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Invited Paper

# Tilted wheel satellite attitude control with air-bearing table experimental results

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ABSTRACT

Gyroscopic actuators for satellite control have attracted significant research interest over the years, but their viability for the control of small satellites has only recently started to become clear. Research on variable speed gyroscopic actuators has long been focused on single gimbal actuators; double gimbal actuators typically operate at constant wheel spin rate and allow tilt angle ranges far larger than the ranges needed to operate most satellite missions. This research examines a tilted wheel, a newly proposed type of inertial actuator that can generate torques in all three principal axes of a rigid satellite using a spinning wheel and a double tilt mechanism. The tilt mechanism tilts the angular momentum vector about two axes providing two degree of freedom control, while variation of the wheel speed provides the third. The equations of motion of the system lead to a singularity-free system during nominal operation avoiding the need for complex steering logic. This paper describes the hardware design of the tilted wheel and the experimental setup behind both standalone and spherical air-bearing tables used to test it. Experimental results from the air bearing table are provided with the results depicting the high performance capabilities of the proposed actuator in torque generation.



## 1. Introduction

There are several existing actuators which can be used to alter the attitude of a satellite inertially. Two common actuators are the momentum wheel (MW) and reaction wheel (RW). The former spins at a fixed speed and the latter at a variable speed, however neither tilt the axis of momentum generation. To achieve three-axis attitude stabilisation about all three axes of a satellite, at least three reaction wheels are required. A typical RW performs an attitude manoeuvre by exchanging momentum with the satellite body and creating an internal torque, but this is limited by power requirement and size for achieving higher torque – the higher the torque required, the bigger the size, power and cost of the wheel.

An alternative class of actuator is control moment gyroscopes (CMGs). These tilt the axis of momentum generation which allows torque amplification and allows a much higher torque to be produced than MWs and RWs. Unfortunately, CMGs also have singularities – a phenomenon whereby CMGs generate no torque at certain command points.

The large power requirements for MWs and RWs, and the singularity issues associated with CMGs necessitate research into other forms of control actuators that will give higher torque at lower power, mass and cost. In this research we propose a new form of actuator that uses a tilting wheel, is effectively singularity-free and has much lower power and mass requirements than a standard CMG for three-axis control. We also underline the dynamics for

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**Nomenclature**

| | |
|---|---|
| $\delta$ | control signal (generic) |
| $\alpha$, $\beta$ | tilted wheel attitude (W) |
| $\dot{\alpha}$, $\dot{\beta}$ | tilted wheel attitude rates (W) |
| $\boldsymbol{B}$ | satellite body frame |
| $\dot{\boldsymbol{H}} = [\dot{H}_1, \dot{H}_2, \dot{H}_3]$ | overall torque (B) |
| $\boldsymbol{H} = [H_1, H_2, H_3]$ | angular momentum (B) |
| $\dot{\boldsymbol{h}} = [\dot{h}_1, \dot{h}_2, \dot{h}_3]$ | tilted wheel torque (W) |
| $\boldsymbol{h} = [h_1, h_2, h_3]$ | tilted wheel angular momentum (W) |
| $\boldsymbol{J}_w$ | tilted wheel inertia |
| $[\chi_B^I] = [\phi, \theta, \psi]$ | air-bearing table attitude (B) |
| $\Omega_w$ | Tilted wheel speed |
| $u$ | Input signal (generic) |
| $[u_\alpha, u_\beta, u_\Omega]$ | Tilted wheel control signals |
| $[u_\phi, u_\theta, u_\psi]$ | air-bearing table control signals |
| $W$ | tilted wheel body frame |

the system and propose a control law that is suitable for its usage.

### 1.1. Literature

The use of CMGs started in the 1960s for use in Skylab [1] and its high precision payload ATM. This study encompassed both hardware and software that is responsible for the control and steering of the CMG. Design of steering logic for the avoidance of singularities associated with CMGs during operation became an active research area. To circumvent the problems posed by singularity issues, Nakamura and Hanafusa [2] first proposed singularity robust logic for single gimbal control moment gyroscopes (SGCMGs) while Wie et al. [3] modified this steering logic by introducing a simple minimum two norm pseudo-inverse solution. The proposed singularities robust logic could not eliminate singularities but provided 'deterministic dither signals' when the SGCMG system approached a singularity. In solving the singularity problems associated with SGCMGs and variable speed control moment gyroscopes (VSCMGs), Schaub et al. [4] used a weighted minimum norm inverse to determine the control vector which allows the VSCMG to operate like a conventional reaction wheel or CMG depending on the used control logic.

Lappas's [5] work also took precedence from Busseuil et al.'s [6] work that provided description of a mini CMG developed in Alcatel that used magnetic bearing technology for attitude control accuracy improvement. Pechev [7] in his work proposed a new control approach for solving the singularity avoidance problem associated with CMGs based on the observation that the gimbal rates can be derived by minimising (in a feedback loop) the difference between the demanded torque and the control moment gyro output torque. Ford and Hall [8] in their work also proposed a gimballed momentum wheel concept that is used for attitude control of satellite with flexible appendages. Post et al. [9] develop a fault-tolerant sliding mode attitude control algorithm for a nanosatellite using a reaction wheel and perform tests using an air-bearing table. An air-bearing table has also been used for attitude control development in [10]. The latest research concerning CMGs is the work by Stevenson and Schaub [11,12] that developed a mathematical model for the operation of a double-gimbal variable speed CMG (DGVSCMG) from control analysis concept. Schaub's work added some terms to the inner loop controller to compensate orbit frame conversion terms (those terms can also cause singularities otherwise) to maintain singularity at 90°.

### 1.2. The proposed actuator

The proposed actuator as shown in Fig. 1 focuses on the use of one spinning wheel and tilt mechanism to generate torque in all three axes of a rigid satellite. Unlike a DGVSCMG [11], the actuator is mounted on flat plate which allows the mounting of RWs or MWs to the plate. Additionally, the tilt mechanism is not constrained to use rotary motors – linear motors could also be used for tilt control. Further advantages include less mass, volume, and greater simplicity than other actuators. The tilted wheel allows full three-axis control of a satellite unlike a DGCMG that only allows two-axis control by itself. Clever formulation of equations of motion for the system allow the actuator to be effectively singularity-free, a key breakthrough from past literature. This is done by moving the singularities to tilt angle locations that would not be practical in nominal operation. The development of the tilted wheel mathematical model and simulation of the tilted wheel is developed in past research [13,14].

## 2. Tilted wheel hardware

This section describes the various components that make up the tilted wheel: the structure, motors, wheel, tilt

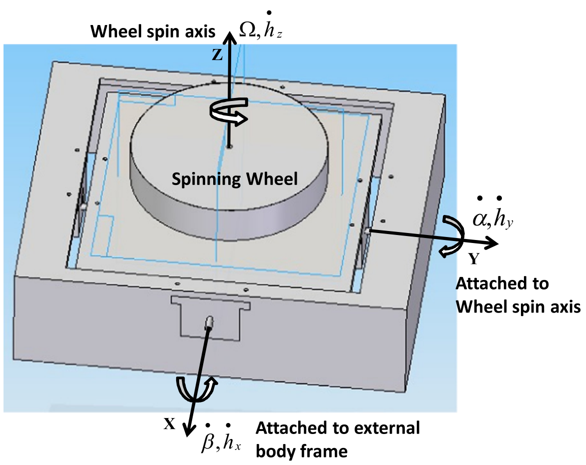


**Fig. 1.** Proposed tilted wheel (combined A-1 and A-2).