constraints. Hence, a low degree of constraint violation is indicative of a reasonable design. From Table 1 it can be gleaned that, with respect to fitness and constraint violation, the GA used in this study is both robust and efficient.

A graphical comparison of the side and top view of the best design found in run 3 with the existing aircraft is shown in Fig. 2. The fuselage dimensions are similar to the existing aircraft because the number of seats found by the GA was identical. Significant changes in horizontal and vertical tail arm and a subsequent reduction in tail area should be given attention. Note also the substantial decrease in wing and horizontal tail span and increase in both the vertical and horizontal tail arm. The low aspect ratio can be attributed to the failure of incorporating second-segment climb constraints. Nonetheless, the GA was capable of finding reasonable aircraft designs in an affordable time, thus aiding in reducing the time required by designers to complete the conceptual design process. The GA-generated designs are uniquely different from the existing Boeing 717 design; these differences usually provided a favorable combination of design variables that lead to a lighter aircraft. Consequently, the GA can be used as a tool to initialize the aircraft conceptual design process to meet design objectives in the event of reduced time frame, which is the main goal of conceptual design.

Conclusions

The capabilities of the GA to handle a population of designs, in a single generation, under the consideration of stability and control, is without question. Consequently, the consideration of stability and control on the aircraft conceptual design did prove to have an impact, resulting in a lower weight and feasible designs in most test runs. Accordingly, the GA was capable of varying design parameters in ways that other design tools cannot. Thus, the problems of interdependency of parameters in design, and the consequences of changing these parameters during designing, or, moreover, forseeability, are eradicated. It is from this standpoint that serious consideration should be paid to the designs found in this and other research utilizing GAs.

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Flutter Supression Using Linear Optimal and Fuzzy Logic Techniques

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I. Introduction

RECENTLY, NASA Langley Research Center, as part of the Benchmarks Models Program, developed a Benchmark Active Control Technology (BACT) wind-tunnel model.[1,2] Among other objectives, the BACT system provides an active control testbed for evaluating new and innovative control algorithms for flutter suppression. Several control approaches were developed including classical Nyquist methods (see Ref. 1), linear quadratic Gaussian (LQG) (see Ref. 1), H_∞, μ-synthesis[3] generalized predictive control,[4] minimax approach,[1] passivity-based robust control,[2] and others.

The BACT wind-tunnel model is a rigid rectangular wing with a NACA 0012 airfoil section. The wing is equipped with a trailing-edge control surface and upper and lower surface spoilers that can be independently controlled via hydraulic actuators. For simplicity, this research effort was restricted to a single input/single output formulation. Hence, we consider the trailing-edge control surface as the only means to control the system. Accelerometers are the primary sensors for feedback control. We assume a single accelerometer located at the wing shear center. The wing is mounted to a device called the pitch and plunge apparatus (PAPA),[2] which, in principle, is designed to permit motion in two modes: rotation (or pitch) and vertical translation (or plunge). The combination of the BACT wing section and PAPA mount will be referred to as the BACT system.

In this effort, three flutter suppression control laws for the BACT problem are developed: 1) full-state LQG, 2) reduced-order LQG, and 3) fuzzy logic techniques. The system dynamics varies with the dynamic pressure. Here, 24 working points have been considered, each one representing a different dynamic pressure (some stable and some unstable). The design criteria of the desired controller correspond to stability, settling times, and control effort for each of the working points.

The paper is organized as follows: The next section descibes the aeroservoelastic (ASE) modeling and the open-loop flutter analysis. The first two controllers, based on linear optimal theory, are presented in Sec. III, and the fuzzy logic controller is developed in Sec. IV. Finally the conclusions are given in Sec. V.

II. ASE MODELING

The ASE formulation in this section follows the state-space formulation of Ref. 5, where models for stability and response analysis are constructed from the separate models of the aeroelastic system, the sensors and actuators, and the control system, all expressed in state-space form. The control system includes the control surfaces

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driven by actuators, sensors that are related to the structural degrees of freedom, and a linear control law that relates the actuator inputs to the sensor signals. The open-loop state-space aeroelastic equations of motion are obtained through rational aerodynamic approximations.

A simple two-dimensional structural model was constructed based on the structural data presented in Ref. 5 (generalized masses and stiffness and damping ratios). The model was used for calculating the natural frequencies and associated normal modes that are needed for ASE modeling and analysis via ZAERO.

Flutter analysis was performed for symmetric boundary conditions at Mach number 0.77. Flutter design points were defined at velocity 119 m/s (in heavy gas) for 24 density values range from 0.0258 to 2.061 kg/m^3.

The ASE plant combines the aeroelastic model, the control surface actuator, and an acceleration sensor located at the wing shear center. The transfer function of the actuator is

$$T(s) = 1/[(s+100)(s^2 + 2\zeta\omega s + \omega^2)] \tag{1}$$

where, according to Ref. 1, $\zeta = 0.56$ and $\omega = 165.3$ rad/s. (The pole at $s = -100$ represents some additional lag because ZAERO employs third-order models for servomodeling.)

The minimum-state method[5,6] with one aerodynamic lag was employed for rational approximation of the aerodynamic forces based on the ZAERO frequency-domain matrices. The approximation was constrained to match the aerodynamic data at the reduced frequency $k = 0$.

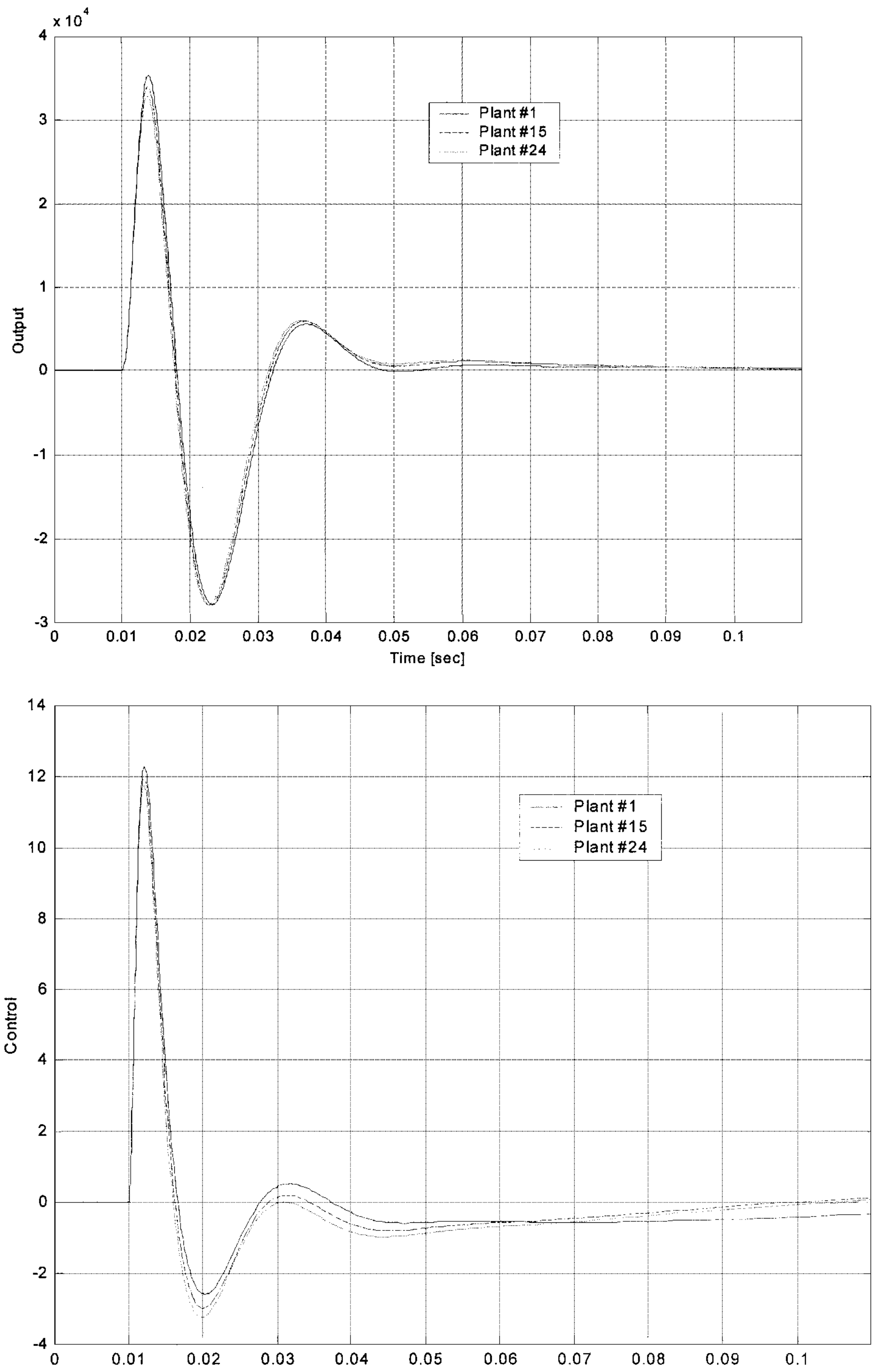

Fig. 1 Full-order LQG performance.

Open-loop flutter analysis was performed using the ZAERO frequency domain G method and the state-space method. Both methods provided practically identical results: flutter dynamic pressure of 153 lb/ft^2 (747 kg/m^2), and flutter frequency of 4.13 Hz, defined by the point of crossing the right side of the Laplace domain. The ASE state-space model is used next for control synthesis. The results are consistent with the known results for BACT.[3]

III. Linear Optimal Control

Optimal Control Problem

Based on the ASE model developed in the preceding section, the equations of motion may be expressed in state-space form as

$$\dot{\boldsymbol{x}}(t) = A\boldsymbol{x}(t) + Bu(t) + \boldsymbol{\zeta}(t) \tag{2}$$

$$\boldsymbol{y}(t) = C\boldsymbol{x}(t) + \boldsymbol{n}(t) \tag{3}$$

$$E\left\{\begin{bmatrix}\boldsymbol{\zeta}(t)\\ \boldsymbol{n}(\tau)\end{bmatrix}[\boldsymbol{\zeta}(t) \quad \boldsymbol{n}(\tau)]\right\} = \begin{bmatrix}\Xi & 0\\ 0 & \Theta\end{bmatrix}\delta(t-\tau) \tag{4}$$

where $\boldsymbol{x}$ is an eighth-order state vector, including two generalized coordinates (x_1 and x_2), two generalized velocities (x_3 and x_4), one aerodynamic state (x_5), and three actuator states (x_6–x_8); u is the actuator input; $\boldsymbol{y}$ is the sensor signal; $\boldsymbol{\zeta}$ is the process noise; and $\boldsymbol{n}$ is the measurement noise.

In the LQG theory,[7] the following cost function is generaly minimized:

$$J = \lim_{T\to\infty} E\left\{\int_0^T [\boldsymbol{x}^T \quad u^T]\begin{bmatrix}Q & 0\\ 0 & R\end{bmatrix}\begin{bmatrix}\boldsymbol{x}\\ u\end{bmatrix}\mathrm{d}t\right\} \tag{5}$$

The LQG feedback can be realized as a full state feedback and

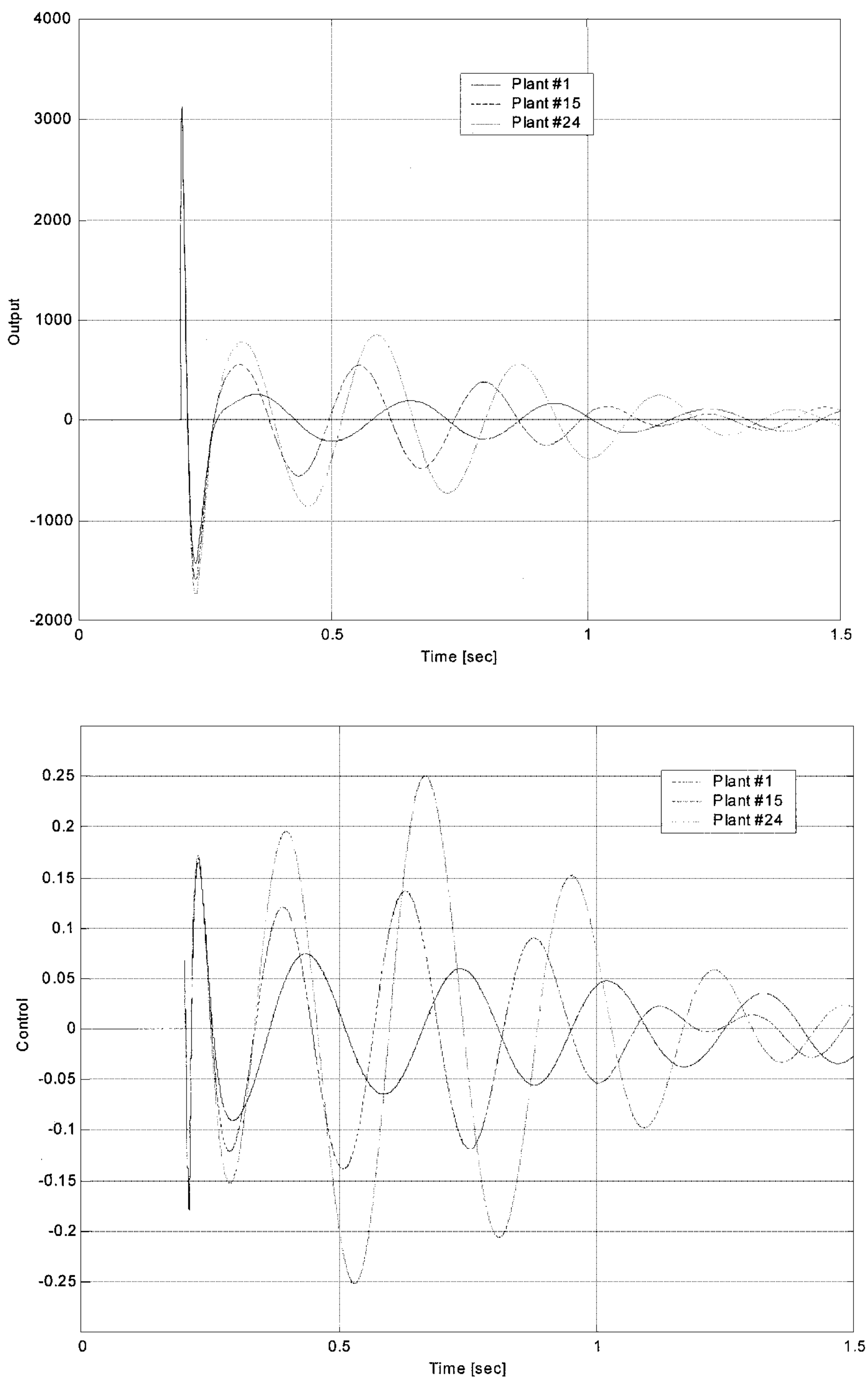

Fig. 2 Reduced-order LQG performance.

Kalman filter

$$u = -K_c\hat{x}, \qquad \dot{\hat{x}} = Ax + Bu + K_f(y - C\hat{x}) \tag{6}$$

The resulting controller is of the same order as the system. As stated earlier, 24 working points are considered with different dynamic pressures q (below and above flutter).

A single controller has been designed around the maximal dynamic pressure point, with the following design parameters:

$$R = 1, \qquad Q = dd^T, \qquad \Theta = 1, \qquad \Xi = I \tag{7}$$

where

$$d = [d_1, d_2, 0, 0, 0, d_6, 0, 0]^T$$

$$d_1 = -2.6989, \qquad d_2 = 4.3104, \qquad d_6 = 0.10264$$

Notice that the carefully chosen matrix Q is nondiagonal. Using diagonal matrices only, we have not been able to find a single controller that would stabilize the 24 points of interest. The choice of these nondiagonal design values is based on the pole-placement technique for LQG designs (details in Ref. 7). This single controller stabilizes all 24 points. The closed-loop step response for the two extreme cases (maximal amd minimal dynamic pressures) and a middle value case (at the onset of flutter) is shown in Fig. 1.

Reduced Controller

Two basic alternatives have been considered. The first method involves the reduction of the plant before the control design. The control then comes out in a reduced form. In the other approach, the system is designed in its full order and then the controller is reduced. The study of the BACT manifested the superiority of the former approach. For the actual reduction of the plant, two techniques were considered: 1) balanced truncation model reduction (BT) and 2) optimal Hankel minimum degree approximation (OH). The idea in both is to approximate the model frequency response and not to eliminate certain eigenvalues. The results obtained for BT and OH were similar, with somewhat superior results of the former. We have reduced the system for the controller design to fourth, fifth, and sixth order. Here the straightforward design with diagonal matrices has

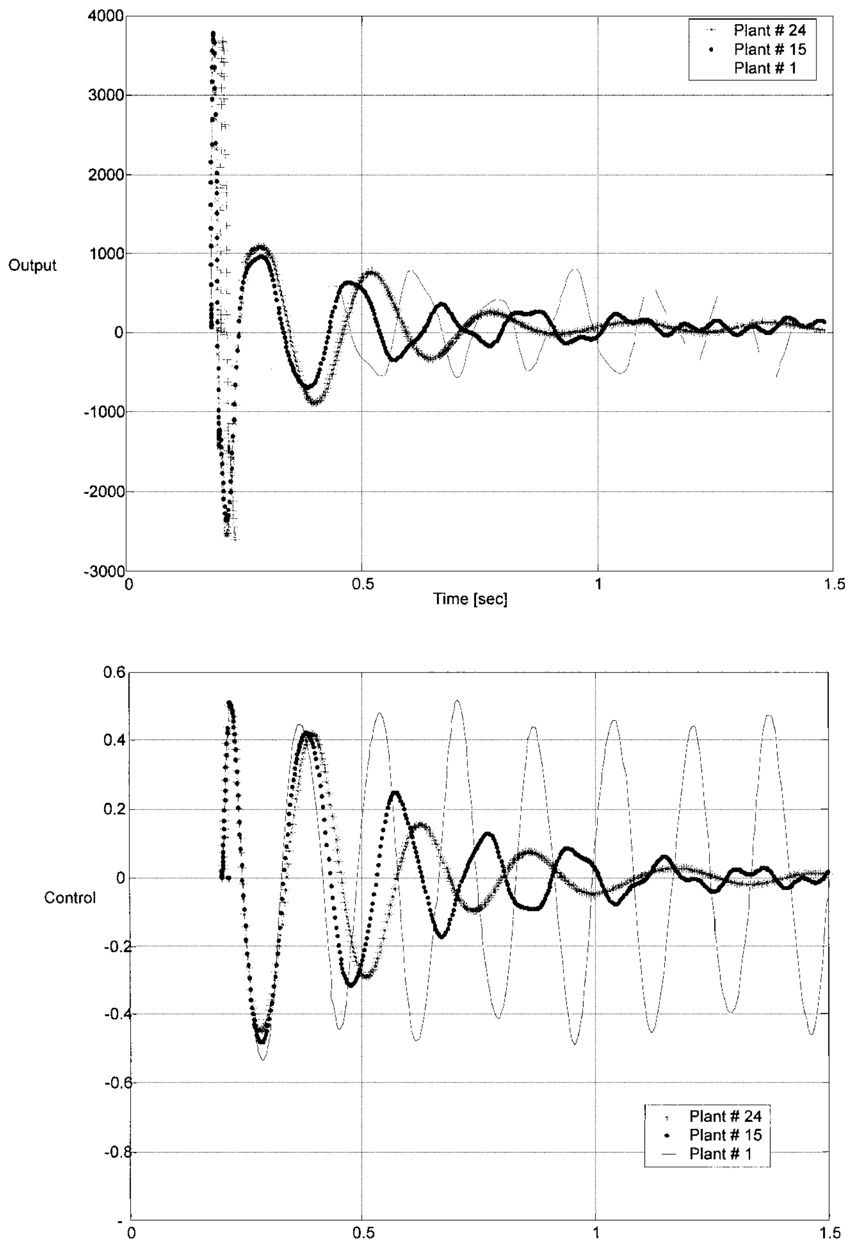

Fig. 3 Fuzzy-logic performance.

Table 1 Fuzzy logic rule base

X_4^{est}	X_2^{est}				
	Negative	Negative small	Zero	Positive small	Positive
Positive	Very small	Small	Medium	Small	Very small
Positive small	Very small	Medium	Large	Medium	Very small
Zero	Medium	Large	Extra large	Large	Medium
Negative small	Very small	Medium	Large	Medium	Very small
Negative	Very small	Small	Medium	Small	Very small

been successfully employed, for example, using

$$R = 1, \qquad Q = 100I, \qquad \Theta = 1, \qquad \Xi = I \tag{8}$$

a single reduced controller, designed around the maximal dynamic pressure point, stabilizes all 24 points of the full-order model. Figure 2 presents representative results with a sixth-order controller.

IV. Fuzzy Logic Control

A fuzzy logic controller for the design point of maximum dynamic pressure was designed. Let the control u be of the form

$$u = -K_3 \cdot \dot{x}_{10}, \qquad \dot{\boldsymbol{x}}_9 = \boldsymbol{x}_{10}$$
$$\dot{x}_{10} = K_1 \cdot (\hat{x}_4 - \boldsymbol{x}_{10}) \cdot (K_{\text{fuzz}})^{K_4} + K_2 \cdot (\hat{\boldsymbol{x}}_2 - \boldsymbol{x}_9) \cdot K_{\text{fuzz}} \tag{9}$$

where x_9 and x_{10} are the controller states; $K_1 = 40.375$, $K_2 = 2697.9$, $K_3 = 2300$, and $K_4 = 0.85$ are constant parameters determined by the tuning process; K_{fuzz} is a time-variable gain determined by a fuzzy logic control algorithm; and $\hat{\boldsymbol{x}}_2$ and $\hat{\boldsymbol{x}}_4$ are the estimates of the state variables $\boldsymbol{x}_2$ and $\boldsymbol{x}_4$, respectively.

The fuzzy controller is implemented as a 25-rule Mamdani fuzzy system with two inputs and one output (see Table 1). The two inputs are the estimates of the state variables $\boldsymbol{x}_2$ and $\boldsymbol{x}_4$ and the output is K_{fuzz}.

Five membership functions are used to describe each of the inputs, namely, positive, small positive, zero, small negative, and negative. K_{fuzz} is represented by very small, small, medium, large, and extra large. The respective membership functions for the input/output parameters are obtained after a tuning process.

The fuzzy adaptation strategy is based on rules of the form IF/THEN that convert inputs to a single output, that is, conversion of one fuzzy set into another. The design is based on previous experience,[8] whereby large values of the inputs require a lightly damped system. However, when the plant state is in the vicinity of the desired state, the damping gain is large.

For aggregation we employ the bounded sum method, and for defuzzification we use the center-of-area scheme. The values of $\boldsymbol{x}_2$ and $\boldsymbol{x}_4$ are estimated using a full-order Luenberger observer based on the measurement $\boldsymbol{y}$. The closed-loop response for all 24 design points, using a single controller, was stable. Figure 3 presents represenative results.

V. Conclusions

NASA Langley Research Center's benchmark model was employed for the development and evaluation of three types of controllers for flutter supression. Of the two linear controllers, the full-order is superior in performance, but requires significanly higher amount of control effort. The fuzzy logic controller performance resembles those of the reduced-order linear controller.

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Optimal Trajectory Analysis for Deployment/Retrieval of Tethered Subsatellite Using Metric

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I. Introduction

TETHERED subsatellite systems are attractive space structure components by which to construct large space structures because they are light in weight, packaged compactly, and sturdy in high tensile strength. The length of tether can be as long as 100 km in a scientific mission, which needs safe and smooth control for the deployment and retrieval of the tethered subsatellite.[1]

Fujii and Ishijima[2] have proposed a control algorithm to close the control loop stabilizing asymptotically the deployment and retrieval maneuver of the tethered subsatellite. Fujii and Anazawa[3] have also obtained an optimal path in the sense that the time integral of squared tension plus the squared in-plane angle is the performance index with inequality constraints on the control tension. Such optimal trajectories for the tethered subsatellite are studied in literatures[3,4] because they have much critical importance for control of such space systems.

The present Note is devoted to obtain an optimal trajectory in the geometric approach by connecting the initial position and final desirable position of the tethered subsatellite by the shortest length. The optimal index is clearly defined as the length of trajectories with sufficient physical meaning. The optimal path is a "straight line" measured by the Riemann metric because the orbiting tethered system is in the force fields of gravitation and orbital rotation. Minimizing the length of the trajectory of the subsatellite implies a process of finding a straight line to connect two positions, that is, a natural path for deployment/retrieval expected to be processed in minimum time and effort when only the length of tether is controlled.

The tethered subsatellite system is simplified in this analysis to a planer space pendulum, which consists of a particle and a tether without flexibility and is affected only by gravity-gradient torque. The present simple model is effectively employed to obtain a reference trajectory for any compensation control algorithm of a more

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