称号及び氏名　　　博士（工学）　Sangwon　Kwon

学位授与の日付　　平成 22 年 3 月 31 日

論　　文　　名　　Attitude Control of Small Satellites Using Single-Gimbal Control Moment Gyros
(単一ジンバル・コントロール・モーメント・ジャイロを用いた小型衛星の姿勢制御)

論文審査委員　　主査　　大久保博志
副査　　真鍋 武嗣
副査　　千葉 正克

## Summary


The term “small satellite” refers to a satellite of mass 500 kg or less. Recently, many space missions have been using small satellites, because small satellites are easier and faster to develop and thereby, provide increased launch opportunities. Some of these missions include tasks that required agile maneuvers. Most of the early small satellites were gravity gradient stabilized, with magnetic torques, acting as a passive actuator. Despite their low torque, momentum wheels (MWs) and reaction wheels (RWs) were also used for the attitude control of small satellites.

In order endow small satellites with the ability to perform high-agile maneuvers, an attitude control system (ACS) using control moment gyros (CMGs) is proposed. In the development of small satellites, the most severe constraints are limited power, mass, or capacity of various devices. Therefore, small-sized CMGs were developed. The installation of small CMGs in a small satellite can provide sufficient torque, angular momentum, and slew rate, while not increasing the power consumption, mass, or volume of the satellite. BILSAT-1, launched in 2003, was the first small satellite that used small CMGs to perform high agility maneuvers. The University of Surrey designed the small CMG used in the ACS of BILSAT-1.

In the past, CMGs have been used for attitude control in large-sized satellites such as Skylab, MIR, and the International Space Station (ISS).  However, attitude control with CMGs is also effective in small satellites, especially for high-speed or large-angle maneuvers.

This thesis describes the development of an ACS for small satellites using a small-sized CMG. The ACS was developed considering the following points:

Singularity avoidance and fixed-star tracking attitude control
Pointing attitude control of an under-actuated small satellite using only two SGCMGs
Attitude control using SGCMGs via linear parameter-varying (LPV) control theory

A CMG is a type of a momentum exchange device (MED) used for attitude control of spacecrafts. It can generate substantially higher maximum output torque and store more angular momentum than reaction wheels. In addition, chemical fuels are not needed as thrusters.

CMG systems can be classified as single-gimbal CMG (SGCMG), double-gimbal CMG (DGCMG), and variable-speed CMG (VSCMG). An SGCMG has the advantages of having a simple mechanical structure and high torque amplification. The flywheel of an SGCMG spins at a constant speed, and torquing of the gimbal results in a precessional, gyroscopic torque, that is orthogonal to both the spin and gimbal axes. However, an SGCMG system has the disadvantage of singularity. A DGCMG has twice the degrees of freedom as that of an SGCMG, but its mechanical structure is complex. A VSCMG can generate a torque along any direction that lies on the plane perpendicular to the gimbal axis; this is because flywheel speed as well as the gimbal rate of the VSCMG is provided as the control input. However, continuous variation of the flywheel speed can lead to vibration in the system; also its steering mechanism is complex.

In this thesis, an SGCMG system with a simple mechanical structure and negligible influence of vibration, is investigated.

The use of SGCMGs (instead of VSCMGs with varying speeds) will decrease the vibration in small satellites, and thereby, lead to an increase in the pointing accuracy of the satellites.

This thesis is divided into six chapters.

Chapter 1 provides a background to this thesis and presents the basic concepts of an ACS using CMGs.

Chapter 2 describes the dynamics of rotational motion of a rigid spacecraft with an SGCMG cluster. It also describes the kinematics of the rotational motion of a rigid spacecraft using several parameters to represent the attitude of a spacecraft.

With respect to attitude control using SGCMGs, the major problem is to avoid singularity. Chapter 3 first describes the singularities seen in a typical pyramid array of four SGCMGs. Singularity exists when there is some direction along which the array of CMGs cannot generate torque. This happens when the gimbal angles of CMGs are aligned in a specific arrangement. There are two types of singularities: external singularities and internal singularities. External singularities represent the maximum workspace of the total angular momentum of the CMG cluster, the so-called the angular momentum envelope. Because the external singularities are gimbal angles states that are reached at the boundary of the angular momentum envelope, the CMG system cannot generate a torque beyond this envelope. Internal singularities exist inside the envelope (i.e., hyperbolic singularities and elliptic singularities). Several techniques to avoid singularity, have been developed in the past. The author presents a simple method to avoid singularity in an SGCMG cluster by applying singular value decomposition (SVD). Using this method, a the direction vector perpendicular to the singularities is obtained. In this chapter, the author considers fixed-star tracking attitude control of a spacecraft using four SGCMGs and applies the SVD method to avoid singularities. A numerical example of the fixed-star tracking control is provided to demonstrate the advantage of the proposed method over conventional singularity robustness (SR) steering method.

Chapter 4 describes a control strategy for the pointing attitude control problem of a spacecraft using two SGCMGs. The presence of singularities in the CMG system necessitates hardware redundancies (e.g., pyramid configuration for four SGCMGs). However, in the case of smaller-sized satellites with limited resources, hardware redundancies are not a suitable option. As a result, attitude control using a lesser number of CMGs has received considerable attention. In the past, several studies on under-actuated spacecraft attitude control have been carried out. Typically, fewer than three actuators are used to provide three-axis control. This chapter investigates the pointing control of a spacecraft using only two SGCMGs. Because the total angular momentum of a spacecraft is conserved in the inertial frame, the total CMG angular momentum is aligned with the total angular momentum of a spacecraft at a final state of rest. This imposes a restriction on the feasible orientations of the spacecraft's resting attitude. To solve this problem, the author proposes a two-step control strategy, i.e., nonlinear control based on the Lyapunov stability theory for all large initial conditions at large followed by the linear quadratic regulator (LQR). The feasibility of the proposed two-step controller is verified by numerical simulation.

In the past decades, several attempts were made to apply linear control techniques to nonlinear systems. Particularly, the gain-scheduled (GS) control based on the linear parameter-varying (LPV) approach has found applications in practical engineering design. For attitude control of a spacecraft using SGCMGs, a new control method based on the LPV control theory has been proposed in Chapter 5. Based on this theory, nonlinear dynamics of the spacecraft with SGCMGs were modeled as an LPV system and a GS controller was applied to this system. This GS controller consists of extreme controllers designed for each of the extremities of the convex hull that covers the operating region of the spacecraft modeled as an LPV system. In this chapter, the author describes a GS control algorithm based on the LPV control theory. The feasibility of the proposed control method is verified by numerical simulation.

Finally, Chapter 6 concludes this thesis, and provides directions for further study.

The author believes that the results of the present work can contribute to the development of the CMGs which are highly useful attitude control actuators for agile small satellites.

# 審査結果の要旨

本論文は、コントロール・モーメント・ジャイロ(ＣＭＧ)を用いた小型衛星の姿勢制御システムについて研究し、特異点問題の解決法、２台の単一ジンバルＣＭＧを用いて３軸姿勢制御を行う方法、およびゲインスケジュール制御による高速かつ大角度姿勢変更制御の方法を提案したものである。本論文では、以下の点についての成果を得ている。

(１)４台の単一ジンバルＣＭＧをピラミッド型に配置する姿勢制御システムについて，特異値分解を用いた特異点を回避するＣＭＧの駆動則を提案し、小型人工衛星の高速大角度姿勢変更を伴う指向制御に適用して、その有効性を示した。

(２)２台の単一ジンバルＣＭＧを平行配置する姿勢制御システムについて、Lyapunov 安定論に基づく非線形制御則と線形制御則を接続する切換え制御則を提案し、有効性を示した。

(３)２台もしくは４台の単一ジンバルＧＭＧを用いた人工衛星の指向制御問題に対し、線形パラメータ変動(ＬＰＶ)制御理論に基づく姿勢制御アルゴリズムを提案し、ゲインスケジュール制御が大角度姿勢変更制御に対して有効であることを示した。

以上の研究成果は、小型衛星の姿勢制御用アクチュエータとしてＣＭＧを採用するための諸課題を解決する上で極めて有益であり、この分野の研究の発展に大きく貢献するものである。また、申請者が自立して研究活動を行う上で必要な能力と学識を有することを証したものである。
学位論文審査委員会は、本論文の審査ならびに学力確認試験の結果から、博士（工学）の学位を授与することを適当と認める。