Satellite Attitude Control System Design Using Reaction Wheels

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Original Citation

Repository Citation
Gouda, Bhanu; Fast, Brian; and Simon, Daniel J., "Satellite Attitude Control System Design Using Reaction Wheels" (2004). Electrical Engineering & Computer Science Faculty Publications. 191.
http://engagedscholarship.csuohio.edu/enece_facpub/191

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• Satellite Attitude Control
  System Design Using Reaction Wheels

  Bhanu Gouda
  Brian Fast
  Dan Simon
Outline

1. Overview of Attitude Determination and Control system
2. Problem formulation
3. Control schemes
   3.1 Modified PI Controller
   3.2 Active Disturbance Rejection Control
4. Conclusion
ADCS

• ADCS: Attitude Determination and Control subsystem

• Attitude Determination - Using sensors

• Attitude Control - Using actuators
Disturbance torques

- Aerodynamic
- Gravity gradient
- Magnetic
- Solar radiation
- Micrometeorites
Attitude control modes

• Orbit insertion
• Acquisition
• Slew
• Contingency or Safe
Spacecraft control type

• Passive control
  - Gravity gradient control
  - Spin control

Explorer 1 (1958) was supposed to be spin-stabilized about its minor axis. It went into a flat spin due to energy dissipation.

Telstar 1 (1962) was spin-stabilized about its major axis, spinning at about 200 RPM.
Spacecraft control type

• **Active control (Actuators)**
  - Reaction wheels
  - Momentum wheels
  - Control - moment gyros
  - Magnetic torquers
  - Gas Jets or Thrusters
Tetrahedron configuration of Reaction wheels

Configuration of energy/momentum wheels.
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Problem formulation

Reaction wheel 1

Reaction wheel 2

\[ w_1 \]

\[ r \]

\[ w_2 \]

\[ r \]

\[ d \]

\[ d \]
Mathematical model

Angular momentum of each disk

\[ H_1 = I_1 w_1 = \left[ \frac{1}{2}mr^2 + md^2 \right] [-w_1] \]

\[ H_2 = I_2 w_2 = \left[ \frac{1}{2}mr^2 + md^2 \right] [w_2] \]

Moment with respect to the space craft

\[ I \ddot{\theta} = \left( Mr^2 + 2Md^2 \right) \ddot{\theta} \]

M = Mass of the space craft

m_i = mass of the reaction wheel

w_i = angular velocity of the wheel

\[ \theta = \text{Angular position of space craft} \]

r = radius of the wheel

I = moment of inertia
Mathematical model

Conservation of angular momentum

\[
\frac{d}{dt} \left[ H_1 + H_2 \right] = I \ddot{\theta}
\]

\[
\frac{d}{dt} \left[ \left( \frac{1}{2} mr^2 + md^2 \right)(-w_1) + \left( \frac{1}{2} mr^2 + md^2 \right)(w_2) \right] = (Mr^2 + 2Md^2)\ddot{\theta}
\]

\[
\frac{d}{dt} (-w_1 + w_2) = 2\frac{M}{m} \dddot{\theta}
\]

\[
\frac{-w_1 + w_2}{2} = \frac{M}{m} \dot{\theta} + c
\]
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Two types of controllers are investigated
- Modified PI Controller
- Active Disturbance Rejection Controller
Simplorer

- Simplorer
  - Circuit element models
  - Electric machine models
  - Data analysis tools
  - Interfaces with Matlab / Simulink
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Modified PI Controller

• This controller is used as the baseline controller
• Only one tuning parameter
• Generalized 2 DOF control structure is proposed

Reference: A Robust Two-Degree-of-Freedom Control Design Technique and its Practical Application
-Robert Miklosovic, Zhiqiang Gao
The diagram represents a control system with a plant transfer function \( k_i S^{-1} \). The equation governing the system is:

\[
\left(\theta_{\text{des}} - \theta_{\text{act}}\right) \frac{k_i}{S} - k_p \theta_{\text{act}} = \left(\theta_{\text{des}} - \theta_{\text{act}}\right) \frac{\omega_c^2}{S} - 2\omega_c \theta_{\text{act}}
\]
Motion profiling

• The desired trajectories as the command input in the closed loop control

• In this case, a profile generator is used to produce desired angle to the system

• Motion profile is used instead of step.
Simulation Results

Motion profile

Modified PI Controller

Plant Model

Random Noise

Error in theta

Control signal

Theta Actual

T_des_d

deg_rad

Motion profile

Random Noise

GAIN

GAIN

SUM!

Disturbance

Theta_d

Theta_act

Random_Nois

Yt

Motion profile

Modified PI Controller

Plant Model

Random Noise

GAIN
### Modified PI Controller

\[(\theta_{\text{des}} - \theta_{\text{act}}) \cdot \frac{k_i}{S} - k_p \cdot \theta_{\text{act}} = (\theta_{\text{des}} - \theta_{\text{act}}) \cdot \frac{\omega_c^2}{S} - 2 \cdot \omega_c \cdot \theta_{\text{act}}\]
Simulation Results

Theta Actual & desired

Noise amplitude: 0.07 - 0.1
Noise interval: 2 sec
Simulation Results

control inputs $w_1$ and $w_2$

Noise amplitude: 0.07 - 0.1
Noise interval: 2 sec
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Active Disturbance Rejection Controller

• New digital controller to motion control problems
• Disturbances are estimated using extended state observer (ESO) and compensated in each sampling period.
• Dynamic compensation reduces motion system to a double integrator which can be controlled using a nonlinear PID controller
Extended State Observer

• It is a unique nonlinear observer
• Proper Selection of the gains and functions are critical to the success of the observer
• Once ESO is properly setup, the performance of the observer is quite insensitive to plant variations and disturbances

\[
\begin{bmatrix}
\dot{z}_1 \\
\dot{z}_2
\end{bmatrix} =
\begin{bmatrix}
-2\omega_o & 1 \\
-\omega_o^2 & 0
\end{bmatrix}
\begin{bmatrix}
z_1 \\
z_2
\end{bmatrix} +
\begin{bmatrix}
b_o & 2\omega_o \\
b_o & \omega_o^2
\end{bmatrix}
\begin{bmatrix}
u \\
y
\end{bmatrix}
\]
Simulation Results

Plant Model

$\text{Sim2Sim}$
Define Simulor inputs and outputs in the property dialog of the SiM2SiM component.
Matlab/Simulink Model

$x' = Ax + Bu$
$y = Cx + Du$

Outputs from the Simplorer

Inputs to the Simplorer
Simulation Results

Theta Actual and Theta desired

Noise amplitude: 0.05
Noise Interval: 0.5 sec
Simulation Results

w1 and w2

Noise amplitude: 0.05
Noise Interval: 0.5 sec
Conclusion and Future work

- The simulation of Modified PI and ADRC showed that ADRC worked well for the system
- 1 DOF problem will be extended to 3 degrees of freedom problem
- Implementation of the controller design in microcontroller/FPGA microchip.
- Comparisons with other controllers