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The point-to-point multi-region energy-saving trajectory planning for a mechatronic elevator system

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ABSTRACT

A mechatronic elevator system driven by a permanent magnet synchronous motor (PMSM) is completely modeled by the mechanical and electrical equations. The electrical energy equation, including input, dissipation, magnetic and kinetic energies, is formulated for energetic analysis. The adjusting fraction, defined as the flight time from null to maximum acceleration with respect to the total acceleration time, is optimized by the self-learning particle swarm optimization (SLPSO) method in minimizing the input absolute electrical energy (IAEE). In this paper, multi-region trajectories of high-degree polynomials with constraints of maximum acceleration and velocity are planned, and the flight time and the IAEE are compared numerically. The main contribution of this paper is to propose a methodology in the point-to-point (PTP) multi-region energy-saving trajectory planning for any mechatronic system.

1. Introduction

The energy consumption is a popular topic and enthusiastically discussed by researchers and engineers nowadays. Human seriously consumes the energy in variable systems. How to save energy is the significant and emergent issue in our life. Therefore, energy saving is an importantly practicable stratagem for any system. In this paper, the trajectory planning and energy analysis will be discussed and investigated in a point-to-point (PTP) motion profile of a mechatronic elevator system. In the previous paper [1] about trajectory planning, the problem of minimum-time trajectory planning was studied for a three degree-of-freedom planar manipulator using a hierarchical hybrid neuro-fuzzy system. The use of finite impulse response filters for planning minimum-time trajectories for robots or automatic machines under constraints of velocity, acceleration, etc. was also presented and discussed [2]. An optimization approach [3] was proposed to generate smooth and time-optimal constrained tool trajectories for Cartesian computer numerical control manufacturing systems. A high smooth trajectory, planning method [4] was designed by a combination of the planning with multi-degree splines in Cartesian space and multi-degree B-spline in a joint space. A hybrid algorithm combining the particle swarm optimization (PSO) algorithm with Legendre pseudo-spectral method [5], was proposed for solving time-optimal trajectory planning problems of under-actuated spacecrafts. Trajectory planning was considered by Lambrechts et al. [6] with given constraints and a feedforward

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controller for single-axis motion control. In the previous papers [1–6], the authors emphasized the optimal-time trajectory planning, but large energies were also consumed in the operation process.

The resulting trajectory was required smooth enough, and an objective function containing a term proportional to the integral of squared jerk along the trajectory was considered in [7], where the fifth-order and B-spline trajectories were used to compose of the overall trajectory. A real-time interpolation algorithm for trajectory planning was studied by Wang et al. [8], where the non-uniform rational basis spline interpolation algorithm was proposed to confine the contour errors and feedrate fluctuations. In planning the linear and circular arc trajectories [9], the robot starts its motion from a start point with zero velocity to the end point on the desired trajectory and stops at the end point. The manipulator trajectory using algebraic-trigonometric Hermite polynomials curves [10] was designed to interpolate data points for the manipulator via given curves. The optimal jerk-limited PTP trajectories for flexible-link robotic manipulators were developed in [11]. On-line smooth trajectory generation for industrial mechatronic systems was addressed in [12]. An optimal trajectory planning technique for suppressing residual vibrations in two-link rigid-flexible manipulators was proposed by Abe [13]. The typical bilateral force constraints of the cables were translated into the velocity and acceleration of the cable-direct-driven-robot end-effecter along the path by Trevisani [14]. The constraints were computed by use of the robot dynamic model, and then incorporated into a suitable trajectory planning algorithm to yield the minimum traversal time.

From the review of the above studies [1–14], the energy consumption was not considered in the trajectory planning for systems' models. On the other hand, [15–19] considered the systems with energy-saving thought, and can be depicted more clearly as follows. A nonlinear constrained optimal control problem [15] was originated from the optimal trajectory planning of servomotor systems. It is noted that the quadratic cost function in [15] is a Hamiltonian function, but not the definition of physical energy for servomotor systems. The manipulator trajectories [16] were modeled by using a parametric path representation, and the optimal trajectory was then obtained by using a hybrid scheme comprising the particle swarm optimization method and the local conjugate gradient method. The PTP trajectory [17–19] was described by a high-degree polynomial, which satisfies the end conditions of displacement, velocity, acceleration and jerk at the initial and final times. The real-coded genetic algorithm method was employed to determine the polynomial coefficients by minimizing the input electrical energy. However, under some constraint conditions (for examples, constraints on the velocity, acceleration or jerk), the proposed method was difficult to find the optimal coefficients of the high-degree polynomials, which satisfy the fitness function and constraint conditions simultaneously.

To obtain both the performances satisfying the minimum input electrical energy and constraint conditions for the trajectory planning, this paper proposed the method of multi-region trajectory planning. Firstly, the modeling of the elevator system is formulated, and the system's electrical energy equation is found. Secondly, the car's maximum velocity, acceleration and final position are specified. A seven-region (7-R) trajectory [20] with five-degree (5-D) polynomial is compared with our proposed method in finding the minimum input absolute electrical energy (IAEE) trajectory. Thirdly, the self-learning particle swarm optimizer (SLPSO) [21,22] is implemented to find the optimal value of the fraction, defined as the flight time from null to maximum acceleration with respect to the total acceleration time, by minimizing the IAEE. It is also found that non-maximum acceleration flight time has the minimum IAEE. Therefore, a 7-R trajectory is substituted for the 5-R to obtain the minimum IAEE trajectory. It can be concluded that when the trajectory has a large input energy, it also has a short flight time. On the contrary, when the trajectory has a small IAEE, then has a large flight time. Fourthly, to simplify the trajectory planning of a 5-R trajectory, a 3-R trajectory with 7-D polynomial trajectory is proposed under the same constraint conditions. The fraction is undetermined, and can also be searched by the SLPSO by minimizing the IAEE. Finally, the 5- and 3-R trajectories are compared in the IAEE and flight time, and it is summarized that the IAEE and flight time are contradictory in the PTP trajectory planning.

2. Modeling of the elevator system

In this section, the equations of the mechatronic elevator system are to be formulated. The complete energy equations including the electrical and mechanical systems are formulated from the physical model.

2.1. Dynamic equations of the mechatronic system

To analyze and investigate the mechatronic system, it is important to formulate the dynamic modeling. The mechatronic elevator system consists of the permanent magnet synchronous motor (PMSM) and elevator mechanism. Fig. 1(a) shows the physical model of the mechatronic elevator system, where T_c and T_w are the tensions in the car and counterweight sides, respectively. The main cable passing over the drive sheave is attached to the car and counterweight. T_l is the torque applied on the reducer, θ and ω are respectively the angular displacement and velocity of the sheave, R is the radius of the sheave, H is the length between the original position and sheave center point, x_{c0} and x_{w0} are the initial positions of the car and counterweight, respectively, m_c, Δm_c and m_w are the car's, passengers' and counterweight's masses, respectively. x_c, v_c, and a_c are the car's displacement, velocity and acceleration, respectively. x_w, v_w, and a_w are the counterweight's displacement, velocity and acceleration, respectively. Fig. 1(b) shows the control block diagram of the elevator system driven by a PMSM. According to the dynamic equation of the elevator mechatronic system [23], the mechanical and electrical equations can be found as follows:

$$\dot{\theta} = \omega, \tag{1a}$$