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Bio-inspired excitation-based on-orbit deviation identification for satellite reaction wheel

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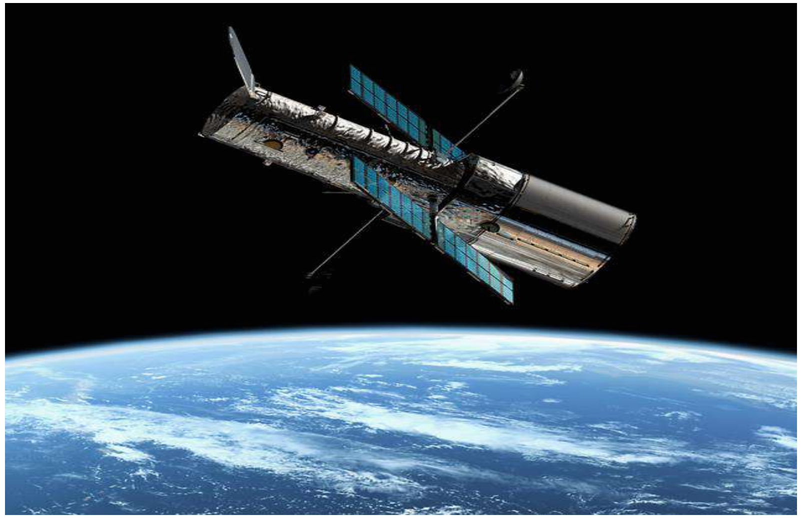
1. Background and Significance

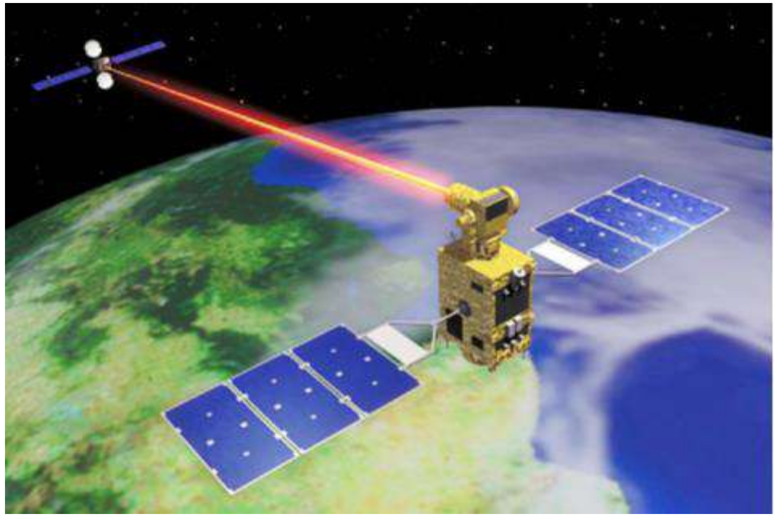
Space Missions: increasingly precise and complicated

◆ The accuracy requirements for satellite attitude pointing are ever increasing for many precise space missions, e.g., space observation, inter-satellite laser communication



Hubble Space Telescope
Attitude pointing error:
0.007 arcsecond

Jilin-1 Satellite
Attitude pointing stability:
5×10^{-4}°/s



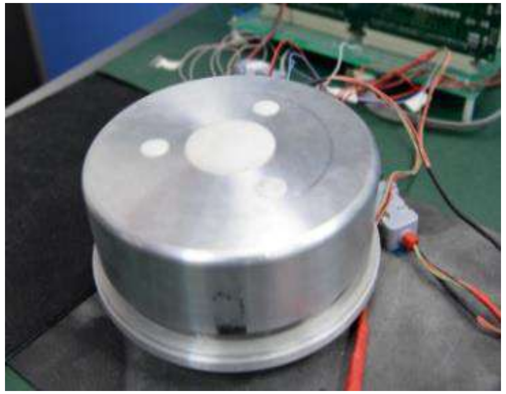
Laser Communication Satellite
Attitude pointing error:
1 μrad

Development trends: Attitude control with ultra-high accuracy and high-stability

1. Background and Significance

Reaction wheel (RW)—one key actuator of attitude control system

- **Advantages: Out torque is continuous; does not consume fuel**
- **As the “muscle” of attitude control system, the output accuracy of RW determines the attitude control performances of satellites directly.**



Partial loss of effectiveness: long-term operation, harsh environment + **Deadzone: Imperfection of mechanical structure** → **Output deviation of RW**

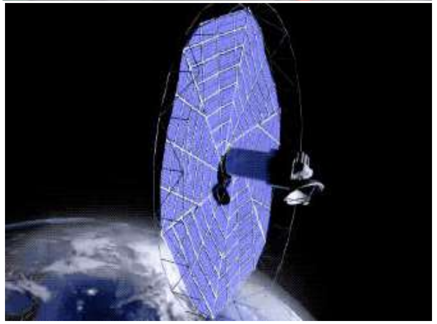
Autonomous on-orbit identification and compensation of RW output deviation —one key technology needs to be overcome due to the inconsistency between orbit and ground environment

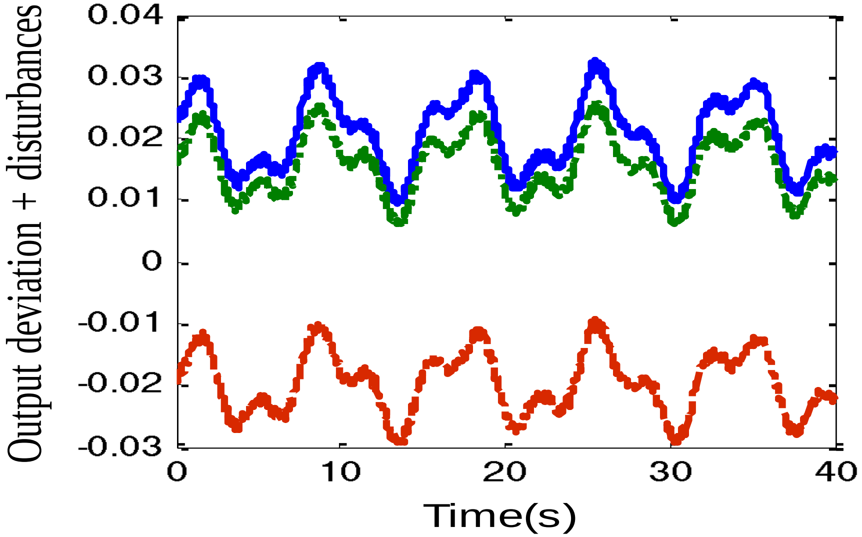
1. Background and Significance

Challenges of autonomous on-orbit identification of RW output deviation: complicated coupling with other disturbances

Challenges:

RW output deviation can not be measured, and it is mixed and coupled with other time-varying disturbances (e.g., flexible vibration) in attitude channel





Mixed signal from RW deviation and disturbance

- **Traditional methods: "lumped disturbance" estimation—the separation of RW output deviation and time-varying disturbance can not be achieved**

Key technology: Signal separation of RW deviation and time-varying disturbance

1. Background and Significance

Human beings and animals have powerful wisdom in indentifying various uncertainties

Railway worker: "Strike" the train wheels and diagnose fault via the "echo"

Woodpecker : "Peck" the trunk and distinguish the location of pest via the "echo"

◆ **For control systems, "Strike" (or "Peck") behavior is analogous to the control input excitation signal, while "echo" is analogous to the corresponding measurement.**

Inspiration: actively construct the control input (excitation signal) for signal separation

2. Description of the Work

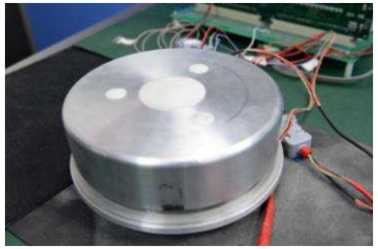
Overall Framework: Bio-inspired RW deviation identification method

Bio-inspired input excitation disturbance separator

- Piecewise constant input excitation signal
- Signal separation of RW deviation and time-varying disturbance

Key parameter identification based on disturbance separator

- Parameter identification of effectiveness indicator, deadzone bandsizes, etc.
- RW deviation compensation

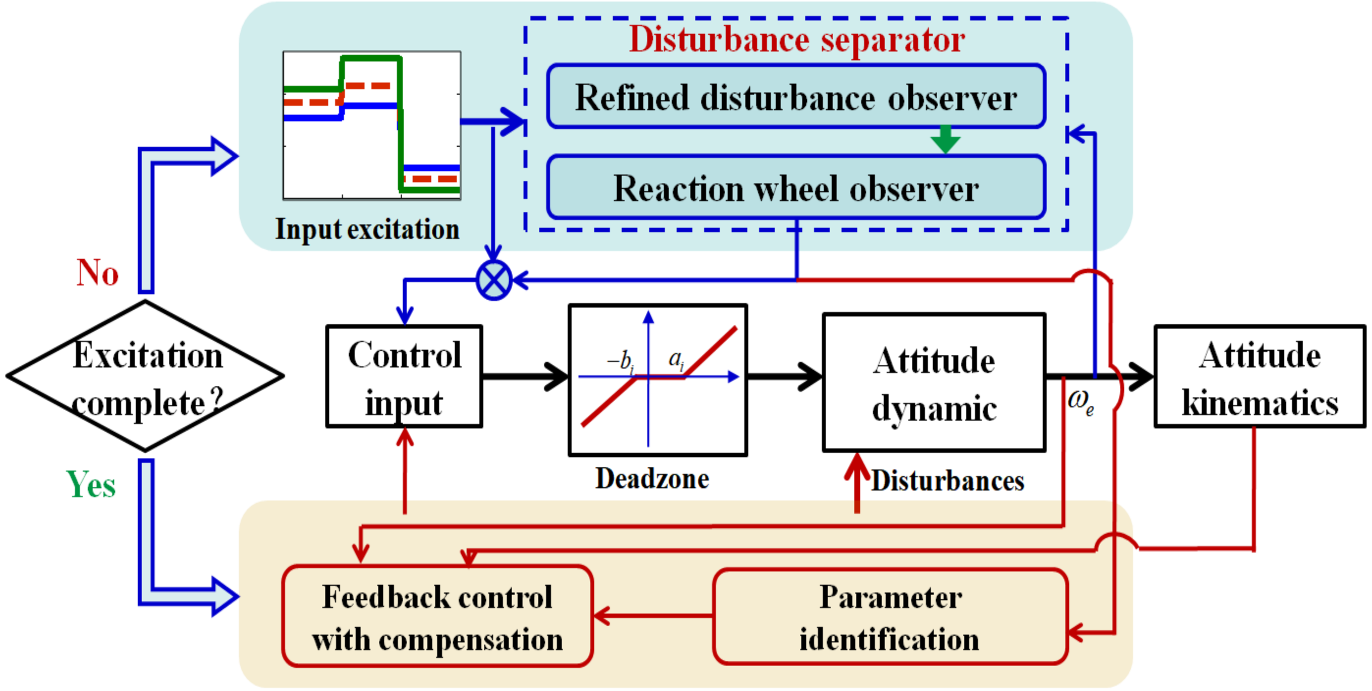


Experiment verification and test

- Multiple working conditions
- Multiple application scenarios
- Multiple indices evaluation

2. Description of the Work

- **We invent a bio-inspired input excitation disturbance separator : accurately separate the RW deviation and time-varying disturbance**
- **Key parameters such as RW effectiveness indicator, deadzone bandsizes can be identified and compensated with the aid of the designed disturbance separator**



$$\hat{a}_i = \frac{\varepsilon_1}{\varepsilon_1-\varepsilon_0}\frac{1}{\frac{1}{3}T_e-T_{r1}}\int_{T_{r1}}^{\frac{1}{3}T_e}\hat{d}_{ui}dt-\frac{\varepsilon_0}{\varepsilon_1-\varepsilon_0}\frac{1}{\frac{2}{3}T_e-T_{r2}}\int_{T_{r2}}^{\frac{2}{3}T_e}\hat{d}_{ui}dt$$

$$\hat{b}_i = \frac{\varepsilon_2}{\varepsilon_1-\varepsilon_0}\left(\frac{1}{\frac{1}{3}T_e-T_{r1}}\int_{T_{r1}}^{\frac{1}{3}T_e}\hat{d}_{ui}dt-\frac{1}{\frac{2}{3}T_e-T_{r2}}\int_{T_{r2}}^{\frac{2}{3}T_e}\hat{d}_{ui}dt\right)-\frac{1}{T_e-T_{r3}}\int_{T_{r3}}^{T_e}\hat{d}_{ui}dt$$

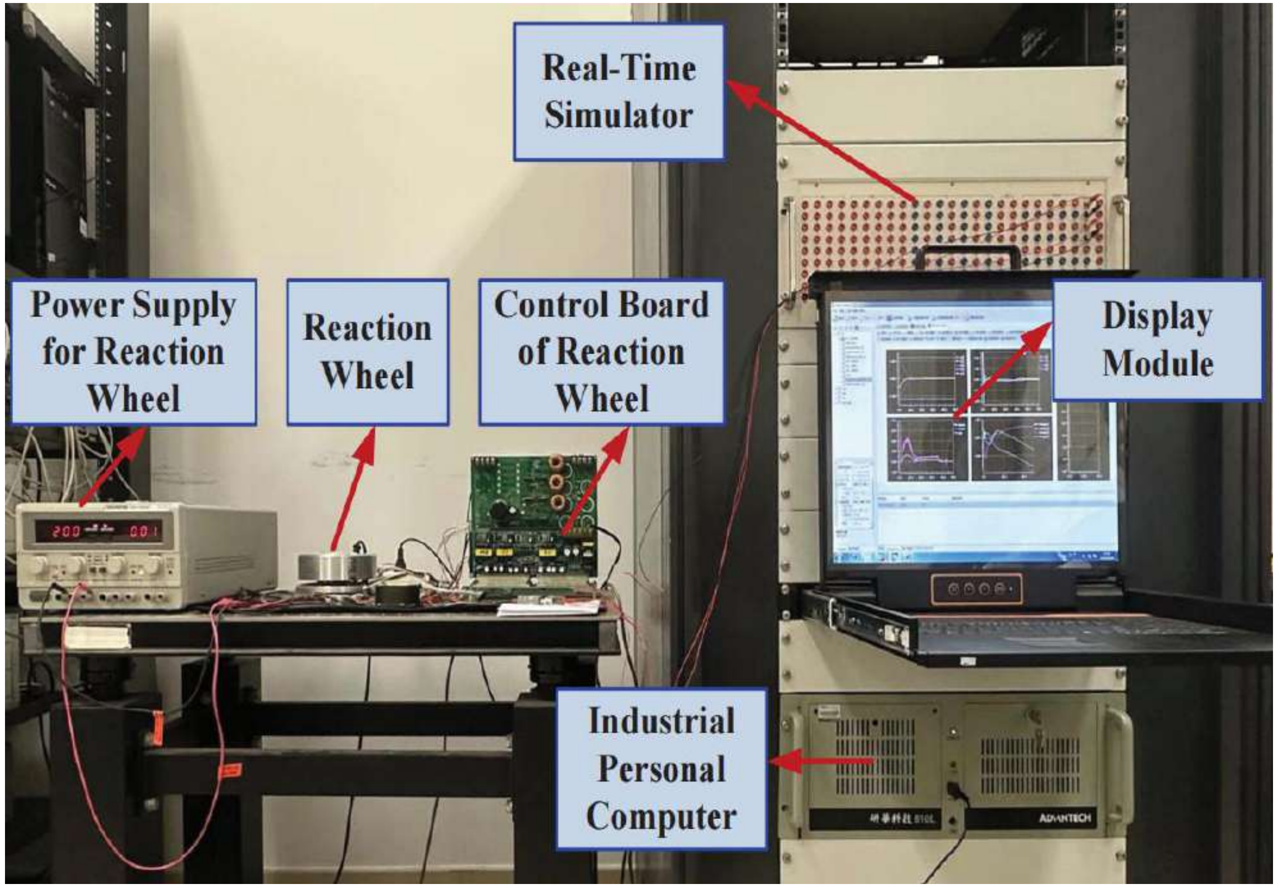
$$\hat{\rho}_i = \frac{\varepsilon_1-\varepsilon_0}{\frac{1}{\frac{2}{3}T_e-T_{r2}}\int_{T_{r2}}^{\frac{2}{3}T_e}\hat{d}_{ui}dt-\frac{1}{\frac{1}{3}T_e-T_{r1}}\int_{T_{r1}}^{\frac{1}{3}T_e}\hat{d}_{ui}dt+\varepsilon_1-\varepsilon_0}$$

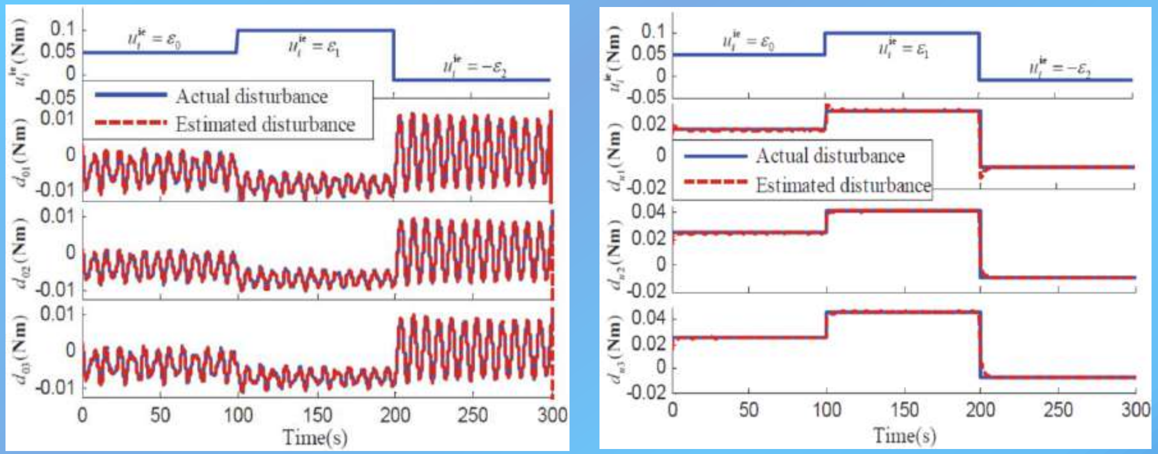
Key parameters identification based on the output of disturbance separator

① U.S. Patent: US9694918 B1 ② China patent: ZL202311626137.3 ③ China patent: ZL202410125706.4

2. Description of the Work

- **Experiment verification and test are carried out for a RW. Experiment platform: RW (maximum speed: 3000rpm), Control board of RW, Real-time simulator, etc.**
- **Experiment test is conducted for multiple conditions and application scenarios**



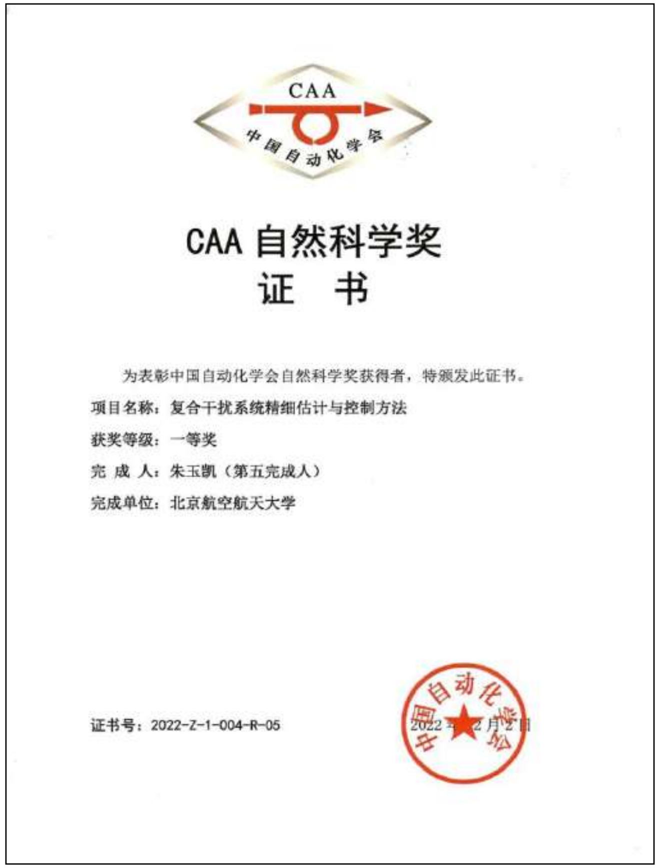


- **Disturbance separation has been achieved; Parameter identification accuracy: better than 95%**
- **Compared with traditional controller without deviation compensation, steady-state accuracy improved by more than 30%**

China patents: ZL202311635163.2; ZL201910778318.5

3. Publications and Award

patents, publications and award



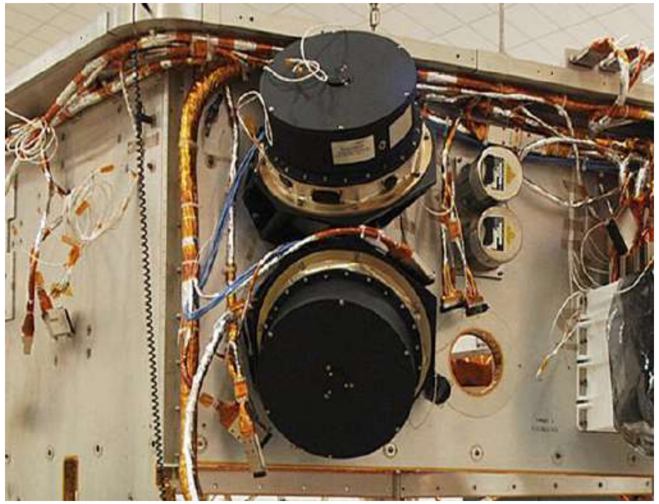
-**10 SCI papers** have been published

-**5 invention patents** authorized (four China patents and one U.S. patent)

- **First prize of Natural Science Award of Chinese Association of Automation**

4. Prospects

Technology advantages and application prospects



◆ **Technology advantages:**

① Signal separation ability: the mixed signals including RW deviation and time-varying disturbances can be separated.

②High-accuracy deviation parameter identification: the deviation parameter can be accurately identified by "isolating" disturbance effect (e.g., flexible vibration).

◆ **Application Prospects**

① Provide technological support in compensating the actuator deviation autonomously for many kinds of high-accuracy satellites, in the presence of inconsistency of orbit and ground environment.

② Extended to other precise satellite devices (e.g., control torque gyroscope, coarse pointing assembly, etc.)