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The solar-tracking optimal trajectory planning research based on minimum energy consumption in SSPS

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ABSTRACT

Following the initial trajectory planning research on Integrated Symmetrical Concentrated architecture (ISC) which is a kind of a space solar power station (SSPS), a new trajectory optimization scheme adopting dynamic programming is presented, which combines the joint energy consumption with particle swarm optimization (PSO) algorithm. The advantage of the optimizing scheme can mitigate the difficulty in regulation and control due to the inertia shock of huge spatial structure during the course of solar-tracking, also it can balance the relationship between energy consuming and concentration efficiency. Firstly, the theory of energy-time integral in velocity space is given for this nonholonomic system; secondly, the angular positions of the joint are expressed as a set of spline interpolating functions expressed by piecewise 4-3-3-4 polynomial interpolation; then the dynamic programming is proposed which is realized by PSO searching algorithm; finally, a geometric method is proposed to analyze the relationship between the optimized position deviation and concentration efficiency, simulation results illustrate that the proposed optimization scheme can great mitigate the velocity sudden change and satisfy the required concentration efficiency. The proposed trajectory optimization strategy has practical engineering value for huge spatial structure especial in mechanism joint accelerant motion.

1. Introduction

With the increase of demand for new and clean energy around the world, developing the SSPS has been one of the most efficient paths to solve the human energy problem [1]. SSPS mainly dedicates itself to providing the existing pollution energy alternatives to alleviate challenges caused by increasing energy demand and natural resources decline caused by the energy crisis. Since the grand idea of building SSPS to collect the solar energy in space was put forward by Dr. Peter Glaser [2] in 1969, many feasibility researches on SSPS had been studied and proposed, among which the Integrated Symmetrical Concentrator (ISC) architecture [3–5] with two joints is generally accepted for its effective sunlight-collection and convenient transmission energy system [6]. Fig. 1 shows a prototype of a space solar power station in Fig. 1(a) and motion in geosynchronous orbit in Fig. 1(b), with the regulating system consisting of a transverse truss *AB* rotating around axis *OC*, two primary concentrators located on *A* and *B* are always kept solar-tracing by cooperative coupling rotation around pivot *A* and *B*, respectively.

However, it's extremely difficult to effectively drive such huge spatial truss *AB* to rotate around fixed *OC*-axis, especially when the sudden velocity sudden change happens at some points within a run cycle along GEO; moreover, the large deflection characteristics resulting from its large-span size can aggravate the occurrence of resonance, consequently, this will excite high-frequency mechanical response and influence negatively on whole system, even make system unstable. The previous research [7] is theoretical and impracticable in engineering application despite it exploit the fact that ideal trajectory planning can thoroughly eliminate the redundant movement and obtain the 100% concentration efficiency. To improve the performance of, it is quite necessary to optimize the initial motion trajectory to improve motion efficiency such that prolong the service life, and a new dynamic programming optimization scheme is presented in the paper which combines joint energy consumption with PSO algorithm.

So far, a lot similar researches have been done on the joint trajectory planning or optimization based on the minimal energy principle. Luo et al. [8] presented to use Lagrange interpolation method to express each joint trajectory function to realize trajectory planning based on the principle of the energy minimization of industrial robotic manipulators; Zeng and Zhang [9] proposed a new design paradigm that jointly considers both the communication throughput and the UAV's energy consumption to study

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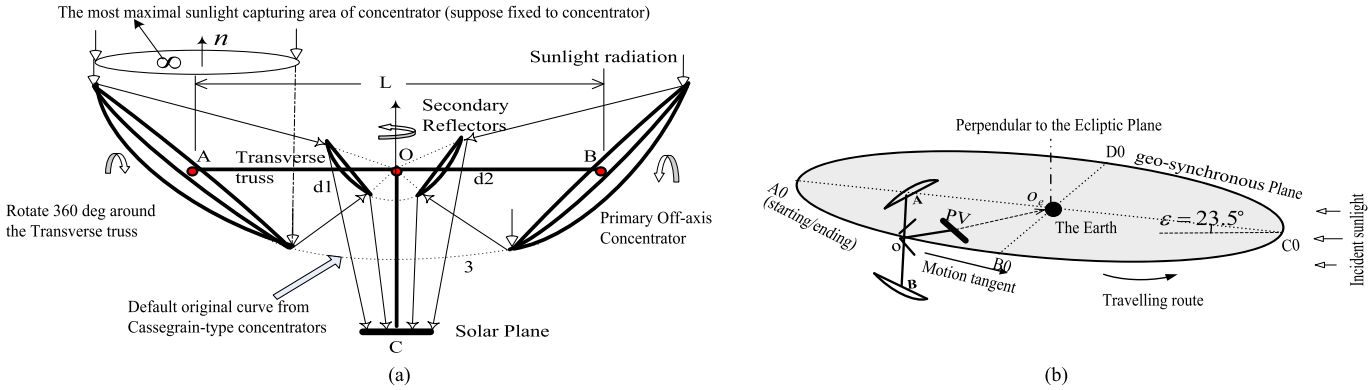

Fig. 1. The prototype of (a) space solar power station and (b) motion in orbit GEO.

energy-efficient UAV communication with a ground terminal via optimizing the UAV's trajectory; Sato et al. [10] presented a trajectories of velocity of a closed-type manipulator for saving energy which was calculated by iterative dynamic programming; Izumi et al. [11] described an optimal path which minimizes the dissipated energy in PTP motions of a vertically articulated manipulator.

Meanwhile, a number of interpolation technologies and methods have been applied to approximate the optimal motion trajectory. Sato et al. [10] used the third order B-splines function for each joint path planning of manipulators to realize optimal trajectory planning but were lack of the consideration of the acceleration to be satisfied. [12] deduced the interpolation analytic calculation formulas and applied the interpolation calculation into the path monitoring and anti-collision scanning. [13] used fifth-order B-splines composing the overall trajectory for primitive to achieve the motion planning based on the energy minimization, however, the method is too complex to be really applied.

As far as optimal control be concerned, solving the optimal control problem generally consists of three basic numerical approaches: indirect methods, direct methods and dynamic programming [14]. Firstly, in indirect methods, the calculus of variations is used to obtain the first-order necessary conditions for optimality. In the following research, Pontryagin's principle proposed by Howlett [15] was used to reformulate the train motion planning as a finite-dimensional constrained optimization problem where the unknown switching times are the variables; the same application in electric sail motion planning [16] was implemented to obtain optimal trajectory with solving the a Hamiltonian boundary-value problem produced with Pontryagin's principle. However, the common drawback of indirect methods is that the boundary-value is often difficult to solve due to strong nonlinearity and instability. Secondly, direct method is that the continuous-time optimal control problem is transformed into a nonlinear programming problem [17], direct methods can easily handle inequality constraints on states and inputs [18]. Pseudo-spectral methods [19] for solving the partial differential equations early in the 1970s was a particular class of direct methods which has risen to prominence for its global characteristics in the numerical optimal control area over the last decade [20], this methods has already been widely applied to solving optimal control problems such as orbit transfers, lunar guidance, magnetic control, etc. However, the happening of the Gibbs phenomenon will seriously affect the solution precision for the model or non-continuous interface with geometrical morphology when utilizing this method. Finally, dynamic programming transforms complex multistage process into a series of single stage process. Discrete dynamic programming and sequential quadratic programming are two forms of the dynamic programming, the former can deal better with the nonlinear optimal problem than the later [21], [22] studies dynamic programming application to airliners' flight trajectory optimization, a four dimensional trajectory

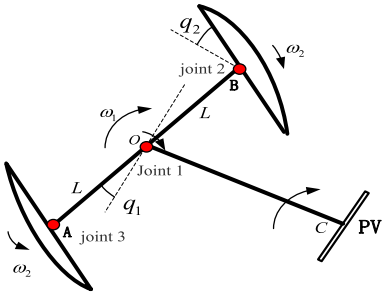

Fig. 2. Structure system of 2-DOF ISC.

optimization tool is developed for airliners' flight and an acceleration technique called moving search space dynamic programming is included to relax the computational time problem in dynamic programming. In this planning strategy, various searching methods like variational approach [23], Genetic Algorithm (GA) [24], Particle Swarm Optimization [25–27] and Sequential Quadratic Programming (SQP) [28] were employed to search the optimal solution to steer the end-effector of a free-floating space robot to a target pose.

However, there have been seldom researches on combination joint energy consumption with other key constraint conditions such as efficiency or accuracy factor, especial for huge spatial structure requiring minimal joint energy and maximum joint velocity. As we know that any continuous curve can be approximated by polynomial interpolation functions within a certain accuracy, and approximate optimal path curve can be obtained with choosing the appropriate algorithm to optimize the relevant controls parameter on the condition that constraint conditions are known. Based on the initial joint trajectory of ISC which have been already derived from previous studies, in this paper the key waypoints from the initial trajectory have been optimized by utilizing the optimization strategy combining joint energy consumption with PSO algorithm, then the global optimal planning curves are obtained under dynamic constraints.

2. Problem description

As is shown in Fig. 2, the parameters of joint 2 are the same to that of the joint 3, and the initial trajectory planning in the previous studies [7] are replotted in the following Fig. 3.

Before the optimization scheme is presented, the vectors corresponding to joint 1 and joint 2 related to proceeding Fig. 3 are defined as

$\boldsymbol{q}_i = [q_{i1}, q_{i2}]$ — denotes ith $(i = 1, 2)$ joint angle position vector;