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Energetics of Control Moment Gyroscopes as Joint Actuators

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This work compares the power and energy used by a robotic linkage actuated by either joint motors or scissored pairs of control moment gyroscopes. The objectives are to establish straightforward sizing equations that provide a basis for deciding on a system architecture and to validate them with detailed models. The resulting parallels between joint motor and control moment gyroscope actuation increase intuition for and inform the design of control moment gyroscopes on a single-body satellite. Control moment gyroscopes are chosen as an energy-efficient means of reactionless actuation that reduce nonlinearities and coupling between the robot and the spacecraft attitude control system. Scissored-pair control moment gyroscopes are well suited for robotics applications because the output torque acts only along the joint axis, eliminating undesirable gyroscopic reaction torques. Both analysis and simulation of a single-link robot demonstrate that the control moment gyroscope power is equal to the equivalent joint motor power for a large range of gimbal inertias and maximum gimbal angles. The transverse rate of the link does not affect this result. A two-link robot with orthogonal joint axes gives results similar to the single-link system unless momentum is not conserved about the joint. For a two-link robot with parallel joint axes, control moment gyroscopes outperform joint motors in power required when the joints rotate with opposite sign; the reverse is true when the joints act in unison. These surprising differences arise because control moment gyroscopes produce body torques with a zero-torque boundary condition at the joint, whereas joint motors produce torques that are reacted onto two adjacent links. The analysis concludes with pros and cons of control moment gyroscopes as robotic joint actuators.

Nomenclature

B = body fixed
G = gimbal fixed
N = Newtonian (inertial)
R = rotor fixed
$\dot{x}$ = time derivative of the scalar x
$\overset{Y}{\dot{\boldsymbol{x}}}$ = time derivative of the vector $\boldsymbol{x}$ taken in frame Y, $({}^{Y}\mathrm{d}/\mathrm{d}t)(\boldsymbol{x})$

Vectors

$\boldsymbol{a}_i$ = inertial acceleration of the ith link's center of mass
$\hat{\boldsymbol{g}}$ = direction of the gimbal axis
$\boldsymbol{H}_x$ = angular momentum of body x, including actuator momentum when applicable, about its center of mass or its joint axis if so indicated
$\hat{\boldsymbol{h}}$ = direction of rotor's spin axis
$\boldsymbol{h}_r$ = rotor angular momentum measured relative to the gimbal frame, $\boldsymbol{I}_r \cdot \boldsymbol{\omega}^{R/G}$
$\hat{\boldsymbol{n}}$ = unit vector normal to $\hat{\boldsymbol{t}}$ and $\hat{\boldsymbol{g}}$
$\boldsymbol{R}_i$ = inertial location of the ith link's center of mass
$\boldsymbol{r}_i$ = body-fixed location of the ith link's center of mass
$\hat{\boldsymbol{t}}$ = direction of desired output torque, along the joint axis for revolute joints
$\boldsymbol{v}_i$ = inertial velocity of the ith link's center of mass
$\boldsymbol{\tau}_{\mathrm{cmg}}$ = torque reacted onto a body by a control moment gyroscope or a scissored pair of control moment gyroscopes
$\boldsymbol{\omega}^{X/Y}$ = angular velocity of frame X with respect to frame Y

Dyadics

$\boldsymbol{I}_x$ = inertia of body x about its center of mass, including actuator inertia when applicable
$\mathbf{1}$ = unit dyadic

Scalars

E = energy
h_r = magnitude of the approximate rotor angular momentum, $\boldsymbol{h}_r \cdot \hat{\boldsymbol{h}}$
I_x = inertia of body or component x about $\hat{\boldsymbol{h}}$ axis; about the joint axis or spherical if not indicated
k_{OA} = output-axis stiffness
n = number of links in the robot not including the base
P = power
θ = joint angle
ϕ = gimbal angle

Subscripts

b = body or link
c = control-moment gyroscope-driven robot link (when a distinction is required, as for $\boldsymbol{H}_c$ vs $\boldsymbol{H}_{\mathrm{cmg}}$)
cmg = control moment gyroscope
g = gimbal
i, k, m = indexing variables
j = joint motor
r = rotor
rel = relative to joint-torque-actuated robot, as in $P_{\mathrm{rel}} = P_{\mathrm{cmg}}/P_j$
sp = scissored-pair control moment gyroscope

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I. Introduction

CONTROL moment gyroscopes (CMGs) are a means of providing attitude control of satellites without expending propellant. Thus, they contribute to reduced launch mass and longer spacecraft life. CMGs have important flight heritage controlling