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論文内容の要旨
Summary of thesis contents

Since the world's first Earth orbiting artificial satellite, Sputnik I, was launched on 4 October 1957, mankind has always been working to reach the better in space missions. Progress in the miniaturization and the increase in the capability of the electronic devices are leading us towards a new era where performing complex space missions with small satellites will be possible.

The nanosatellite term refers to the satellites with mass less than 10kg. The main motivation behind the nanosatellite missions is the significant cost decrease which is the direct result of reduced mass and complexity. Enabling COTS (commercial of the shell) technology in space and short system development periods are other advantages of nanosatellites. Since the investment cost is not high the developer may take the risk of using self-developed hardware or software for the mission and the satellite can be developed from scratch in a considerably shorter time than bigger satellites. Moreover the nanosatellite missions are generally single-aimed, so the satellite is not complex and the mission failure risk is lower than usual.

Although there are numerous researches on nanosatellites and this number is increasing day by day, the investigations are still far from being concluded. In this sense maybe the most important topic for researchers to deepen their investigations is the attitude determination and control for such satellites. Despite the advanced technology for other subsystems, the attitude determination and control system (ADCS) and the subsystems that rely on the ADCS accuracy are underdeveloped for nanosatellites. The biggest challenge for nanosatellites is achieving high attitude control performance especially in terms of dynamic control and control accuracies. The main reason underlying this problem is the mass, size and power restrictions. Unlike the big satellites high accuracy high-tech attitude sensors and actuators such as star-trackers and reaction wheels cannot be easily used for nanosatellite missions since they are heavy, big and do consume high power. The attitude must be determined and controlled precisely by using coarse sensors and actuators which are smaller and lighter. In this context the possible candidate for attitude sensing is economic, light and small magnetometers whereas the control might be performed by magnetic torque rods (magnetorquers). Therefore the primary problem is how to get high ADCS performance by using magnetometers and magnetorquers.

The typical attitude determination accuracy for sole magnetometer based methods is 1-2deg. The dominating error sources are the magnetic field uncertainty and bias in the measurements which is caused by several reasons such as magnetic charging during the launch and electrical charge on the other subsystems. Sun sensors are usually used for aiding the magnetometer measurements but in this case the attitude determination accuracy significantly degrades during the eclipse when the sun sensors are not usable. In this sense another candidate for using together with magnetometers is the gyros since they are also light and small instruments, especially after the recent developments ended up with MEMS (Microelectromechanical systems) gyros. As for now magnetometers are the most preferable attitude sensors for the nanosatellite missions along with the sun sensors, whereas gyros come off second best in terms of preferability.

As for the attitude control, the magnetic control is the most popular method for the nanosatellites either as passive control with magnets or active control with magnetorquers. The magnetorquers are lightweight and energy-efficient. Besides they do not have any mechanical part so they are more reliable compared to the reaction wheels and control moment gyroscopes. However the control accuracy is limited for these actuators because of the inherent complexity of the problem and pointing accuracy higher than 1deg. ($<$1deg) is not possible using only magnetic actuators in practice. The spacecraft should be magnetically clean also for satisfying high pointing precision with magnetorquers.

The main motivation of this study is to provide an accurate attitude determination and control method for the case that nanosatellite has magnetometers and gyros as the attitude sensors, and magnetorquers as the actuators. The aimed attitude determination and control accuracies are 0.1 and 1 deg, respectively. This is challenging because the attitude determination accuracy that can be satisfied by the regular algorithms for a nanosatellite carrying magnetometers and gyros is usually around 1deg. Moreover although the angular rates can be controlled accurately by pure magnetic control approach the accuracy for the attitude itself cannot be reduced below few degrees and usually the yaw angle estimation is worse than the others. Mainly there are two reasons for such poor ADCS accuracy when the magnetometer, gyros and magnetorquers are used:

- Inherent complexity of the problem: Magnetometers are not accurate sensors due to the factors such as the disturbance fields caused by the spacecraft electronics, modeling errors in the Earth’s geomagnetic field and the external disturbances like ionospheric currents. For increasing attitude determination performance an accurate in-orbit calibration of the magnetometers is necessary. Moreover attitude control by using only magnetorquers is significantly challenging since at any instant the satellite is controllable in two-axes that are perpendicular to the magnetic field vector. For three axis controllability the spacecraft must experience the variation of the magnetic field along the orbit.
- The size of the spacecraft: Because of the spacecraft’s compactness, the interaction between the subsystems is higher than the bigger spacecrafts and that affects the magnetic cleanliness of the satellite which is a necessity for

accurate attitude estimation and control with magnetic sensors and actuators. Besides the attitude hardware is more vulnerable against external disturbances because of the same reason. As for the control accuracy any disturbance source will make achieving higher accuracy more challenging so a magnetically clean satellite is a preliminary necessity.

Therefore for an accurate ADCS by using magnetometers, gyros and magnetorquers these issues should be analyzed carefully and appropriate solution techniques should be given. This thesis contributes to the literature within this context. Different than the existing studies we address the problems such as in-orbit estimation of magnetometer biases and residual magnetic moment and try to increase the system accuracy by using more powerful estimation algorithms, which are proposed by the authors. First of all each problem is addressed individually and possible solution methods, which are mostly based on the adaptation of the attitude estimator algorithms, are given. Then these solution techniques are integrated in order to propose an overall attitude determination scheme for the satellite. The theory is supported by the demonstrations and performance analysis for the proposed attitude determination method.

In general this thesis proposes a simple yet accurate attitude determination method for increasing ADCS performance of nanosatellites with magnetic sensors and actuators. In order to achieve that first we increase the accuracy of the magnetometer outputs by proposing an appropriate in-orbit calibration algorithm. The tuning problem for the filter that is used for calibration as well as the attitude estimation is overrun by the adaptive Kalman filtering approach. The same filter is made robust against faults in the measurements. That is a necessity in the severe space environment especially for nanosatellites which are highly vulnerable against internal and external disturbances. As the next step, the RMM is estimated in order to cancel out the effects of the magnetic disturbance and assure the magnetic cleanliness of the satellite for the attitude control purpose. The instantaneous changes in the RMM are regarded and the estimator UKF is adapted as it gives accurate estimations at any case. In the final section, which may be regarded as the core of this study, the given UKF adaptation techniques are integrated and an overall attitude determination scheme is introduced. The scheme is demonstrated for the attitude determination of the nanosatellite and its performance is analyzed by comparisons with the existing algorithms. Moreover in the appendix a brief discussion about novel methodologies for pure magnetic attitude controller, which can work independently from the orbital periodicity of the geomagnetic field, is given.

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博士論文の審査結果の要旨
Summary of the results of the doctoral thesis screening

本論文は、UKF(Unscented Kalman Filter)と呼ばれる推定フィルタについて、フィルタの構成要素でありフィルタ推定特性と密接な関係のある３つの行列（R, Q, P行列）の適応則を新たに提案し、これらの適応則をひとつのフィルタに統合した上で、これを超小型衛星の姿勢推定問題に応用することを提案するものである。

論文は全八章からなる。第一章では、数kg級の超小型衛星（nanosatellite）が今後広く応用されるために、超小型衛星に適した姿勢決定・制御手法を開発して姿勢制御の機能・性能を向上することが重要となること、その際、強いリソース制約のもとでは、磁気センサ・磁気アクチュエータの活用が重要であることが述べられている。第二章では基礎となる数式が、第三章ではセンサモデルがそれぞれ説明された後、第四章では、UKFによりジャイロセンサと磁気センサのバイアス誤差を同時に推定する手法が提案されている。ジャイロバイアスの推定は、衛星姿勢制御では一般に行われているが、超小型衛星の場合には搭載機器間の電磁気的な干渉が顕著となるため、これに加えて磁気センサのバイアス誤差推定が必須となる。このような推定においては、UKFにおいて推定対象のノイズ特性を示すプロセスノイズ行列（Q行列）の設定が重要となるが、ジャイロセンサと磁気センサのバイアスを同時に推定する場合には理論的・解析的には適切なQ行列を定めることが難しい。そこで第四章では、推定誤差に基づく適応則によってQ行列を適切に調整する新しい手法を提案している。

第五章では、同様に超小型衛星では機器間の干渉が顕著になることから、磁気センサに一時的に大きなノイズが加わりうると想定し、このような誤差に対する感度を低減した”Robust UKF”が提案されている。具体的には、センサノイズの強度を示すUKF中のパラメータ行列Rに対して係数行列を導入し、その値を適応則によって動的に調整することで、一時的に加わる大きなノイズの影響を低減する手法となっている。

第六章では、UKFを元にした衛星残留磁気モーメントの推定手法が新たに提案されている。残留磁気モーメントにより生じる外乱トルクは、一般に、衛星が小型・軽量となるに従って支配的な外乱要因となるため、超小型衛星の姿勢制御においては、残留磁気モーメントの推定は特に重要である。軌道上でこれを推定する手法は過去にも提案があるが、第六章では新たに、時変の残留磁気モーメントまで推定可能な手法が提案されている。特に、周辺機器の電源ON/OFFに伴ってステップ状に変動するような残留磁気モーメントを想定した上で、素早い推定性能を得るために、残留磁気モーメントの急変を検出し、これに応じてP行列を適応的に調整する新たな手法が提案されている。

第七章では、第四章から第六章で提案された個別の適応則を、ひとつのUKFフィルタとして統合する手法が提案されている。統合されたフィルタは、磁気センサのバイアス誤差や瞬間的なノイズなどに対してロバストで、衛星姿勢と同時に残留磁気モーメントまで推定できる特徴を有している。第七章では、過去の小型衛星における実際のセンサパラメータなどに基づく現実的な評価ケースを設定した上で、この統合型フィルタの性能が定量的に論証されている。評価結果は、従来の超小型衛星では実現が難しかった高い姿勢決定性能が実際に得られることを示すものであった。

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　このように、本論文はカルマンフィルタ（UKF）の適応化という提案を理論的な基礎とした上で、これを超小型衛星の姿勢制御に応用した場合に得られる効果について具体的かつ現実的な評価を行っており、理論的な側面でも、また今後の実際の超小型衛星開発に対しても、大きく貢献するものである。従って、申請された論文は博士論文としてふさわしいものであると判断して、合格と判定した。