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Frederick A. Leve
Brian J. Hamilton
Mason A. Peck

Spacecraft Momentum Control Systems

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Frederick A. Leve • Brian J. Hamilton
Mason A. Peck

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Frederick A. Leve
Space Vehicles Directorate
Air Force Research Laboratory
Kirtland A.F.B., NM, USA

Brian J. Hamilton
Honeywell
Glendale, AZ, USA

Mason A. Peck
Cornell University
Ithaca, NY, USA

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Preface

It's remarkable how often we, the authors, have had a similar experience. At a conference, or during a break at a technical meeting, someone asks "can you recommend a good book about CMGs and reaction wheels?"

The answer is always about the same: "Well, there's this spacecraft dynamics book and that spacecraft design book, and the new edition of that old reference book we all use, but none of them really talk about momentum control in any depth. You probably already know as much as you'll find there." Then there's a pause. "Not that those books are bad; I'm not saying that. They're a decent start for a certain audience, such as students who have never worked on a flight program."

"How about academic articles?"

"Sure, there are a few helpful survey papers and some useful older stuff—especially from the '70s. For some reason they really seemed to know what they were doing back then." Another awkward pause. "I don't really want to go digging into all that." Then, inevitably, "maybe you should just write a book."

So that's what we did.

The reader will find that this book differs from other books on spacecraft dynamics and control. Others provide a broad overview of actuators, sensors, and feedback-control architectures without ever going into these important matters of implementation. And while there exist whole books on propulsive actuators, offering useful depth in the design and operation of rocket engines such as those used for reaction control, there is nothing analogous for momentum actuators. But omitting momentum actuators from a treatment of spacecraft design is like explaining all about automobiles, except for the engine and the transmission. So, finally, there's a book that addresses the crucial matters of what kind and how many momentum devices to implement, how they should be sized, and how to control the array of them.

This book is an effort to offer a complete picture of momentum actuators—spinning rotors and gimbaled devices—for use in attitude control of spacecraft. It's a picture that combines our diverse experience in government space systems (satellites for the Air Force, Navy, and NASA) as well as in the commercial space industry and academia. The scope of this book extends from electromechanical details of individual actuators to space-system architecture issues of interest in spacecraft concept development. We discuss the foundational rigid- and flexible-body dynamics, the subtle mathematics of steering multiple devices within an array, and the applications of these technologies.

These momentum actuators are at the heart of contemporary spacecraft that perform Earth imaging. The rapid growth of commercial success in this application area since the beginning of the twenty-first century is ultimately due to the technological capabilities that these actuators offer. In the decades to come, our industry is likely to see new applications: asteroid mining, in-orbit servicing and repair of satellites, and new human-space missions, all of which will require high torque and momentum storage. Small spacecraft, now the most commonly launched type of satellite, are only just beginning to incorporate sophisticated momentum control, thanks to entrepreneurial investment and a new generation of passionate spacecraft technologists. The momentum devices described in this book enable contemporary spacecraft and will make the future possible.

The authors hope that the breadth of information offered here, most of which has never been collected in one place, will serve the needs of this new generation of spacecraft engineers. And, at least as important, we'll have an answer to that perennial question, "can you recommend a book about this stuff?"

Kirtland A.F.B., NM, USA Frederick A. Leve
Glendale, AZ, USA Brian J. Hamilton
Ithaca, NY, USA Mason A. Peck

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Author Biographies

Frederick A. Leve, Research Aerospace Engineer at the Air Force Research Laboratory, Space Vehicles Directorate, received his Ph.D. in Aerospace Engineering from the University of Florida in 2010. While at the University of Florida, he received the IAF Silver Hermann Oberth Medal and the AIAA Abe Zarem Award for Astronautics. Currently, he is the technical advisor to the Guidance, Navigation, and Controls Group and has published many papers in the area of attitude dynamics and control, specifically with respect to momentum control systems and also performs research in under-actuated control, fault tolerant control, control allocation, analytical mechanics, and system identification. Dr. Leve is a recipient of the 2014 AFRL Early Career Award.

Brian J. Hamilton, Engineering Fellow at Honeywell Aerospace, received a BSEE with Honors from the University of Illinois, 1976. Mr. Hamilton has nearly 40 years of experience at Honeywell (formerly, Sperry) and has participated in the development of CMG technology since its infancy. In recent years, his research focus has been on CMG array control and steering, and the general application of momentum systems to agile spacecraft attitude control. Other areas of specialty include nonlinear modeling, controls design, system optimization, and active magnetic suspension. Mr. Hamilton holds 12 patents.

Mason A. Peck, Associate Professor at Cornell University in Mechanical and Aerospace Engineering, received his Ph.D. in Aerospace Engineering from the University of California, Los Angeles, in 2001. He has worked as an aerospace engineer since 1994 and has been on the faculty at Cornell since 2004. From late 2011 through early 2014, he was NASA's Chief Technologist. In that role, he served as the agency's chief strategist for technology investment and prioritization and advocate for innovation in aeronautics and space technology. His research lab focuses on fundamental research in space technology that can be advanced through flight experiments. Examples include Violet, a nanosatellite for demonstrating CMG steering laws, and KickSat, the world's first crowdfunded spacecraft. Dr. Peck holds 19 patents in the USA and the E.U. and has over 100 academic publications. He received the NASA Distinguished Public Service Medal in 2014.

Acronyms

CMG	Control moment gyroscope
DGCMG	Double-gimbal control moment gyroscope
IGA	Inner gimbal assembly
IV	Induced vibration
LOS	Line-of-sight
MBS	Mass balancing system
MCS	Momentum control system
rms	Root mean square
rpm	Revolutions per minute
RWA	Reaction wheel assembly
SGCMG	Single-gimbal control moment gyroscope
VSCMG	Variable-speed control moment gyroscope

Symbols

F_{N}	Inertial reference frame
F_{G_i}	ith CMG gimbal reference frame
F_{R_i}	ith CMG rotor reference frame
A	Arbitrary point in spacecraft reference frame
p_i	CMG nominal center of mass reference point at the intersection of the gimbal and rotor axes assumed fixed in the spacecraft body reference frame
C_B	Spacecraft body center of mass point
C_{G_i}	ith CMG gimbal center of mass point
C_{R_i}	ith CMG rotor center of mass point
$\boldsymbol{\rho}$	Differential mass vector position from center of mass of a component
$\mathbf{r}_{B/A}$	Vector from point A to spacecraft body center of mass, C_B
$\mathbf{r}_{p_i/A}$	Vector from point A to point p_i
$\mathbf{r}_{G_i/p_i}$	Vector from point p_i to CMG gimbal center of mass point
$\mathbf{r}_{R_i/p_i}$	Vector from point p_i to CMG rotor center of mass point
$\hat{\mathbf{b}}_i$	Spacecraft body coordinate axis "i"
$\hat{\mathbf{s}}_i$	ith CMG spin coordinate axis
$\hat{\mathbf{o}}_i$	ith CMG output torque coordinate axis
$\hat{\mathbf{g}}_i$	ith CMG gimbal coordinate axis
m_{B}	Spacecraft bus mass
$m_{\mathrm{G},i}$	ith CMG gimbal mass
$m_{\mathrm{R},i}$	ith CMG rotor mass
m_{G,p_i}	ith CMG gimbal particle imbalance mass
m_{R,p_i}	ith CMG rotor particle imbalance mass
$\mathbf{J}_s$	Spacecraft rigid body inertia dyadic
$\mathbf{J}_t$	Rotor transverse inertia
$\mathbf{J}$	Spacecraft inertia dyadic for the spacecraft's mass center, including the spacecraft as a rigid body and all momentum-control devices
$\mathbf{J}_B^{\mathrm{B}}$	Inertia dyadic of spacecraft about its own center of mass
$\mathbf{J}_A^{\mathrm{B}}$	Inertia dyadic of spacecraft about point A

$\mathbf{J}_{G_i}^{G_i}$	Inertia dyadic of ith CMG gimbal about its own center of mass
$\mathbf{J}_{A}^{G_i}$	Inertia dyadic of ith CMG gimbal about point A
$\mathbf{J}_{R_i}^{R_i}$	Inertia dyadic of ith CMG rotor about its own center of mass
$\mathbf{J}_{A}^{R_i}$	Inertia dyadic of ith CMG rotor inertia about point A
$J_{r,i}$	Scalar inertia component of ith CMG rotor about its spin axis
$J_{gr,i}$	Scalar inertia component of ith CMG gimbal-wheel assembly about its gimbal axis
$\mathbf{J}_{g,i}$	IGA inertia dyadic, i.e. everything that contributes to the IGA rigid-body inertia in all axes
$J_{g,\text{eff}}$	Effective scalar IGA inertia. This inertia includes everything rigid that the gimbal must accelerate along with the output-axis stiffness (K_{OA}) effect: $J_{g,\text{eff}} = J_g + \frac{h^2}{K_{\text{OA}}}$
$\mathbf{J}_{g,\text{eff}}$	Effective IGA inertia dyadic. This inertia includes everything that contributes to the IGA rigid-body inertia in all axes, along with the output-axis stiffness effect along the gimbal axis direction.
$\mathbf{h}_A^{B}$	Angular momentum of spacecraft bus about point A
$\mathbf{h}_B^{B}$	Angular momentum of spacecraft bus about its own center of mass
$\mathbf{h}_{p_i}^{G_i}$	Angular momentum of ith CMG gimbal about p_i
$\mathbf{h}_{G_i}^{G_i}$	Angular momentum of ith CMG gimbal about its own center of mass
$\mathbf{h}_{p_i}^{R_i}$	Angular momentum of ith CMG rotor about p_i
$\mathbf{h}_{R_i}^{R_i}$	Angular momentum of ith CMG rotor about its own center of mass
$\mathbf{h}_r$	Angular momentum vector of a single CMG rotor
$\mathbf{h}$	Angular momentum vector for a momentum system such that $\mathbf{h} = \sum_{i=1}^{n} \mathbf{h}_{r_i}$
h	Angular momentum body coordinate matrix representation for an array of CMG or RWA
h_s	Superspin
$\tau_{gf,i}$	Internal friction torque of ith CMG gimbal
$\tau_{rf,i}$	Internal friction torque of ith CMG rotor
$\tau_{r,i}$	ith scalar rotor torque for a single-gimbal CMG (for a perfectly aligned and rigid rotor)
$\tau_{g,i}$	ith scalar gimbal torque for a single-gimbal CMG (for a perfectly aligned and rigid IGA and gimbal)
τ_d	Scalar drag torque
$\boldsymbol{\tau}_o$	Vector output torque for a single-gimbal CMG (for a perfectly aligned and rigid IGA and gimbal). This torque acts on the spacecraft and is therefore is equal in magnitude but opposite in direction to the torque that acts on the CMG.
${}^{\text{B}}\boldsymbol{\omega}^{\text{B/N}}$	Angular acceleration vector of a spacecraft-fixed reference frame B relative to an inertial frame N. The overdot associated with a scalar derivative has been replaced with the letter B to indicate that the derivative has been taken relative to the B reference frame

$\boldsymbol{\omega}^{B/N}$	Angular velocity vector of spacecraft body with respect to the inertial reference frame
$\boldsymbol{\omega}^{G_i/B}$	Angular velocity vector of *i*th CMG gimbal with respect to the spacecraft body reference frame
$\boldsymbol{\omega}^{R_i/G_i}$	Angular velocity vector of *i*th CMG rotor with respect to the *i*th CMG gimbal reference frame
ω	Scalar spacecraft angular rate or body coordinates matrix representation of spacecraft angular velocity (context sensitive)
$\mathbf{v}_A$	Translational inertial velocity of point A
$\Omega_{r,i}$	*i*th scalar CMG rotor rate
$\Omega_r, \dot{\Omega}_r$	Matrices of CMG rotor spin rates and accelerations
$\Delta, \dot{\Delta}, \ddot{\Delta}$	Matrices of CMG gimbal angles, rates, and accelerations
$\delta_i, \dot{\delta}_i, \ddot{\delta}_i$	*i*th CMG gimbal angle, rate, and acceleration
β	CMG array skew angle
γ	CMG array clocking angle
K_{OA}	Output axis stiffness
K_a	Performance ratio (maximum rate over maximum acceleration)
K_c	Performance ratio (maximum acceleration over maximum jerk)
K_T	Motor torque constant (torque per unit current)
K_{MD}	Motor K_M density (ft-lb/sqrt(W) per lb)
i	Index for a single CMG within a multiple-CMG array
n	Number of CMGs in a multiple-CMG array
m	Singularity measure
α	Singularity parameter and scalar angular acceleration (context sensitive)
j	Scalar angular jerk (context sensitive)
${}^{B}Q^{A}$	Direction-cosine matrix that relates the representation of a vector v in B coordinates (${}^{B}v$) to its representation in A coordinates (${}^{A}v$)

Chapter 1
Introduction

1.1 Spacecraft Design, Commercial Space, and Angular Momentum

The WorldView I Spacecraft shown in Fig. 1.1, successfully reached orbit on September 18, 2007.

Ball Aerospace, the prime contractor, and DigitalGlobe, the owner and operator of the satellite, celebrated this event as a technical success and commemorated the occasion with a press release that called it "a major contribution towards the advancement of the commercial remote-sensing industry by providing higher collection capabilities, more frequent revisit time, and greater imaging flexibility" (Ball Aerospace [1]). This satellite is one of several that now provides commercial earth imagery for customers that include Google Earth. It is an agile satellite, meaning that the satellite achieves comparatively high angular rates and accelerations. As a commercial agile spacecraft, it is the first of its kind.

A technology known as the control-moment gyroscope (CMG) makes Worldview uniquely agile. Until WorldView's launch, the USA and Russian governments were the only owner/operators of spacecraft that use this technology. Examples include NASA's Skylab, the Soviet/Russian space station MIR, and the International Space Station. These momentum-control devices enable spacecraft to absorb large external torque disturbances and to slew payloads quickly from one attitude to another. Power is a precious resource on even the largest spacecraft. So, the fact that CMGs apply these high torques with tens to hundreds of times greater power efficiency than other momentum actuators makes them an appealing choice in the design of contemporary earth-observation spacecraft.

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Fig. 1.1 WorldView I satellite (Image Courtesy of DigitalGlobe Inc.)

Fig. 1.2 OrbView 4 Satellite (Image Courtesy of Orbital ATK)

Other commercial agile satellites, such as Orbview (see Fig. 1.2), DigitalGlobe's QuickBird (Fig. 1.3), Ikonos (Fig. 1.4), and GeoEye (Fig. 1.5), depend not on CMGs but high-torque reaction wheel assemblies (RWAs) as attitude-control actuators. By 2007, RWAs had been used for decades, in a variety of applications, despite that CMGs were known to offer orders-of-magnitude higher torque for the power. With the launch of WorldView I, momentum-control technologies that had been used

Fig. 1.3 QuickBird satellite (Image Courtesy of DigitalGlobe Inc.)

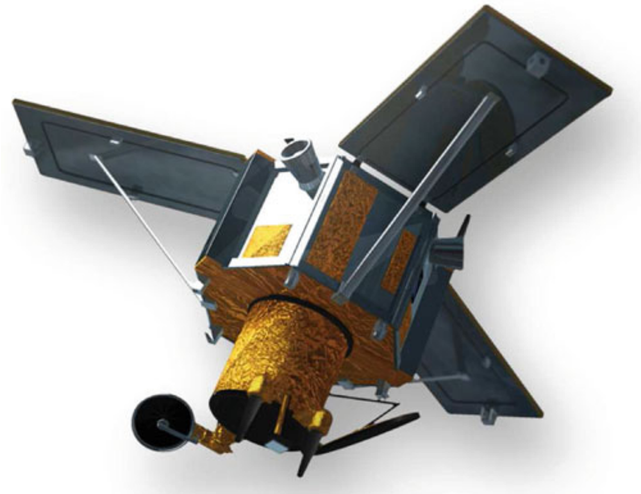

Fig. 1.4 Ikonos Spacecraft (Image Courtesy of GeoEye/DigitalGlobe)

only for government-sponsored spacecraft programs entered the commercial realm. Honeywell International provides the CMGs for the WorldView spacecraft. Ball was Honeywell's first commercial customer for its M95 CMGs, the smallest flight-qualified class of CMG available at that time.

Fig. 1.5 GeoEye Spacecraft (Image Courtesy of GeoEye/DigitalGlobe)

Now, nearly a decade later, CMG technologies are not only mainstream in commercial Earth observation, they are also appearing in new applications. CMGs have found their way into small spacecraft with scientific objectives, such as Cornell University's Violet nanosatellite shown in Fig. 1.6.

Violet is a 50 kg spacecraft with an ultraviolet spectrometer that is designed to make observations of the Earth's upper atmosphere to help astronomers calibrate observations of exoplanets. It has eight small CMGs, built by Goodrich Corporation. Honeybee Robotics has created golf-ball size CMGs suitable for 10–40 kg nanosatellites. The University of Florida built and launched similarly small CMGs (see Sect. 4.8). And Honeywell's miniature momentum control system (MMCS) provides a plug-and-play solution for 100–1000 kg spacecraft that require high-precision pointing performance (see Sect. 2.1.4).

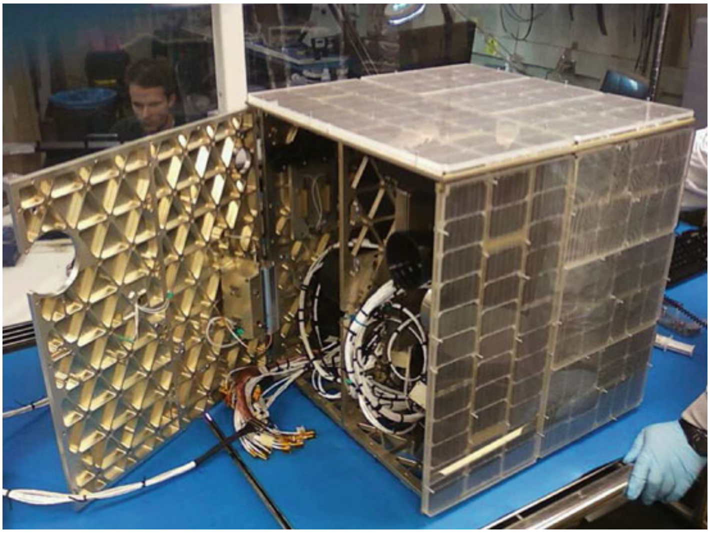

Fig. 1.6 Violet nanosatellite (Image Courtesy of Cornell University)

1.2 Momentum Control Devices and Attitude Control Systems

Spacecraft attitude control involves sensors and actuators, along with a feedback-control architecture that embraces the subtleties of spaceflight dynamics. Sensors such as star trackers and rate gyroscopes measure spacecraft motion, which on-board computers compare to desired kinematics. To correct this error, i.e., the difference between the measured and desired state, actuators such as momentum-control devices and thrusters apply torques to the spacecraft. The nature of these actuators—their torque and momentum capabilities, as well as their precision and speed of response—determines their usefulness for the range of missions that spacecraft are intended to achieve.

This book focuses on CMGs and RWAs, which are known as momentum-control devices. A spacecraft typically includes several such devices in an array. This array of actuators, along with electronics, high-level software, structural components, and possibly vibration isolators, comprises a momentum-control system (MCS). In turn, an MCS is part of the attitude-control system for a spacecraft. Figure 1.7 is a diagram that shows the relationships among these many nested elements.

Momentum devices produce torque by changing their stored angular momentum, realized in a spinning disc. Because momentum is a vector quantity, the product of angular velocity and inertia, there are two ways to effect this change. The simplest way is exploited in an RWA. The vector direction of the angular momentum of an RWA bolted to the spacecraft is constant-fixed in a spacecraft-fixed reference frame. The length or magnitude of the momentum vector changes as the wheel spins

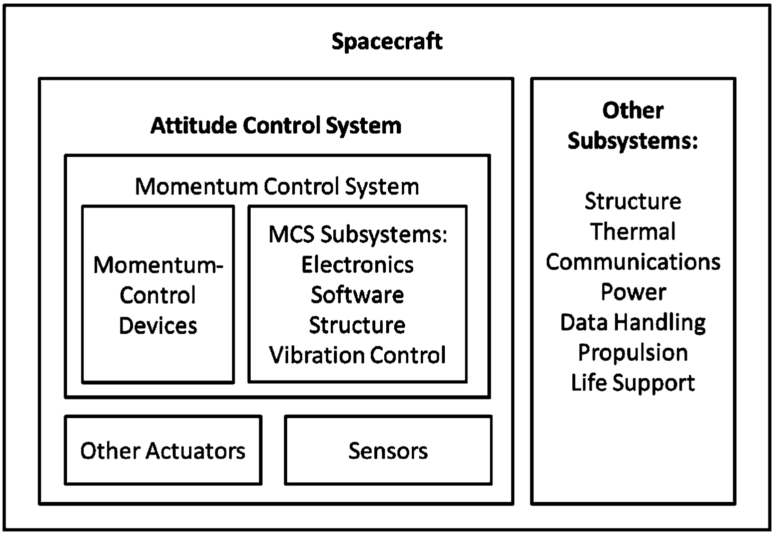

Fig. 1.7 Attitude-control centric view of spacecraft subsystems

faster or slower. In the case of a CMG, the wheel speed (and thus the magnitude of the momentum vector) is relatively constant, but a gimbal tilts the spinning rotor to change the direction of the momentum vector. The trades between these two technologies are many, and this book discusses them at some length. In each case, the device can store momentum up to a design maximum. That maximum value exists because a rotor of a given size is designed to spin at some maximum speed, typically determined by the tensile-strength limit of the rotor's material and its geometry. Going beyond that speed would incur excessive mechanical stress and fatigue, resulting in failure. Diagrams of a CMG and RWA are shown in Figs. 1.8 and 1.9.

The spinning rotors in an MCS serve two functions: momentum storage and torque application. From elementary physics, the MCS accumulates momentum as it imparts torque to the spacecraft (or reacts torque from the spacecraft, depending on one's perspective). This torque is internal, in the sense that the angular momentum of the overall spacecraft is a constant, regardless of what the MCS is doing. The MCS and the spacecraft body exchange angular momentum, but none is created. In this respect, an MCS is fundamentally different from a reaction-control system comprised of thrusters or jets. Momentum devices offer clear benefits in spacecraft design: years of operation without expending resources, the highest precision of any actuator, and freedom to place these actuators anywhere in the bus structure. But these benefits come with limitations. In a thruster-based system, the thrusters can apply torque in a given direction until the expendables have been exhausted, which may be hours to months. However, an MCS can apply torque in a single direction for only a limited time because the hardware can only accumulate a limited amount of

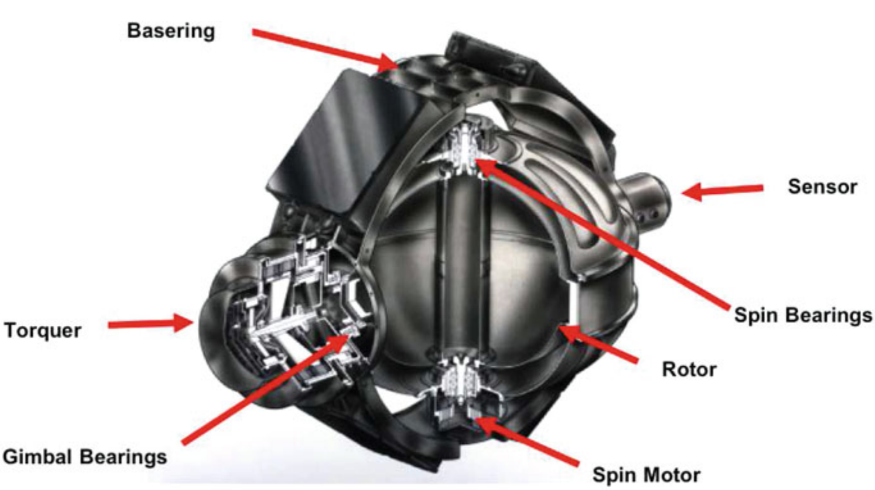

Fig. 1.8 Key components of a single-Gimbal CMG (Image Courtesy of Honeywell, Inc.)

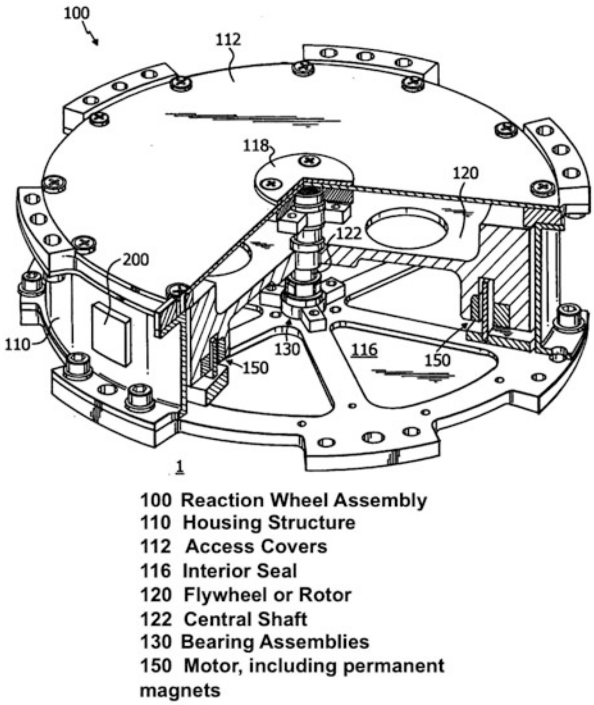

Fig. 1.9 Key components of a reaction wheel (Bialke [2])