal path planning with RHC with PSO solver is studied. The simulation results show that it's possible to carry out the task of tracking target for a longer time for SUAV, with the advantages of simple principle, high computation efficiency and good real-time performance. This paper has the following contributions.

First, by analyzing the relationship between the aircraft's attitude and the solar angle, an integrative model is presented, by which the radiation on the SUAV's surface can be calculated at anytime and anywhere in the world.

Second, the method of RHC with PSO solver is utilized here, to plan the on-line energy-optimal trajectory of SUAV for tracking ground moving target.

Finally, an important conclusion has been drawn that it's possible to carry out the task of tracking target for a longer time for SUAV with the right conditions, e.g. the sufficient solar radiation and the reasonable speed of target.

2. Problem formulation

In this section, the model and multiple constraints of SUAV are presented. The integrated model of the aircraft kinematics and energetics, the constraints consisting of maneuvering patterns, and the airborne electric-optical pod model are formulated, by referring to literatures [3,23,26–31].

Fig. 1 shows the overall view, including the composition of sun, earth, target and aircraft. All their information about position and attitude is expressed in the navigation frame (*P-NED* in Fig. 1) which has its origin at the location of the navigation system, point P, and axes aligned with the directions of north, east and the local vertical (down). The computational rules of solar angle are referred in [31], and the definitions of axes and notation are used the same with Ref. [30].

2.1. Modeling

2.1.1. Aircraft kinematic model

In this paper, the wind axes system is used for SUAV. To simplify the problem, the aircraft is assumed to fly in still air at a constant altitude with the bank-to-turn control scheme, and the path angle is zero. Hence, aircraft kinematic model is as follows:

$$\frac{dx}{dt} = V\cos\psi \tag{1}$$

$$\frac{dy}{dt} = V\sin\psi \tag{2}$$

$$\frac{d\psi}{dt} = \frac{g\tan\phi}{V} \tag{3}$$

where x is the value of N-axis, y value of E-axis, V is the speed of aircraft, ψ the yaw angle, α the angle of attack, g the constant of gravity, and ϕ is the bank angle.

2.1.2. Solar radiation model

Solar thermal energy can be converted into the electric energy of UAVs by photovoltaic cell. Solar irradiance, I (W/m^2), is the rate at which radiant energy is incident on a unit surface. The sun's radiation is subject to many absorbing, diffusing, and reflecting effects within the earth's atmosphere. The extraterrestrial solar radiation perpendicular to the horizontal surface may be calculated by the following approximate relationship:

$$I = I_0\left(1 + 0.034\cos\frac{2\pi n_{day}}{365.25}\right)^2 \tag{4}$$

where I_0 is the solar constant, and n_{day} is the number of days (start from January 1 as 1).

In this work, the terrestrial solar radiation is calculated with ASHRAE Clear Sky Model in [31]. This is a simple statistic model which is developed based on a large number of simulations using sophisticated spectral simulations and validating with ground based measurements, which is widely used in the world. This model is reasonable that the radiation on the wing's is calculated, when the SUAV flies in the stratosphere with almost completely cloudless sky. The model is described as follows: