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REVIEW ON ATTITUDE ESTMATION ALGORITHM OF ATTITUDE DETERMINATION SYSTEM

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ABSTRACT

Attitude Determination System (ADS) is a process to determine the attitude of a satellite by using on board sensors and attitude estimation algorithms to determine the orientation of the satellite which is relative to inertial reference frame such as Earth reference frame. The ADS is consists of an attitude sensor which provides the attitude and orbital position of the satellite to the Attitude Control System (ACS). This paper presents a comprehensive review of attitude estimation algorithms in an ADS and its application in satellite control sub-systems to increase accuracy, robustness and efficiency of attitude estimation. Deterministic methods such as QUEST, FOAM, and TRIAD, recursive method (utilizing algorithm) such as EKF, UKF, PF and several improvement algorithms are discussed. ADS sensors including sun sensor, magnetometer, star tracker, earth horizon and gyro are also discussed. Several suggestions to improve the estimation algorithm of ADS also discussed in this paper.

Keywords: attitude determination system (ADS), attitude estimation algorithm, recursive, deterministic.

INRODUCTION

In satellite systems, Attitude Determination Control System (ADCS) is one of the satellite sub-systems which play an important role to stabilize the satellite systems in carrying out its mission during its entire mission. The ADCS consists of two parts; the Attitude Control System (ACS) which controls and stabilizes the satellite system, and the Attitude Determination System (ADS) which measures the vector of inertial reference and computes the orientation of satellite relative to the Earth [1-6]. The measurement vector of inertial reference and computation orientation will be sent to ACS which is used as references to make a correction during the satellite is on the orbit as shown in Figure-1.

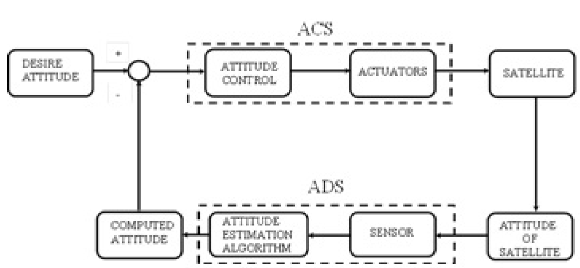

Figure-1. Block diagram of ADCS [4].

The attitude of the satellite is represented by the angular position (Euler angle, Quaternion) and angular velocity of satellite body-fixed coordinate frame which is relative to the inertial reference frame. However, the accuracy of attitude position and angular velocity are always affected by several errors such as sensor noise, bias, and misalignment. Therefore, accuracy in prediction will effects the attitude estimation [7-9]. Therefore, attitude estimation is very important. Attitude estimation is basic nonlinear estimation problem in which the objects of investigation in the system consist of noisy nonlinear state equation and corresponding measurement equation.

Attitude estimation can be determined by deterministic approach or by recursive method (utilizing algorithm) which combines dynamics and/or kinematic model with the sensor. The three axis deterministic methods such as TRIAD (algebraic method), Quaternion Estimator (QUEST) and Fast Optimal Attitude Matrix (FOAM) require measurement of at least two vectors to determine the attitude (direction-cosine) matrix. The advantage of the QUEST and FOAM is the attitude of spacecraft can be estimated by using measurement of more than two vectors. However, all deterministic methods can fail when only one measurement vector is available (e.g. magnetometer). Recursive method or utilizing algorithm utilizes a dynamics model and subsequently can estimates the attitude of spacecraft using measurement of a single reference vector. Although all spacecrafts in used today have at least two on-board attitude sensors, estimation techniques can be used to determine the attitude during anomalous period, such as solar eclipse and/or sensor co-alignment [10].

The attitude position of a satellite such as roll, pitch, yaw and angular velocity is commonly analyzed. Most studies use the deterministic method, recursive method (utilizing algorithm) and several improvement

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algorithm from both methods. Sun sensors, magnetometers, star trackers, earth horizons and gyro are often used as attitude sensors. A review was conducted to determine accuracy, robustness and efficiency of attitude estimation in satellite missions and to minimize uncertain signals from internal or external disturbances when satellite is on the orbit.

ADS SENSOR

The attitude of satellite is measured by using ADS sensor to get the accuracy of attitude estimation [11]. ADS sensors can by divided into reference sensor and inertial reference sensor. Reference sensor comprises of sun sensor, magnetometer, star tracker, and horizon scanner which provides vector observation. Reference sensor usually consists of noisy vector measurement at low frequency [12]. Reference sensor commonly needs two or more sensors to overcome the problem of inability to observe. Inertial sensor such as gyroscope can improves the measurement which provides angular rate relative to the inertial frame. However, the disadvantages of inertial sensor are the accuracy of the sensor is limited by noise and bias error and cannot work alone during unbounded error in attitude estimation over time [11]. Figure-2 shows the example of ADS sensor which is used by RazakSAT.

Figure-2. (a) Sun Sensor (b) Magnetometer (c) Gyroscopes.

Table-1. Type of ADS sensor – Advantages and disadvantages [6][11][12][13].

Sensor Type	Advantages	Disadvantages
Star Tracker	High accuracy	Dependent on star identification.
		Lost in space function. - Expensive.
		Heavy and large.
		High power consumption.
		Sensitive to spin rates.
		No output when pointing towards the sun
GPS antenna array	Resistant against spin rates	Expensive
	Provide position, velocity and time	Large antenna array setup
		High power consumption
Sun Sensor	Simple sensor.	Disturbed by Earth Albedo.
	Low power	No output during eclipse.
	Analog sun sensors are cheap.	Digital 2-axis sun sensors are expensive
Horizon Sensor	View of Earth always available	Accuracy affected by the sun and moon
	Simple sensor.	Not as widely used as sun sensors.
Magnetometer	Very cheap	Only applicable in LEO.
	Very small	Coarse accuracy
	Always availabe	Magnetic field not completly known
	Simple sensor and always available	Affected by on-board electronics.
Gyroscopes	Low power	The size too big for Pico satellite

ATTITUDE ESTIMATION ALGORITHM

Attitude estimation algorithm method has been studied, developed and applied in many satellite projects around the world. The NCube project [14], the EKF is used to determine the initial state and deviation from predicted trajectory. Based on [15], modeling of the amount of energy reflected from the earth is necessary to obtain really useful information from the crude solar cell

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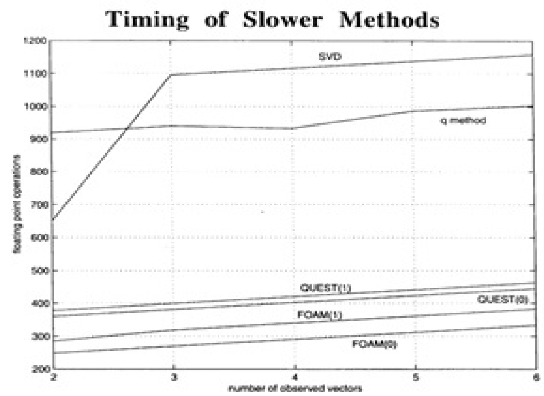
sun sensor. Method used in [16] is to implemented and improve the EKF by using microcontroller. As a result, the implementation of sensor communication has not been fully completed, and suggestion from [16] is to use light dependent resistors which can be implemented with few changes to the system.

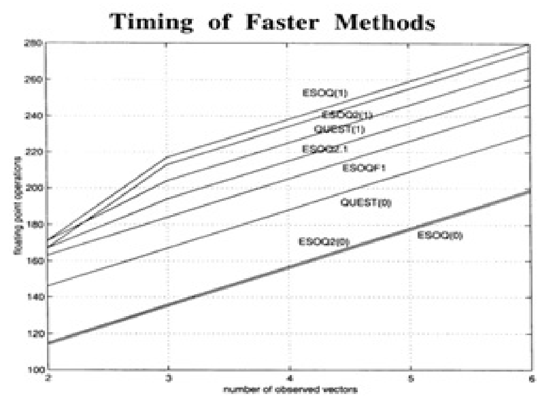
Earth albedo model was developed by [17] to improve the accuracy of sun vector from 5.9 deg to 3.82 deg RMS. The results from [17] show that three-axis attitude determination can only be determined from the sun sensor, by applying earth albedo and enhancing sun sensor current model directly into the Unscented Kalman Filter (UKF). EKF is recommended over the UKF in term of computation requirement of measurement model. UKF can use sun sensor to determine three-axis attitude. Meanwhile, a design for low cost attitude determination using EKF due earth albedo occurring is described in [18]. From [18], EKF is robust to unknown disturbance torques (up to 10-5 Nm), inertial uncertainties in the moment of inertial (5% error), modeling error and measurement noise. The Sliding Mode Observer (SMO) was conducted to compare with EKF during eclipse and limited view [19].

The results show that SMO response is fast, and its estimation error is less than of EKF, besides its robustness to the noises. The performance of SMO exceeds EKF for large initialization error. These characteristics make the SMO is preferable and more attractive than EKF. An analysis was conducted to analyze the accuracy of point to point data and execution time for small satellite [20]. The most robust estimators minimizing Wahba's loss function are Davenport's Q method and Single Value Decomposition (SVD) method.

Robustness is only an issue for measurements with widely differing accuracies, so the fastest algorithms, QUEST, Estimator of the Optimal Quaternion (ESOQ), and ESOQ2, are well suited to star sensor applications as shown in Figure-3 (a) and (b). An evaluation of different algorithms regarding accuracy, speed and their output format in case two observation is shown in Table-2 [5]. Previous research such as described in [21] stated that UKF is more robust than EKF under realistic initial attitude-error condition by using Magnetometer, Gyroscopes as a sensor and EKF and UKF attitude estimation algorithms. Each approach is respected to attitude and angular rate estimation accuracy, convergence rate under uncertain initial condition and sensitivity to disturbances for gauging the performance by using accelerometer, magnetometer and Regularized PF, EKF, UKF as stated in [22].



(a)



(b)

Figure-3. (a) Timing of Slower Method (b) Timing of Faster Method.

Table-2. Evaluation of different algorithm regarding accuracy, speed and output format [5].

Algorithm	Accuracy	Speed	Output Format
TRIAD	Low	Very High(120 flops)	Rotation Matrix
q-Method	High	Low (> 900 flops)	Quaternion
SVD	High	Low (< 650 flops)	Rotation Matrix
QUEST	Low	High (< 400 flops)	Quaternion
FOAM	Medium	High (< 300 flops)	Quaternion
ESOQ/ESOQ 1	Low	High (< 400 flops)	Quaternion
ESOQ2	Low	High (< 200 flops)	Quaternion

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New filter (SOAR) was developed by [23], using gyroscopes and star sensor. SOAR Filter can only accept two types of measurements: unit vector measurement and complete attitude estimation [23]. The modified MMAE algorithm was proposed to calibrate the low frequency error in the satellite attitude determination system [24]. Deterministic approach produced better performance than recursive during not in eclipse by comparing QUEST, EKF and using sun sensor and magnetometer [25].

By switching continuously from QUEST to EKF during eclipse will produces insignificant effect on satellite dynamics [26]. Beside that, estimated QUEST and EKF for r = 0.28 deg, p = 0.28 deg, y = 4.8 deg and velocity x and z is acceptable. Velocity of y needs calculation. Rao-Blackwellized particle filter can reduces the computational load, provides an attractive convergence rate, and successfully preserves the performance of the standard particle filter obtained for three-axis attitude estimation [27]. Simulation results verified that the method improves robustness and environmental of attitude determination algorithm under the condition of system with large model error and colored noise using nonlinear predictive and unscented particle filter [28]. The convergence rate and determination accuracy were improved by using EKF, PF, Cubature Kalman Particle filter and Gyro/Star sensor as a sensor as shown by [29]. Robust Kalman filtering more reasonable in case of measurement faults and simulation under error measurement as obtained by [30] by using UKF, EKF, RUKF and REKF. TLE was used by [31] for initial orbital parameters and TRIAD algorithm for initial state values for the EKF operation makes the whole process of attitude estimation closed and independent. All estimation algorithms in this section are shown in Table-3.

Table-3. Summary of estimation algorithms and sensors used.

Ref.	Sensor Used						Estimation Algorithm																									
	Sun	Star	Magnetometer	Gyroscope	Horizon	Accelerometer	EKF	UKF	PF	REKF	RUKF	MEKF	RBPF	NPUKF	NPUPF	MRPs	CKPF	RPF	TRIAD	q-davenport	SOAR	SVD	ESOQ1	ESOQ2	QUEST	MME	SMO	REQEUST	Optimal REQUEST	SBO	FOAM	MMAE
[5]	√		√																			√										
[7]				√			√																				√					
[8]	√		√				√																									
[9]	√		√				√																		√							
[10]	√	√	√																√							√						
[11]	√		√	√			√	√														√										
[12]	√						√																									
[14]	√		√				√																									
[15]	√		√				√																									
[16]	√		√				√																									
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[21]			√	√			√	√																								
[22]			√			√	√	√										√														
[23]		√		√								√									√				√			√	√			
[24]		√		√			√																									√
[25]	√		√				√																		√							
[26]	√		√				√																		√							
[27]			√			√	√	√					√																			
[28]			√			√								√	√	√																
[29]		√		√			√		√								√															
[30]			√				√	√		√	√																					
[31]	√		√	√			√												√													

CONCLUSIONS

This paper presents attitude estimation methods of ADS used on current satellite research. Accuracy, robustness and computation time (processing speed) are very important elements in attitude estimation. Sun sensor and magnetometer are usually utilized in ADS of satellite because mass limitation and power consumption (mini satellite) have forced researchers to use lightweight sensor, small and low power consumption. The star tracker is the most accurate sensor compared with sun sensor, magnetometer, gyroscopes, scan horizon and accelerometer. Nevertheless, a star tracker cannot be applied in a Pico satellite especially because of its weight and cost. There are estimation methods and sensors used in ADS. Two algorithm methods commonly used are deterministic method and recursive method in estimating the accuracy of ADS. Based on Table-2 and Figure-3, SVD and q-Method are good algorithms in term of accuracy regarding to minimizing Wahba's problem, but computation time is too slow compared with other estimations. EKF, UK, PF are conventional estimations commonly used in ADS estimation. EKF is one of estimation method usually applied in many satellite researchers. However, recently UKF, RUKF, REKF are more robust compared with EKF by using magnetometer.

The REKF, RPF, RUKF are from modified algorithms of EKF, PF, UKF and are more robust than conventional estimations. For the eclipse phenomena, the satellite needs

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deterministic method that operates during no eclipse and recursive method during eclipse phase. Accuracy of EKF during earth albedo phase can be improved by earth albedo modeling as done by [17] and [18]. Other estimations proposed to attitude estimation improve the accuracy and computation burden, but no real data are available for comparison.

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